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Final Disposal of Spent Nuclear Fuel in Finnish Bedrock — Romuvaara Site Report

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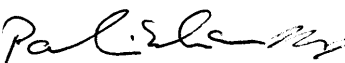
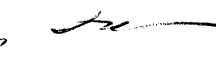
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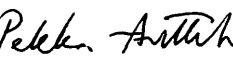

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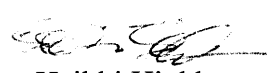
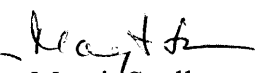
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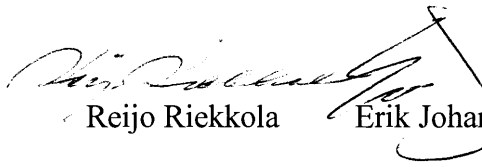
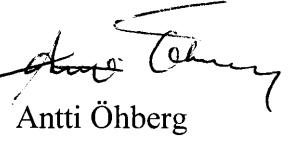
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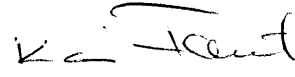
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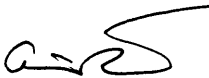
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Tiivistelmä – Abstract Posiva Oy is studying the Finnish bedrock for the geological disposal of spent nuclear fuel. The study is based on the site selection research programme started originally in 1983. The programme is in accordance with the decision in principle by the Council of State in 1983 and aims at the selection of one site in 2000. Four sites, Hästholmen in Loviisa, Kivetty in Äänekoski, Olkiluoto in Eurajoki and Romuvaara in Kuhmo, have been studied in detail. This report summarises the results of the site investigations carried out at Romuvaara. The bedrock of Romuvaara belongs to the Archean basement complex, whose oldest parts date back over 2800 million years. The bedrock consists mainly of migmatitic banded gneisses (tonalite, leucotonalite and mica gneiss), which are cut by granodiorite and metadiabase dykes. The rocks, excluding the metadiabase, have undergone a polyphase Archean deformation. Altogether 31 bedrock “structures” (R-structures) have been modelled at the investigation site, most of them representing steeply dipping fracture zones. The rock mass between the fracture zones represents what is termed “intact rock”, which is typically hard, unweathered and sparsely fractured. The R-structures are generally hydraulically more conductive than the intact rock and their mean transmissivity is $1.6 \cdot 10^{-7} \text{ m}^2/\text{s}$. The corresponding mean of the hydraulic conductivity values for the intact rock measured using a 2 m packer interval is $8 \cdot 10^{-12} \text{ m/s}$, if a lognormal distribution for all measured values is assumed. A clear decrease in hydraulic conductivity with depth has been found, for both the R-structures and the intact rock. In addition, the hydraulically conductive fractures seem to be more frequent and their transmissivities higher in the uppermost 100 - 200 m of the bedrock than at greater depths. The groundwater of Romuvaara is classified as fresh water and the Total Dissolved Solids (TDS) and chloride contents increase with depth. The chemically most evolved groundwaters are found in borehole KR3 with a TDS value of 265 mg/l and a chloride content of 109 mg/l. Reducing conditions are expected to exist at depth, which are favourable in terms of low radionuclide solubility and slow canister corrosion. Potentially suitable bedrock blocks have been identified at the site for locating a repository for spent fuel in the depth range of 400 - 700 m. No significant geotechnical, hydrogeological and hydrogeochemical constraints have been found to its construction, although it is recommended that certain fracture zones should be avoided when locating the deposition tunnels and disposal holes.	
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Tiivistelmä – Abstract Posiva Oy tekee Olkiluodon ja Loviisan ydinvoimalaitosten käytetyn polttoaineen loppusijoitusta varten kallioperätutkimuksia, jotka tähtäävät lopullisen sijoituspaikan valintaan vuonna 2000. Yksityiskohtaisia tutkimuksia on suoritettu neljällä paikkakunnalla; Kuhmon Romuvaarassa, Äänekosken Kivetyssä, Eurajoen Olkiluodossa ja Loviisan Hästholmenilla. Tässä raportissa esitetään yhteenveto Kuhmon Romuvaarassa tehdyistä tutkimuksista ja niiden tuloksista. Romuvaaran alueen kallioperä on osa arkeista pohjakompleksimuodostumaa, jonka vanhemmat osat ovat iältään yli 2800 miljoonaa vuotta. Tutkimusalueen kivilajit ovat enimmäkseen migmaattisia ja raitaisia tonaliitti-, leukotonaliitti- ja kiillegneissejä. Näitä kivilajeja leikkaavat nuoremmat granodioriitti- ja metadiabaasisuonet. Metadiabaasia lukuunottamatta kivilajit ovat läpikäyneet monivaiheisen arkeisen deformaation. Tutkimusalueen kallioperästä on mallinnettu yhteensä 31 pääosin jyrkkäkaateista rako- tai rikkonaisuusvyöhykettä. Rikkonaisuusvyöhykkeiden välinen kallio on enimmäkseen kiinteää, rapautumatonta ja harvakseltaan rakoillutta. Se saattaa kuitenkin sisältää myös yksittäisiä rikkonaisia vyöhykkeitä, joita ei ole luokiteltu kalliomallin rakenteiksi. Mallinnetut rikkonaisuusrakenteet ovat yleensä merkittävästi vettäjohtavampia kuin niiden välinen ehjä kallioperä. Rakenteiden transmissiviteetti on keskimäärin $1,6 \cdot 10^{-7}$ m²/s. Vastaava ehyessä kalliossa 2 m tulppaväleillä mitattu vedenjohtavuusarvojen keskiarvo on $8 \cdot 10^{-12}$ m/s, mikäli oletetaan kaikkien mittausarvojen jakautuneen lognormaalisti. Sekä rakenteiden että ehjän kallion vedenjohtavuus pienenee syvyyden kasvaessa, niinikään vettäjohtavia avoimia rakoja esiintyy runsaammin kallion pintaosassa noin 100 - 200 metrin syvyydelle. Romuvaaran kallioperän pohjavesi on luokiteltu kauttaaltaan makeaksi, vaikkakin liuenneiden suolojen kokonaismäärä, TDS (Total Dissolved Solids) sekä kloridin määrä kasvaa syvyyden mukana. Kemiallisesti kehittyneintä pohjavettä on tavattu kairanreiässä KR3, missä TDS-arvo on 265 mg/l ja kloridin määrä 109 mg/l. Loppusijoitussyvyydellä pohjavesiolosuhteet ovat pelkistäviä, mikä hidastaa radionuklidien liukenemista ja jätekapselin korroosiota. Romuvaaran kallioperästä, noin syvyydeltä 400 - 700 m on paikannettu kalliolohkoja, jotka soveltuvat hyvin loppusijoitustilojen rakentamiseen. Kallioperästä ei ole tavattu sellaisia ominaisuuksia, jotka estäisivät loppusijoitustilojen rakentamisen tavanomaisin kalliorakennusmenetelmin, joskin tilojen sijoittelussa on suositeltavaa välttää tiettyjä rikkonaisuusrakenteita.	
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PREFACE

Posiva established a site evaluation project PARVI in 1997 for summarising, the investigations conducted at the four investigation sites for the deep disposal of spent fuel. The project was set up with the view completing the site selection research programme commissioned and for assessing the safety of the proposed final disposal system. The current report summarising the site conditions at Romuvaara has been prepared by a group of authors from several organisations and the work has been supervised by the PARVI project led by Aimo Hautojärvi. The authors of this report wish to thank them and all their other colleagues at Posiva and at the other investigation institutes, universities and consulting companies who participated in the preparation of this report by correcting and commenting on the various drafts. The comments by Petteri Pitkänen and Ari Luukkonen of VTT Communities and Infrastructure, and Paula Ruotsalainen and Eero Heikkinen of Fintact Oy have been especially important in this regard.

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1 INTRODUCTION

In Finland, two companies utilise nuclear energy to generate electric power, Teollisuuden Voima Oy (TVO) at the Olkiluoto Nuclear Power Plant (NPP) (2 x 840 MWe BWR) and Imatran Voima Oy (IVO) (at present Fortum Power and Heat Oy) at the Loviisa NPP (2 x 488 MWe PWR). TVO and IVO have already at an early stage prepared themselves to take care of all activities associated with the management of the nuclear waste they produce and also collect funds necessary for the future activities. Both companies have committed themselves to a policy which enhances the responsibility for the environment. One part of this policy is the development of solutions for safe nuclear waste management. Practical results of this are the interim storage facilities for spent fuel and the underground repositories for final disposal of low- and intermediate-level operating waste at Olkiluoto and at Hästholmen. Based on the current law, the Nuclear Energy Act, all nuclear waste generated as a result of electricity production shall be disposed of in Finland.

The power plants at Olkiluoto and Hästholmen were built during 1970s. The return of the spent fuel from the Loviisa power plant back to Soviet Union (later Russian Federation) was included in the original agreement. The planning on the spent fuel management of Olkiluoto power plant was started during the construction of the power plant. The work included studies on the availability of reprocessing services, as well as, planning of the interim storage capacity at the power plant area. The preparatory work for nuclear waste management resulted in 1978 in a report (Imatran Voima Oy & Teollisuuden Voima Oy 1978), drafted jointly by TVO and IVO, in which the power companies assessed that nuclear waste management can safely be implemented as a whole in Finland. For the coordination of the future work TVO and IVO established the Nuclear Waste Commission of Finnish Power Companies (YJT).

For the final disposal of spent nuclear fuel TVO and IVO founded in 1995 a jointly owned company, Posiva Oy. Posiva is in charge for the final disposal of spent nuclear fuel. The total amount of spent fuel to be disposed in the repository is currently estimated to be about 2 600 tU.

The studies for the final disposal of spent fuel were started already in the early 1980s'. The general guidelines and schedules for implementing the work, especially for the site selection of the deep repository, were set forth in the Council of State's decision in principle in 1983. According to the decision the research and development shall make progress so that by the end of 2000 there has been selected and characterised a site which can be used for the construction of the deep repository. The content of this decision has been included later in the decisions of the Ministry of Trade and Industry, in charge for the supervision concerning the implementation of the nuclear waste management.

The site selection research programme has progressed in a good compliance with the Council of States's decision. After screening of the whole country in 1983 - 1985 a great number of areas were identified for further investigations. In parallel, technical plans for encapsulation and final disposal of spent fuel were developed and safety studies were carried out. Five areas, Kivetty in Äänekoski, Olkiluoto in Eurajoki, Romuvaara in Kuhmo, Syyry in Sievi and Veitsivaara in Hyrynsalmi (Fig. 2. 1-1), were selected for preliminary

site characterisation to be performed over the period from 1987 to 1992. The results of these investigations were reported and presented to the authorities in 1992 (Teollisuuden Voima Oy 1992a). The TVO-92 safety analysis showed that the proposed safety requirements could be met at all the five sites investigated (Vieno et al. 1992). Kivetty, Olkiluoto and Romuvaara were selected for further characterisation (Fig. 1-1).

The first stage of the detailed site characterisation programme was carried out over the period 1993 - 1996, and the results presented in an interim report in 1996 (Posiva Oy 1996a). At the same time site-specific technical plans (Posiva Oy 1996b), as well as the safety assessment, TILA-96 (Vieno & Nordman 1996), were presented to the authorities. In addition to these three sites, Hästholmen in Loviisa (Fig. 1-1) was included in the site selection research programme in the beginning of 1997.

The research programme for 1997 - 2000 is focussed around the need to complete the site selection by the end of 2000. The current work is divided into two parts, of which the PARVI project includes the site evaluation of the four candidates and site-specific safety assessment of final disposal. The other project is the work organised to carry out the Environmental Impact Assessment (EIA) process according to the law and aiming at the compilation of the EIS report (Environmental Impact Statement).

The objective of the PARVI project is to summarise the characterisation conducted at the sites, with a view to selecting the final disposal site and assessing the safety of the suggested final disposal system. Studies under the project have supplemented the detailed site characterisation programme carried out earlier at Kivetty, Olkiluoto and Romuvaara. At Hästholmen in Loviisa, investigations have been performed with a view to enabling the suitability of this site for final disposal to be assessed in a similar manner to the other sites. The project involves geological, geochemical, geophysical and hydrogeological investigations. In addition, the quality and quantity of rock potentially suitable for final disposal at each study site is being assessed.

Posiva aims at the selection of a disposal site by the end of 2000. After the selection the purpose is to develop an underground characterisation facility at the site and carry out confirmatory characterisation for ten year's time. The construction of the encapsulation facility and the deep underground repository is planned to start around 2010, so that final disposal could commence in 2020. After emplacement of spent fuel canisters, it is planned for the repository to be sealed around 2050. The final time schedule for the closure of the repository is very dependent on the operating times for the present or possible future nuclear power plants.

According to the Nuclear Energy Act before any significant nuclear facility can be built in Finland, a Council of State's decision in principle is required. The decision, however, does not grant a license for a construction or operation of the facility in question, the construction permit and operation license have to be applied separately afterwards. The purpose of the decision is to judge whether "the facility is in line with the overall good of society". As part of this decision the Radiation and Nuclear Safety Authority (STUK) have to make a preliminary statement on the safety of the facility and the candidate municipality (or municipalities if several candidate sites exist) must state their acceptance of siting the

facility. A positive decision can only be made by the Council of State if both STUK's and the municipalities' statements are positive, and this decision has still to be ratified by the Parliament. Posiva aims to submit the application for the Council of State's decision in principle in 1999. This decision has been found essential in connection of the site selection.

This report on the Romuvaara site in Kuhmo summarises the geological, geochemical and hydrogeological characteristics of the site based on the large amount of data and material gathered since 1987. The report also presents the updated bedrock models, indicates which parts of the rock mass are believed to show most promise for locating a repository and discusses the general principles associated with the design and construction of the repository. The report concludes by discussing the particular features of the site and its overall suitability.

The report is designed to be used as background information for the environmental impact assessment, the technical design of the repository and the site evaluation and safety assessment TILA-99 (Vieno & Nordman 1999). The groundwater flow and transport modelling for the Romuvaara site will be reported separately (Kattilakoski & Koskinen 1999 and Poteri & Laitinen 1999). The hydrogeochemical evolution of the groundwater in the area has been reported by Pitkänen et al. (1996a).



Figure 1-1. Investigation sites for final disposal of spent nuclear fuel in Finland. Sites for detailed investigations are bold faced.

2 SITE CHARACTERISATION

2.1 Site Selection Research Programme

The power companies started the studies on bedrock properties and their investigation in Finland in the late 1970s. The initial phase consisted of the mapping and examination of general bedrock features that would have to be taken into account in connection with final disposal (Niini et al. 1982) and a description of the macrostructure of the bedrock of Finland (Vuorela & Hakkarainen 1982). The essential elements of an long-term programme for selecting a disposal site were set out in 1982 (Äikäs & Laine 1982) in connection of publishing the first feasibility study on final disposal of spent fuel in 1982 (Teollisuuden Voima Oy 1982).

In November 1983, the Council of State issued its decision on the nuclear waste management which established the objectives and timetable for the site selection research in Finland. The general principle is that the site should be selected by the end of the year 2000 as a result of a stepwise programme of bedrock investigations, involving three stages according to the following timetable:

- **stage 1:** 1983 - 1985 **site identification survey**, to select sites for preliminary characterisation
- **stage 2:** 1986 - 1992 **preliminary site characterisation** in a number of potentially suitable areas
- **stage 3:** 1993 - 2000 **detailed site characterisation** in a small number of the above areas, which are believed, on the basis of the preliminary investigations, to be the most suitable (Teollisuuden Voima Oy 1992a).

The principal aim of the work in the first stage was to identify areas suitable for fieldwork, and in which the bedrock was believed to provide sufficiently good conditions for the safe disposal of spent fuel. The first phase in this work consisted of a survey of the main bedrock units and structures in Finland, with reference to the geological factors generally accepted as relevant to final disposal. The conclusion of this stage of the work was that it was indeed possible to select potential disposal sites in Finland by geological means (Salmi et al. 1985). A flow chart for the site selection process and the principle of the site identification survey in locating suitable bedrock blocks is presented in Figure 2.1-1. In parallel with the nationwide screening of potential candidate sites, a separate feasibility study on the island of Olkiluoto and its surrounding area (Hakkarainen 1985, Kuivamäki & Vuorela 1985) was carried out because of its unique position as the location of the nuclear power plant. According to the study a sufficiently large block of bedrock potentially suitable for housing a repository was located in the island of Olkiluoto.

At the end of 1985 TVO presented the results of the first stage, site identification survey, to the Ministry of Trade and Industry for the review. A great number of areas were judged suitable when considering the selection of the areas for preliminary site characterisation (Fig. 2.1-1). During the spring of 1987 TVO selected five sites for the second stage, preliminary site characterisation, to be carried out between 1987 and 1992. The sites, shown in Figure 2.1-1, were Romuvaara in Kuhmo, Veitsivaara in Hyrynsalmi, Kivetty in

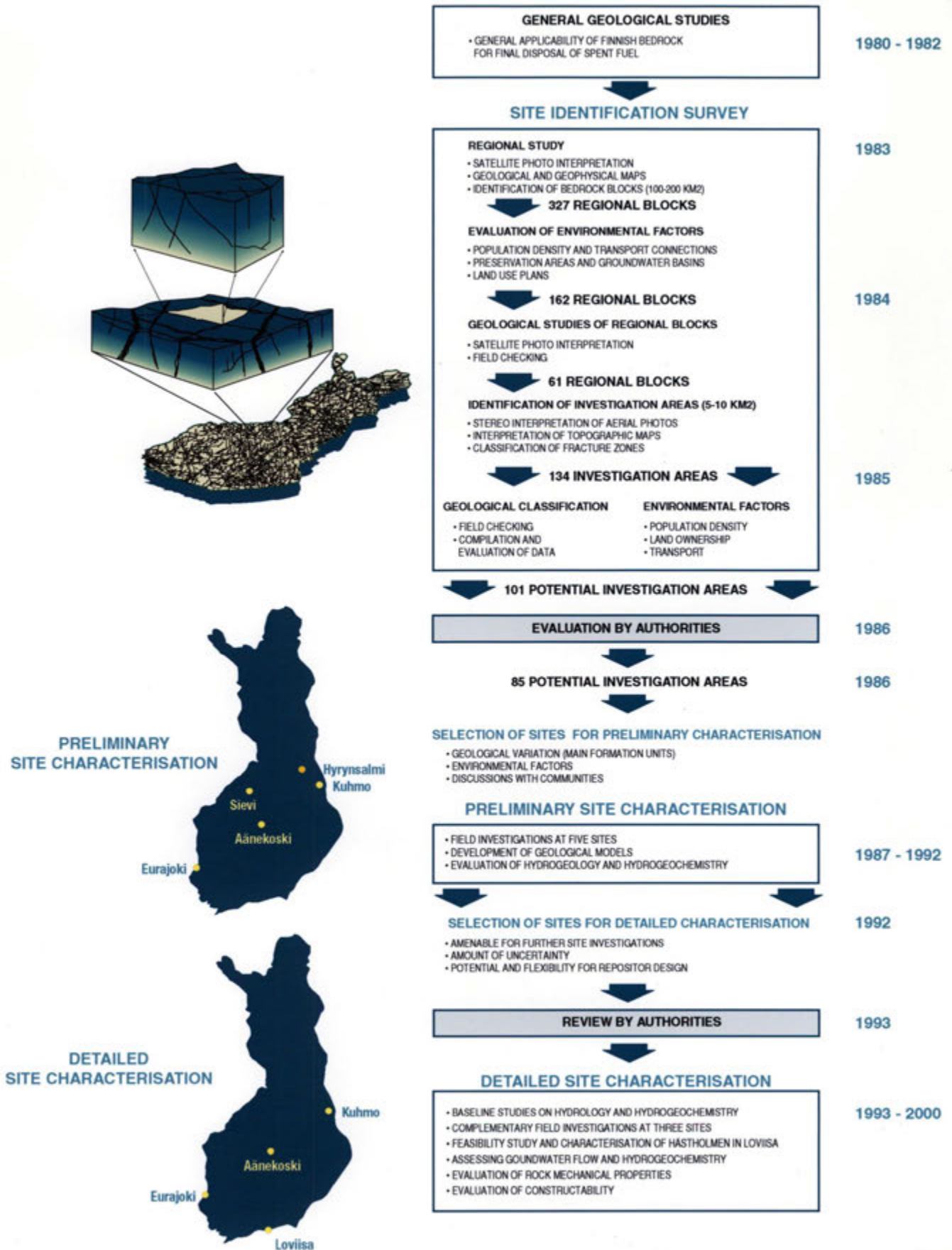


Figure 2.1-1. The progress of site selection process.

Äänekoski, Syyry in Sievi and Olkiluoto in Eurajoki (Teollisuuden Voima Oy 1987). The bedrock block of Romuvaara is shown in Figure 2.1-2 as an example of an area located during the site identification survey. Figure 2.1-3 shows an aerial view of a typical example from the Romuvaara investigation area. The five sites were characterised by means of an extensive investigation programme with closely-related modelling, and were reported to the Ministry of Trade and Industry in 1992 (Teollisuuden Voima Oy 1992a).

On the basis of the preliminary investigations, in 1992, TVO proposed to continue site characterisation at three sites: Romuvaara in Kuhmo, Kivetty in Äänekoski and Olkiluoto in Eurajoki. The reason for selecting these three sites was that there were fewer uncertainties in the bedrock models developed and the explorability of these sites was considered to be superior to the two other sites investigated (Teollisuuden Voima Oy 1992a).

A complementary study on the basic rock types of Finland and their potential to final disposal was carried out during 1991 - 1994 (Teollisuuden Voima Oy 1993a). An inventory of mafic plutonic rocks and basic volcanic rock types was made and the properties of the formations were evaluated. The study could not assess any properties of these rock types more favourable than the properties of the felsic granitic rocks under characterisation. Moreover, the rather sparse basic rock formations have very often associated ore mineralisations which can increase the possibility of adverse human intrusion in a form of ore exploration purposes.

Hästholmen, the island of the Loviisa Power Plant, was included by Posiva in the list of potentially suitable sites for disposal of spent nuclear fuel in the beginning of 1997 (Fig. 2.1-1). The decision was based on the feasibility study which was started by IVO in 1995 and completed by Posiva at the end of 1996 (Posiva Oy 1996c). According to the results of this study Hästholmen exhibited potential for the location of a repository for spent fuel and also has advantages similar to those of Olkiluoto, an existing nuclear technical infrastructure and less spent fuel to be transported, for example.

Detailed site characterisation is now under way at Romuvaara, Kivetty, Olkiluoto and Hästholmen, the main emphasis being at Hästholmen. The research programme, initiated in 1983, is approaching its completion and one of the candidates will be selected to host a deep repository by the end of 2000. The selection, however, is a rather complex process which comprise also the consideration of other criteria than geological. One important process affecting the selection process is the application of the Council of State's decision in principle during which the communities in question have to give their answers to the Council of State, as well as, the regulator STUK have to give the preliminary safety evaluation, too. Finally, the Finnish Parliament have to ratify the decision.

The selection of the site is to be followed by further confirmatory characterisation lasting approximately another ten years, so that the construction of the repository is planned to commence in 2010 with final disposal planned for 2020. The investigations would also continue in some form even during the construction and operation phases of the repository.

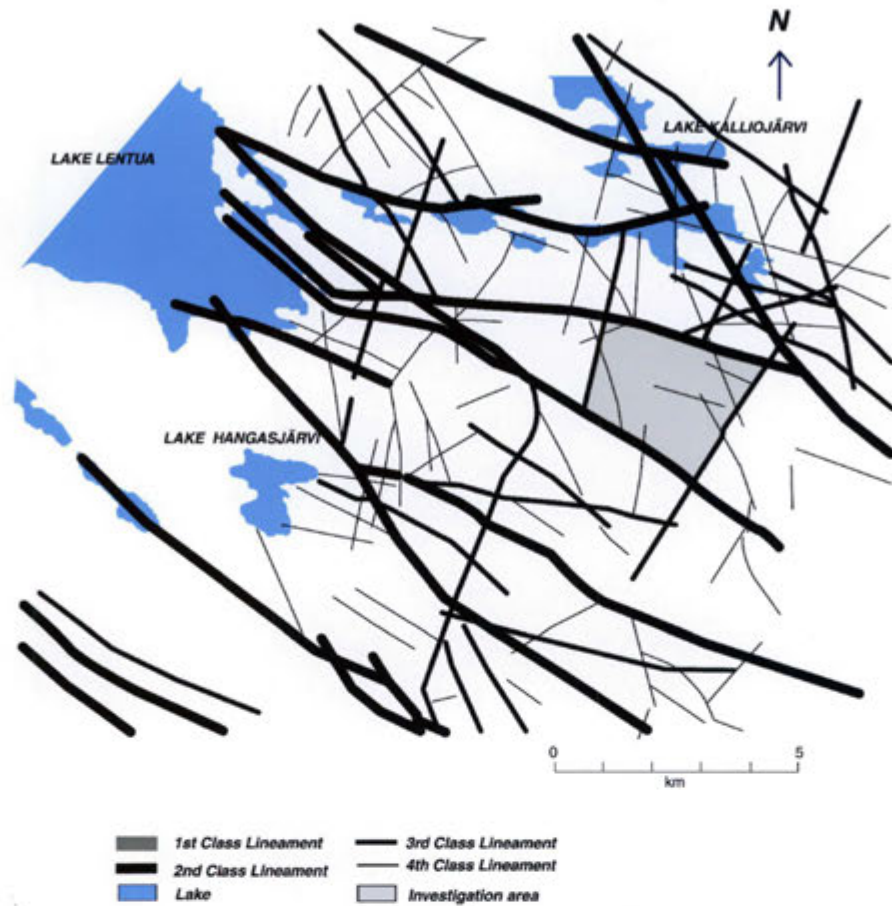


Figure 2.1-2. Bedrock structures determined for the Romuvaara area during the site identification survey of 1983 - 1985 (Salmi et al. 1985). The classification of the lineaments is presented at Table 2.5-1.

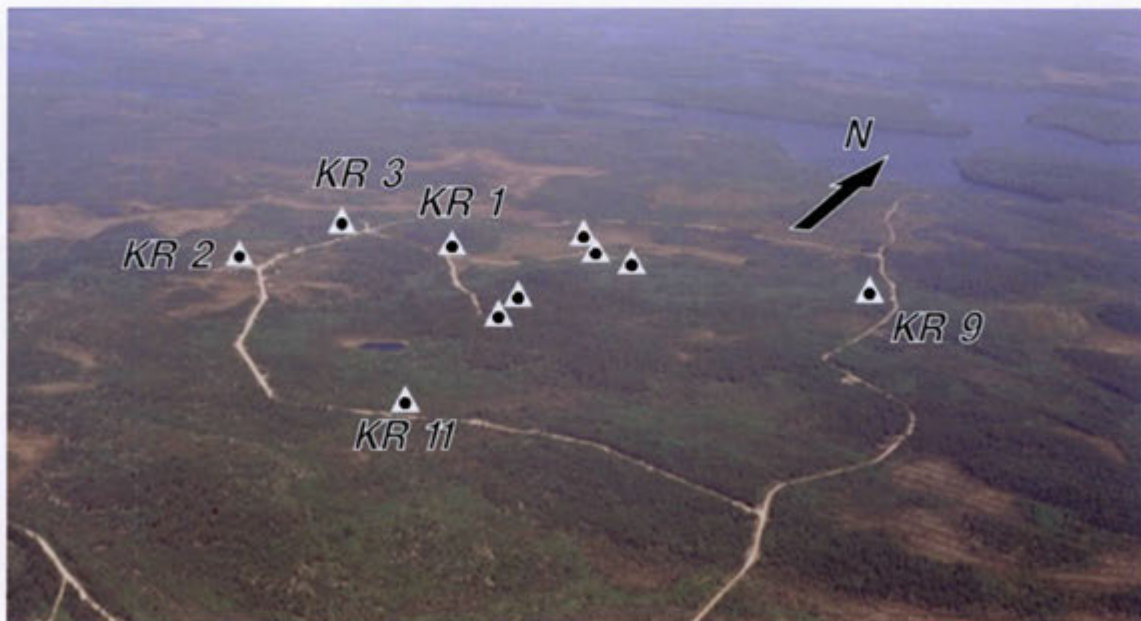


Figure 2.1-3. An aerial view of the Romuvaara investigation area from SE. KR1 to KR11 are boreholes drilled in the area. The distances between KR1 and KR11 is 1100 m and between KR2 and KR9 1300 m (see Fig. 2.2-4).

2.2 Preliminary Site Characterisation 1987 - 1992

2.2.1 Characterisation Programmes

Programmes for the site investigations associated with the final disposal of spent nuclear fuel were published in 1982 and 1985 (Äikäs & Laine 1982, Äikäs 1985). These programmes present the general aims of the proposed investigations, the investigation methods to be used and any development work required in site investigation techniques. Äikäs (1985) also laid down guidelines for the preliminary site investigations to be performed over the period 1987 - 1992.

In addition to the above, a specific fieldwork programme was drawn up for the Romuvaara site (Äikäs 1987), containing descriptions and timetables of the work to be carried out and specifying the content and extent of the investigations in each case.

The starting-point for the fieldwork was to assess whether the geological and hydrogeological environments of the site were in line with the assumptions made at the time of its selection. An important aspect of this assessment was to ascertain whether there were any unexpected features which could possibly jeopardize its use as a site for disposal purposes. Features in this category would include the presence of broad subhorizontal crush zones, ore deposits or unacceptable hydrogeochemical conditions.

The goal of the site investigation was thus to obtain information on the site to allow models to be constructed which could depict those features that were considered of relevance to the safety and feasibility for final disposal. The emphasis of the investigations was on determining the structure of the rock mass and the effect of this on the groundwater flow system at the site. The principal measures employed in examining the groundwater flow regime were:

- measurement of the hydraulic conductivity of the rock mass
- determination of the geometry and hydraulic parameters of the more transmissive zones (normally fracture zones and faults) and
- measurement and analyses of hydrogeochemical conditions.

The extent of the investigation area and the number and location of boreholes that were required were determined by the need to observe the major fracture zones and to provide means of reducing conceptual uncertainties regarding the site.

The main elements of the investigations and their general aims are presented below (Äikäs 1985, 1987). An outline of the investigations at Romuvaara is presented in Appendices 1 - 12, which contain lists of the investigations carried out, their timing, the methods used, their aims and references to the work reports (field work and interpretation) where more detailed information and the results concerning each individual investigation can be found.

1. Geological and geophysical investigations

- determination of the occurrence and composition of the rock types present both regionally and with depth,

- mapping of crush and fracture zones in terms of fracture indices, mapping of other discontinuities (Fig. 2.2-1), determination of their properties and development of conceptual models of these structures,
 - petrographic and mineralogical descriptions of the rock types and their geochemical properties in order to assess the interaction between rock mass and groundwater,
 - measurement of the state of stress in the rock mass and an evaluation of its significance,
 - determination of the general tectonic processes affecting the bedrock,
 - modelling of the bedrock (3D visualisation of structures and distribution of rock types),
 - placement of new boreholes.
2. Hydrogeological investigations
- measurement and mapping of the hydraulic properties of the rock mass, investigation of the hydraulic connectivity and the determination of hydraulic head distributions,
 - determination of the manner in which local groundwater movements in the rock mass are controlled by the geological structures (e.g. crush zones and contacts between different rock types) and their properties,
 - groundwater flow modelling,
 - the generation of initial data for use in a safety assessment of the site to include estimations of groundwater movement, hydrogeochemical conditions and radionuclide transport in the rock mass, and including potential effects of the proposed repository.
3. Hydrogeochemical investigations
- production of general data on the chemical composition of the groundwater and its variations areally and with depth,
 - production of data on the origin and residence time of the groundwater and changes in its composition.



Figure 2.2-1. All outcrops at the site were mapped during the preliminary investigation phase.

The overall aim of the preliminary site investigations was to allow the selection of two or three sites for more detailed evaluation. This, in turn, required the ability to generate a sufficient amount of suitably precise data for each site and the construction of models that could represent each site to an acceptable level, in order to enable fair evaluations to be made.

2.2.2 Preliminary Site Characterisation - Approaches and Extent

In order to produce specifications for the investigation programme, several studies were carried out prior to the start of the preliminary investigations on different methods that could be applied in the investigations (Anttila 1983, Lampén 1983, Rouhiainen 1984 and Äikäs 1984). These studies resulted among other things in an equipment development programme which is reported by Öhberg (1991). The general and local investigations performed at Romuvaara during site selection programme, i.e. pre-1987, are presented by Salmi et al. (1985).

The investigation programme at the site was divided into four consecutive phases, each of which had specific objectives (Äikäs 1985), the whole programme taking about three years and being completed within the period 1987 - 1992. The aim was to delimit the volume of the rock mass which had earlier been selected during the site selection programme (Salmi et al. 1985) more precisely and to determine:

- its structural setting,
- the distribution of rock types within it,
- the near-surface expression and location of crush and fracture zones.

The first phase of the preliminary investigations (Fig. 2.2-2) consisted of a general survey of the geology and hydrogeology of the area with geological field mapping, sampling of the exposed rock mass, airborne (low altitude airborne survey from helicopter, magnetic measurement, measurement of natural radiation, electromagnetic VLF and dipole source multifrequency measurements) and ground geophysical surveys (VLF magnetic and resistivity measurements, magnetic total field and vertical gradient, Fig. 2.2-3) and reference water sampling from surface waters and drilled domestic wells in the vicinity of the site. The above mentioned ground geophysical methods were used first as reconnaissance surveys on seven lines, in total 32 km across the site, then systematically on a line grid. For the reconnaissance survey ground penetrating radar was also used on lines totalling 20 km. Seismic refraction survey was used on four lines to locate and confirm suspected fracture zones in the mica gneissic bedrock. Gravimetric surveys on line grid were performed at Romuvaara to map rock type distributions and to detect possible weakly magnetised metadiabase dykes. The geophysical airborne and ground surveys conducted at Romuvaara are described briefly in Appendix 1.

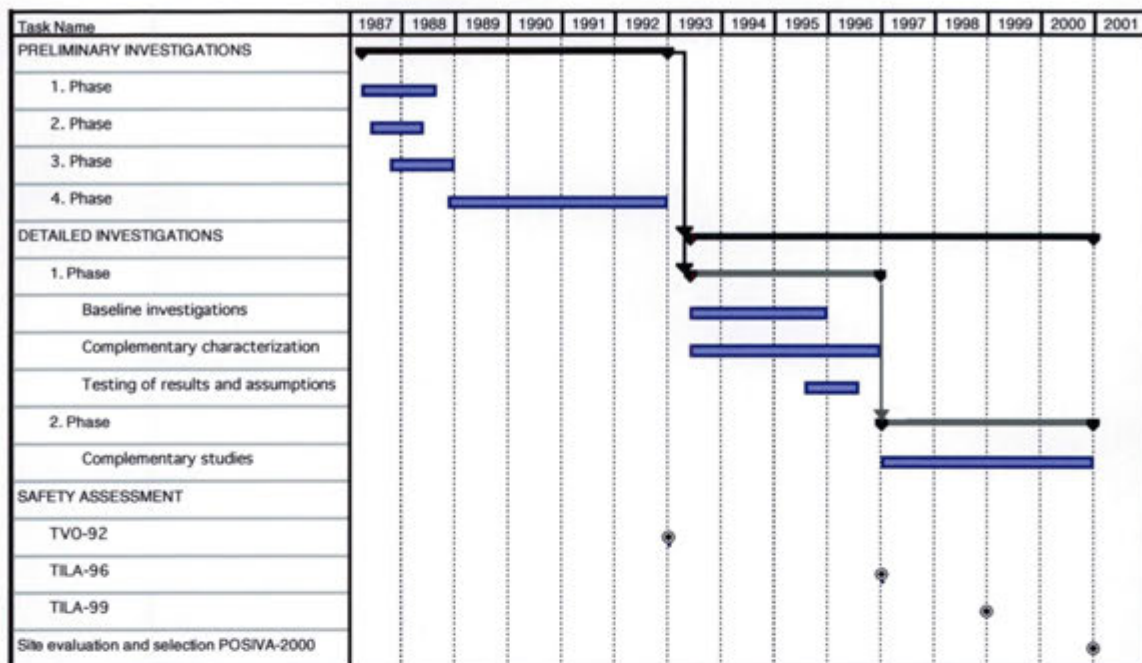


Figure 2.2-2. The programme of site investigations at Romuvaara illustrating their phased nature and the relationship of the investigations with the various safety assessments.

The second phase of these investigations (Fig. 2.2-2) involved the drilling of one approx. 1 000 m deep borehole KR1 with associated sampling and geophysical logging (Appendix 2). The aim was to acquire data on the rock types and fracturing at depth and to determine the position of any fracture zones encountered. The first deep borehole KR1 was located in a part of the area where existing data suggested that the rock mass was least fractured. The deep investigation boreholes, KR1 - KR11, and the most important shallow investigation boreholes on the site are shown in Figure 2.2-4. The drilling technique is described in Figure 2.2-5.

The third phase of the investigations (Fig. 2.2-2) consisted of hydrogeological and hydrological monitoring in boreholes and at the surface, the drilling of four additional boreholes KR2 - KR5 (Hinkkanen & Öhberg 1989) and borehole logging as well as VSP (Vertical Seismic Profiling) and radar investigations to characterise larger volume of the bedrock (Appendices 3 - 6) and supplementary ground geophysical surveys (Saksa et al. 1991), Appendix 1. An additional borehole (KR6) was also drilled for sampling purposes in order to examine the properties of a regional fracture zone more precisely (Appendix 7). Shallow boreholes and a network of 100 m deep multi-level piezometers (EP1 - EP7 in Figure 2.2-4) were used to measure hydraulic heads, and records were kept of precipitation, water equivalents of snow and runoff. Groundwater samples were taken from the deep boreholes to provide initial data for the evaluation of the hydrogeochemical conditions. Finally, information collected on specific structures, such as fracture zones, allowed a preliminary structural model of the site to be developed after interpretation of the field data.

Models of the site were compiled and used for describing the rock types, fractures, fracturing structures and hydrogeological conditions, the main emphasis being on the examination of bedrock fracturing and the related distribution of hydraulic conductivity.

Three-dimensional models were used for the classification of the various properties of the bedrock structures. The descriptive models (Saksa et al. 1992) were gathered together in a computerized system to facilitate illustration and storage. Modelling of fracture geometry in the preliminary site investigations for a nuclear waste repository is presented by Poteri & Taivassalo (1994).

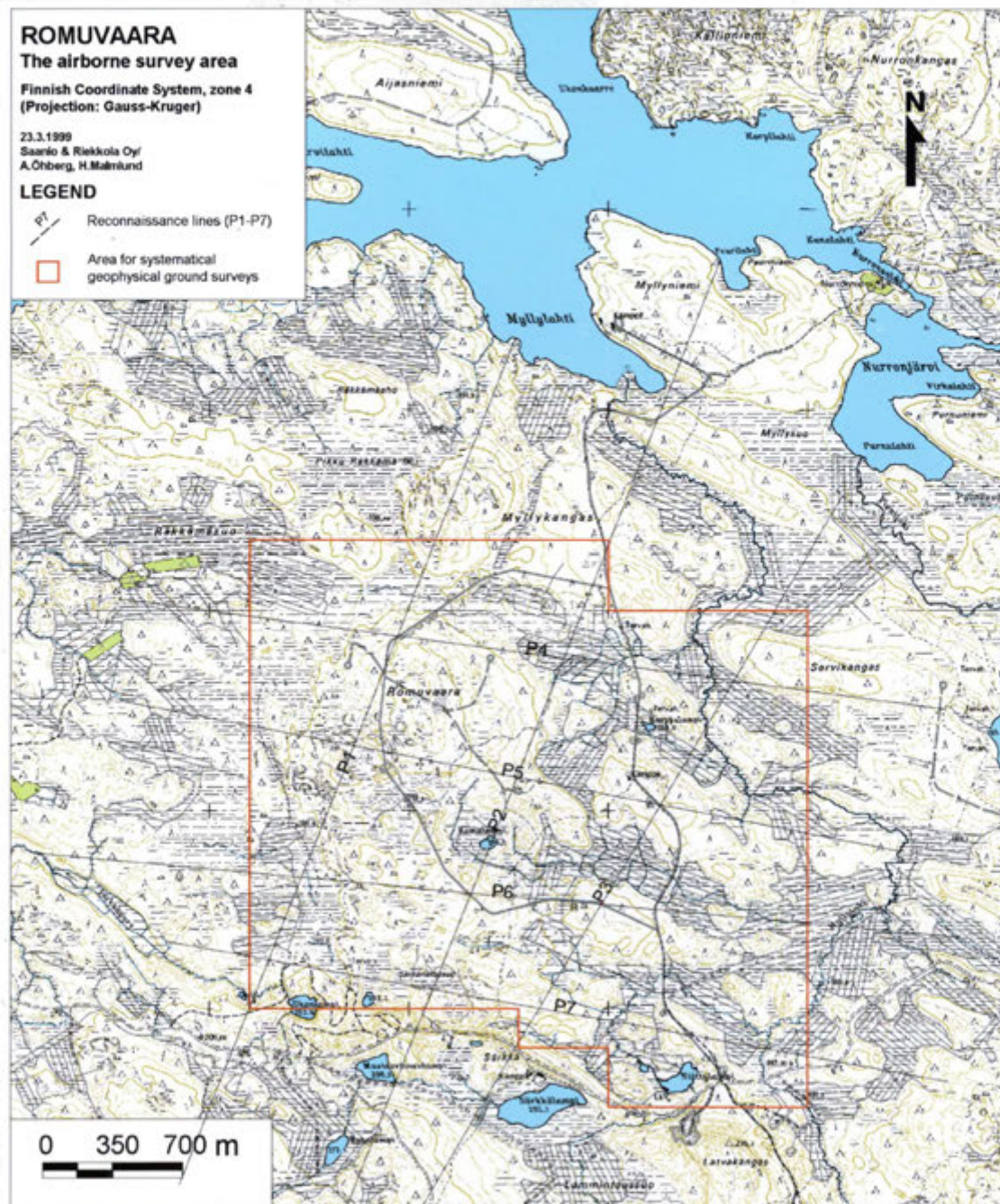


Figure 2.2-3. The airborne survey area (30 km²) and the area for ground geophysical surveys (6.7 km²).

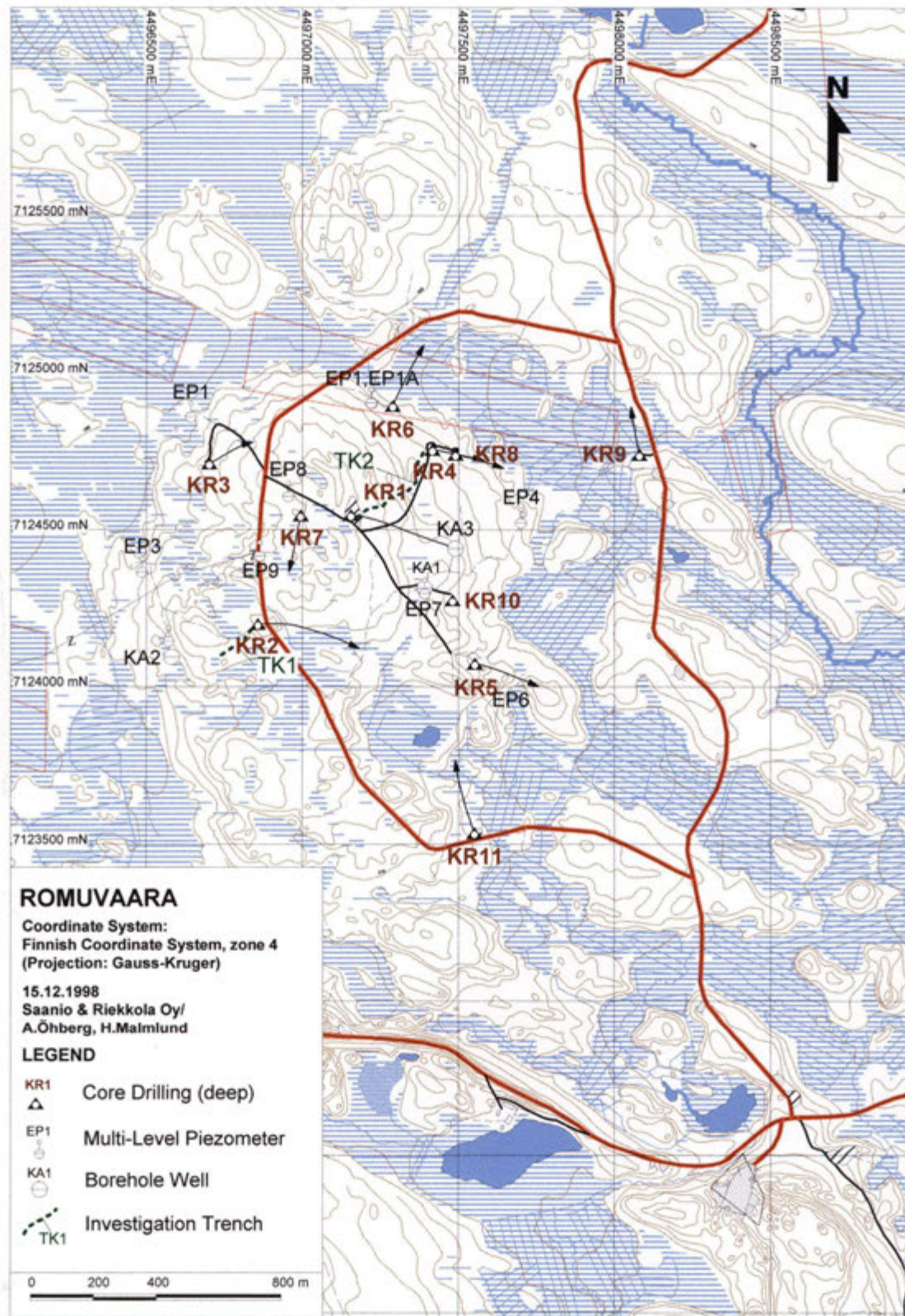


Figure 2.2-4. Romuvaara site showing the location of most important investigation boreholes and the investigation trenches. The area of exposed bedrock is about 1% of the total investigation area.

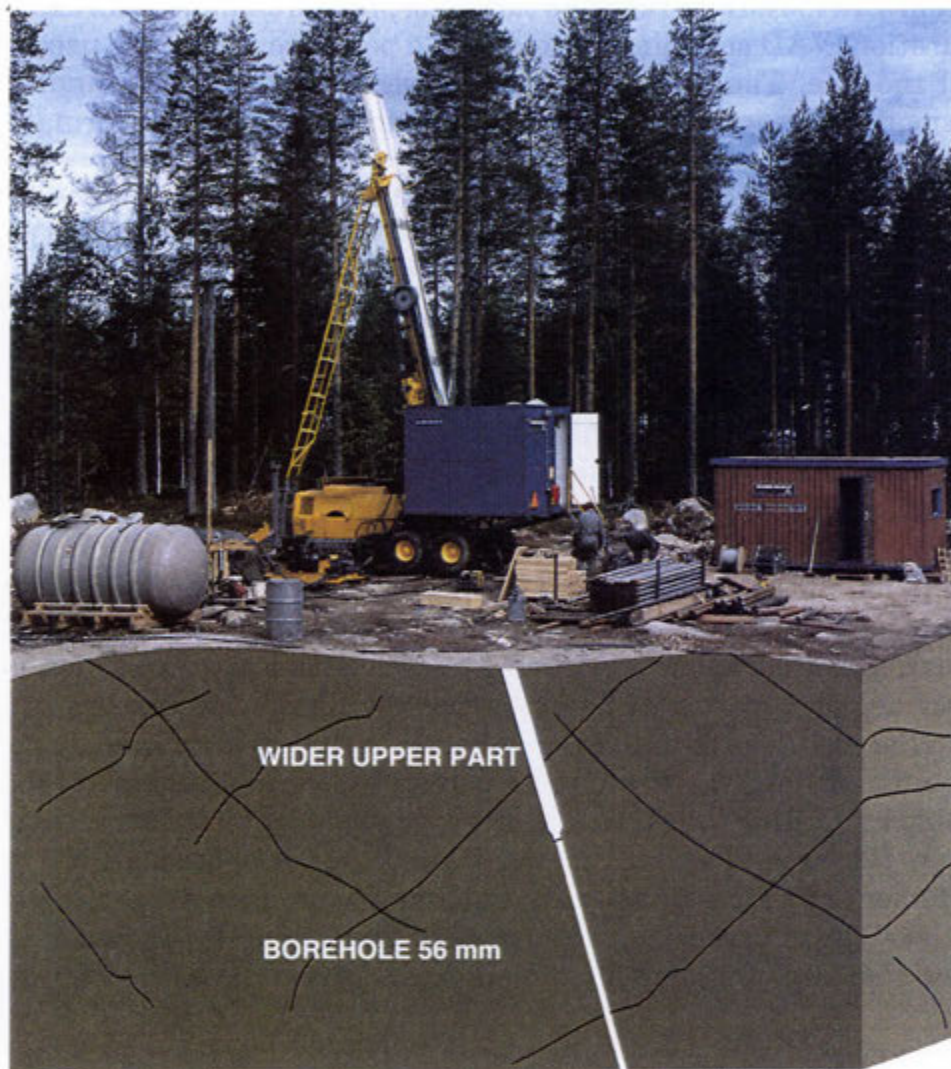


Figure 2.2-5. Core drilling technique used in the site investigations. The upper part was drilled with the down-the-hole technique to a depth of approx. 40 m and lined with steel casing. The lower part of the borehole was then sunk with a T-56 mm core bits.

The conceptual bedrock models were used to develop conceptual flow models to represent the groundwater flow and enable an examination to be made of these and the amounts of groundwater flowing in the intact bedrock. Groundwater flow analyses in preliminary site investigations, the modelling strategy and the computer codes applied are reported by Taivassalo et al. (1994). The interrelation of different models is depicted also in the summary report of the preliminary site investigations (Teollisuuden Voima Oy 1992a).

The fourth phase of the investigations (Fig. 2.2-2) was devoted to hydrogeological and hydrological monitoring, pumping tests in boreholes, rock stress measurements and further analyses of the hydrogeochemical conditions. Hydraulic heads were measured in shallow boreholes, and multi-level piezometers and borehole measurements were used to determine vertical hydraulic head gradients over different borehole sections. Monitoring of precipitation, runoff and the water equivalent of snow continued. Pumping tests were used to determine the hydraulic conductivity of larger volumes of the rock mass, to investigate the potential hydraulic connectivity between certain boreholes and to provide further evidence for use in the interpretations of individual transmissive structures.

A summary report on geological investigations in the Romuvaara area is presented by Anttila et al. (1990). The main objective associated with the location of the deep boreholes, especially in the early drillings, was not to examine the nature and location of fracture zones deduced from the interpretation of earlier ground geophysical surveys, but to locate the boreholes independently of all previous concepts of the geological structure of the site. Not all the boreholes were, however, located in this manner, and some of them were positioned in an attempt to determine the geometry and character of zones deduced from earlier investigations. The boreholes drilled during the preliminary investigation phase are described in Hinkkanen & Öhberg (1989).

A wide range of the best available applied geophysical techniques were used and these occupied a prominent position in the preliminary site investigations. A summary report on all the geophysical investigations (airborne and ground surveys, borehole investigations) carried out in the Romuvaara area during the preliminary investigation phase is presented by Saksa et al. (1991). Borehole radar measurements performed at Romuvaara are discussed even in more detail by Carlsten (1991) and seismic VSP measurements by Keskinen et al. (1992).

Graphical presentations of the observations were compiled during the data processing of the results, a total of 25 thematic maps (Suomen Malmi Oy 1988). Four maps each were plotted of the magnetic field (Fig. 2.2-6) and the VLF results, three maps of flight information, five radiometric maps, and seven maps of the electromagnetic results. As a derivative of the results of the electromagnetic survey of 51,250 Hz, a map of the apparent resistivity of the homogeneous half-space was calculated by the pseudolayer model technique. The profile map of the thickness variation in the pseudolayer was obtained as a byproduct.

The purpose of the hydraulic borehole measurements during the preliminary investigation phase was to acquire information on the hydraulic conductivity of the bedrock for use as initial data for groundwater modelling. The method chosen for this purpose in single boreholes was the constant head injection test, on the grounds of technical simplicity, ease

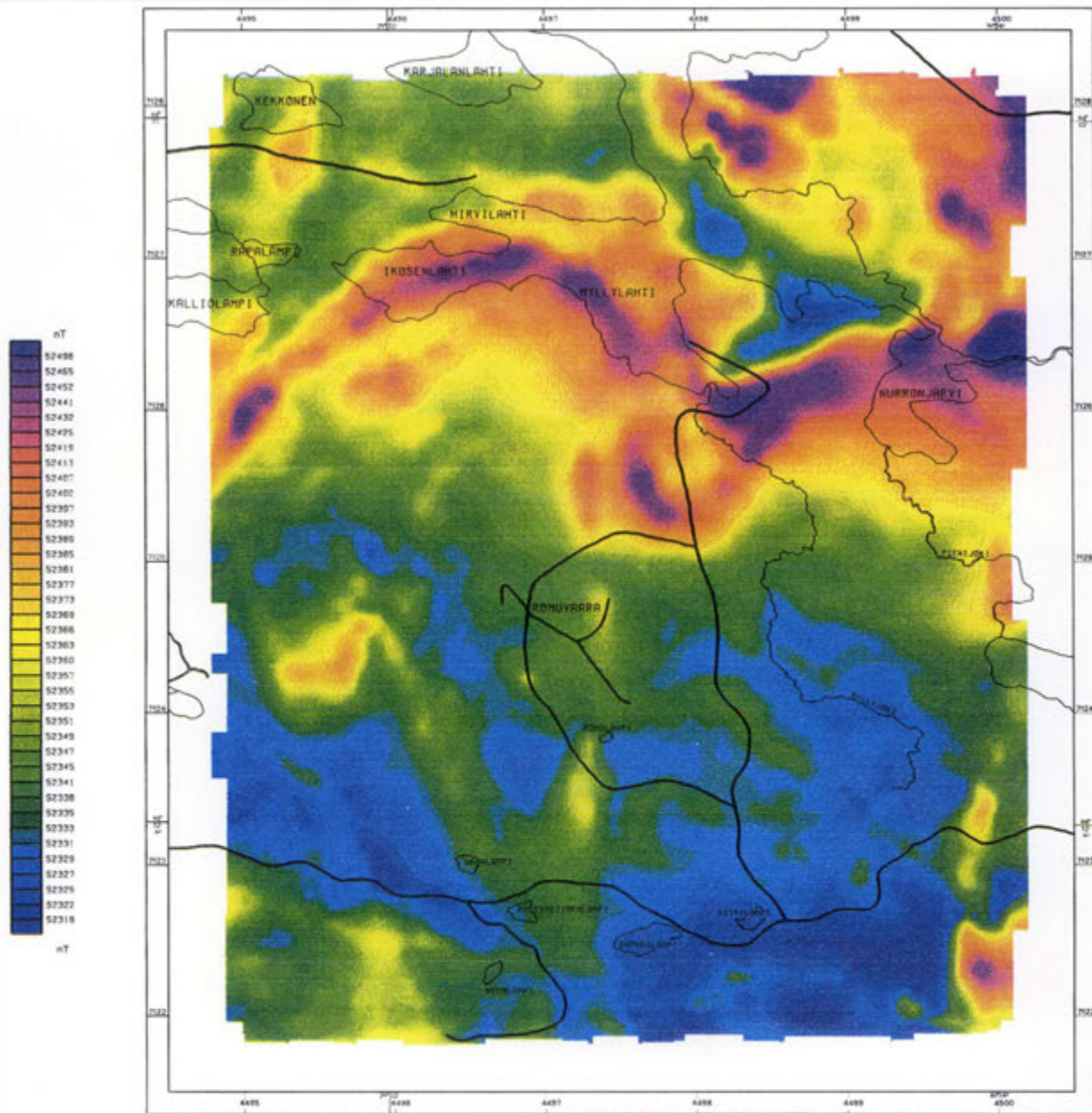


Figure 2.2-6. Aeromagnetic total field map (Saksa et al. 1991).

of control and the comprehensiveness of the measuring range covered. The tests were performed with the Hydraulic Testing Unit (HTU) presented in Figure 2.2-7. The interpreted results are presented by Pingoud et al. (1988), Kuusela-Lahtinen et al. (1989a, b, c). Geostatistical analysis of hydrological data is reported by Niemi & Kontio (1993).

Pumping tests were also carried out to investigate the hydraulic connections between boreholes and to test the conceptual assumptions incorporated in the development of the structural model, the main focus of interest being an investigation of the more transmissive, major structures. Summary report of the interpretation of the hydraulic interference tests is presented by Ylinen & Väättäinen (1993).



Figure 2.2-7. Hydraulic testing unit (HTU) mounted on a trailer. The data acquisition and processing equipment are in a separate compartment in the front part of the trailer. The hydraulic cable winch and instruments for measurement, control and operating can be seen in this picture. The cable is lowered into the borehole through a hatch in the floor.

Hydraulic head measurements were performed in order to determine the hydraulic gradient in the rock mass and obtain reference values for calibrating the groundwater model. Measurements were made in three ways, by monitoring the free groundwater table in a number of the shallow boreholes in different parts of the area, by use of multi-level piezometers down to a depth of 100 m, and at depths up to 1 000 m in the deep boreholes by use of multi-packer system. A summary of the hydrogeological observations is presented by Ahokas (1992).

The goal in terms of groundwater chemistry was to obtain information on the chemical nature of the groundwater for characterisation of the local hydrogeochemical conditions and for use as input data for geochemical modelling. The field work carried out to study the groundwater chemistry of the Romuvaara area is described by Lampén (1988, 1990), Wickström (1988) Wickström & Nurmi (1989), Tuominen (1990), Lampén & Snellman (1991) and Helenius (1991, 1992). The range of studied parameters was comprehensive.

The results are discussed in the summary report by Lampén and Snellman (1993) and the geochemical modelling study by Pitkänen et al. (1996a).

The approaches and the extent of the preliminary site investigations are presented in more detail by Teollisuuden Voima Oy (1992a). Some experiences are also presented by Öhberg et al. (1994). In general terms best available methods and equipment were employed to study the rock mass and the surficial deposits.

There are few major fracture zones at Romuvaara which appear to have a significant effect on the groundwater flow. The location and orientation of these structures is fairly clear in spite of the complex deformation history of the area, and because of this the Romuvaara site was selected for the detailed site investigation stage. The level of knowledge after the preliminary phase was considered to offer good possibilities for planning and implementation of the next investigation phase at Romuvaara (Teollisuuden Voima Oy 1992a).

2.3 Detailed Site Characterisation 1993 - 2000

2.3.1 Characterisation Programmes

The guidelines for this investigation period at the selected three sites were presented in 1992 (Teollisuuden Voima Oy 1992b). The eight-year investigation period extending from 1993 to 2000 was considered to be too long in practical operational terms to allow for the development of a single programme and it was considered more appropriate to divide it into successive sub-programmes. A general investigation programme was compiled for the first phase (1993 - 1996) (Teollisuuden Voima Oy 1993b), and attention was paid to the particular features of each site, which meant that the site investigation programmes varied slightly from site to site. The main components of the programme were:

- building confidence in the results of the earlier site investigations and confirming the justification of the exclusion of two sites made on the basis of these investigations,
- extending the scope of the investigations at the sites concerned and supplementing these investigations with data on rock mass properties in general,
- acquisition of further data on those properties of the rock mass that are considered most significant in a safety assessment, e.g. groundwater chemistry and fracture properties in the near field, and
- acquisition of further information on each of the areas for the purpose of developing final disposal techniques and for designing the repository.

The aim at the initial stage was thus to improve the accuracy of the results obtained in the preliminary site investigations, the motive behind this being the need to evaluate the validity of the assumptions included in the conceptual models and to examine in detail the conceptual uncertainties regarding the rock mass structure. In addition to verifying that the existing results could be confirmed, the aim was also to assess the suitability of the techniques which had been employed during the investigation, interpretation and modelling.

A site-specific investigation programme was prepared for the characterisation work for the period 1994 - 1995 at Romuvaara (Teollisuuden Voima Oy 1994). The proposed investigations were presented in the programme as a series of themes. The published programme also included the investigation schedule.

In parallel with the investigation programmes, several memoranda were prepared as part of the investigation project in order to steer the investigation activities (Öhberg 1997). These memoranda included, for example, detailed instructions for the investigation work.

The most important tasks for the 1997 - 2000 (complementary studies) period were presented in the 1996 status report for the project (Posiva Oy 1996a). These tasks were:

- preparation of a summary evaluation of the geological, hydrogeological and geochemical properties of the sites by carrying out the required field and laboratory investigations and the associated interpretations and modelling programmes,
- an evaluation of the state of knowledge regarding the overall understanding of the sites and an evaluation of the remaining uncertainties,
- the definition of potentially suitable volumes of the rock mass for housing a repository and an evaluation of the overall suitability of the sites for final disposal in terms of technical and safety aspect and
- the preparation of a performance assessment for the potential disposal sites.

The proposed investigations associated with the complementary studies over the period 1997 - 2000 are presented in more detail in the proposed investigation programme for the years 1997 - 2010 (Posiva Oy 1996d). The PARVI project, which was established for planning and carrying out the practical work, compiled a programme for its own internal use.

In addition to the detailed descriptions of the investigation programmes, summaries of the investigations for the following year were also presented in the annual investigation programmes of the Nuclear Waste Commission of Finnish Power Companies (1992, 1993, 1994, 1995), and more recently, in the radioactive waste management programmes of the nuclear power plants of Olkiluoto and Loviisa (Posiva 1996e, 1997).

2.3.2 Detailed Site Characterisation - Approaches and Extent

The investigation programme for the period 1993 - 1996 (Teollisuuden Voima Oy 1992b) concentrated on three main subject areas:

1. Baseline investigations at the three sites, which were aimed at defining the prevailing conditions to an acceptable level and acquiring reference data on the sites which were required for long-term monitoring,
2. Characterisation of the site, aimed at gathering additional information on its bedrock, and
3. Verification of the results and the conceptual models of the geology, hydrogeology and hydrogeochemistry of the sites, which had been developed in the earlier stages of the investigations with the aim of evaluating the extent to which they could be substantiated.

Baseline investigations during this phase included groundwater sampling and hydrogeological measurements. The purpose of the groundwater sampling was to map the groundwater quality both in an areal sense and in a vertical direction and, at the same time, to verify the initial estimates of groundwater recharge and residence times. The results of these investigations were designed to serve as basic data for comparisons with the future investigations and for the evaluation of possible future changes in bedrock conditions. Water sampling was carried out from packer intervals in multipackered boreholes and from precipitation, wells, springs and brooks in the surrounding area. Hydrogeological measurements included measurements of the hydraulic heads and the hydraulic conductivity of the packed-off borehole sections using slug and bail tests. Continued monitoring of hydraulic heads in the multi-level piezometers took place as did monitoring of the groundwater table in the shallow boreholes.

The characterisation of a site concentrated on complementing the conceptual models developed, on eliminating hydrogeological and geophysical uncertainties in the models by drilling new boreholes and by carrying out additional measurements on the ground and in the boreholes, including hydrogeological interference tests. The work also concentrated on examining the hydrogeochemical evolution of the site and on an initial characterisation of the potential near-field rock mass using hydraulic measurements and groundwater sampling.

Examination of the results of earlier investigations and modelling assumptions that had been applied, resulted in the drilling of one additional deep borehole for each site, at Romuvaara, Kivetty and Olkiluoto. These boreholes were drilled in the areas of the sites which contained several existing boreholes and where the uncertainties in the geological structure and the hydrogeological environment were believed to be low. The results obtained from these boreholes were subsequently compared with the predictions made in advance of the drilling (Hellä et al. 1996). The ability to predict rock mass properties in a part of the site where limited field data is available by deductions from empirical results and existing models was tested by drilling a new borehole in this area (Niinimäki 1996). Conceptual assumptions were tested by carrying out supplementary measurements in some existing boreholes. These measurements included directional radar surveys and other geophysical measurements (Julkunen et al. 1996, Strähle 1996, Laurila & Tammenmaa 1996) to determine the extent and geometry of the fracture and lithological zones deduced earlier, and seismic VSP soundings (Cosma et al. 1997) and hydraulic interference test to assess the continuity of the structures (fracture zones) (Niva 1996, Hänninen 1997).

Over the period 1997 - 2000 the investigations at Romuvaara have concentrated on:

- groundwater sampling which has been carried out in order to determine the hydrogeochemical conditions deeper parts of the bedrock and especially the redox conditions,
- fracture mineral studies, which have been carried out as part of an analysis of the paleo-hydrogeological evolution of the site and
- pumping tests and complementary hydraulic measurements in the boreholes for the purpose of assessing the continuity of the structures and the determination of their hydraulic properties.

Improved equipment and new methods have been used in the detailed site investigations (Hinkkanen et al. 1996). The investigation methods used over the period 1993 - 1998 can be found in Appendices 1 - 12.

Baseline investigations included groundwater sampling from packed-off boreholes. A slim membrane pump was developed for pumping from polyamide hoses connected to the packer intervals. The sampling sections were located originally for observation of hydraulic head and, therefore, the lengths of the sections were several tens of meters. A new sampler for obtaining pressurised water samples was developed (Ruotsalainen et al. 1996, Hinkkanen et al. 1996). Sampling with this PAVE groundwater sampling system allowed high quality samples to be taken from individual fractures or fracture zones. The pressurized water samples were used in microbial studies and in the analyses of dissolved gases. Also groundwater pipes were installed and sampled in order to have information on recharge conditions.

The development of investigation equipment has been most active in hydrogeology. For example the software and hardware of the HTU (Hydraulic Testing Unit) were replaced, which improved the resolution of the tool and enabled the routine interpretation of hydraulic conductivity measurements in the field. New flowmeters for difference flow and transverse flow measurements (Hinkkanen et al. 1996) have systematically been used for measurements within the new and the older boreholes at all sites. The principle of transverse flow measurement is presented in Figure 2.3-1. The fluid logging (repeated measurements of fluid resistivity and temperature) which was carried out systematically during the preliminary investigations has been replaced with difference flow measurements. The method gives the locations of hydraulically-conductive fractures, without the requirement to replace the borehole water with de-ionized water, as is the case in fluid logging. The good correlation between the results from the HTU and the difference flow measurements has given confidence in the use of the two methods. In addition to systematic measurements in single boreholes, transverse flow measurements have been carried out in connection with pumping tests. At Romuvaara successful measurements have been conducted at two depth levels in borehole KR8 during pumping in borehole KR4 (Fig. 2.2-4). The influence of this pumping could be detected by changes in the magnitude and direction of flow of groundwater (Niva & Rouhiainen 1996).

The aim of the geophysical studies has been to supplement the bedrock data obtained earlier in the site investigations and to obtain more precise data on the rock mass. The studies have mainly been focussed on the boreholes and on their immediate surroundings. Fracturing has been studied using new kinds of borehole wall scanning techniques: borehole-TV, dipmeter and acoustic televiewer (Hinkkanen et al. 1996). The tools have provided data on the orientation of fractures, on contacts between the different rock types, on foliation and on veins. The borehole-TV and dipmeter tools proved to be the most valuable methods when scanning borehole sections where oriented core data were not available (Okko & Paulamäki 1996). The results obtained with the scanning techniques have in many cases made it possible to determine the locations of single, potentially conductive fractures and to provide better fracture data coverage from the densely fractured sections (Hellä et al. 1997).

Borehole radar measurements were performed as single hole measurements with a directional antenna. The radar method has been found to be very useful in the fresh groundwater conditions at Romuvaara. Cross-hole measurements were tested between boreholes KR4 and KR8 (Carlsten 1996) which are separated by about 80 - 150 m (Fig. 2.2-4). Altogether seven structures could be interpreted, some of which were very prominent in the tomographic maps. VSP-surveys were continued using a 3-component geophone system and a new processing and interpretation technique (Cosma et al. 1994a, b, c), which allows for more reliable and better characterisation of the structures, their orientation and their continuity. This method was also found to be suitable for gently dipping structures. Not all the reflectors intersecting the boreholes could be correlated with fracture zones observed in the boreholes. Galvanic charged potential surveys were carried out in the boreholes to map the orientation of four fracture zones and cross-hole measurements could be carried out between boreholes KR4 and KR8 (Silvennoinen 1994, 1995). The existence of saline groundwater and the

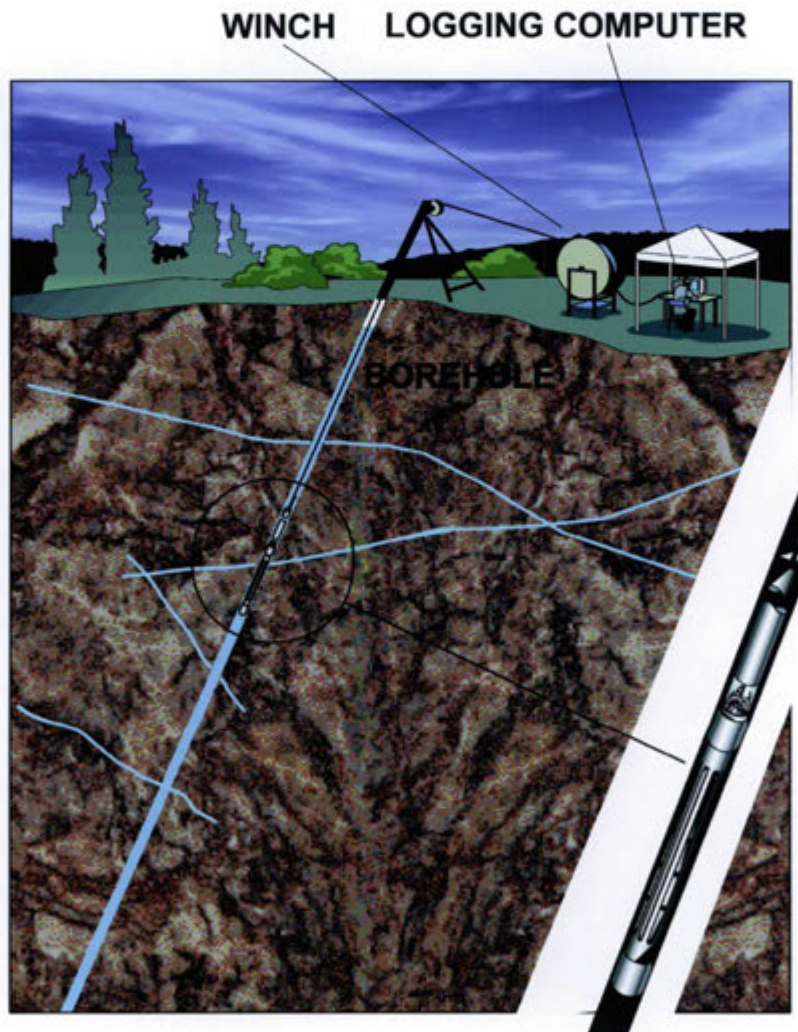


Figure 2.3-1. Principle of transverse flow measurement (left). The section to be measured is 2 m long with inflatable packers at both ends. Four longitudinal sealings separate the section into four sectors. The flow magnitude (ml/h) and the approximate direction of flow is measured with heat pulse flow sensor (right). Radial distribution of hydraulic conductivity can also be measured in connection with flow measurement.

location of conductive fracture zones were investigated with electromagnetic frequency soundings, but no indications of saline groundwater were found (Suomen Malmi Oy 1994, Paananen et al. 1994, Okko & Paulamäki 1996).



Figure 2.3-2. Investigation trench TK1 seen from SW. The drilling rig behind the trench is on the borehole KR2. In the depression in front the fracture zone R11 crosses the trench. The trenches were landscaped after completion of the mapping.

Rock stress measurements were carried out using the 3D overcoring technique in borehole KR10 and the 2D hydraulic fracturing method in four boreholes. The overcoring measurements at three depths of 300, 450 and 600 m in borehole KR10, gave valuable information on the in situ stress state in the bedrock. The hydraulic fracturing method did not prove as useful at Romuvaara because only a few fractures parallel to a borehole could be induced (Ljunggren & Klasson 1996).

Geological investigations have included the excavation and mapping of two investigation trenches TK1 and TK2 at Romuvaara (Fig. 2.2-4, 2.3-2). The trenches have produced more bedrock and fracturing data in areas with no exposure, and have enabled some of the lithological contacts and the fracture zones predicted earlier in the preliminary investigations to be located precisely (Kärki 1995, Paulamäki 1995).

The Romuvaara, Kivetty and Olkiluoto investigation sites have been equipped with integrated GPS monitoring systems to investigate any current deformation of the bedrock (Hinkkanen et al. 1996). The stability of the bedrock at Romuvaara is monitored with a permanent central station (Fig. 2.3-3) and six local stations, which cover the rest of the investigation site (Chen 1996). The central station is fitted with a continuous satellite receiver, which is linked to the central antenna system of the Finnish Geodetic Institute which covers the entire country. The locations of the local stations are such that their distances from each other and from the central station optimize the resolving power of the system and also include what are considered to be the most important fracture zones on the site. The local network is measured twice a year. The accuracy of the GPS measurements between the stations in a horizontal direction is of the order of 1 mm and in a vertical direction 2 - 3 mm (Chen & Kakkuri 1994).



Figure 2.3-3. The permanent GPS-station at Romuvaara.

2.4 Rock Modelling

2.4.1 Interpretation Process

The interpretation and model development process has had a very central position in the site investigations, starting from the processing of data and the interpretation of models for each geological and geophysical survey and continuing to the multidisciplinary integration and assessment of all the results. Geophysical surveys which have a high resolution combined with significant investigation ranges have been important in the investigation of large volumes of the rock mass. An assessment of the particular methods of interpretation of such surveys is beyond the scope of this report, however, examples of practical work in this area can be found in Paulamäki & Paananen (1990), Pitkänen et al. (1990), Paulamäki & Paananen (1995a) and Front et al. (1995). The major categories of interpretation work have been those associated with surface surveys, borehole measurements, from surface to borehole interpretation and vice versa, cross-hole surveys and the interpretation of surveys which could not be tied into borehole data. Summaries of interpretation methods are given in Saksa et al. (1992) and Front et al. (1997). Hydrogeological interpretations and the techniques applied are summarised by Ylinen & Väättäinen (1993) and Ahokas et al. (1997). A description of the process associated with the transfer of the interpreted data to the geological conceptual model is presented in Saksa (1995).

An important issue is the conceptual basis which is applied in the interpretation process. Of particular interest in this regard with reference to the Romuvaara site is how fracture zones have been defined and what assumptions have been made regarding their properties, their planar geometry and their mutual relationships. Different classes of fracture zone have been used which have been based on the intensity of the fracturing and weathering and on the hydraulic properties, and also on expert judgement. A description of the development of these classes of fracture zone is presented in the summary reports listed above. In addition, the properties of these zones and the definition of their boundaries have been analysed by principal component analysis and using the so-called Fracture Zone Index (Olsson et al. 1992, Korkealaakso et al. 1994). The genesis of fracture zones and their geometries was investigated by carrying out a literature review (Front & Okko 1994) to find out whether the modelling approach being applied should be modified. The main conclusion of this review was that the number of drilled boreholes in an investigation programme should be large enough to enable reliable structural interpretation of the fracture zones to be carried out. Deviations from planarity in fracture zones in similar rocks to those at Romuvaara have been detected in underground research laboratories (URLs). However, rock mass models applied in URL programmes have been developed successfully using this planar fracture zone approach, and a similar assumption of planarity has been assumed to be appropriate here.

One theme of the characterisation programme for the period from 1993 to 1996 was testing the assumptions and hypotheses regarding the rock mass parameters and the models developed. Several supplementary field investigations were associated with testing the established structural and lithological models. Included in such testing were the construction of two investigation trenches TK1 and TK2 (see Section 4.3.1 and Fig. 2.2-4) and a blind prediction test, which was carried out in borehole KR10. The results from the

investigation trenches were in good agreement with the predictions of the rock mass model (Kärki 1995, Paulamäki 1995). In borehole KR10 rock types, fracture density and hydraulic conductivity were predicted in advance of drilling (Luukkonen & Korkealaakso 1995, Paulamäki & Paananen 1995b). Subsequent analysis of data from borehole KR10 showed that the rock types were correctly predicted. Significant statistical differences between the predicted and measured fracture densities and hydraulic conductivities were noted, but more than 90% of the values were within the estimated 90% confidence limits (Hellä et al. 1996). In addition, the evolution of the three versions of the rock mass models developed over a period of several years from 1996 was studied. The results of this analysis indicated that there was a generally good agreement between the rock mass models developed and the actual rock conditions found (Hellä et al. 1996).

2.4.2 Computer Modelling

Lithological and structural models of the rock mass have been developed for the Romuvaara site. All the structures described consist of varying types of fracture zones. These two models are used to develop a bedrock model which is compiled using computer-aided geological ROCK-CAD modelling system (Saksa 1995) containing all the necessary modules to allow for the efficient construction of complicated 3-D geological models. It is able to handle boreholes and their associated data, a variety of coordinate systems and grids and can display geological fill symbols and colour patterns. It features a rock object database and possesses its own parametric high-level definition language. Surface topography can be included in the modelled objects. ROCK-CAD takes care of the 3-D assembly and the graphics presentation. Different submodels, representing specific volumes of the rock mass, can be constructed and viewed. The system has been used in modelling the spatial distribution of rock types, structures and the geometry of hydraulically important features. Output can be presented as maps, cross-sections or perspective views in vector or raster format.

The software has improved the assessment of the sites studied and has provided a better method of documenting the interpretation and modelling work. It has replaced hand-drawing and has enabled the digital transfer of data for numerical analysis, such as in the development of groundwater flow models or in repository design. The data flow in the software and use of the system is illustrated in Figure 2.4-1.

The development of the models for the Romuvaara site has been an interdisciplinary and iterative process and several modifications to the models have taken place. The preliminary site characterisation programme from 1987 to 1992 resulted in the development of the first model of the rock mass for the Romuvaara area (version 1.0). Supplementary investigations from 1993 to 1996 expanded the volume of the rock mass studied and increased the understanding of the site. The number of lithological and structural units identified in the model of the rock mass increased accordingly (version 2.0). Investigations at the site as well as the assessment of the site have continued over the period from 1997 to 1998. A revised model, version 3.0, has been produced (Saksa et al. 1998). This model includes the data from recently completed boreholes KR10 and KR11.

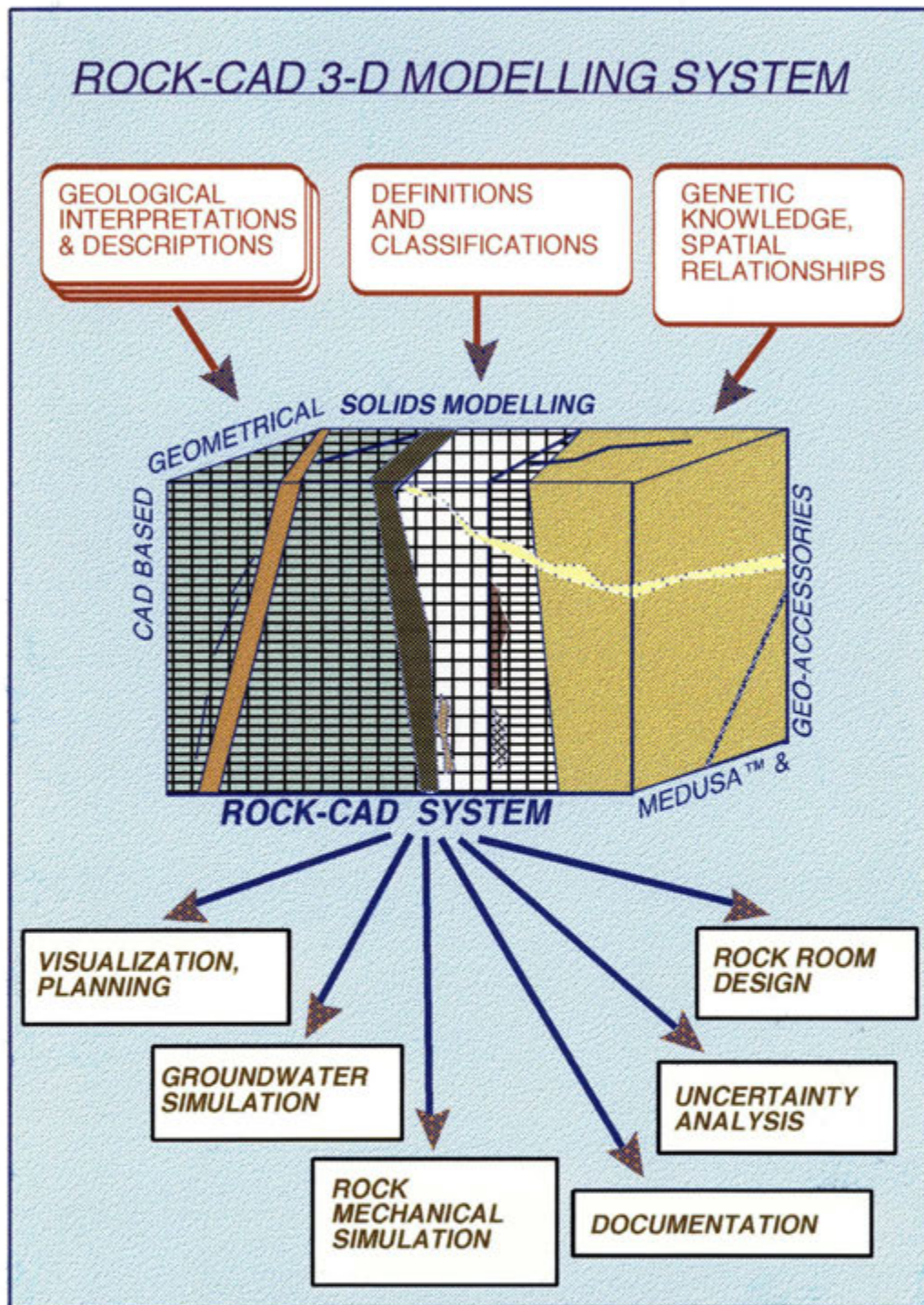


Figure 2.4-1. ROCK-CAD system use and data flow (Saksa 1995).

Modelling work has focussed mainly on the interpretation of the geometry of the hydraulically-conductive fracture zones and the parameters describing their properties. The geometry and properties of the fracture zones were also assessed in cases when there was no direct observation of hydraulic conductivity that was greater than what might be expected in the intact rock. This was considered necessary because the hydraulic conductivity of structures can vary greatly from one observation point to another (i.e. values of hydraulic conductivity within what might be considered, from other evidence, to be a fracture zone could, in places, be no greater than those expected for the intact rock).

A starting point for the 3-D structural interpretation has been the assumption of a linear continuity in structural properties and the planar form of fracture zones. The extrapolation or interpolation of structures between boreholes, or between these and the ground surface, has been based almost entirely on the assumption of planar continuity, unless other additional geological information were available. The assumptions made and the specific aim of combining the observations in the manner described led to a straightforward manner of visual presentation for these zones. The assumptions made also resulted in a simplification of the geological structures used in the models (compared with their actual, but largely unknown properties) and may have resulted in an increase in their continuity, i.e. making them more continuous than would be the case in reality.

2.5 Definition of Structural Terms Describing the Bedrock

The terminology used in the present report has been developed over the period of the site characterisation programmes in Finland and has been previously applied in several of the reports. The terms mainly concern the description of the geological and structural features of the bedrock, and those most frequently used in the reports are defined below.

A classification of the lineaments (which, from the outset of the site selection programme have been assumed to be fracture zones) was developed by the Geological Survey of Finland for the site selection studies (see Section 2.1) in order to describe the regional structures of the bedrock (Salmi et al. 1985). The classification is based on the interpretation of lineaments from maps, aerial photos and satellite images, with the assumption that these lineaments represent more densely fractured or crush zones of the bedrock, which can typically be seen as elongated depressions. This assumption can be shown to be generally valid for the geological environment of Finland and is, in any case, a conservative assumption with regard to the disposal of radioactive waste. In a regional context, the terms *lineament* and *fracture zone* or *crush zone* can be regarded as being synonymous. The classification of these lineaments or fracture zones is presented in Table 2.5-1.

The Finnish engineering geological classification has been applied in this report, in particular for the description of the fracturing of the rock mass, and for the structural modelling of the bedrock. The classification (Korhonen et al. 1974, Gardemeister et al. 1976), which is published only in Finnish, was developed with reference to the specific bedrock conditions found in Finland, and was designed to be applied to construction activities.

The criteria used in this classification system are:

- the properties of the rock mass (consisting of its state of weathering, the orientation of any internal structure, its grain size and its major minerals) and
- the fracture properties (geometry of fracturing, fracture frequency and type of fractures) which together determine the rock quality.

A simplified description of rock quality based on this classification system is given in Table 2.5-2.

The structural solidity of the rock mass is divided into three classes: *intact*, *loose* and *broken rock mass*. In this report only the classes intact and broken are applied, because rock in the loose rock mass class has not been found. The rock is regarded as broken if the number of fractures is more than 10 fractures/m (pieces of core samples per metre), it is dominated by filled and/or open fractures, or it is mesoscopically weathered.

The key terms used in the structural modelling (cf. Sections 2.4 and 5) are defined as follows:

A *structure* in a rock is any geological feature defined geometrically (Kearey et al. 1993). A *tectonic structure* is produced by deformation and is synonymous with the use of the term *deformation structure*. In this report the use of the term *structure* implies a tectonic structure, unless otherwise stated. Every *structure* (or R-structure) in the bedrock model has a unique object name (i.e. R(number)) and is accompanied by information which describes the attributes of the structure, e.g. its fracture density, its transmissivity, etc. The term R-structure is specially used in Section 6 for separating the modelled structures (fracture zones) from other hydraulically conductive features included in the rock mass.

A *fracture zone* is a general term describing varying types of fracture structures as shown in Table 2.5-1 or a structure in the bedrock model with block-structured or fracture-structured properties (RiII or RiIII), as explained in Table 2.5-2.

A *major fracture zone* contains crush-structured (RiIV) portions (Table 2.5-2). A *crush zone* contains clay-structured (RiV) portions. The classification of such zones can also be based on the quantitative interpretation of their properties or, where only indirect evidence is available, on expert judgement (Table 2.5-1).

In this report the term *intact rock* is synonymous with the term *averagely fractured rock* which has been used commonly in other radioactive waste disposal programmes (e.g. that in Sweden). The intact rock contains all types of fractures and fracture zones, both known and unknown, but only those which are *not* defined as structures in the bedrock model for the site.

The term *zone* (e.g. fracture zone) refers to a geometry in which the dimensions along the strike and along the dip direction of the zone are considerably larger (≥ 10) than its perpendicular thickness.

The geological terms used in Sections 3 and 4 are defined, e.g. in Bates and Jackson (1980).

Table 2.5-1. Classification of the lineaments / fracture zones according to Salmi et al. (1985).

Class	Width of the fracture zone	Length of the fracture zone	Supposed depth extent of the fracture zone
I	> 1 km	from tens to hundreds of kilometres	> 10 km
II	100 - 1 000 m	from 5 to tens of kilometres	from several kilometres to 10 km
III	10 - 100 m	2 - 5 km	> 1 km
IV	<< 10 m	100 m - 2 km	<< 1 000 m

Table 2.5-2. Rock quality description according to the Finnish engineering geological classification (Korhonen et al. 1974, Gardemeister et al. 1976).

Structural solidity of rock mass	Structural types of rock mass	Structural types and frequency of fractures (described in terms of the most dense fracturing) ¹	Hardness and toughness of main rock types
Intact rock mass	Mass-structured	Sparsely fractured Slightly fractured Abundantly fractured	Soft Brittle Tough Hard
	Schistose structured	Sparsely fractured Slightly fractured Abundantly fractured	
	Mixed-structured	Sparsely fractured Slightly fractured Abundantly fractured	
	Loose-structured	Sparsely fractured Slightly fractured Abundantly fractured	
Loose rock mass	Weathered-structured (Rp0 - Rp3) ²	Should be described as thoroughly as possible bearing in mind the degree of weathering	
	Cleft-structured (RiI)	Planar fractures divide the rock mass into two or more separate sections	
	Block-structured (RiII)	Abundantly fractured	No fracture filling
Broken rock mass	Fracture-structured (RiIII)	Densely fractured	Little filling in fractures
	Crush-structured (RiIV)	Abundantly or densely fractured	Fractures filled with clay minerals
	Clay-structured (RiV)	–	Abundantly clay material in rock mass

¹ Sparsely fractured: <1 fractures/m
Slightly fractured: 1-3 fractures/m
Abundantly fractured: 3-10 fractures/m
Densely fractured: >10 fractures/m

² Rp0: Unweathered
Rp1: Slightly weathered
Rp2: Strongly weathered
Rp3: Completely weathered

3 LOCATION AND REGIONAL SETTING

3.1 Location and Topography

The Romuvaara site is situated about 30 km northeast of the centre of Kuhmo, about 30 km from the Russian border. The size of the principal investigation area is approx. 7 km².

The area has a relatively subdued topography, relative altitude differences being about 10 - 30 m with the greatest elevation being approx. 227 m at the hill of Romuvaara (see Fig. 2.1-3). The area is poorly exposed, with outcrops comprising only 1% of the total area, and mainly occurring in the western and southwestern parts of the investigation area. The soil cover mainly consists of unsorted till, which is usually a few metres thick, but may be over 25 m in some places. In the peat bogs the till is covered by 1 - 2 m of peat. The area is bounded to the south by a WNW-ESE trending esker, comprised of sand and gravel.

The study site is located above the so-called “highest shoreline”, which means that it has been in a supra-aquatic position since the last glaciation (Eronen & Lehtinen 1996). The postglacial uplift rate is currently about 6 mm a year (Kakkuri 1987).

3.2 Regional Geology

The crystalline bedrock of Finland (Fig. 3.2-1) is a part of the extensive Precambrian Fennoscandian Shield. The oldest part of the Finnish bedrock formed by the Archean basement complex (3 100 - 2 500 million years in age) in northeastern Finland consists mainly of tonalitic and granodioritic gneisses (Gaál & Gorbatshev 1987). Within the basement complex are narrow Archean greenstone belts, which are composed of metavolcanics and metasediments.

The majority of the Finnish bedrock is comprised of Palaeoproterozoic metamorphic and igneous rocks. Its long history of volcanism, sedimentation and igneous activity culminated in the Svecofennian orogeny (1 900 - 1 800 million years in age) (Koistinen 1996). Later the crust was intruded by anorogenic rapakivi granites, 1 650 - 1 540 million years in age, which originated from partial melting of the lower crust. The youngest basement rocks are the Jotnian sandstones (1 400 - 1 300 million years) cut by post-Jotnian olivine diabase dykes (1 270 - 1 250 million years) and the 1 100 and 1 000 million years old dykes of Salla and Laanila in northern Finland.

The bedrock was eroded almost to its present level before the beginning of the Cambrian (about 600 million years ago). Due to erosion and continuous continental conditions, the Finnish bedrock is almost totally lacking in sedimentary rocks younger than the Precambrian.

The regional geology of the Romuvaara investigation site is shown in Figure 3.2-2. The Romuvaara site is situated in the Archean basement complex, the oldest rocks in the region being banded amphibolites, over 2 840 million years in age, which represent the oldest basic crust in the area (Luukkonen 1992). The most common rock types are folded and migmatitic

tonalite/trondhjemite gneisses, which were probably formed by partial melting of pre-existing basic crust. Towards the Kuhmo greenstone belt, they gradually grade into cataclastic leucotonalites, representing the re-crystallisation and/or partial melting of the tonalite/trondhjemite gneisses.

The lower part of the north-south trending Kuhmo greenstone belt consists of komatiitic and tholeiitic metavolcanites with minor banded iron formations, mica schists and chlorite schists (Luukkonen 1989). The upper part of the belt is composed of conglomerates, metapelites, sericitic quartzites, felsic pyroclastic breccias and metavolcanites.

The most common granitoids are 2 740 - 2 690 million years old tonalites, quartz diorites and granodiorites, which were formed by partial melting of pre-existing tonalite/trondhjemite gneisses and banded amphibolites. Early Proterozoic porphyritic, rapakivi-like potassium granite intrusions, $2\,435 \pm 12$ million years in age, occur east of the Kuhmo greenstone belt (Luukkonen 1988).

The youngest rocks of the area are E-W, NW-SE and NE-SW trending metadiabase dykes. E-W trending dykes, 2 500 - 2 400 million years in age, are pyroxene-rich and are only present east of the Kuhmo greenstone belt, whereas NW-SE and NE-SW trending dykes are 2 200 - 2 100 million years old and occur both east and west of the greenstone belt.

The bedrock, apart from the potassium granites and the metadiabases, has suffered a complex polyphase deformation history, including folding, faulting, metamorphism and igneous activity (Luukkonen 1988). At least six Archaean deformation phases have been defined, with the metadiabase dykes representing the reactivation of the late Archaean fault zones in the early Proterozoic.

The bedrock on the Russian side of the border consists mainly of the same kind of granodioritic or tonalitic granitoids and migmatitic gneisses (see Gaál & Gorbatshev 1987).

The lineaments shown in Figure 3.2-2 are based on the interpretation of hill-shaded topographic relief maps at a scale of 1:400 000 and are interpreted as regional fracture zones, which are reflected in the surface topography in the form of elongated depressions and lakes. The Romuvaara area is dominated by NW-SE trending lineaments or fracture zones, which are often associated with the metadiabase dykes. Other lineament orientations are NE-SW, N-S and ENE-WSW. These fracture zones divide the bedrock into blocks of variable shape and size and it is estimated that this kind of block structure of Finnish bedrock was formed as early as the Precambrian (Tuominen et al. 1973).

The Quaternary geology of the surrounding area has been studied by Saarnisto et al. (1980) and Saarnisto & Peltoniemi (1984) and three till units have been recognized. A loose, uppermost ablation till containing poorly oriented clasts overlies a massive basal till, which, in turn, overlies a dense till containing weathering products of the bedrock. The till landforms of the area include large fields of hummocky moraines comprised of the ablation till and NW-SE trending drumlins comprised of the basal till deposited during the Weichselian deglaciation about 10 000 years ago. Eskers are common in the area, mainly

Bedrock of Finland

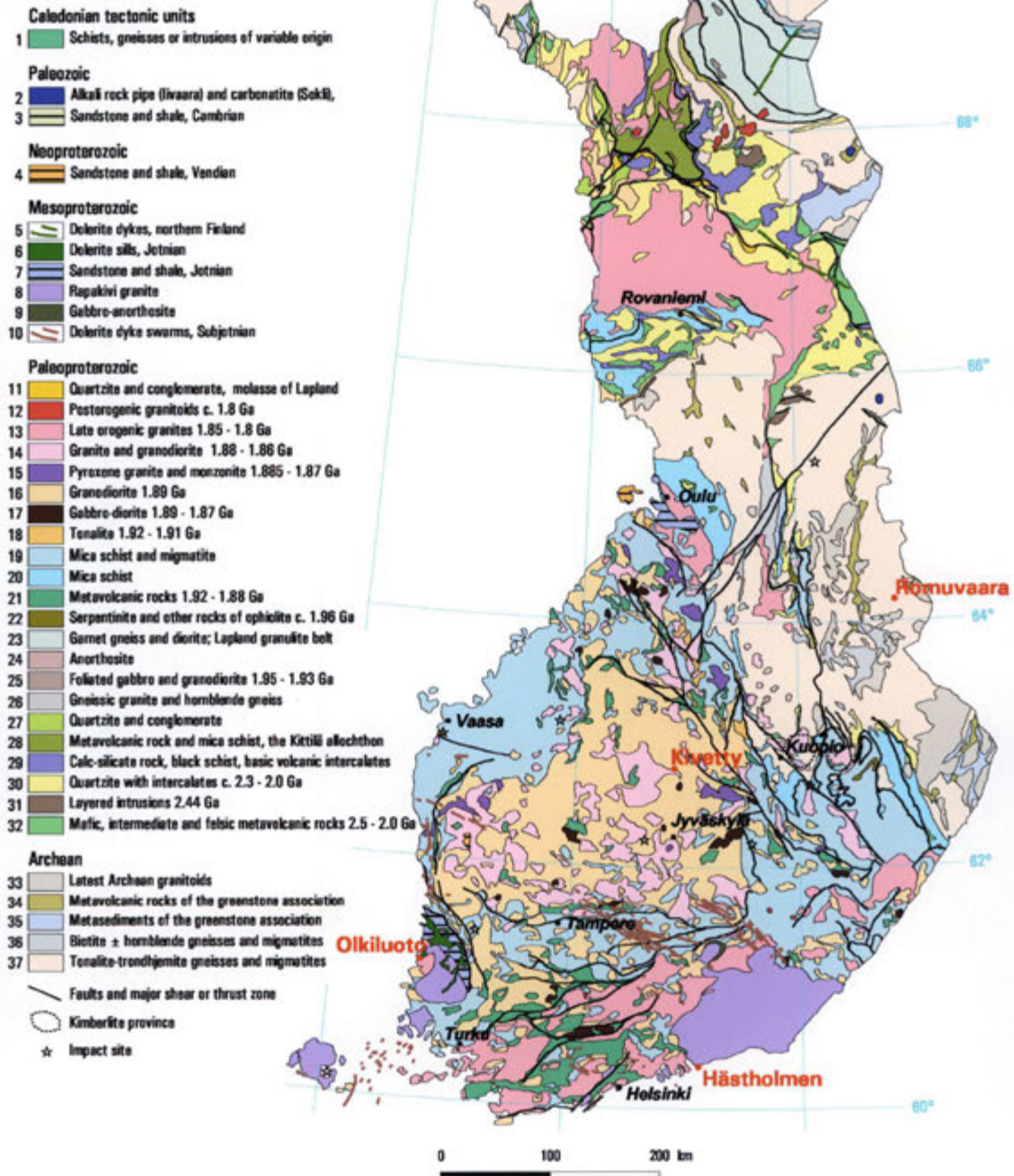
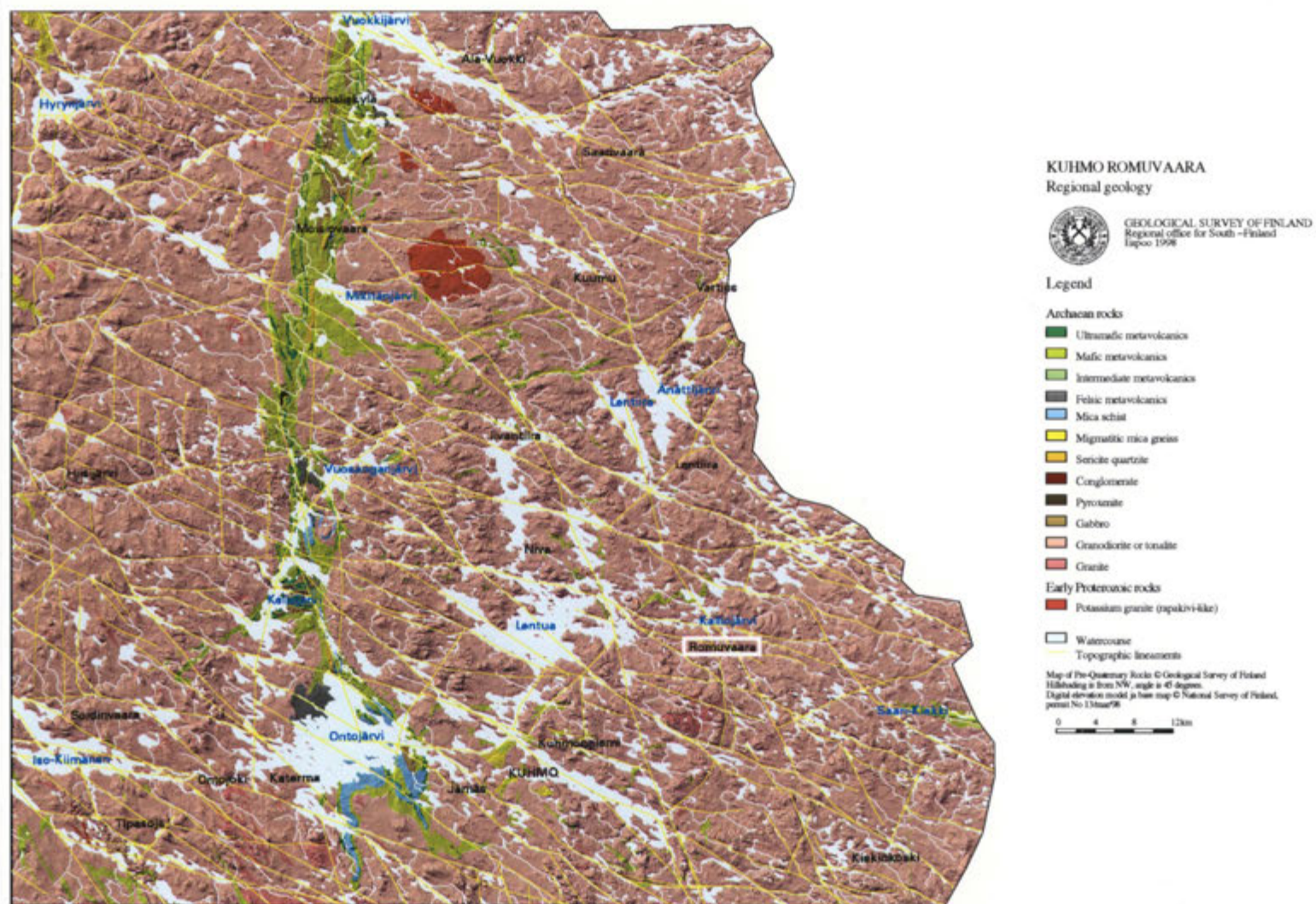


Figure 3.2-1. The bedrock of Finland (Geological Survey of Finland 1999).

Figure 3.2-2. Regional geology of the Romuvara area.



trending NW-SE, and reflecting the most recent directions of ice flow during the deglaciation. Large areas are covered by peat bogs, which are often located in the valleys, and lie between the elongated moraine ridges.

3.3 Regional Hydrology

Romuvaara is located in an extensive drainage basin, the surface waters from which flow via the Sotkamo watercourse into Lake Oulujärvi and subsequently into the Bothnian Bay, which lies at the northern tip of the Gulf of Bothnia (Fig. 3.3-1). The official annual precipitation figure for this region in 1961 - 1990 was 605 mm (National Board of Waters and the Environment 1992), although actual precipitation, after correction for observational errors, is likely to be some 10 - 20% greater (National Board of Waters 1983). About a half of this precipitation evaporates and half provides runoff into streams, rivers and lakes (Solantie 1987).

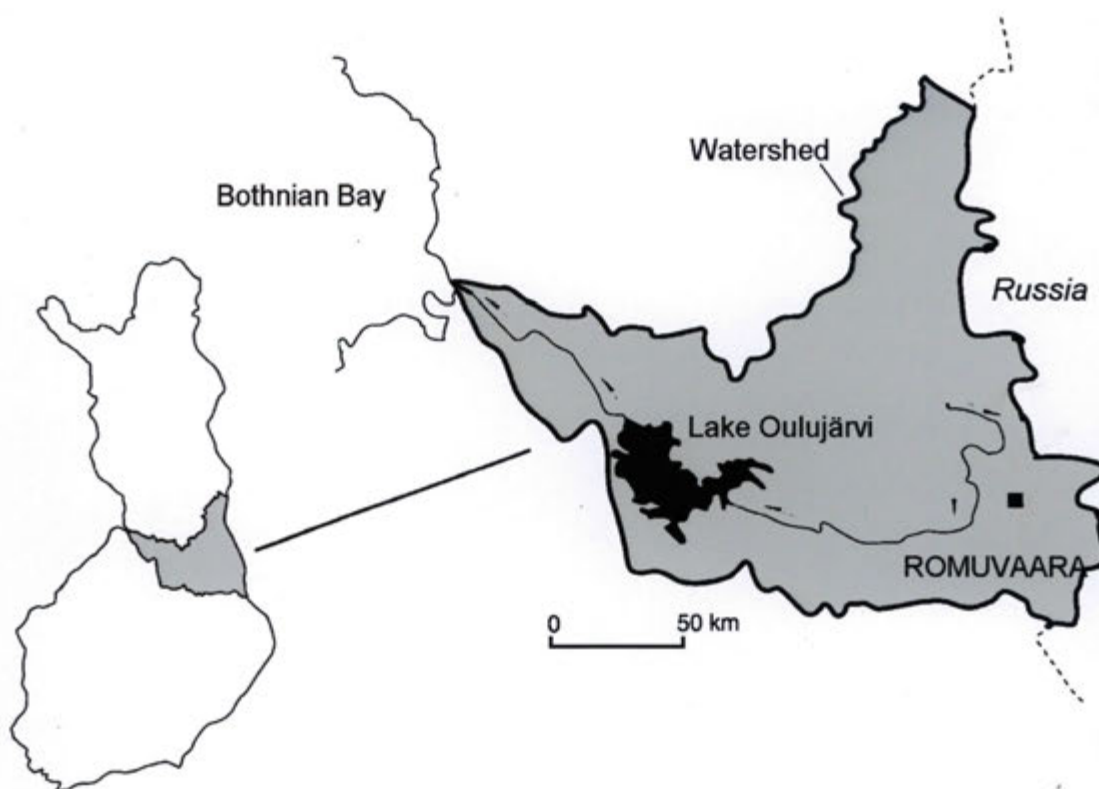


Figure 3.3-1. Location of Romuvaara relative to the Oulujoki river basin (Teollisuuden Voima Oy 1992a).

3.4 Climate

3.4.1 Climate Past and Present

Glaciations have occurred periodically for at least the last 900 000 years (Eronen 1991). There is also overwhelming evidence that the timing and extent of glaciations are triggered by small periodic changes in the Earth's orbit around the Sun (the so-called Milankovich orbital parameters), resulting in changes in the solar radiation reaching the Earth.

The most reliable evidence for the impact of previous glacial advances is obtained from the most recent ones, which are known as the Saalian and the Weichselian. The Saalian began about 200 000 BP (Before Present), and is sub-divided into an older period known as the Drenthe and a younger period, the Warthe. During the Drenthe period an extensive ice sheet covered the whole of Scandinavia, northern Europe and the majority of Ireland and Great Britain (Eronen 1991), and may be the largest to have developed in Europe in the last few hundred thousand years. The centre of the Saalian ice sheet was most probably located over the northern part of the Gulf of Bothnia or in northern Sweden, where its thickness was over 3 km (Eronen & Lehtinen 1996). Deglaciation at the end of Saalian was rapid and semi-continuous. The Saalian ice sheet spread to the Romuvaara area from the west-northwest and was about 2.5 km thick (Eronen & Lehtinen 1996), and the Romuvaara area was covered by ice during the whole of this period.

Rapid climatic warming began in the Eemian interglacial (warm period) about 130 000 BP. During the Eemian maximum temperatures were generally considerably higher than at present and the sea level has been estimated to have been 5 - 6 m higher (Zagwijn 1983). During this period the Eemian Sea was saline and was connected to the Arctic Ocean through the Karelian Sea and the White Sea and also to the Atlantic Ocean through the strait of Denmark. Isostatic uplift, however, caused the Karelian connection to be closed in the early Eemian (Forsström 1999).

The Romuvaara area was free from ice cover during the Eemian, and was also not covered by the Eemian Sea. The climate at this time was probably humid and warm with a mean annual temperature at the beginning of Eemian 2 to 4°C higher than at present in the Romuvaara area. Development of vegetation during this period followed the normal sequence and during the warmest period birch forests were dominant in the Romuvaara area (Eronen & Lehtinen 1996).

According to Eronen & Lehtinen (1996), the climate became rapidly colder in the late Eemian resulting in glaciation at the beginning of the early Weichselian, about 117 000 BP. The extent of ice sheets during early Weichselian times is unknown. Information about this period, when the Romuvaara area may have been free of ice, would be interesting, since long periods of cold climate with no ice cover could have resulted in the formation of deep permafrost. At present the depth of freezing during the winter in the Romuvaara area is usually < 2 m (Eronen & Lehtinen 1996).

Climatic deterioration began 75 000 BP and the climate was at its coldest 20 000 - 18 000 BP when the ice sheet was largest, extending to eastern and central Europe (Fig. 3.4-1). The

centre of the ice sheet was in northern Sweden, where it was also thickest, at over 3 km (Fjeldskaar 1994, Ehlers 1994, 1996). At the southern and eastern margins of the ice sheet a broad zone of tundra vegetation and permafrost extended over large parts of Europe (Eronen & Olander 1990). Climatic deterioration about 75 000 BP resulted in the Romuvaara area being covered by ice again. Romuvaara was located about 600 km from the assumed centre of the ice sheet and the ice thickness at Romuvaara area was thought to have been less than 2.5 km during the coldest phase of the Weichselian glaciation (Eronen & Lehtinen 1996). It seems that the Weichselian ended rather abruptly at 13 000 BP when the climate underwent rapid warming and temperatures became close to those of today. Climatic deterioration however occurred again around 11 000 BP with mean annual temperatures being lowered by 5 - 7°C in few decades (Mangerud 1987, Mayewski 1994) and with a concomitant advance in the ice sheets. About 10 000 BP temperatures again increased rapidly and evidence from glaciers in Greenland, in the form of oxygen isotope analyses, show that the mean annual temperature rose about 7°C in 10 years (Dansgaard et al. 1993, Mayewski 1994) with the result that Finland was free from ice about 9 000 BP (Taipale & Saarnisto 1991). The Romuvaara area became free of ice about 9 600 BP (Kemiläinen 1982, 1986) and may have subsequently been covered by shallow water of the Sotkamo Ice Lake (Eronen & Lehtinen 1996). The maximum crustal downwarping during the last glaciation in the Romuvaara area may have been over 500 m (Eronen & Lehtinen 1996). Uplift rates cannot be determined for the Romuvaara area, since Romuvaara lay above the highest Baltic Lake shoreline and evidence from ancient shorelines is therefore lacking, but are likely to have been many times greater than the present rate of about 6 mm a year (Eronen & Lehtinen 1996).

Temperatures at 9 000 BP were probably close to those of today and summers are likely to have been warmer. The climate was at its warmest at 6 000 - 5 000 BP. Over the last 5 000 years the climate has slowly become generally colder, and from about 2 500 BP generally more humid. Temperature oscillations have also occurred, for example the period between 1 500 and 1 850 AP is known as the Little Ice Age, because of the lower average temperatures and very uncertain weather, whereas temperatures have risen throughout most of this century (Eronen 1990, 1991, 1996, Eronen & Zetterberg 1996).

The past development of vegetation in the Romuvaara area has been investigated by pollen analysis (Hyvärinen 1972, Donner 1995). Even though the climate about 5 000 - 6 000 BP was warmer than at present, it was not favourable enough for the development of deciduous hardwoods in the Romuvaara area, instead pine forests mixed with birch were followed by the later development of pine-spruce-birch mixed forests (Eronen & Lehtinen 1996).

3.4.2 Future climates

It is believed that the world's climate will be dominated by glaciations in the near few hundred thousand years in the same way as it has been for the past million years. This forecast is based on the last 20 years of investigation, which have concluded that future predictable changes in the Earth's orbit enable general predictions to be made of future climate changes. These predictions are based on climate models, such as ACLIN (Astronomical Climate Index) (Kukla et al. 1981), the Imbrie & Imbrie (1980) model of future

Scenario A

The climate at Scandinavia will gradually become colder, permitting the growth of glaciers at 5 000 AP (After Present) in the mountainous area of Norway and Sweden. Gradually the ice sheet will enlarge, so that c. 20 000 AP ice will cover the most part of Sweden and Finland and there will be permafrost in the ice-free areas. During a milder period between 25 000 and 50 000 AP the ice sheet will slowly become smaller, however, northern Finland will remain covered by ice. Permafrost will occur generally and periglacial conditions similar to those in present Greenland will dominate the ice-free areas. The previous period's cold climate will make the ice sheet respond rapidly during the cold glacial phase between 50 000 and 70 000 AP. Ice advance is expected to culminate at 63 000 AP with an ice sheet extending over the whole of Finland. The thickness of the ice sheet in the central part is expected to be 2 km. During the subsequent interstadial phase (a warmer period, which is not as warm as an interglacial), which will culminate in about 75 000 AP, the ice sheet will retreat, however, the Stockholm-Helsinki region is expected to remain covered by ice. During the maximum phase of the glaciation, 80 000 - 100 000 AP, the ice sheet is expected to extend to northern Poland and Germany, and have a maximum thickness of 2.5 km. The associated crustal downwarping will be 600 m in its central part and the global sea level 100 m below the present. The next warm phase, from 110 000 - 125 000 years AP, is expected to have a climate similar to the present, with the ice sheet melting almost completely. The global sea level will rise to the present level and the highest shoreline in areas around Stockholm and Helsinki will be 100 m above the present.

Scenario B

During the next 25 000 AP the climate at Scandinavia will become cooler, mountain glaciers will enlarge, permafrost will occur in mountainous areas and sea level will drop some meters globally. Between 25 000 - 50 000 AP the climate will become a little warmer than at present, mountain glaciers will melt, the areas of permafrost will reduce in size and sea level will rise some metres to above the present coastline. Around 65 000 AP a rapidly growing ice sheet will cover the whole of Finland and reach as far as Estonia. During the maximum phase of the glaciation, 80 000 - 110 000 AP, the ice sheet will advance and cover almost the whole of the Baltic basin. The next warmer period, 110 000 - 125 000 AP, will result in a retreat of the ice sheet, but the areas around Stockholm and Helsinki will remain covered by ice and the global sea level will be 25 m below the present. According to Crawford and Wilmot (1998) there will be the possibility of a return to climatic conditions similar to those of the present day after 120 000 AP.

The differences between these two scenarios are especially great for the period of the next 50 000 years. However, which ever scenario is assumed, the Romuvaara area is expected to be covered by ice some time during the next 100 000 years.

According to Forsström (1999) permafrost occurs both during the advance and retreat of ice sheets. The extent and thickness of permafrost during a glaciation phase could, however, vary considerable due to global as well as local conditions. It is therefore not possible at present to suggest a probable maximum permafrost depth, as it could vary from shallow depths to more than 500 m. Crawford & Wilmot (1998), however, suggest that permafrost will develop to the depth of 250 m at the Romuvaara area during the climatic cooling at 15 000 to 20 000 AP. Regardless of the depth of the permafrost, during the freezing process

dissolved ions will tend to be concentrated below the permafrost due to a process known as cryogenic metamorphism. If this process continues for a long time, the salinity of the groundwater beneath the permafrost might rise and a downward percolating saline front could develop and extend to great depths due to density inversion, along large-scale penetrating fracture zones (Ahlbom et al. 1990).

In the region close to the ice front, non-saline and oxidising glacial meltwater with high alkalinity may infiltrate to the bedrock due to the development of large groundwater heads (Ahlbom et al. 1990).

According to Bäckblom & Stanfors (1989) evidence of postglacial fault movements have been found in several parts of northern Sweden and Finland, where the postglacial movements have occurred by the reactivation of existing fracture zones. The postglacial reactivation of faults seems to occur at the early phase of rebound, or shortly after the ice front has left an area which had been covered by a thick ice sheet for an extensive period (Forsström 1999). No evidence has been presented to suggest that these reactivated faults extend to repository depths, and no evidence for the post-glacial reactivation of existing faults nor the formation of new faults has been found in the Romuvaara area (Ahlbom et al. 1990).

The average erosion during a glaciation cycle in the low relief areas of Finland and Sweden, including Romuvaara, is estimated to be 5 - 10 m (Ahlbom et al. 1990) with plucking as probably the most important erosional process related to ice sheets (Forsström 1999).

Climatic conditions immediately in advance of glaciation, when tundra and steppe are present and permafrost may form, result in a decrease in the groundwater recharge. The subsequent ice sheet may, therefore, advance over frozen ground. Immediately behind the frontal section of the ice sheet, which may be frozen to the surface of the ground, the ice will be warm based, i.e. glacial meltwater will be generated at the base of the ice sheet and groundwater recharge could result. The extent of any such recharge will be dependent on the transmissivity of the ground, which will be in turn related to the extent of any previous permafrost. Infiltration rates may be similar to those of the present day. The subsequent advance of the ice sheet, combined with an increased thickness of ice, will result in the ice at the site becoming cold based. Glacial meltwater will no longer be generated at the base of the ice sheet, the ice will be frozen onto the underlying rock and ice flow will take place predominantly within the ice sheet and not along its base. Deglaciation releases large volumes of water, local run-off is likely to be great and water will flow towards the ice margin on the surface of the ice and inside the ice in crevasses. Most water is likely, however, to be discharged in tunnels at the ice-rock interface. Large groundwater heads (up to 400 m) and the hydraulic conditions at the ice front may temporarily result in extensive infiltration of groundwater into the bedrock. At the same time great amounts of meltwater would be present at the surface and strongly dilute and disperse any groundwater discharged from below (Ahlbom et al. 1990).

3.5 Seismicity

This section summarises the main conclusions of the study of the seismicity of the Romuvaara area (Saari 1999). The study is based on the latest updating of the earthquake catalogue for Northern Europe (Ahjos & Uski 1992). The data set has been homogenised by excluding the events below magnitude $M_L = 1.5$ (M_L = Richter's local magnitude scale) and has also been divided into two subsets, macroseismically- (1542 - 1964) and instrumentally-located (1965 - 1997) earthquakes, representing locational accuracies of the order of 20 - 100 km and 5 - 10 km, respectively. The seismic characteristics of Finland suggest that an area within a distance of 500 km from the Romuvaara site is considered large enough to include all significant seismic events.

Earthquakes in the Romuvaara area are small and sparse, even by the standards of the Fennoscandian Shield. The nearest areas of higher seismic activity are in the Bothnian Bay region in the west (Fig. 3.5-1), in western Lapland to the NW as well as in northern Bothnia-Kuusamo and the White Sea regions to the north (Fig. 1 - 1). In addition, a NW - SE oriented belt of relatively high seismic activity lies south from the site: from the southern part of the Bothnian Bay towards Ladoga (Saari 1998). All significant ($M \geq 3.5$) earthquakes in the region seem to relate to the above mentioned areas (M = Magnitude scale in general). The largest events of the study area (1626, $M = 5.1$ and 1967, $M = 5.2$) occurred in the White Sea about 300 km from the Romuvaara site (Fig. 1 - 1). Romuvaara is within the belt of lower seismicity, which is separated by more than 100 km from the northern Bothnia-Kuusamo zone and the southern Bothnian Bay-Ladoga zone.

Possible seismic and aseismic movements of the bedrock are likely to occur along existing fractures or fracture zones. A thorough mapping of the fracture zones within a radius of 200 km from Romuvaara was performed by the Geological Survey of Finland (see Fig. 3.5-1). The vicinity of the investigation site is dominated by long, NE - SW oriented, I-class fracture zones (see Table 2.5-1). The other orientations for fracture zones of N - S and SW - NE, are less common. Romuvaara is at the northern end of a long, 1 200 km² bedrock block, and lies approximately 8 km from the nearest I-class fracture zones (Fig. 3.5-1).

The area within a distance of 100 km from Romuvaara is characterised by low seismicity with relatively small earthquakes. The area includes 9 events with a magnitude of $M = 2.2 - 3.3$. The nearest event (1971, $M_L = 2.4$) occurred 35 km west from the site. This event and the events north from it seem to be related to the N - S oriented Kuhmo greenstone belt (see Fig. 3.2-1) running towards Kuusamo.

Altogether, 124 earthquakes have occurred within a distance of 200 km from Romuvaara, over a period of 370 years (1626 - 1996). In general, macroseismically- (63 events, $M = 2.7 - 4.7$) and instrumentally-located (61 events, $M_L = 1.5 - 3.3$) events obey the same spatial distributions. The clear majority of the events can be associated with the northern Bothnia-Kuusamo zone in the northwestern quadrant (Fig. 3.5-1). The other clustering of seismicity, over 150 km SW from Romuvaara is related to the southern Bothnian Bay - Ladoga zone. The segment east from Romuvaara is almost aseismic.

The most pronounced clustering of seismicity is in the Kuusamo area (Fig. 3.5-1). In this area is the 365 Ma old Iivaara alkaline intrusion, which is one of the youngest intrusions in Finland. In addition, several I-class fracture zones intersect the Kuusamo area, and both these geological characteristics are indicative of a relatively weak bedrock.

One of the I-class fracture zones of the Kuusamo area runs through the other clustering of seismicity in Puolanka. According to instrumental recordings, this fracture zone seems to continue NE towards the White Sea. In that area, over 200 km from Romuvaara, is a NW-SE-oriented chain of epicenters (Fig. 3.5-1).

The most important earthquakes in the area are located 115 km (1902, $M = 4.7$) and 145 km (1626, $M = 4.6$) west from the Romuvaara site. The events are located in the Lake Oulujärvi area, which was largely unpopulated, especially in 1626, and the location accuracy of these events is, therefore, rather poor. There has been only one earthquake (1977, $M_L = 2.6$) in that area since the beginning of the 19th century, and it is, therefore, reasonable to assume that the true location of these previous events is probably closer to the instrumentally-located epicenters, for example in Puolanka or Kuusamo. However, the NW-SE oriented I-class fracture zone running through the three indefinite epicenters (1626, 1902 and 1911) ($M \geq 4.0$) cannot be ignored when the seismic risk of the Romuvaara site is considered. This zone of weakness has branches of fracture zones, which may be associated with the 1971 and 1983 epicenters, as well as with the I-class fracture zones bordering the block which includes the Romuvaara site (Fig. 3.5-1).

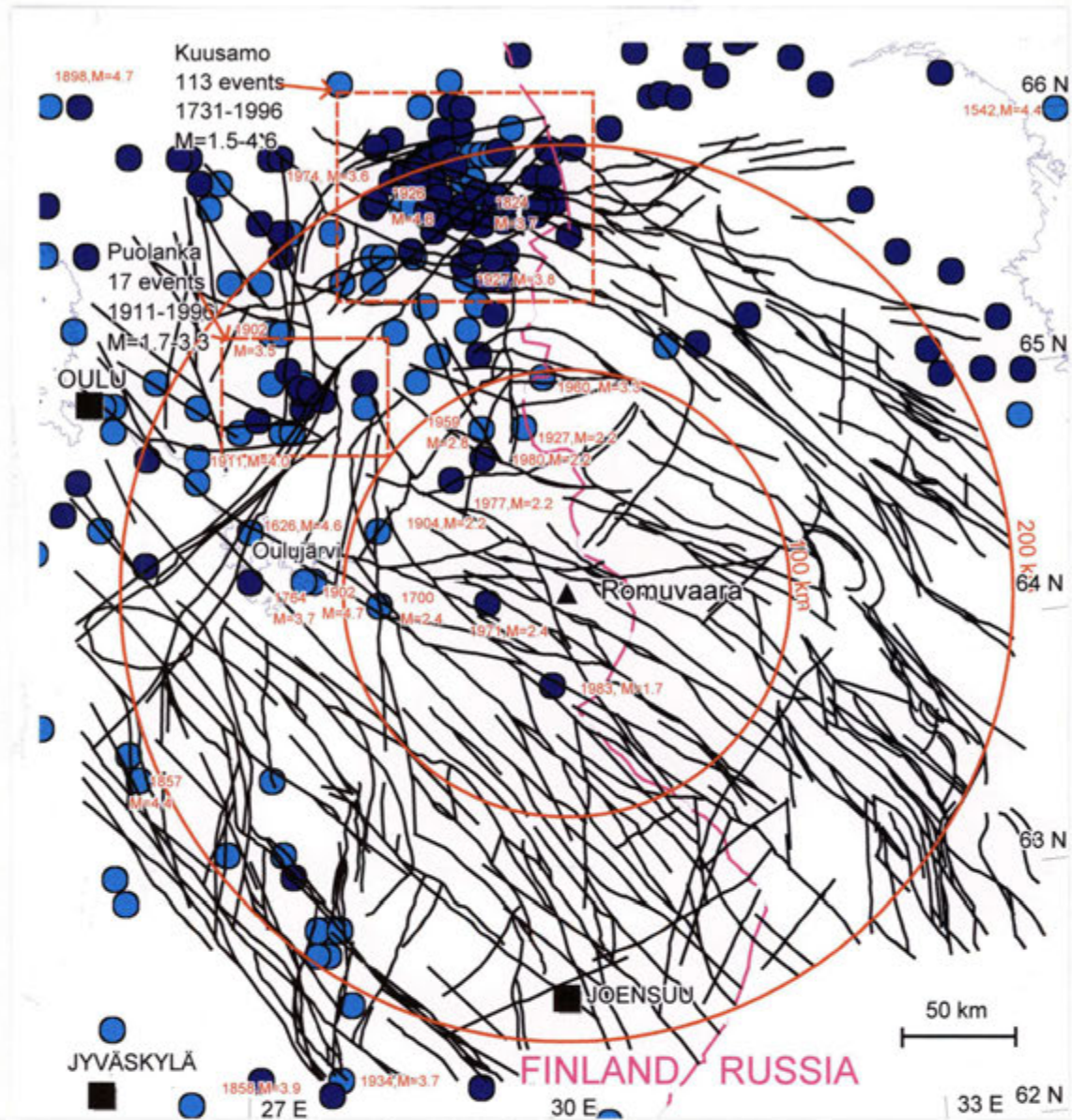


Figure 3.5-1. I-class fracture zones and earthquake observations (Ahjos & Uski 1992) in the Romuvaara area. Romuvaara is marked by a triangle. Macroseismically- (1542 - 1965) and instrumentally-located (1965 - 1997) earthquakes are shown by light and dark blue filled circles, respectively. Years of occurrence and magnitudes for the closest (distance < 100 km) and largest ($M \geq 3.5$) events are given.

4 GEOLOGY

4.1 Rock Types

The bedrock of the study site consists of migmatitic tonalite, leucotonalite and mica gneisses, which are cut by felsic and mafic dykes (Fig. 4.1-1). Determination of rock types has been based on visual, microscopic and lithogeochemical investigations of rocks in outcrops, investigation trenches and core samples (Paulamäki 1987, 1995, Kärki 1990, 1995, Lindberg & Kukkonen 1988, Lindberg & Paananen 1989, 1990, 1991, Gehör et al. 1996a, b). The rock types are named by reference to a QAP diagram by determining the proportions of quartz (Q), potassium feldspar (A) and plagioclase (P). Since only a small portion of the bedrock is exposed (224 exposures, usually less than 20 m² in area), the maps presented in Figures 4.1-1 and 5.2-3 are an interpretation, which combines the direct observations of the rock types and their contacts in outcrops, investigation trenches and boreholes with the interpretations of the structural elements and the geophysical ground survey (magnetic, electromagnetic and gravimetric) and airborne geophysical measurements (magnetic, radiometric and VLF). The outcrops and the deep boreholes are concentrated in the western and southwestern parts of the area, and, consequently, the reliability of the map is best there. The eastern part of the area is very poorly exposed, and the map in this area has been prepared mainly on the basis of a few shallow boreholes and geophysical interpretations.

Grey, banded and migmatitic *tonalite gneiss* (Fig. 4.1-2) is the most abundant rock type in the eastern and western parts of the study site. The older component, or palaeosome, of the migmatite consists of alternating leucocratic, quartz-feldspar rich bands and mesocratic, mica ($\pm$ amphibole) rich bands (Paulamäki 1987, Kärki 1990). The palaeosomes are tonalites, granodiorites or sometimes granites in their modal mineral composition, containing 35 - 50% plagioclase, 25 - 45% quartz, 5 - 40% potassium feldspar and 5 - 15% biotite (Lindberg & Kukkonen 1988, Lindberg & Paananen 1989, 1990, 1991, Gehör et al. 1996a, b). In the granitic varieties the mineral composition is most likely secondary and is due to K-metasomatism. The younger component of the migmatite, or neosome, is tonalitic to granitic in composition and occurs as veins a few centimetres in width. The neosome typically accounts for not more than 10 - 15% of the total volume of the rock and is a product of at least five deformation phases (Kärki 1990). The tonalite gneiss can be correlated with the migmatitic tonalite/trondhjemite gneisses in the surrounding areas (see Section 3.2).

The major and trace element compositions of the tonalitic and granodioritic palaeosomes (Table 4.1-1) are quite similar to typical Archean grey gneisses (c.f. e.g. Martin 1994). The compositions of granitic palaeosomes are more variable than those of the other palaeosomes.

Figure 4.1-1. Geology of the study site. The cross-section A-A' is shown in Fig. 4.1-4. The contours are at 5 m intervals.

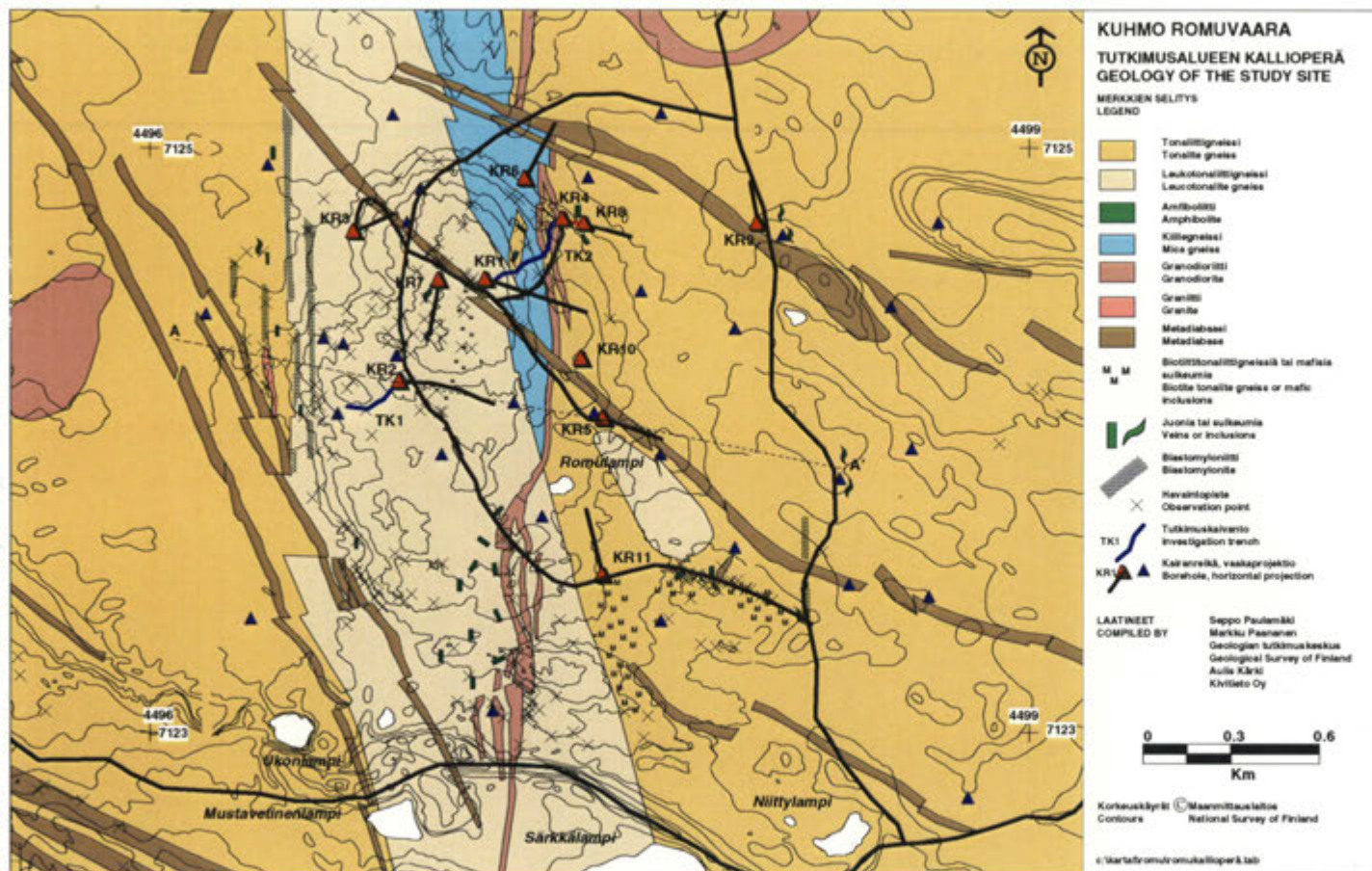


Table 4.1-1. Representative analyses of the main rock types at Romuvaara. TONGN = tonalite gneiss, LTONGN = leucotonalite gneiss, MGN = mica gneiss, GRDR = granodiorite, AFBT = amphibolite, MDB = metadiabase. Analyses 1 - 3, 5 - 7 after Gehör et al. (1996a), analysis 4 after Lindberg & Paananen (1991), analysis 6 after Lindberg & Kukkonen (1988) and analysis 8 after Lindberg & Paananen (1990). X-ray fluorescence (XRF) analyses, unless otherwise stated.

Sample	1	2	3	4	5	6	7	8
Borehole	KR8	KR8	KR7	KR6	KR2	KR1	KR2	KR5
Depth (m)	76.05	193.70	46.10	56.00	675.85	86.00	931.70	254.00
Rock type	TONGN ¹⁾	TONGN ²⁾	LTONGN	MGN	GRDR	AFBT	AFBT	MDB
SiO ₂ %	68.7	69.3	73.0	63.2	64.6	47.1	58.4	49.6
TiO ₂ %	0.335	0.365	0.25	0.45	1.16	0.88	0.676	1.53
Al ₂ O ₃ %	15.1	15.7	14.5	16.6	15.0	15.4	15.2	13.8
Fe ₂ O ₃ %	2.92	2.55	1.53	5.50 ³⁾	4.44	9.87 ³⁾	6.74	13.3 ³⁾
MnO %	0.04	0.02	0.03	0.08	0.03		0.13	0.22
MgO %	1.56	1.16	0.84	2.19	1.14	6.63	4.14	5.54
CaO %	3.01	2.95	3.98	2.89	2.32	10.60	7.54	9.90
Na ₂ O %	4.59	4.71	4.41	4.96	3.50	2.93	3.98	2.46
K ₂ O %	1.73	2.13	0.82	2.69	4.88	1.17	0.94	0.57
P ₂ O ₅ %	0.12	0.11	0.03	0.24	0.33	0.1	0.24	1.53
Th ppm ⁴⁾	8.8	6.4	3.6	9.8	31	2.2	3.2	1.7
Rb ppm	54	76	36	98 ⁴⁾	146	40 ⁴⁾	33	0
Y ppm	13	<10	20	3	26		12	28
Ba ppm	485	654	128	800 ⁶⁾	2150	140	301	100 ⁶⁾
Zr ppm	113	174	125	200 ⁶⁾	793	70	118	200 ⁶⁾
Ti ppm	2010	2190	1500		6950		4050	
Nb ppm	<10	<10	<10	20	13		<10	17
P ppm	520	480	130		1440		1050	1900 ⁶⁾
Sr ppm	403	412	389	400 ⁶⁾	267	360	249	20
Cs ppm ⁴⁾	<1	1	1	1.4	2	<1	<1	<0.4
U ppm ⁴⁾	0.5	0.5	1.1	1.4	<0.5	<0.6	<0.5	0.3
Cl ppm ⁵⁾	302	231	200	220 ⁷⁾	191		214	940 ⁷⁾
Br ppm ⁴⁾	6	5	1	3.3	<1	2.8	2	<10
Cr ₂ O ₃ %	<0.01	<0.01	<0.01	0	<0.01	0.33	0.01	0.01
S % ⁸⁾	0.03	0.04	0.01		0.08		0.05	
Total	98.8	99.7	100.5		98.8		98.6	

- 1) tonalitic palaeosome
 2) granodioritic palaeosome
 3) FeO
 4) neutron activation analysis

- 5) ion selective electrode
 6) as oxide
 7) XRF
 8) sulphur analyser (LECO)

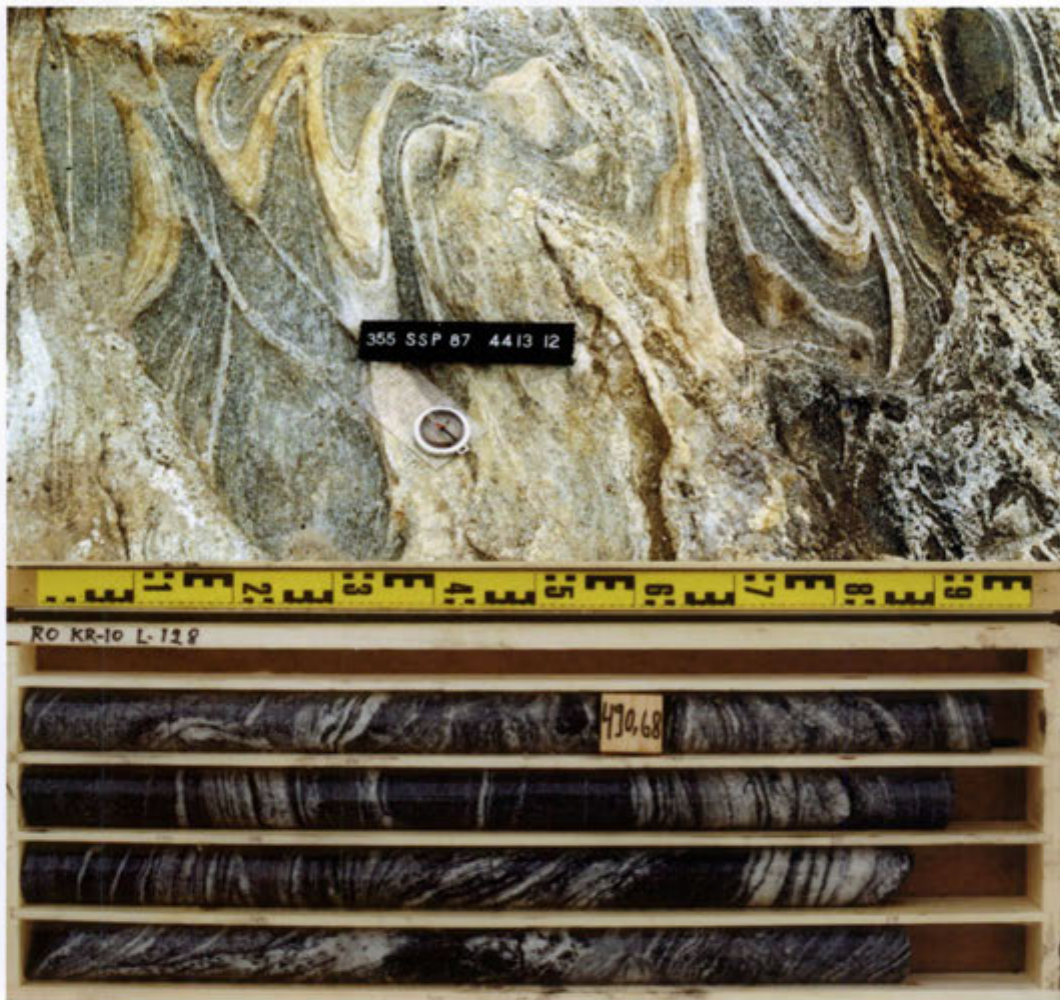


Figure 4.1-2. *Migmatitic tonalite gneiss on the outcrop and as core drilled rock samples.*

The predominant rock type in the central part of the area is *leucotonalite gneiss* (Fig. 4.1-3). Its palaeosome is commonly only slightly banded and the amount of neosome is typically smaller than that in the tonalite gneiss (Paulamäki 1987, Kärki 1990). The rock has a nebulitic appearance, where the palaeosome and the neosome are not always distinguishable with certainty. It is tonalitic or granodioritic in its modal composition, consisting of plagioclase (45 - 50%), quartz (30 - 40%), potassium feldspar (5 - 10%) and biotite (3 - 10%) (Lindberg & Kukkonen 1988, Lindberg & Paananen 1989, 1990, 1991, Gehör et al. 1996a, b). The eastern contact of the leucotonalite gneiss with the tonalite gneiss and mica gneiss is interpreted as dipping 30 - 45° westwards based on the depths of its intersection in boreholes KR1, KR2 and KR3 (Fig. 4.1-4) (Paulamäki & Paananen 1995a, Front et al. 1998). The leucotonalite gneiss is blastomylonitic near the western contact with the tonalite gneiss, which, based on the dip of foliation, dips approx. 75° westwards. Leucotonalite gneisses resemble the typical trondhjemites in their chemical composition (c.f. Barker & Arth 1976) (Table 4.1-1). The trace element composition differs clearly from the typical Archean tonalite gneisses (Gehör et al. 1996a).

Mica gneiss occurs in the northern part of the area lying between the tonalite gneiss and the leucotonalite gneiss. It is medium-grained, rather homogeneous and only slightly migmatitic rock, and contains 13 - 42% biotite, 30 - 54% plagioclase and 20 - 28% quartz. It sometimes contains inclusions, which have amphibole as the only mafic mineral, indicating that it might have originated as an amphibole-bearing tonalite gneiss (Kärki 1990). The mica gneiss is intersected by borehole KR1 between 90 - 316 m and 720 - 780 m and by borehole KR6 between 0 - 246 m. To depths of 300 m the eastern contact of the mica gneiss with the granodiorite dyke cutting it (see below) dips 65 - 70° to the west (Fig 4.1-4). At greater depths it is in contact with the tonalite gneiss and dips more gently (c. 30 - 45°) based on the dip of the foliation (Paulamäki & Paananen 1995a, Front et al. 1998). The western contact of the mica gneiss has been interpreted as following the leucotonalite gneiss and dipping 30 - 45° to the west (Fig. 4.1-4). The size and form of the lower mica gneiss in borehole KR1 is unknown, but according to the observation of the foliation in TV-logging, it is probably dipping gently (38°) to the SW (220°).



Figure 4.1-3. *Folded, cataclastic leucotonalite gneiss on the outcrop and as core drilled rock samples.*

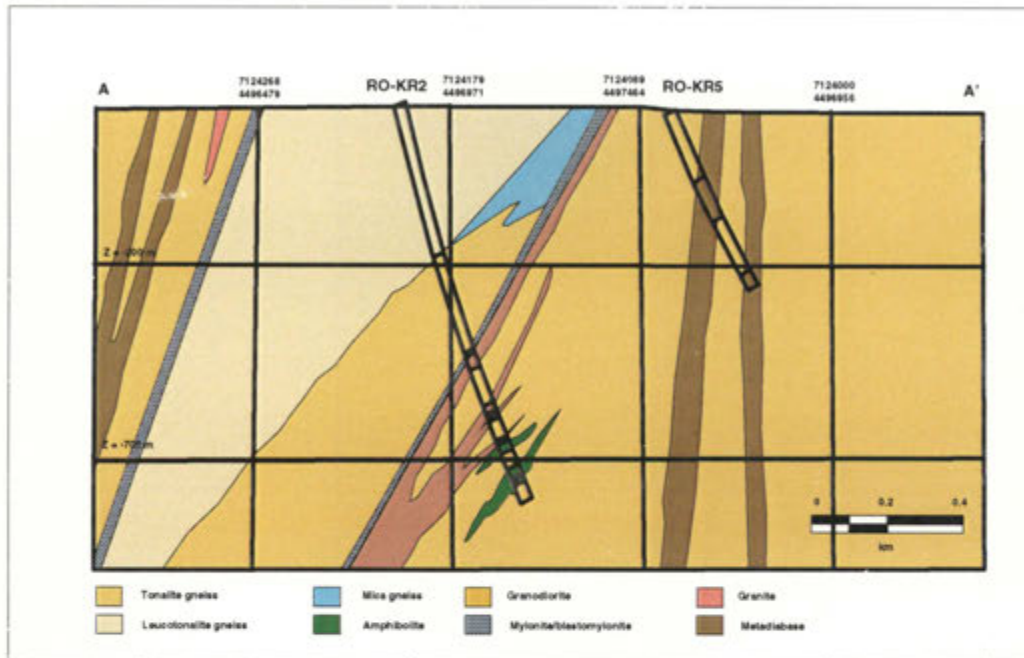


Figure 4.1-4. Schematic cross-section of the bedrock through the boreholes KR2 and KR5 (Front et al. 1998).

Amphibolites, consisting of green hornblende and plagioclase, occur in both the tonalite gneiss and the leucotonalite gneiss as narrow vein-like inclusions and larger xenoliths (Paulamäki 1987, 1995, Kärki 1990). The vein-like inclusions lie parallel to the banding of the host rock, and may be mafic veins (diabases) in origin. The amphibolites occurring in larger xenoliths are breccia migmatites, where the coarse-grained tonalitic and granitic neosome intersects the slightly-banded amphibolite palaeosome without any clear pattern. In boreholes KR2 and KR9 the amphibolites are locally altered to biotite and chlorite schists (Gehör et al. 1996a). Amphibolites present in borehole KR1 at 84 - 96 m, 795 - 837 m and 946 - 963 m, in borehole KR2 at 919 - 947 m and 972 - 1 040 m (Fig. 4.1-4) and in borehole KR4 at 140 - 197 m have been modelled as small, local units analogous to the observations on the outcrops, however, nothing certain can be said about their shape or location. Two lower amphibolites in borehole KR1 are believed to dip 20 - 30° to the SW based on the strike and dip of the foliation and the VSP reflection, which can be seen to extend for up to 200 m around the borehole (Front et al. 1998).

Biotite tonalite gneiss units, a few metres to perhaps tens of metres in diameter, are found in both the tonalite and the leucotonalite gneiss. Their simpler deformation history suggests that they may be younger than the tonalite and leucotonalite gneisses (deformation phase D₃ is the oldest event preserved within them, see Section 4.2). However, the age difference between the tonalite/leucotonalite and biotite tonalite gneisses is not indisputable (Kärki 1990). It is not possible to determine the distribution of biotite tonalite gneiss on the basis of outcrops, and their distribution is based on interpretation of magnetic and gravimetric ground surveys (Kukkonen 1988, Paananen & Paulamäki 1989).

The previously described rock types are cut by N-S trending *granodiorite* dykes, which can be clearly distinguished as magnetic anomalies on the geophysical maps (see Kukkonen 1988). The contacts of the dykes with the country rocks seen in the outcrops in the southern part of the area are either very sharp or brecciated (intrusive breccia). On the basis of the interpretation of the magnetic ground survey and the intersection of one of the dykes in boreholes KR1 and KR2, the dykes are shown to be dipping 65 - 75° to the west (Kukkonen 1988, Paulamäki & Paananen 1995a) (Fig. 4.1-4). In the boreholes the western margin of the country rock with this particular dyke is marked by a mylonite zone a few metres in width. The granodiorite dykes consist of two generations of dyke emplacement, with the older component being banded and glomeroporphyric in texture and containing deformed, intersecting veins (Kärki 1990), whilst the younger component is porphyric and less markedly deformed. The structural elements in the latter have been interpreted as representing the fifth deformation phase (see Section 4.2). The granodiorites are quite similar to the typical granodiorites in their chemical character and SiO₂ content, the major differences being the high K₂O content and low CaO content in the Romuvaara granodiorites (Gehör et al. 1996a) (Table 4.1-1). The trace element composition of the granodiorite is clearly different from that of the typical Archean gneisses, the concentrations of Rb, Ba, Th, Zr and Y being higher and the concentrations of U, Sr and Cs lower.

Tonalites and granites are present in some of the boreholes, both as medium-grained plutonic varieties containing biotite, and as aplitic veins consisting only of felsic minerals (Gehör et al. 1996a, b).

Medium-grained, almost undeformed *metadiabase* (Fig. 4.1-5) is the youngest rock in the study area. It cuts all the other rock types mainly as NW-SE trending, 20 - 40 m wide dykes, and can thus be correlated with the early Proterozoic, 2 200 - 2 100 million years old metadiabase dykes of the surrounding areas (see Section 3.2). The contacts of the dykes with the country rocks are sharp and usually fractured. The metadiabases are fine-grained near the contact, with chilled margins and sometimes contain unmelted Archean gneiss xenoliths near the contact (Paulamäki 1987). The metadiabase dyke crossing the middle of the study area is intersected by boreholes KR3 and KR5. In borehole KR3 the dyke dips 55° to the SW and in KR5 85 - 90° to the SW (Fig. 4.1-4) (Paulamäki & Paananen 1995a). The two dykes in the northern part of the area dip 85° to the SSW and 70° to the NE (Paananen & Paulamäki 1989, Paulamäki & Paananen 1995a). The magnetic ground survey suggests that the metadiabase dykes in the southwestern part of the area are dipping 75° to the SW (Fig. 4.1-4) (Kukkonen 1988).

The main minerals in the metadiabases are amphibole and plagioclase. In borehole samples two groups can be recognized, one having 15% plagioclase and 74 - 76% amphibole (borehole KR3) and the other 24 - 37% plagioclase and 56 - 72% amphibole (borehole KR5) (Lindberg & Paananen 1989, 1990). The metadiabases in borehole KR5 are rich in sphene (2.3 - 2.9%), which is lacking in the metadiabase intersected in borehole KR3.



Figure 4.1-5. The contact of a metadiabase dyke and leucotonalite gneiss.

4.2 Tectonics

The bedrock at Romuvaara, excluding the metadiabase, shows evidence of complex, polyphase Archean deformation. Based on refolding and cross-cutting relationships, six plastic and at least four brittle phases can be recognized (Fig. 4.2-1) (Kärki 1990, see also Anttila et al. 1990).

The oldest structural feature recognized is a penetrative metamorphic banding or gneissic foliation S_1 (Kärki 1990). It is folded isoclinally by F_2 folding of the second deformation phase (D_2) producing sharp fold hinges and intrafolial fold structures. The foliation now visible in the outcrops is a composite foliation S_1/S_2 . Migmatization began during this phase at the latest. Evidence for D_1 and D_2 can only be found in tonalite gneiss, leucotonalite gneiss and amphibolite, the other rock types being intruded at a later date.

The elements of the third deformation phase (D_3) vary from tight or isoclinal to chevron folds. Faults developed parallel to the axial plane of the folding (ENE-WSW) and tonalitic pegmatites occur parallel to the fault planes. The fourth deformation phase (D_4) produced quite open folds with subvertical, N-S trending fold axis. Partly brittle, partly ductile faults

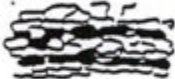
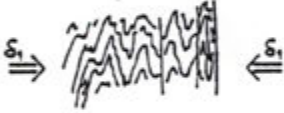
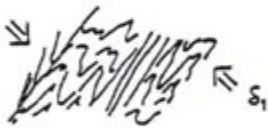
Deformation phase	Structure	Mean orientation	Intrusion event
			Tonalite, leucotonalite, protolith of amphibolite
D_1		S_1	Biotite tonalite
D_2		S_2	
D_3		$S_3=165/85^\circ$	
D_4		$S_4=270/90^\circ$	Granodiorite
D_5		$S_5=300/90^\circ$	Tonalite veins
D_6		$S_6=270/90^\circ$	Granite veins
			ca. 2500 Ma
d_7		$S_7=60/90^\circ$	Diabase
d_8		$S_8=330/90^\circ$	
d_9		$ST_9=30/90^\circ$	
d_{10}		$ST_{10}=0/90^\circ$	

Figure 4.2-1. Summary of the structural development of the bedrock at Romuvaara and related intrusion events (Kärki 1990). S = foliation, banding, axial plane or some other planar structure, ST = fault plane.

and pegmatite veins, typically less than 5 cm in width, occur parallel to the axial plane. The D_4 deformation has a zonal occurrence and the intensity of the folding varies distinctly from one zone to another. The fifth deformation phase (D_5) is similar to D_4 , but faulting and shearing are more dominant in the former. The most significant structures are NE-SW striking, vertical faults, shear zones and asymmetric folds. Pegmatite veins occur parallel to the axial plane. The structures of the sixth deformation phase (D_6) are left-handed, N-S striking, subvertical fault or shear zones showing blastomylonitic features. The width of the fault zones ranges from a few tens of centimetres to apparently tens of metres, consequently, it can be assumed that the most prominent of these zones are several kilometres in length. No earlier structures can be seen within the shear zones, the rock having been totally mylonitized.

The younger deformation events, post-dating D_6 , have produced faults cutting the older structures sharply. The faults have been classified according to their mutual intersections, the nature of the fault and their fracture fillings. The order of these latest events, referred to as $d_7 - d_{10}$, does not necessarily refer to their relative ages, since one deformation phase can generate individual faults running in different direction and cutting one another (Kärki 1990). The d_7 and d_8 faults (dip direction/dip: $60/90^\circ$ and $330/90^\circ$, respectively) are ductile or semi-ductile and the veins parallel to the faults are mainly composed of pegmatite. The d_9 and d_{10} faults ($30/90^\circ$ and $0/90^\circ$, respectively) are brittle and the veins related to the fault planes consist of epidote, quartz and feldspars. All these younger faults involve both horizontal and vertical movements.

The structures described above can mostly only be seen in the outcrop scale. It is not possible to identify larger scale structures because of the lithological homogeneity of the bedrock. The $d_7 - d_{10}$ fault planes can sometimes be seen in the site scale as discontinuities in the metadiabase and granodiorite dykes (see Fig. 4.1-1), whose distribution and orientation are mainly based on interpretations of the geophysical anomalies from the ground and aerogeophysical maps. Based on direct observations (boreholes, investigation trenches) and indirect evidence (vertical seismic profiling, borehole radar, electromagnetic measurements, seismic refraction and reflection soundings), nine of these site scale faults are included in the bedrock model either as certain or probable fracture zones (see Section 5.4).

4.3 Fracturing

4.3.1 Surface Fracture Studies

In the course of the geological mapping fracture measurements have been made both from the outcrops (Paulamäki 1987) and in two 150 m and 350 m long, 1 - 4 m wide investigation trenches (Kärki 1995, Paulamäki 1995). During the fracture mapping all the fractures, equal to or longer than one metre, were investigated. Strike and dip, rock type, length, form (straight or curved), type (tight, open or filled), width and infilling, where present, were recorded for each fracture. A total of 1 553 fractures were investigated. Fracture orientations were examined using Schmidt equal-area, lower hemisphere stereographic projection. In addition, the orientation data were also presented using rose diagrams.

The distribution of all fracture orientations measured in the outcrops and in the investigation trenches is shown in Figure 4.3-1 and that of different rock types in Figure 4.3-2 and 4.3-3. The main sets of fracture orientations by rock types in order of decreasing frequency are presented in Table 4.3-1. No clear main fracture directions can be seen when examining the

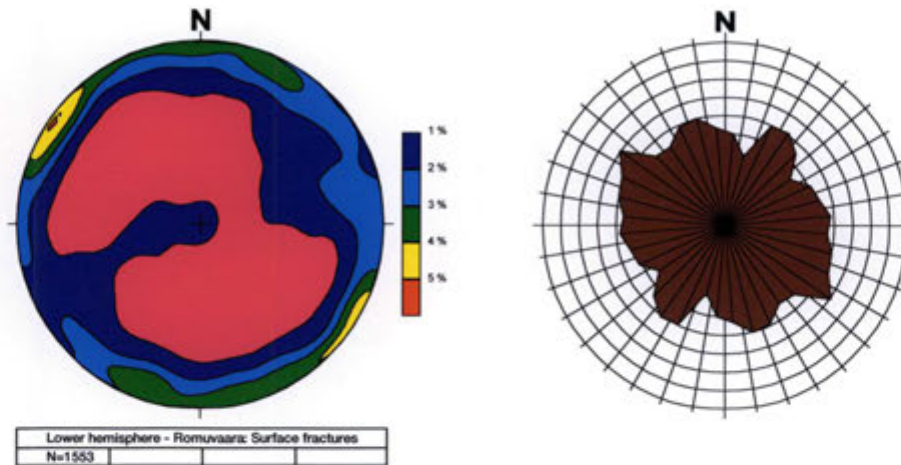


Figure 4.3-1. Distribution of fracture orientations measured in outcrops and investigation trenches TK1 and TK2 ($N = 1\ 553$), Schmidt equal-area, lower hemisphere projection and rose diagram (Front et al. 1998). Each ring in the rose diagram represents 5% of the distribution.

Table 4.3-1. Distributions of fracture orientations by rock types in outcrops and investigation trenches TK1 and TK2. TONGN = tonalite gneiss, LTONGN = leucotonalite gneiss, GRDR = granodiorite, MGN = mica gneiss (Front et al. 1998).

Rock type	Main sets fracture directions (°): mean* and orientation range	Dip direction/dip (°): mean* and orientation range
TONGN ($N = 310$)	I 065-085 (032-110) II 350-005 III 320-345	332-358/78-88 (302-020/70-90) 153-178/80-88 (122-197/76-90) 260-276/78-90 050-075/69-86
LTONGN ($N = 899$)	I 290-310 (255-320) II 020-045 (010-075) III 335-360	164-230/72-90 347-050/70-90 110-135/83-90 (100-157/76-90) 292-302/86-90 (280-347/80-90) 243-270/70-90
GRDR ($N = 115$)	I 265-310 II 000-035	173-220/65-88 351-042/76-86 089-131/76-90 269-307/80-90
MGN ($N = 170$)	I 345 (320-012) II 030-055	 255/69 (230-282/35-80) 120-143/76-88

* The mean is equal to the pole maximum on the Schmidt projection.

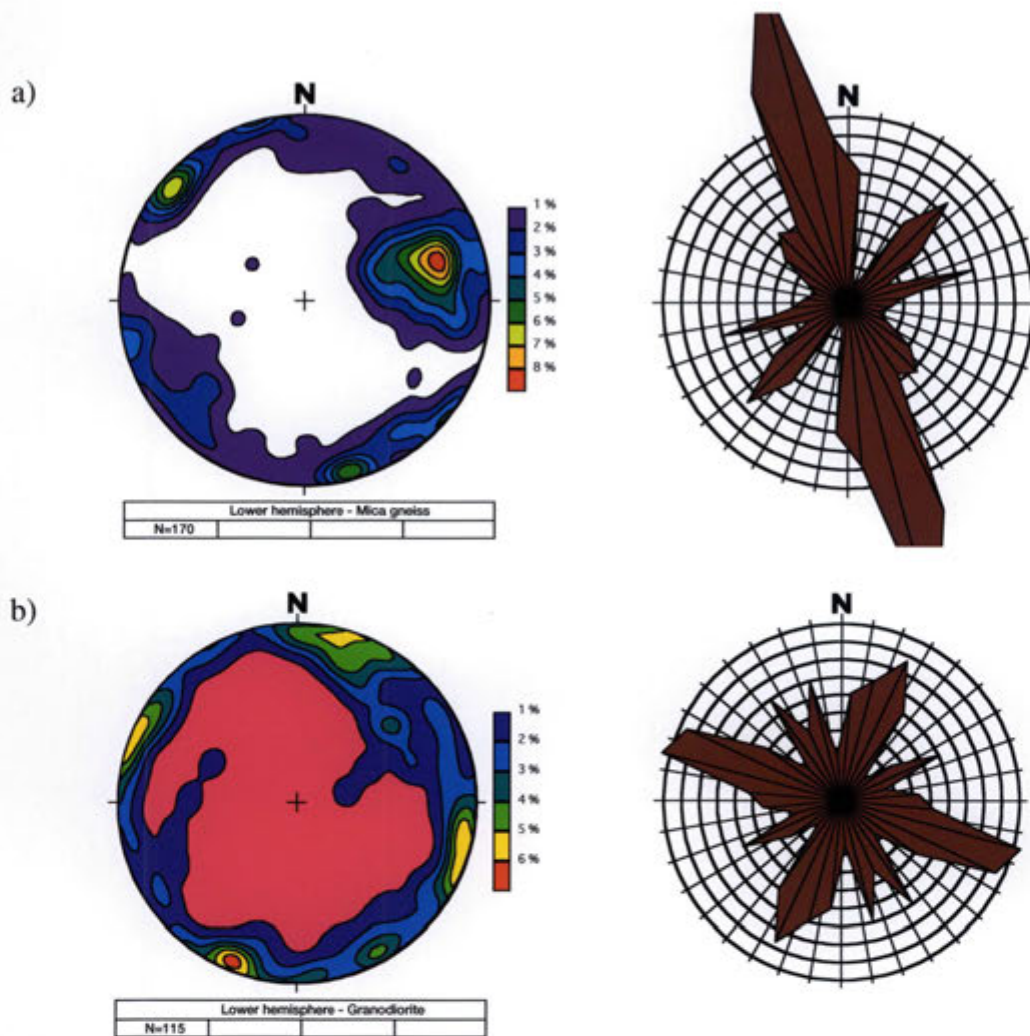


Figure 4.3-2. Distribution of fracture orientations by rock types measured in outcrops and investigation trenches TK1 and TK2 (Front et al. 1998). a) tonalite gneiss ($N = 310$), b) leucotonalite gneiss ($N = 899$). Schmidt equal-area, lower hemisphere projection and rose diagram. Each ring in the rose diagram represents 5% of the distribution.

combined fracture data. However, when examining the fractures by rock types, it can be seen that the fractures are mainly striking ENE-WSW in the tonalite gneiss (set I), NW-SE and NE-SW in the leucotonalite gneiss and granodiorite (sets I and II), and NNW-SSE in the mica gneiss (set I). The majority of the fractures are steep, almost 90% having a dip 70 - 90°. However, gently dipping or horizontal fractures are under-represented in these datasets, because of the rather flat surface of the outcrops and the limited access provided by the trenches. Instead, they are present in the drill core data described later in this section.

When examining statistically the relation of fractures to tectonic elements (see Section 4.2) it can be seen that fracture set I in the tonalite gneiss corresponds with the orientation of fault and fold planes of deformation phases D_3 and d_8 , whereas set II parallels the fault planes of D_4 and D_6 . In the leucotonalite gneiss and the granodiorite, fracture set II correlates well with the orientation of faults and shear zones of deformation phase D_5 . Set I in the leucotonalite gneiss and the granodiorite can also be correlated with the orientation of the fault planes in d_9 . Evidence from the outcrops clearly demonstrates that the main fracturing (set I) in the

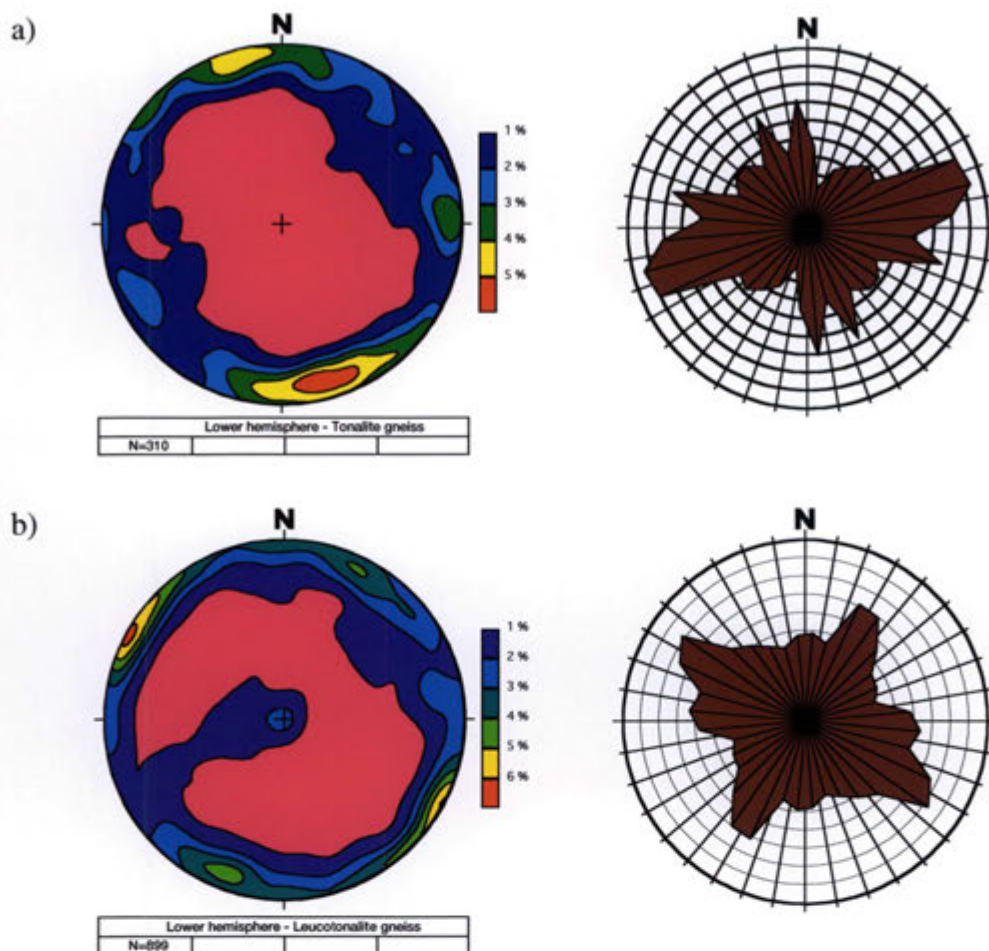


Figure 4.3-3. Distribution of fracture orientations by rock types measured in outcrops and investigation trenches TK1 and TK2 (Front et al. 1998). a) mica gneiss ($N = 170$), b) granodiorite ($N = 115$), Schmidt equal-area, lower hemisphere projection and rose diagram. Each ring in the rose diagram represents 5% of the distribution.

mica gneiss parallels the foliation/banding S_1/S_2 . Although the orientations of the fracture sets can be related statistically to the orientations of the structures produced during the plastic deformation phases, there is no direct genetic connection between them. Structures developed during the plastic deformation phase are hydraulically insignificant. They may, however, have acted as mechanically weaker planes, along which the fractures were later preferentially formed.

Fracture frequency was measured across each outcrop in N-S and E-W traverses. In investigation trenches the fractures cutting the median line of the trench were recorded. In the outcrops the average fracture frequencies are 0.4 fractures/m, 0.5 fractures/m and 0.7 fractures/m for the tonalite gneiss, leucotonalite gneiss and granodiorite, respectively (Paulamäki 1987). In the investigation trenches TK1 and TK2 the average fracture frequency for the leucotonalite gneiss is 3.0 fractures/m (Kärki 1995, Paulamäki 1995). In the investigation trench TK2 the average fracture frequencies are 1.7 fractures/m, 3.1 fractures/m and 1.8 fractures/m for the leucotonalite gneiss, mica gneiss and granodiorite, respectively. The fracture frequencies are much higher in the investigation trenches than in the outcrops, indicating that the outcrops probably represent the most intact (i.e. least

fractured) bedrock in the area, whilst the more fractured parts are unexposed. During the period of glacial erosion the more fractured bedrock has been eroded more deeply than the less fractured bedrock, and is now covered by glacial deposits.

There are no essential differences in fracture lengths between the rock types. The mean length of the fractures is 1.8 m in both the tonalite gneiss and the leucotonalite gneiss, 1.9 m in the mica gneiss and 1.5 m in both the granodiorite and the metadiabase. However, due to the relative small size of the outcrops, long fractures are under-represented in the analysis. The percentages of singly- and doubly-truncated fractures are, for example, 49% and 15%, respectively.

4.3.2 Fracturing in Core Samples

The fracturing in drill cores KR1 - KR11 was determined by measuring the proportion of broken rock and the numbers of fractures as a function of the depth and of the rock types (Pitkänen et al. 1989, 1990, Front et al. 1995, Luukkonen et al. 1997). According to the Finnish engineering geological bedrock classification (Gardemeister et al. 1976), which was used in describing and logging the core material, a core sample is regarded as broken, if the number of fractures is more than 10 fractures/m, if it is dominated by filled and/or open fractures, or if it is mesoscopically weathered (see section 2.5).

The broken sections of the Romuvaara core samples (KR1 - KR11) represent about 9% of the total length of the core material (5 579 m). In most of them (86%) the rock is densely fractured (>10 fractures/m), whilst 14% of the broken samples represent crush-structured rock (>10 fractures/m with grain- and clay-fillings).

There are no great differences between the rock types with respect to fracture frequencies. However, short metadiabase and amphibolite sections are slightly more fractured than the gneisses. The mean fracture frequencies in the main rock types, tonalite gneiss, leucotonalite gneiss and granodiorite, lie in the range of 2 - 4 fractures/m in the "intact" (i.e. least fractured) rock (Pitkänen et al. 1989, 1990, Front et al. 1995, Luukkonen et al. 1997). Table 4.3-2 lists the mean fracture frequencies with respect to the various types of fracture (open, filled and tight) present in intact rock. Open fractures, which are the most significant in determining the hydraulic conductivity of the bedrock, are abundant in the upper parts of the boreholes (to depth of 100 - 200 m), but typically single open fractures can be found at all depth levels in every borehole. The most common low-temperature fracture-filling minerals are calcite, Fe sulphides, Fe hydroxides and clay minerals (kaolinite, montmorillonite and other smectites) (see Table 7.3-1). The calcite-Fe hydroxide-clay mineral assemblage is the most abundant low-temperature fracture mineral assemblage in the core samples (Gehör et al. 1996a). The fracture fillings are described in detail in Section 7.3.

Oriented cores were taken in connection with the drilling and the observations examined using Schmidt equal-area, lower hemisphere stereographic projection. The most typical fracture orientation in the boreholes is horizontal or dipping gently to the NE (Front et al. 1997). In addition, the leucotonalite gneiss has fractures dipping gently between SW and NW (240 - 320/0 - 30° dip) and the tonalite gneiss has fractures dipping to the S or SW

Table 4.3-2. Mean fracture frequencies (fractures/m) of open (Op), filled (Fi) and tight (Ti) fractures in the intact bedrock sections of boreholes KR1-KR11 (Front et al. 1998).

Borehole	Depth (m)	Op	Fi	Ti	Tot
KR1	0 - 500	0.31	0.59	1.50	2.40
	500 - 974	0.04	0.66	1.61	2.31
KR2	0 - 500	0.16	0.18	1.59	1.93
	500 - 1 100	0.40	0.63	1.84	2.87
KR3	0 - 477	0.34	0.36	1.82	2.52
KR4	0 - 500	0.35	0.34	1.97	2.66
KR5	0 - 500	0.25	0.17	2.03	2.45
KR6	Not analyzed				
KR7	0 - 302	1.17	0.52	2.03	3.72
KR8	0 - 301	0.90	0.67	3.81	5.38
KR9	0 - 300	0.88	0.83	2.29	4.00
KR10	0 - 500	0.35	0.61	2.10	3.05
	500 - 618	0.27	0.25	1.67	2.19
KR11	0 - 500	0.51	1.92	1.62	4.05
	500 - 604	0.00	0.60	0.95	1.55

(180 - 210/10 - 30° dip). The most common fracture orientation with moderate dip is 230 - 280/30 - 70° dip, which occurs in the tonalite gneiss. The fractures with steep dip have orientations of 170 - 180/80 - 90° dip in the tonalite gneiss and 210 - 230/60 - 80° dip in the leucotonalite gneiss. The orientations of the steeply dipping fractures correlate well with the directions measured in the outcrops.

Potentially water-conductive fractures are under-represented in the oriented cores, because of the lack of data in the densely fractured sections. It is difficult to ascertain, using only drill core data, whether a fracture is open or hydraulically tight. Highly fractured sections of cores are usually fragmented, or core loss has occurred, making the detection of possible water-conductive fractures or fracture zones difficult or impossible to achieve. TV-logging affords the possibility of making *in situ* observations of the fracturing and TV-logging performed in boreholes KR1, KR8 and KR10 (Stråhle 1996) has significantly increased information on the fracture types and their orientations.

This new oriented fracture data from TV-logging supplements and supports the general picture of the fracturing determined earlier. Figure 4.3-4 shows the orientation of potentially water-conductive fractures in boreholes KR1, KR8 and KR10. In borehole KR1 the open fractures in the tonalite gneiss dip between S and W the pole maximum having an orientation of 265/50°. The short amphibolite section in borehole KR1 consists of two orthogonal fracture orientations: 20/70° and 215/50°. In borehole KR8 the open fractures form an

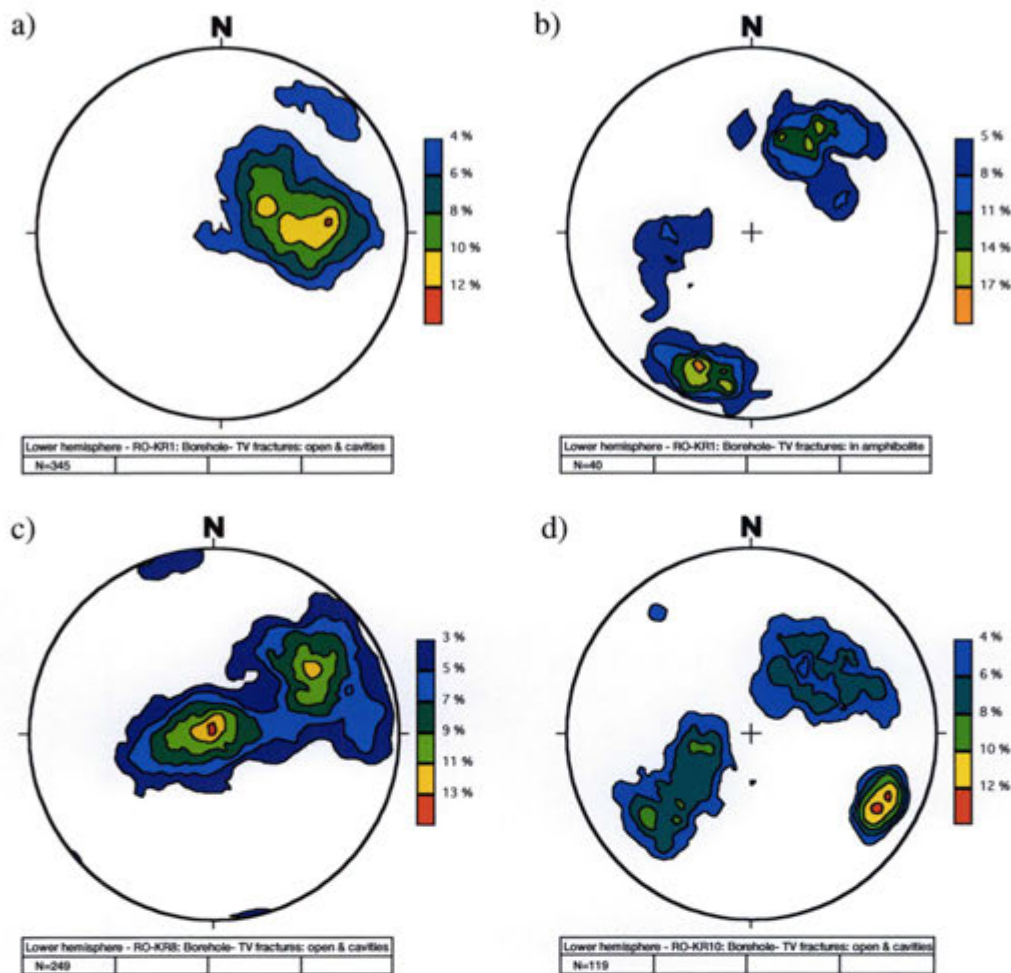


Figure 4.3-4. Orientation of potentially water-conductive fractures in boreholes KR1, KR8 and KR10 according to TV-logging, Schmidt equal-area, lower hemisphere projection. a) KR1: gneisses, b) KR1: amphibolites, c) KR8, d) KR10 (Front et al. 1995).

almost orthogonal system with three main fracture orientations: horizontal, 240/55° and 165/85°. The fracture orientation 240/55° correlates with the borehole radar reflections (190 - 240/40 - 77°) from borehole KR8 (Front et al. 1995). In the vertical borehole KR10 the maxima of the open fractures have three orientations. The most prominent cluster of open fractures is 300/70° imitating the local structure R13. The other two maxima have more variation both in strike and in dip.

4.3.3 Combined Fracture Data

Since the fracture data obtained from both the rock outcrops and drill cores are biased by the orientation and scale of both the outcrops and the borehole, a correction method was developed to reduce this bias by compensating for the under-represented fractures (Paananen & Paulamäki 1989, Paulamäki & Paananen 1995a). The outcrop and core data were combined for the three-dimensional analysis. In the earlier investigation stages the area was divided into sub-areas on the basis of lineament interpretation, and the main fracture orientations then determined for each sub-area. Further investigations have resulted in a

better knowledge of the location and orientation of fracture zones and it has been realized that this initial sub-division is no longer valid. Moreover, in some of the sub-areas scaling problems existed because of the significant imbalance that existed between the extent of the outcrop and drill core data. Instead, fracture data were chosen, which could be interpreted to represent the study site as a whole (Front et al. 1998). The fracture data from borehole KR1 and investigation trench TK2 were chosen for the three-dimensional analysis of fracturing, since they lie close to each other in the central investigation area and have a similar distribution of rock types.

Schmidt equal-area, lower hemisphere stereographic projections were prepared based on the corrected and combined fracture data (a total of 18 071 fractures) (Fig. 4.3-5 a, b). Since definition of the fracture maxima from the stereographic projections is often a subjective matter, a method was developed for the systematic examination of the data. The method involves the division of the fractures into classes at 10° intervals according to their orientation (dip direction) and dip, i.e. values $5 - 14^\circ$ are given the value 10° , values $15 - 19^\circ$ the value 20° etc., resulting in a total of 307 classes. The percentage share of the data is then calculated for each class. Those classes representing 50% of the fracturing when summed up in descending order of magnitude, are defined as the main fracture classes (Fig 4.3-5 c).

The classified data indicates that fractures with steep dips ($70 - 90^\circ$) having the following predominant dip directions $280 - 360^\circ$, $110 - 140^\circ$, $200 - 250^\circ$ and $170 - 180^\circ$ dominate the data. Fractures with moderate or gentle dips can be observed in the directions $230 - 290/40 - 60^\circ$, $160 - 200/30 - 40^\circ$ and $10 - 80/20 - 40^\circ$. Steeply dipping fractures account for 51% of all fractures, whilst the proportions of moderately and gently dipping fractures are 33.0% and 16% respectively.

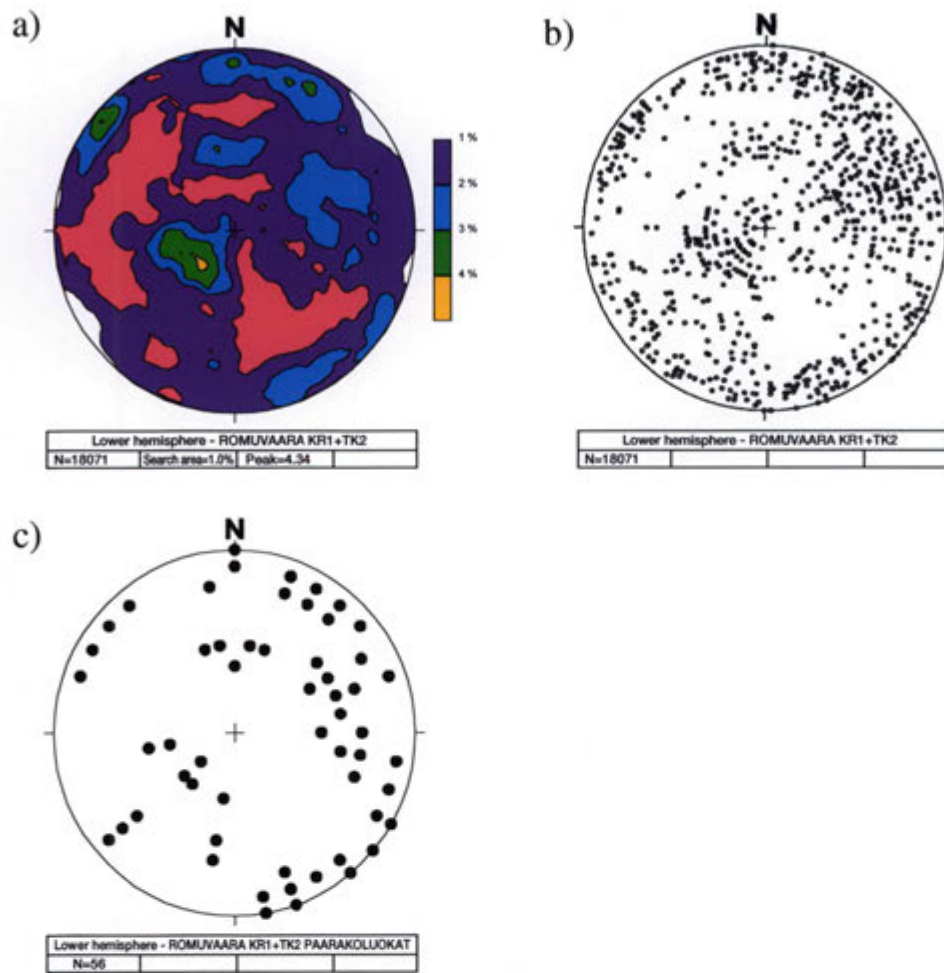


Figure 4.3-5. Corrected and combined fracture data (a and b) and the main fracture classes (c), borehole KR1 + investigation trench TK2. Schmidt equal-area, lower hemisphere projection (Front et al. 1998).

4.4 Rock Mechanical and Thermal Properties

Knowledge of rock mechanical and thermal properties are of importance when planning a deep repository. The rock strength, in situ state of stress and the stress-strain behaviour of the rock affect the choice of repository depth, as well as the shape and orientation of the deposition tunnels and disposal holes. The thermal properties of the rock must be taken into consideration, too, because temperatures are expected to increase in the immediate vicinity of the repository due to the radiogenic heat produced by the spent fuel.

4.4.1 Strength Properties

The strength properties of the different rock types have been studied by carrying out preliminary loading tests in the field with more detailed tests taking place in the laboratory. Table 4.4-1 presents the mean values for the uniaxial compressive strength (σ_{ucs}), tensile strength (σ_t), Young's modulus (E) and Poisson's ratio (ν) (Matikainen & Simonen 1992, Kuula 1994, Tolppanen et al. 1995, Johansson & Autio 1995, Heikkilä & Hakala 1998). The majority of the tests took place on tonalite gneiss which is the dominant rock type at Romuvaara. The large deviation in the strength values is a good reflection of the heterogeneous nature of the rocks. In particular, the concentration of mica in layers tends to decrease the rock strength, and this is the reason for the mica gneiss being the weakest rock type in the area. The values presented in Table 4.4-1 are those measured on dry rock samples, and strength values are lower for water-saturated samples of tonalite gneiss by 20 - 30%. Samples tested under confining pressure exhibit considerably higher strength values, as expected.

4.4.2 In Situ State of Stress

In situ stresses have been measured in four deep boreholes (KR1, KR2, KR3 and KR10) both by hydraulic fracturing and also by overcoring methods (Klasson & Leijon 1990, Ljunggren & Klasson 1996). The results show that the stresses increase with depth, with the maximum horizontal stress (Sig-H) having a value of about 28 - 30 MPa at a depth of 500 m (Fig. 4.4-1). The maximum principal stress is sub-horizontal with an average dip of nine degrees and is oriented about south-east - north-west over the depth interval 250 - 450 m, rotating to lie approximately east - west at greater depths (Fig. 4.4-2).

Table 4.4-1. Strength and deformation properties of the rock types at Romuvaara. Values presented are arithmetical means, standard deviation is given in brackets, n = number of samples.

Rock type	Uniaxial compressive strength σ_{ucs} (MPa)	Tensile strength σ_t (MPa)	Young's modulus E (GPa)	Poisson's ratio ν
Tonalite gneiss	197.4 (51.4) $n=26$	11.0 (3.0) $n=25$	72.7 (7.0) $n=40$	0.26 (0.06) $n=40$
Leucotonalite gneiss	214.1 (41.6) $n=6$		75.9 (4.3) $n=6$	0.28 (0.03) $n=6$
Mica gneiss	99.4 (11.1) $n=6$		49.9 (10.0) $n=6$	0.29 (0.05) $n=6$
Granodiorite	171.6 (2.7) $n=2$		70.0 (0.1) $n=2$	0.3 (-) $n=2$
Metadiabase	239.9 (101.7) $n=3$		100.5 (8.7) $n=3$	0.28 (0.01) $n=3$

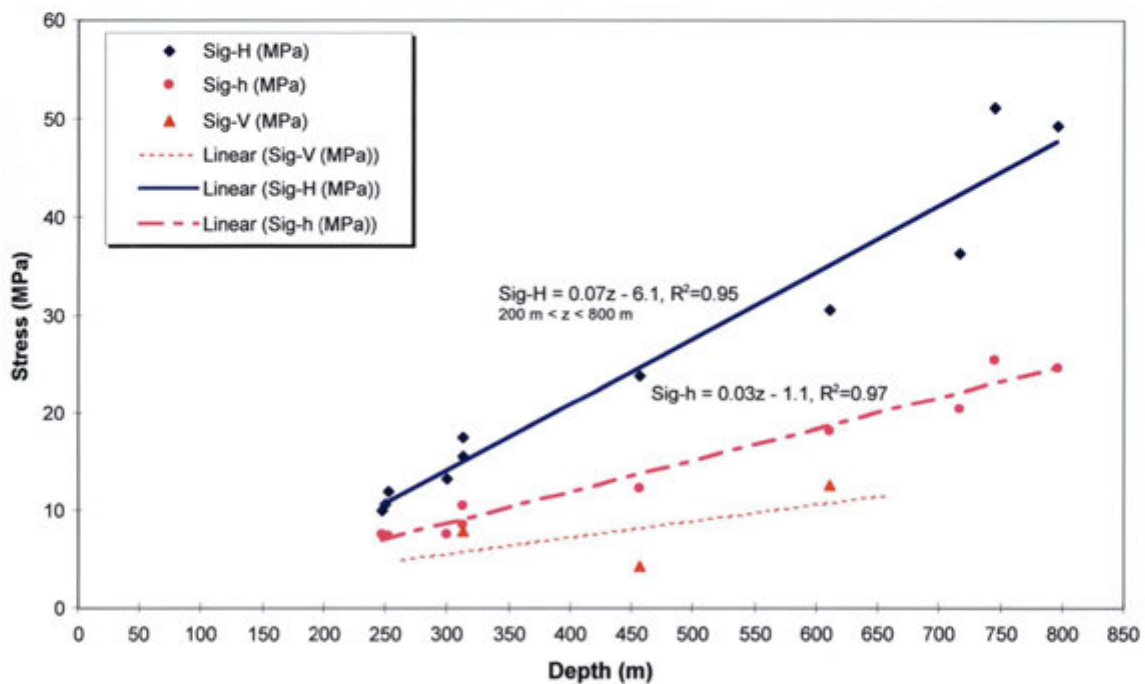


Figure 4.4-1. The magnitudes of maximum and minimum horizontal (Sig-H, Sig-h) and vertical (Sig-V) in situ stresses with depth at Romuvaara.

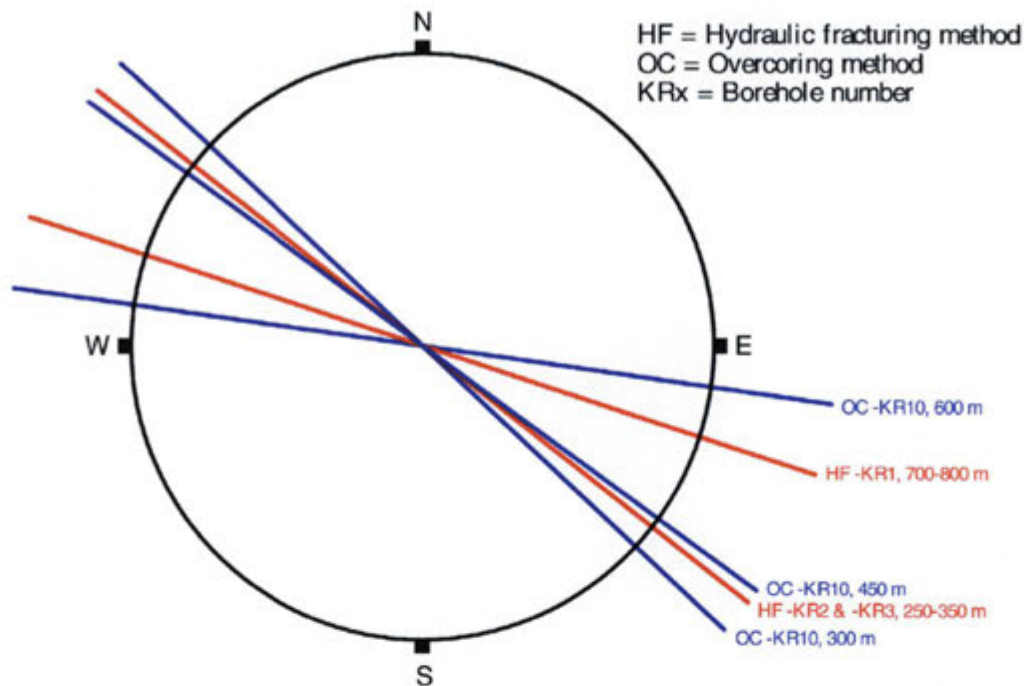


Figure 4.4-2. The orientation of the maximum horizontal in situ stress (Sig-H) at Romuvaara.

4.4.3 Thermal Properties

The thermal properties of rock samples taken from four deep boreholes (KR1, KR3, KR4 and KR5) have been studied in laboratory (Kjørholt 1992, Kukkonen & Lindberg 1995, 1998). The means of the thermal conductivity, specific heat capacity, thermal diffusivity and coefficient of thermal expansion for the different rock types are presented in Table 4.4-2.

The results indicate that the bedrock of Romuvaara is relatively homogeneous as regards its thermal properties. The mylonite appears to be thermally the most conductive, but there is little of this rock type on the site. The in situ temperature of the rock is 4 - 5°C at a depth of 100 - 200 m, and the temperature at 500 m is approximately 7°C, demonstrating that the geothermal gradient is very low (Okko et al. 1995, Paulamäki & Paananen 1995b, Okko & Paulamäki 1996, Luukkonen et al. 1997).

Table 4.4-2. Measured thermal properties of the rock types at Romuvaara. Values presented are arithmetic means, standard deviation is in brackets, n = number of samples.

Rock type	Thermal conductivity (W/mK)		Specific heat capacity (J/kgK)	Thermal diffusivity (m ² /s) · 10 ⁻⁶		Coefficient of thermal expansion (10 ⁻⁶ · °C ⁻¹)
Temperature range	20°C		60-99°C	20°C		10-60°C
Tonalite gneiss	2.6 (0.4) n=5	3.2 (0.4) n=46	817 (7.9) n=7	1.26 (0.10) n=4	1.26** (0.09) n=3	8.1 (0.3) n=3
Mica gneiss	2.4 (0.3) n=4	3.0* (0.4) n=29	829 (18.0) n=3	1.09 (0.14) n=3		
Amphibolite		2.8* (0.5) n=7				
Granodiorite		3.3* (0.3) n=5				
Mylonite		5.6* n=2				

*sampling profile with 10 m interval from KRI (a study related to the geothermal flow studies by Geological Survey of Finland, rock type definition is based on the lithological model)

**value calculated

5 MODELS OF THE ROCK MASS

5.1 Lithological Model

5.1.1 Regional Scale

The dominating rock type at the regional scale is tonalite gneiss which forms the host rock of the regional model. The regional model also includes the mapped occurrences of granodiorite bodies and the network of metadiabase dykes. The locations and orientations of these units are based on interpretations of geophysical airborne magnetic measurements. The notation used for the lithological model is given in Figure 5.2-2.

5.1.2 Site Scale

Surface lithological maps at the site scale are shown in Figures 5.2-3 and 5.2-4. The host rock is tonalite gneiss which is cut by a leucotonalite gneiss body which runs across the site and has a width of approximately 1 km. Its eastern edge dips moderately 40° W, whilst its western boundary has a steeper dip of about $65 - 75^\circ$ W (see Fig. 5.2-5). Numerous metadiabase dykes, oriented NW-SE or ESE-WNW and with vertical or steep dips have been included in the model as has one N-S trending granodiorite dyke. Most of the lithological units are assumed to extend to great depths based on their surface expression and related assumptions regarding their surface trace to depth ratio, or based on knowledge regarding their genesis.

Minor occurrences of granodiorite, amphibolite, granite and mylonite have been incorporated into the lithological model. It is assumed that they extend to shallow depths and that their orientations at depth are consistent with the general trends mapped locally at the surface. Where the direction and angle of dip are unknown, the lithological units are modelled as having vertical boundaries.

In the northern part of the site area a mica rich gneiss has been distinguished. Its surface expression and continuity have been interpreted from boreholes KR1, KR2, KR3 and KR6, where mica gneiss intersections are found. The data indicate that the unit is probably present to a depth of 400 - 500 m.

The form of the contacts between the lithological units and between the units and the fracture zones is generally unknown. However, there is some evidence regarding the character of these contacts, for example:

- The footwall contact of one north-south oriented granodiorite dyke is a known mylonitic and fracture zone (structure R20).
- A fracture zone (labelled as R8) is part of the footwall contact of the metadiabase dyke crossing the Romuvaara hill in a NW-SE direction.
- The site is bounded to the southwest by a set of NW-SE metadiabase dykes and the interpretation of geophysical anomalies and shallow boreholes has revealed associated fracture zones.

- Most of the lithological contacts do not have levels of fracturing or weathering above that found in the intact rock.

5.2 Structural Model

5.2.1 Regional Scale

The regional fracture zone model, based on satellite images, aerial photographs, geological mapping and ground level and airborne geophysical surveys (Paulamäki 1987, Paananen & Paulamäki 1989, Paulamäki & Paananen 1990, Kärki 1990, Front et al. 1997), shows regional fracturing in the Romuvaara area to be dominated by long, narrow NW-SE-oriented crush zones (regional major fracture zones) which in places can be tens of kilometres in length. Regional fracture zones often have metadiabase dykes associated with them. Crush zones also trend NE-SW, though such zones are shorter and less persistent.

It was assumed for the purposes of the regional model that these crush zones continue deep into the earth crust, i.e. much deeper than the depth limit of 1 500 m used in the model of the rock mass. The locations of the regional major fracture zones and watersheds are depicted in Figure 5.2-1 (see also Fig. 2.1-2). Figure 5.2-1 also identifies the position of the investigation site, bounded to the north and south by parts of the main regional fracture zones, which continue for many kilometres.

5.2.2 Site Scale

The site scale model is concerned with the investigation area itself, as referred to above, and its immediate surroundings, and depicts the fracture zone structures. In the development of the structural model, fracture zones have been divided into four *classes*, in increasing levels of uncertainty, with reference to the level of confidence that can be ascribed to their existence and geometry, as: *directly observed*, *probable*, *possible* and *other features*.

- A structure belonging to the *directly observed* (certain) class is one identified by direct observation (outcrop, drill core) at least at one location. Its geometrical dimensions are nevertheless to a great extent based on interpretations and estimates.
- A structure in the *probable* class is one that has been observed by two or more indirect methods, for example from the interpretation of geophysical surveys or lineament investigations.
- A structure in the *possible* class includes structures deduced from one indirect method of investigation.
- The class *other* has been used to incorporate uncertain geometric features or alternatives into the model which can be useful during interpretation and during the planning of subsequent investigations.

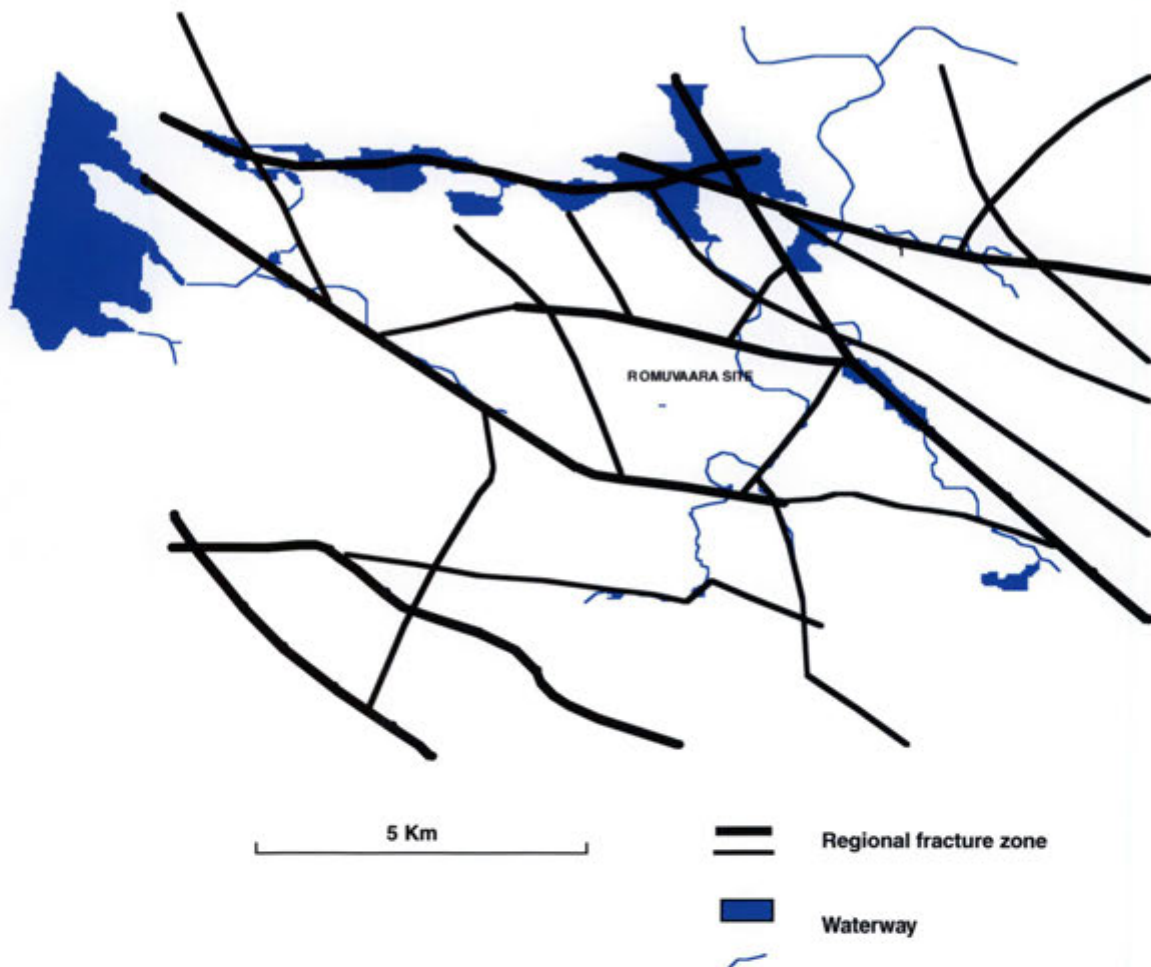


Figure 5.2-1. Regional fracture zones of the Romuvaara area. The dips of the structures are assumed to be either vertical or as established in the site scale model. Thickness of the lines refers the deduced significance and intensity of the structures.

These fracture zones have also been divided into different *types* based on their overall properties, ranging in scale and effect from *crush zones*, through densely fractured (>10 fractures/m) and altered *major fracture zones*, to *fracture zones* containing an abundance of fracturing, *to open or more abundant fracturing*, which may consist of only one open fracture. The fracturing and weathering values used to classify the structures and the graphical representations used in the models are shown in Figure 5.2-2.

Most of the volume of the site model consists of the sparsely-fractured *intact* rock mass. Its general lithological composition, tectonic evolution and fracturing have been described previously in Section 4 of this report. Data from boreholes KR1 - KR11 show that 9% of the core was more densely fractured. This fractured portion has been divided into fracture-structured (sc. RiIII) and crush-structured (sc. RiIV) categories in which 86% lie in the RiIII-class and 14% is even more fractured or tectonised and is placed in the RiIV-V classes (Front et al. 1997). A total of 18% of the core samples indicated a measurable degree of weathering which was most frequent in the surficial part of the rock mass.

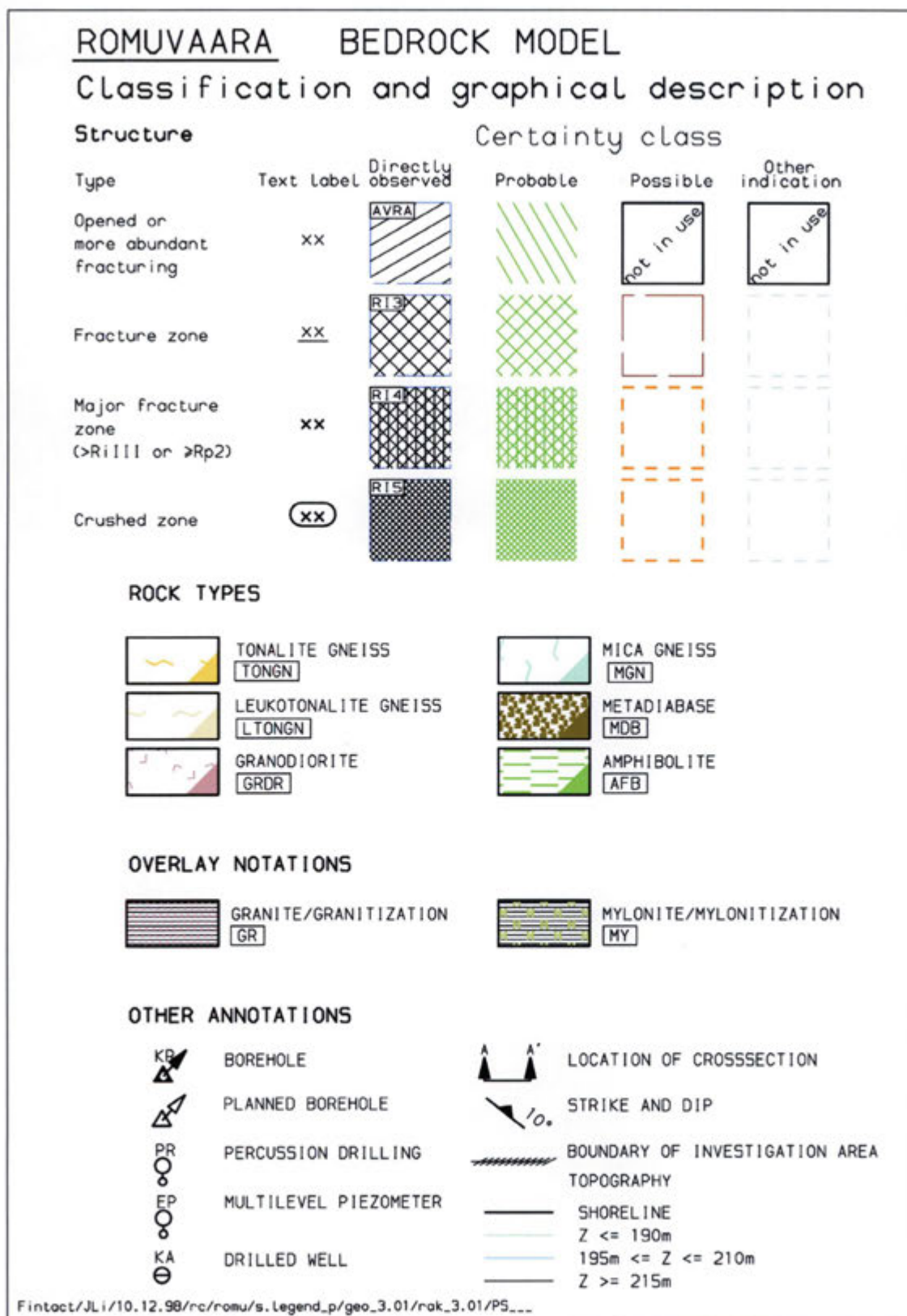


Figure 5.2-2. Legend used in the Romuvaara bedrock model.

The site scale model covers an area of 12 km² and has a volume of 18 km³. The model contains 31 structures each of which is described more in detail elsewhere and labelled as R+number structures (Front et al. 1997, Luukkonen et al. 1997, Saksa et al. 1998). In addition, other structures occur. Altogether 16 R-structures have been estimated to be fracture zones of major type, 10 R-structures belong to the class of fracture zones and five R-structures take properties of other minor types. The majority (29) of the R-structures are evidenced from direct observations, mainly from borehole intersections or from investigation trenches. Two structures lie in the probable category. The fracture zone model is most accurate and reliable within the volume of rock bounded by the cored boreholes KR1 - KR11. The boreholes KR9 and KR11 are slightly off from the best characterised area. The existence and extent of fracture zones lying in the certain category is often supported by reflections from geophysical vertical seismic profiling (VSP), borehole radar soundings, electrical cross-hole measurements or hydraulic pumping tests. The continuity of such zones is also supported by this type of indirect evidence.

The majority of the fracture zones are steeply dipping (dip > 60°). Seven zones have inferred moderate dips and five are gently dipping (dip < 30°). The surface maps of the model illustrating the lithology and the structures are shown in Figures 5.2-3 and 5.2-4. Figure 5.2-5 displays an east-west cross section across the central part of the investigation area and across the Romuvaara hill (for place names, see also Fig. 2.2-3). The dominant steeply-dipping nature of the fracture zones can be seen, as well as their westerly dip. Certain fracture zones are conformable with metadiabase, granodiorite or mylonitic zones. Some structures, such as those labelled as R13 and R14, are now interpreted as being more continuous and having greater lateral extent than was considered in previous structural models (e.g. those described in 1992 and 1996 (Saksa et al. 1992, Front et al. 1997)). The structures which are not visible in Figures 5.2-3 - 5.2-5 are typically local in extent and subhorizontal.

What has been defined as fractured sections make up 15.9% (18.8% in 1996) of the total length of the boreholes and investigation trenches. This is a higher value than at Kivetty and Olkiluoto and can be partly explained by the inclusion of data from boreholes KR6 and KR9, which were deliberately drilled into crush zone R2 - R3 nearby. The presence of structures R1 - R31 can be used to explain 75.0% of the fractured sections in the boreholes. There is slight increase when compared to the situation in 1996 when the equivalent figure was 74.1% and the situation in 1992 when the equivalent figure was 62.5%.

The intensity of fracturing and degree of weathering, alteration and tectonitization varies within the structures. Rock which displays similar fracture densities to those of the intact rock is frequently present over large portions of the rock mass included within their boundaries. This is particularly noticeable within two wide fracture zones labelled as R3 and R10 (Fig. 5.2-3). A summary of the properties and characteristics of the structures is given in Table 5.2-1 with the associated, relevant background data. Structures R1 and R9, which are discussed briefly below, exemplify the data associated with the fracture zones and the interpretations required for their delineation. Structure R1 is an example of a less well understood fracture zone and structure R9 is a major fracture zone which has been directly observed. Summary descriptions of all the structures can be found in Saksa et al. (1992) and Front et al. (1997), which also contain further references to the detailed data available.

Structure R1 is located in the NW mire area of the study site and runs NNE-SSW (Fig. 5.2-3 and 5.2-5). It has been detected by geophysical electromagnetic VLF and ground penetrating radar measurements and two shallow boreholes were drilled into it to check the anomalies. The rock is fractured and weathered in classes RiIII-IV and Rp2 - 3. The fractures are mainly open and filled, the most common filling materials being kaoline and iron hydroxide. The rock type within R1 is amphibolite in one borehole and amphibolite and granite in the other. The hydraulic conductivity has not been measured.

Outside the study area structure R1 has been located with reconnaissance geophysical VLF measurements and the structure has been placed in the possible class. It has not been classified as a major zone because its electrical conductance is < 1 S. The dip of R1 is unknown and has been assumed to be vertical. Were the structure to dip towards the SE, the dip would have to be steep, since R1 does not appear to be present in the nearby KR3 borehole. Its extension to depth is interpreted to be similar to its total surface trace and, as such, it is assumed to extent down to depths between 800 - 1 200 m in the model.

Structure R9 is an extensively characterised and hydrologically significant major fracture zone (Fig. 5.2-3 - 5.2-5). It strikes NNW-SSE in the north and N-S in the south and dips $38 - 40^\circ$ W. Towards the south it is identifiable in a peaty depression which runs northwards from Romulampi pond (place names, see Figure 2.2-3). Its continuity south of Romulampi pond is uncertain. Direct observations of R9 have been made from boreholes KR1, KR2, KR3 and from the investigation trench TK2. Its interpreted geometrical form is a result of correlations between surface geophysical VLF and ground radar anomalies and orientations derived from borehole data. Its location and orientation has been mapped by VSP reflections from boreholes KR2, KR3 and KR7 and it has shown up on a large number of borehole radar reflections. Examination of a pumping test performed in the depth interval 150 - 180 m in borehole KR1 and the responses measured in boreholes KR2 and KR3 indicate a hydraulic connection between the boreholes along R9 (Ylinen & Väättäinen 1993). One reason for the construction of investigation trench TK2 was to check the occurrence of structure R9 and it was detected very close to its predicted location.

Structure R9 intersects boreholes KR1, KR2 and KR3 within the tonalite gneiss. The degree of weathering within R9 usually ranges from unweathered to slightly weathered (Rp0 - 1), and to completely weathered (Rp3) in KR1. Fracturing is generally of the fracture or crush-structured type (RiIII - IV). Open and tight fractures predominate, but filled fractures also occur. Detailed data on fracturing are available from borehole-TV studies (Strähle 1996) or from the fracture database (Hellä et al. 1997). The degree of fracturing and weathering is also high within the zone in trench TK2, where the fractures have a dip of 60° W and the zone has a width of about 12 m.

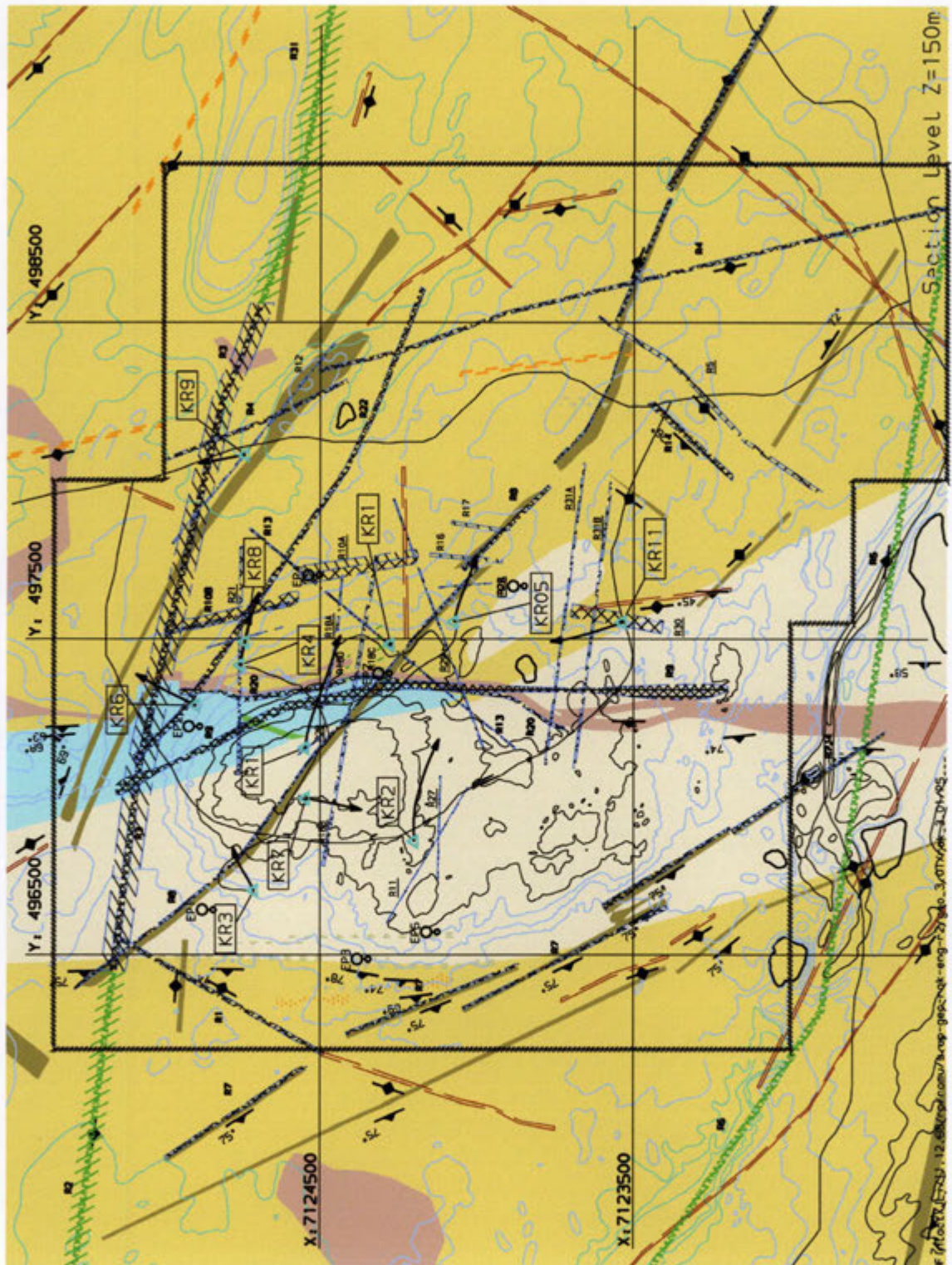


Figure 5.2-3. Surface map of the Romuvaara bedrock model.

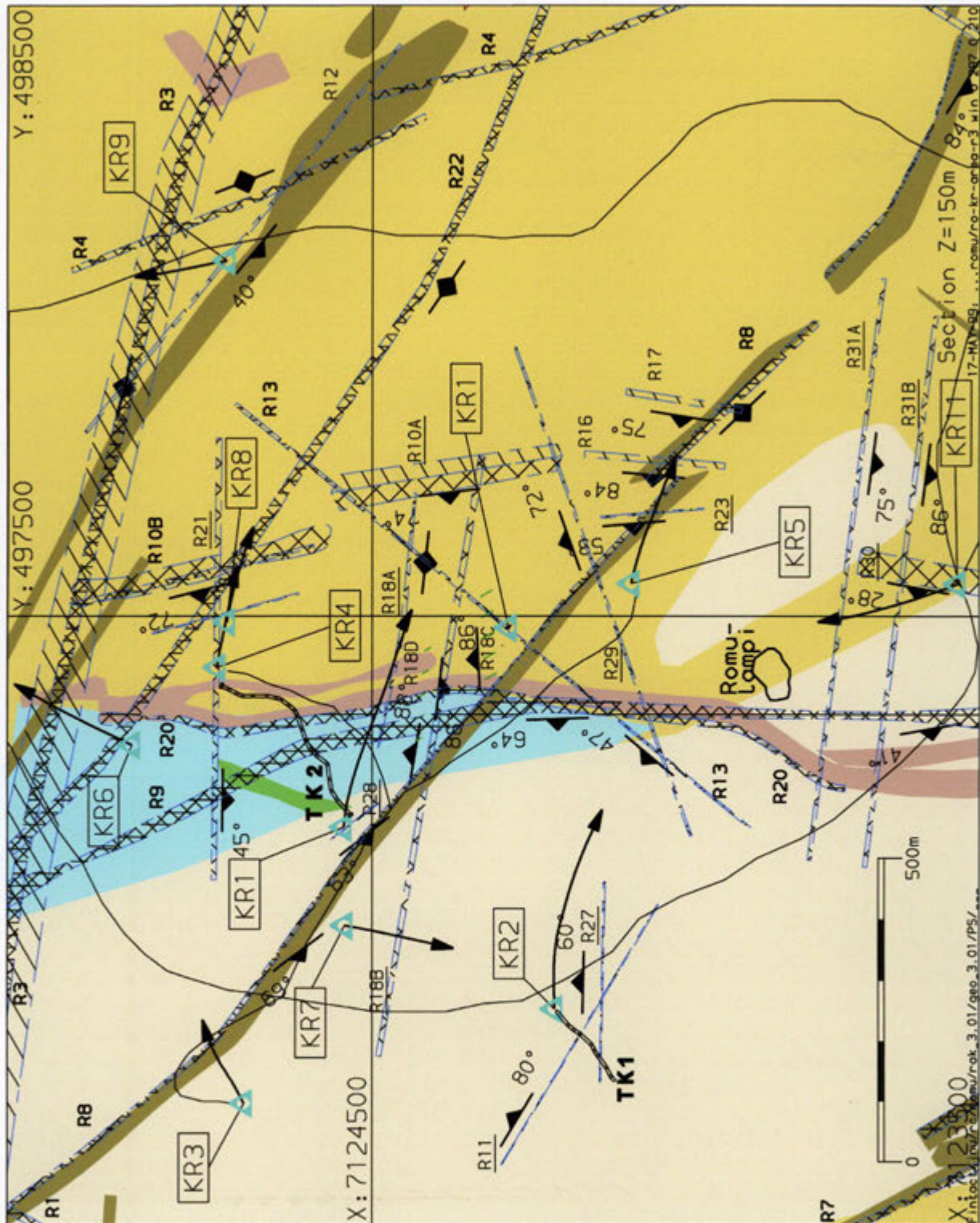


Figure 5.2-4. Surface map from the central area of the Romuvaara site scale bedrock model. Structures in classes certain and probable are displayed. The dips of geological bodies are shown.

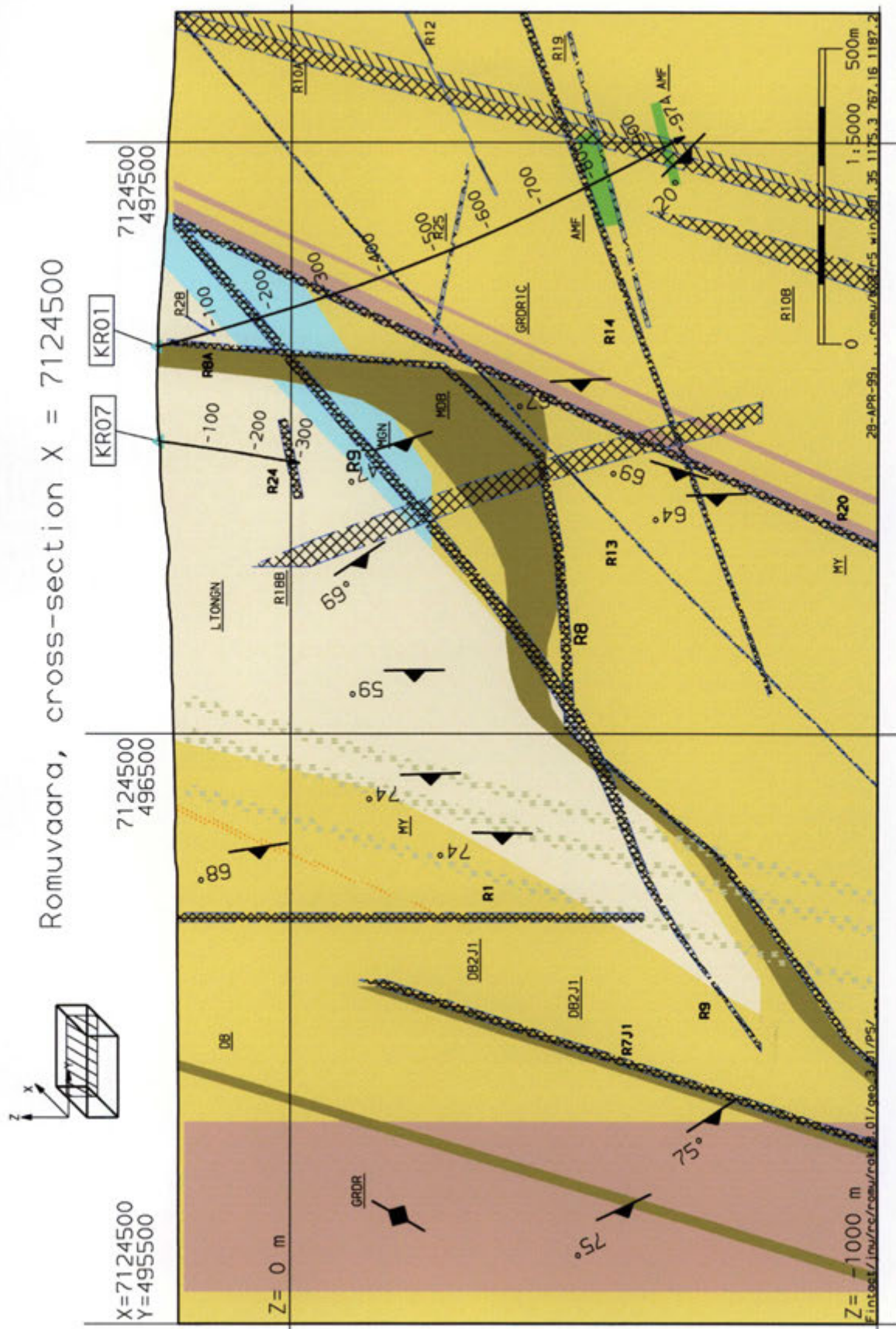


Figure 5.2-5. Vertical cross section of the Romuvaara site scale model. Locations of the boreholes KR1 and KR7 which are located close to the section line are shown. Structures in classes certain and probable with their average dips are displayed.

Table 5.2-1. Summary of the properties of the fracture zones R1 - R31 in the bedrock model.

NOTATION: ☐ is observed or deduced property of the structure

CHARACTERISTICS OF STRUCTURES		MODEL STRUCTURE																															
		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30	R31	
Average orientation	Dip direction, °	119	187	193	69	317	9	240	230	260	260	31	220	310	312	85	275	279	186	230	268	181	215	265	260	140	270	1	232	340	280	187	
	Dip, °	90	90	90	90	90	90	75	70	41,3	74	80,1	40	47,4	26,4	37	83,7	74,7	90	20	63,9	45	90	53,1	12	17	68	59,9	63	72	28	80	
Surface trace length																																	
- regional																																	
- more than 1000 m																																	
- less than 1000 m																																	
Extension to depth																																	
- large, more than 1500 m																																	
- 750 - 1500 m																																	
- less than 750 m																																	
Structure concordant with the lithology																																	
Tectonized, mylonitized																																	
Continuous, compact structure /																																	
Discontinuous structure																																	
Certainty level																																	
- based on direct observations, 'certain'																																	
- based on several indirect interpretations and estimations of different types, 'probable'																																	
- based on one indirect interpretation or uncertain in other respects, 'possible'																																	
Engineering geological classification:																																	
Weathering degree:	Rp0 - Rp3	2-3	0-1	0-1	1-2	0-1	1-3	2-3	0-2	0-3	0-1	0-1	0	1-3	0-1	1	0-1	0	0-1	0-1	0-1	0-1	0-1	0-2	1	0-1	1	0-1	0	1	0-2	0-3	0-1
Fracturing degree:	Ri I - Ri V	III-IV	III-IV	III-IV	III-IV	III	III-IV	III-IV	II-III	III-IV	III-IV	II-III	II	II-IV	III-IV	III	II	II	III	III	III-IV	II-III	III-IV	II	III-IV	III	III	III	III	IV	III-IV	III-IV	
Important for rock engineering																																	
Important for groundwater hydraulics																																	
Direct observations																																	
in deep boreholes KR1-KR11																																	
and investigation trenches TK1-TK2																																	

The zone varies from 12 m to 27 m in true thickness and possesses a ramiform structure in borehole KR2. Its course and dip follow the contact between the leucotonalitic and migmatitic tonalite/mica gneisses, but it is located 10 - 50 m into the tonalite gneiss. Its continuity has been estimated from its known surface trace and it is assumed to reach at least 1 000 m depth in the model. The highest hydraulic conductivities in R9 found from double packer tests exceeded the measurement limit of the equipment, i.e. 10^{-5} m/s. On the basis of the flowmeter and long-term pumping tests, its estimated transmissivity is $\sim 10^{-5}$ m²/s. An example of the properties of this fracture where it intersects borehole KR3 is shown in Figure 6.1-2 and its hydraulic properties are discussed further in Section 6.4.

5.2.3 Alternative Models

An alternative model has been developed for the structure R3 and for the combination of structures labelled as R10, R15, R16, R17 and R19 (Front et al. 1997). The lay-out of these alternative structures is shown in Figure 5.2-6.

Structure R3 is a major regional zone bounding the site in the north and its orientation has great importance for the development of the geometrical framework of the site. In the site-scale model described above structure R3 is interpreted as having a vertical dip. The alternative suggested here is that zone R3 dips approximately 60° S, which provides an explanation for the fractured sections associated with R10 in borehole KR4 between 270 - 330 m depth and in borehole KR8 between 104 - 120 m depth. This alternative model for the zone is labelled as R3-ALT1, its surface trace is the same as R3 and is shown in Figures 5.2-3 and 5.2-4. If the R3-ALT1 interpretation is assumed, structure R10B no longer exists. It is possible, however, although unlikely, that structures R3 and R10 have coincident intersections in boreholes KR4 and KR8.

The alternative interpretation that R10 exists and dips west is supported, for example, by geophysical electric cross-hole measurements. The orientation of fractures and reflections from directional borehole radar surveys both support an alternative interpretation. Radar reflections in borehole KR4 in the depth interval 220 - 330 m have orientations in the range 186 - 218/53°. In a corresponding section of borehole KR8 radar reflections have orientations in the range 190 - 237/41 - 76°. In addition, a radar reflection has been mapped parallel to borehole KR8 and perpendicular to the strike of the R10 structure. Its surface trace is the same as that shown in Figures 5.2-3 and 5.2-4.

Structure R10 being divided into two parts R10A and R10B, as shown in the site scale model, forms a thick major fracture zone but is present over a relatively small area. An alternative interpretation requires the connection of zone R10 to other structures R15, R16, R17 and R19. When joined together these discrete localised portions would form a larger north-south oriented major fracture zone. This interpretation would make the fracture zone larger in volume as a single zone than would be the case if the volumes of all these fracture zones were summed separately. This, in turn, would indicate a greater volume of rock that might need to be avoided when locating the repository. Such a geometrical or hydraulic continuity of this zone has not yet been observed, however, either from geophysical surveys or from hydraulic cross-hole testing within the volume of rock containing boreholes KR1, KR4, KR5, KR8 and KR10.

6 HYDROGEOLOGY

6.1 Hydraulic Conductivity of the Bedrock

Hydraulic conductivity (K , m/s) is a parameter commonly used in hydrogeological characterisation of a geological media. Two methods have been used to measure hydraulic conductivity:

- the Hydraulic Testing Unit (HTU) (Fig. 2.2-7)
- the Flowmeter (Rouhiainen 1997).

Double-packer injection tests with constant head have been performed by HTU. Measured values lie between $2 \cdot 10^{-12}$ - $5 \cdot 10^{-5}$ m/s (Hämäläinen 1995a, b, 1996a, b, c, 1998a, b). The flowmeter has been operated using the constant head method without any pressure difference between the measuring section and the remaining of the borehole. Values of hydraulic conductivity determined using this method vary from $2 \cdot 10^{-11}$ to $1 \cdot 10^{-5}$ m/s (Rouhiainen 1996 a, b, Pöllänen & Rouhiainen 1996). The total number of hydraulic conductivity determinations at Romuvaara measured over 10 m and 2 m test sections is 530 for the HTU and 1 487 for the flowmeter.

On the basis of studies of flow dimension, based on transient curves of HTU tests, most common flow dimensions are between 2 and 2.5 (Kuusela-Lahtinen & Niemi 1995, 1996). For this reason the radial flow equation or Moye's equation (Moye 1967) for the interpretation of hydraulic tests has been used.

The results of hydraulic conductivity measurements using both the HTU and flowmeter methods in borehole KR3 are compared as an example in Figure 6.1-1. Hydraulic conductivities measured over 31 m and 7 m test sections are from the year of 1989 (Kuusela-Lahtinen et al. 1989a). Overall there is good agreement between the values of K determined using both methods. There are some exceptions but these are mainly due to measurement errors. In borehole KR3 more conductive sections are clearly more frequent in the uppermost 250 m, although highly conductive sections are also present at greater depths. In some boreholes only the uppermost 100 m is generally more conductive. On the basis of results from studied boreholes it is apparent that the hydraulic properties of the uppermost 100 - 200 m of the bedrock, are distinct from those at greater depth, i.e. hydraulically conductive fractures are more frequent and their transmissivity is higher in the near-surface zone.

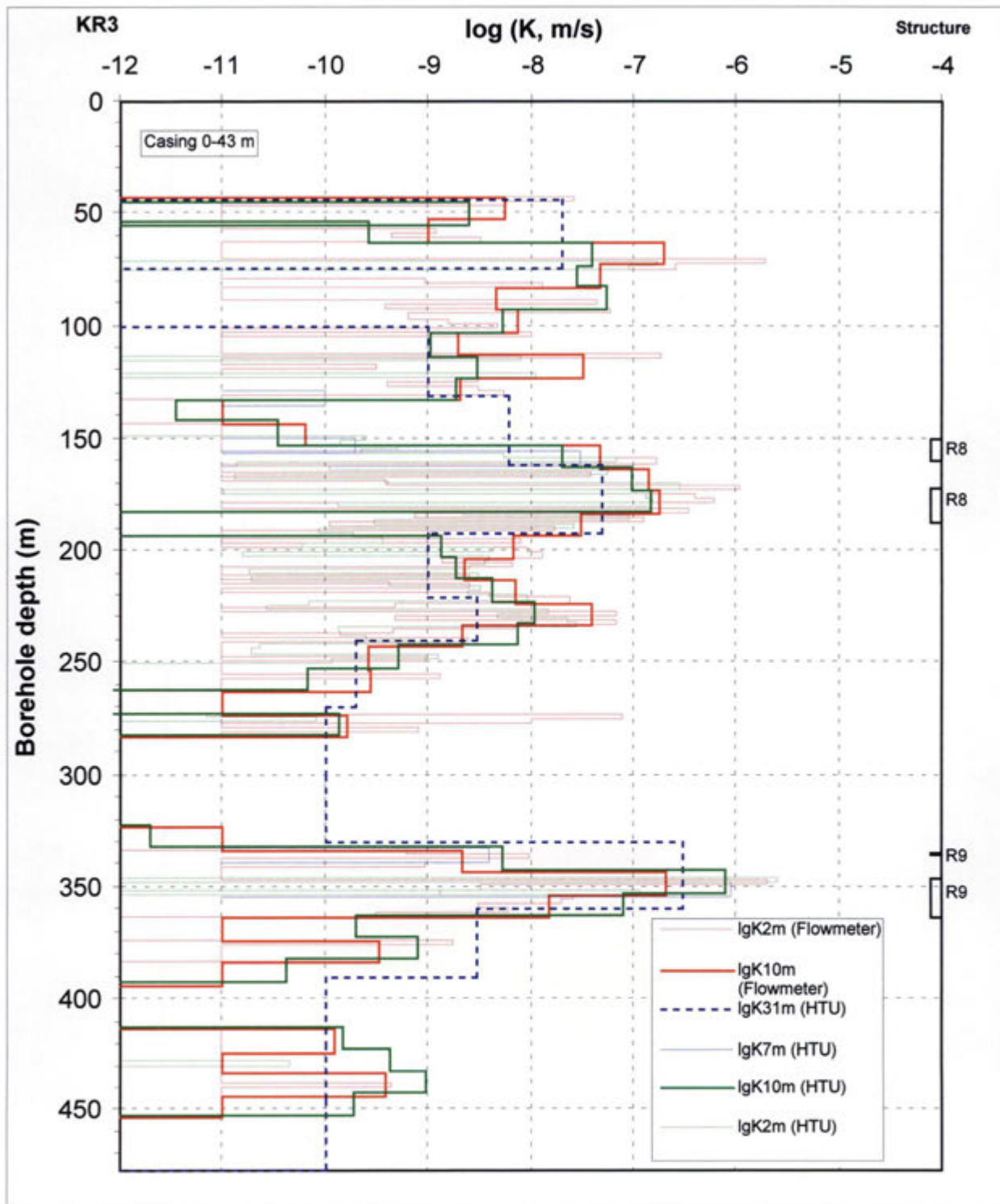
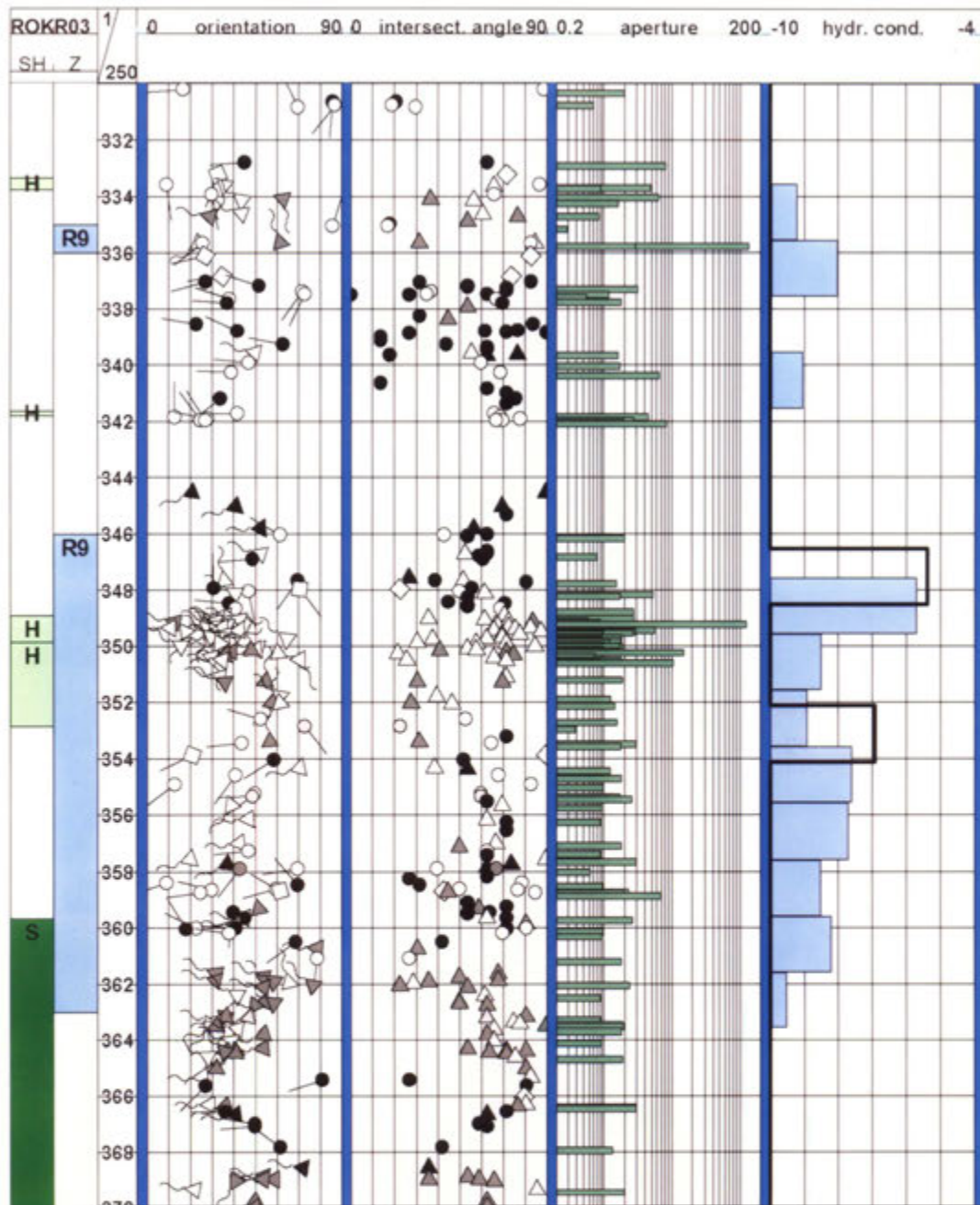


Figure 6.1-1. Hydraulic conductivities measured with different methods and different test section lengths in borehole KR3.

Figure 6.1-2 shows in detail the relationship between fractures and measured values of K in borehole KR3 over a short range of depth (Hellä et al. 1997). The hydraulic properties of the rock mass are dominantly controlled by the presence of structure R9, which is a fracture zone with a width of 18 m. One 2 m wide section within the R9 structure controls its transmissivity and this section is about two orders of magnitude more hydraulically conductive than the next most conductive section. The most conductive section contains several open, mostly slickensided fractures. In general, there is a good relationship between measured values of K and the presence of open fractures, especially when they form a narrow section of several open fractures. A new, recently developed fracture detection system (Rouhiainen & Pöllänen 1998), allows for the accurate logging of individual flowing fractures or sets of fractures which are in close proximity. Recent results using this system have enabled a more accurate examination of the correlations between fractures and their hydraulic properties to take place. This may help, for example, in the compilation of more representative fracture networks, which can be used for groundwater flow modelling and for the planning and development of grouting techniques, for example.

To examine the difference between the hydraulic properties of fracture zones and intact rock, all hydraulic conductivities measured over 2 m test lengths were divided into two groups to represent known R-structures (see Section 5) and the intact rock. What is termed "intact rock" also includes some fracture zones, which are normally narrow and are interpreted to be of limited extent with their orientation being unknown. Known R-structures are commonly composed of several separate transmissive elements. For this reason the hydraulic properties of such zones are described in Figure 6.1-3 in terms of their transmissivities (T). The mean value of T for such R-structures is given as $1.6 \cdot 10^{-7} \text{ m}^2/\text{s}$ ($\log T = -6.8$, $s = 1.9$ (s = standard deviation)), the corresponding value of K for the intact rock being $8 \cdot 10^{-12} \text{ m/s}$ ($\log K = -11.1$, $s = 2.0$). These statistics are based on regression lines in Figure 6.1-3. The regression line for the intact rock is visually-fitted and based on values of $\log K$ lying between -9 and -6, which are considered to be the most credible. The main conclusion from this analysis is that the majority of the known R-structures are hydraulically more conductive than the intact bedrock, even in situations in which several hydraulically non conductive R-structures and several hydraulically very conductive fractures and minor fracture zones, which are located outside known R-structures i.e. in the intact rock, are known to exist.

The properties of the hydraulically most conductive fractures and minor fracture zones in the intact rock, i.e. in the rock lying between R-structures, have been investigated by analysing their spatial distributions and transmissivities in all boreholes, where there are systematic values of hydraulic conductivity measured over 2 m test lengths. In this analysis the limit of transmissivity was set to about $1 \cdot 10^{-8} \text{ m}^2/\text{s}$ and the selection of this kind of conductive feature was made on the basis of a visual analysis of measured K values. A *conductive feature* is associated with an individual fracture or a group of fractures in which the results from several 2 m long measuring intervals indicate an enhanced transmissivity. Distances between identified R-structures without any hydraulically conductive feature between them were also taken into account. Identified R-structures were also used as boundaries in determining the distances between hydraulically conductive features. A schematic illustration of the procedure is shown in Figure 6.1-4. Results of the analysis are presented in Figure 6.1-5. Depth classes are 0 - 100 m, 100 - 300 m and over 300 m.



Columns from left to right: S = oriented sample, H = core loss, Z = fracture zone, orientation = orientation by fracture type: open = ○, tight = ●, weathered = ⊙, unknown = □, open slickenside = △, tight slickenside = ▲, filled slickenside = ▴, weathered slickenside = ▴, the tail of the mark shows the orientation, intersect. angle = intersection angle by fracture type, aperture = fracture aperture (mm) and hydr. cond. = hydraulic conductivity (log K (m/s)): Flowmeter = bar, HTU = line.

Figure 6.1-2. A detailed presentation of fractures and their properties in borehole KR3 for the depth interval 328 - 372 m (Hellä et al. 1997). Structure R9 lies in the depth range 346 - 363 m. A narrow section at 335 - 336 m depth is also believed to be a part of structure R9.

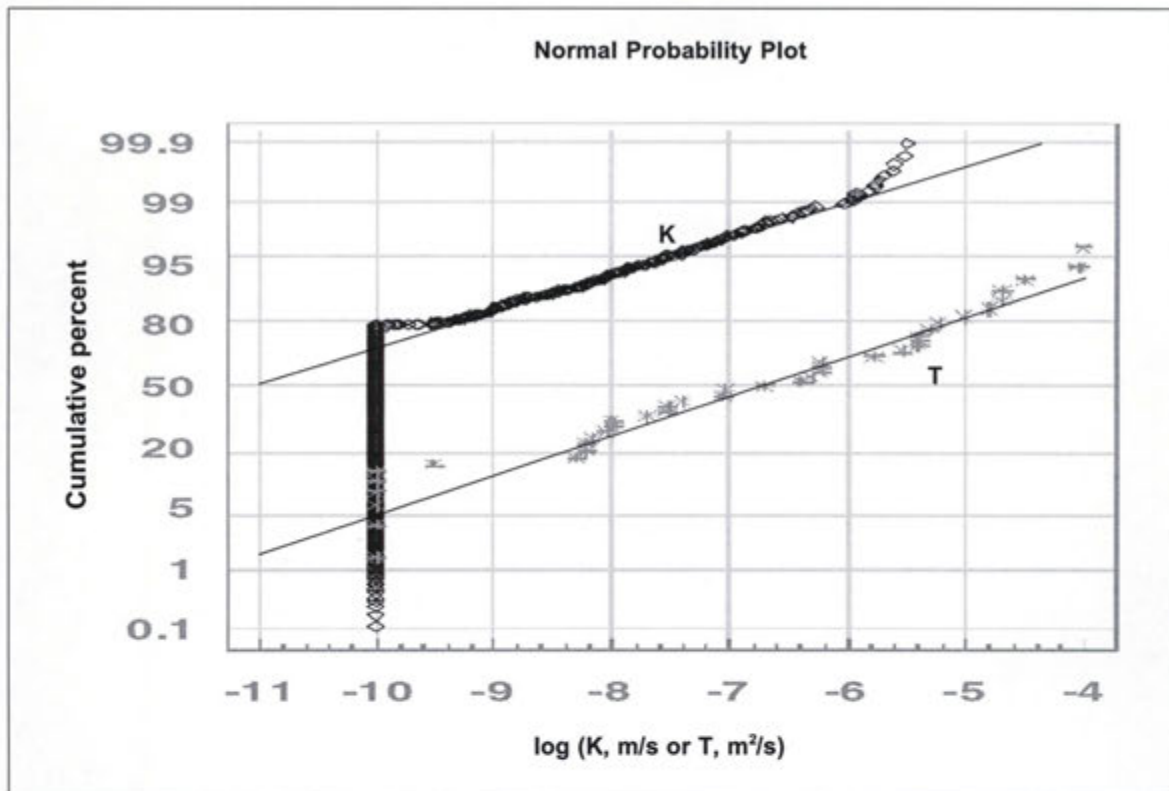


Figure 6.1-3. Transmissivities ($\log T$) of R-structures and hydraulic conductivities ($\log K$, measured over 2 m) of intact rock as cumulative distributions (normal probability plot). Visually-fitted regression line (approximate) for the intact rock is based on the assumption of a normal distribution for most credible values of K .

The depth dependency of hydraulic properties was investigated by dividing the transmissivity values of R-structures into two depth classes and the hydraulic conductivity values of intact rock into three classes (Fig. 6.1-6). On the basis of regression lines, the log mean transmissivity ($\log \text{m}^2/\text{s}$) of R-structures in the uppermost 200 m of the rock mass was found to be -6.0 with an equivalent value of -7.5 for greater depths. Depths are real vertical depths calculated from the reference level of +200 m.a.s.l. (metres above sea level). Corresponding means of hydraulic conductivities ($\log \text{m/s}$) for intact rock for three depth classes (0 - 200, 200 - 400 and 400 - 900 m) are -9.8, -12.3 and -15.6. Value for the deepest class is very uncertain due to the assumption of normal distribution made for a small number of data points. The statistics of means and standard deviations (σ) are presented in Table 6.1-1. The differences between the means are statistically significant at a level of significance of 0.01. The conclusion from this analysis is that there is a real decrease in the hydraulic conductivity of the intact rock and the transmissivity of R-structures with depth. These results have been used for the compilation of initial values of hydraulic properties for numerical groundwater flow modelling and for the extrapolation of transmissivities within R-structures, where only one measured value of T is available.

Hydraulic connections between boreholes have been studied by means of long-term pumping (interference) tests (Ylinen & Väättäinen 1993, Luukkonen et al. 1996, Niva & Rouhiainen 1996, Hänninen 1997). Several hydraulic connections have been found between the pumped section of one borehole and packed off intervals of other boreholes,

which are separated by several hundreds of meters (Fig. 6.1-7). It has been possible to determine the cross-hole transmissivity of some of these conductive R-structures. R-structures, which penetrate or are close to the pumping section in borehole KR4 and intervals exhibiting response in boreholes KR1 and KR8 and in monitoring well EP4, are presented in Figure 6.1-7. The interpretation of this pumping test has allowed the existence of structure R13 to be prescribed with increased confidence.

Table 6.1-1. Means and standard deviations (σ) of transmissivities ($\log T$) of R-structures and hydraulic conductivities measured over 2 m of intact rock in different depth classes. Values are based on the regression lines presented in Figure 6.1-6.

Transmissivity of R-structures			Hydraulic conductivity of intact rock		
Depth class	Mean	σ	Depth class	Mean	σ
0 - 200 m	-6.0	2.0	0 - 200 m	-9.8	1.8
200 - 900 m	-7.5	1.8	200 - 400 m	-12.2	2.3
			400 - 900 m	-15.8	3.6

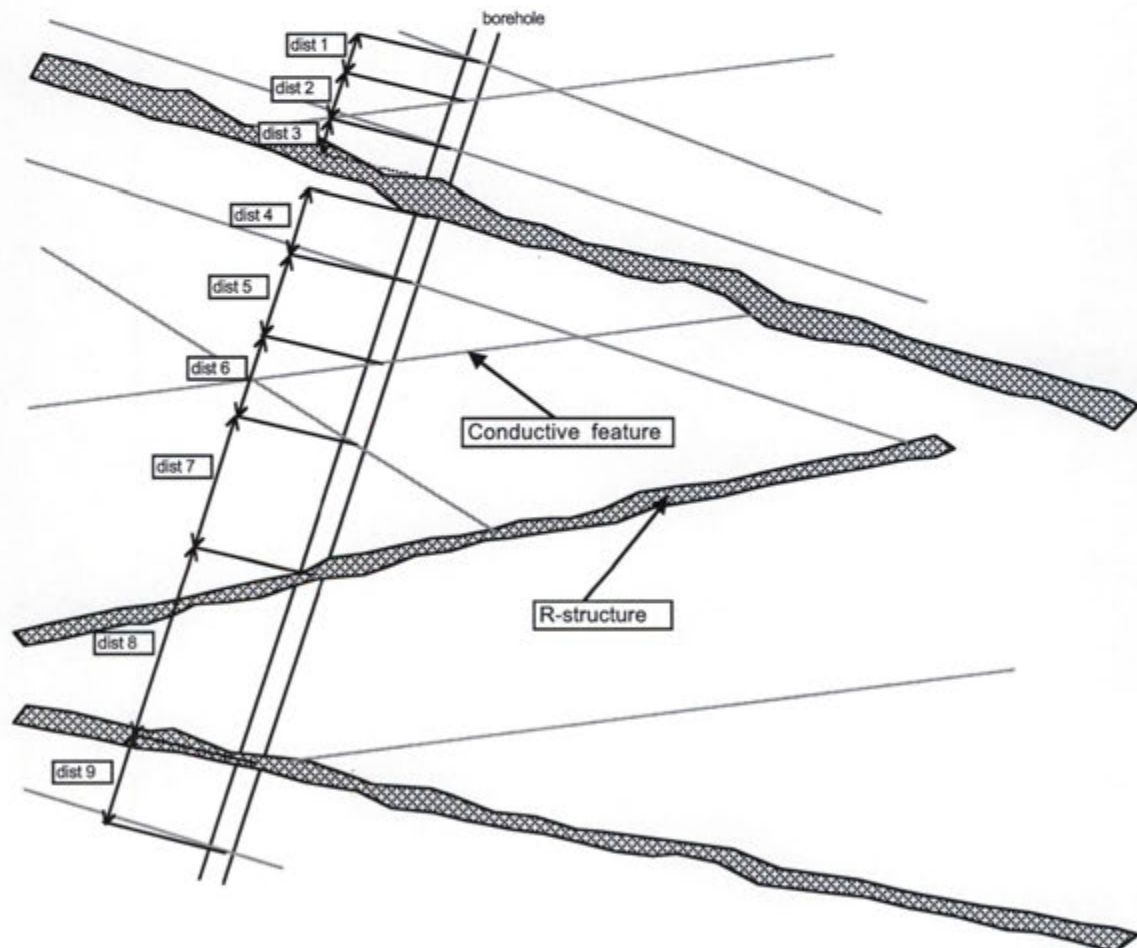


Figure 6.1-4. Determination of distances between hydraulically conductive ($T \geq 1 \cdot 10^{-8} \text{ m}^2/\text{s}$ or greater) features in intact rock (rock lying between known R-structures) and their transmissivities.

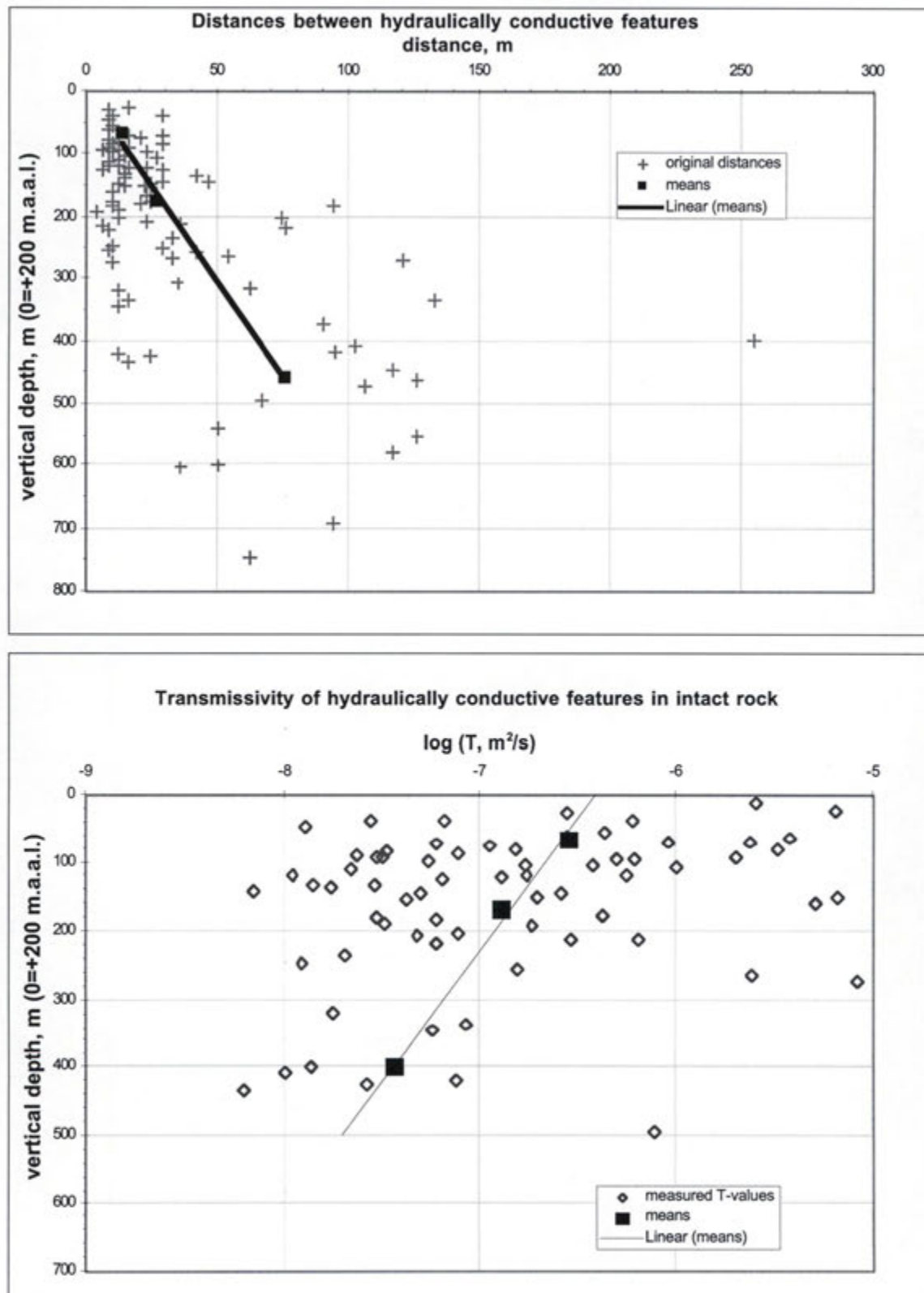


Figure 6.1-5. Distances between hydraulically conductive ($T \approx 1 \cdot 10^{-8} \text{ m}^2/\text{s}$ or greater) features in intact rock (rock lying between known R-structures) and their transmissivities (log) with depth.

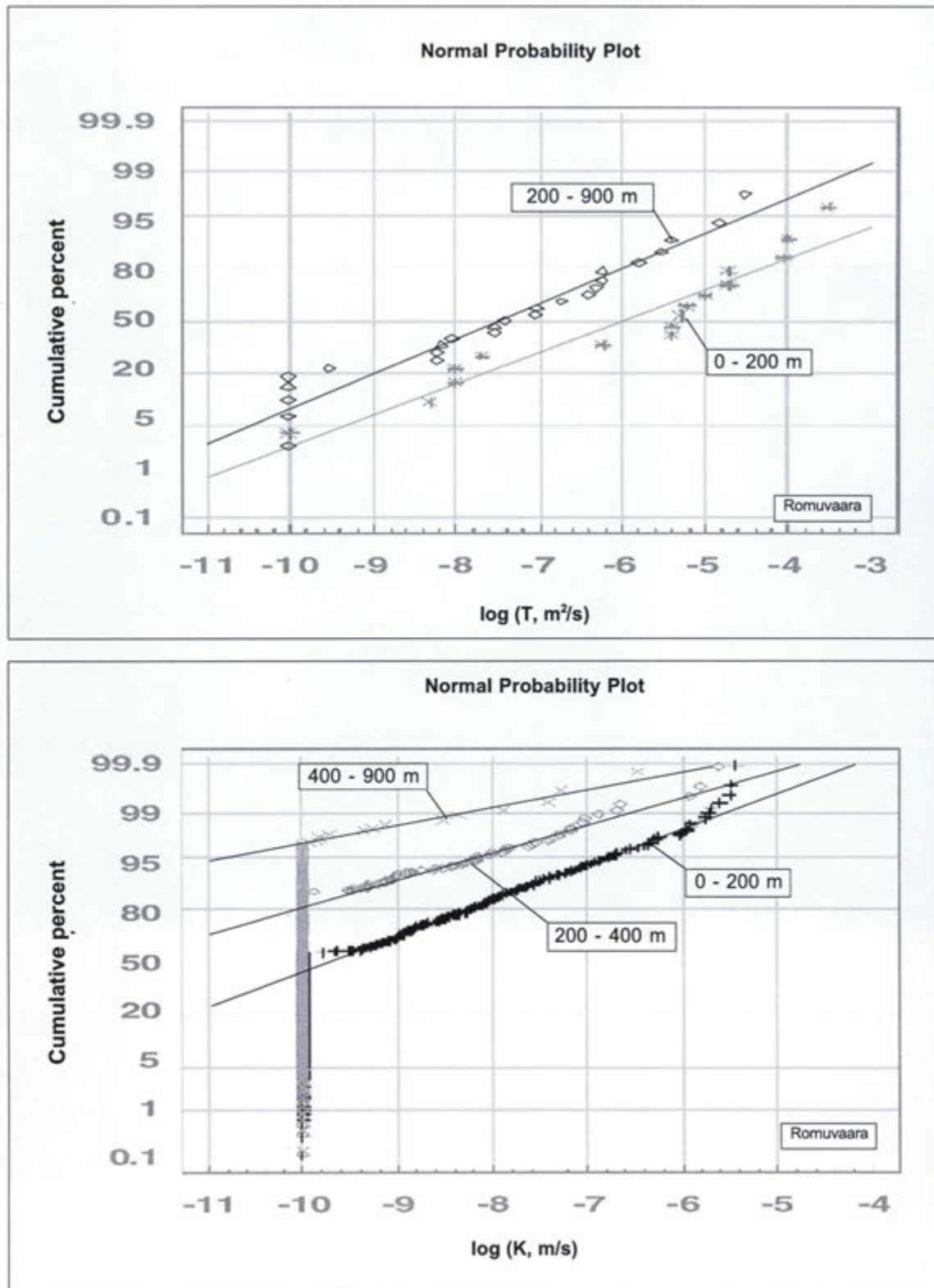


Figure 6.1-6. Cumulative distributions (normal probability plot) of transmissivities ($\log$) of R-structures and hydraulic conductivities measured over 2 m ($\log$) of intact rock in different depth classes.

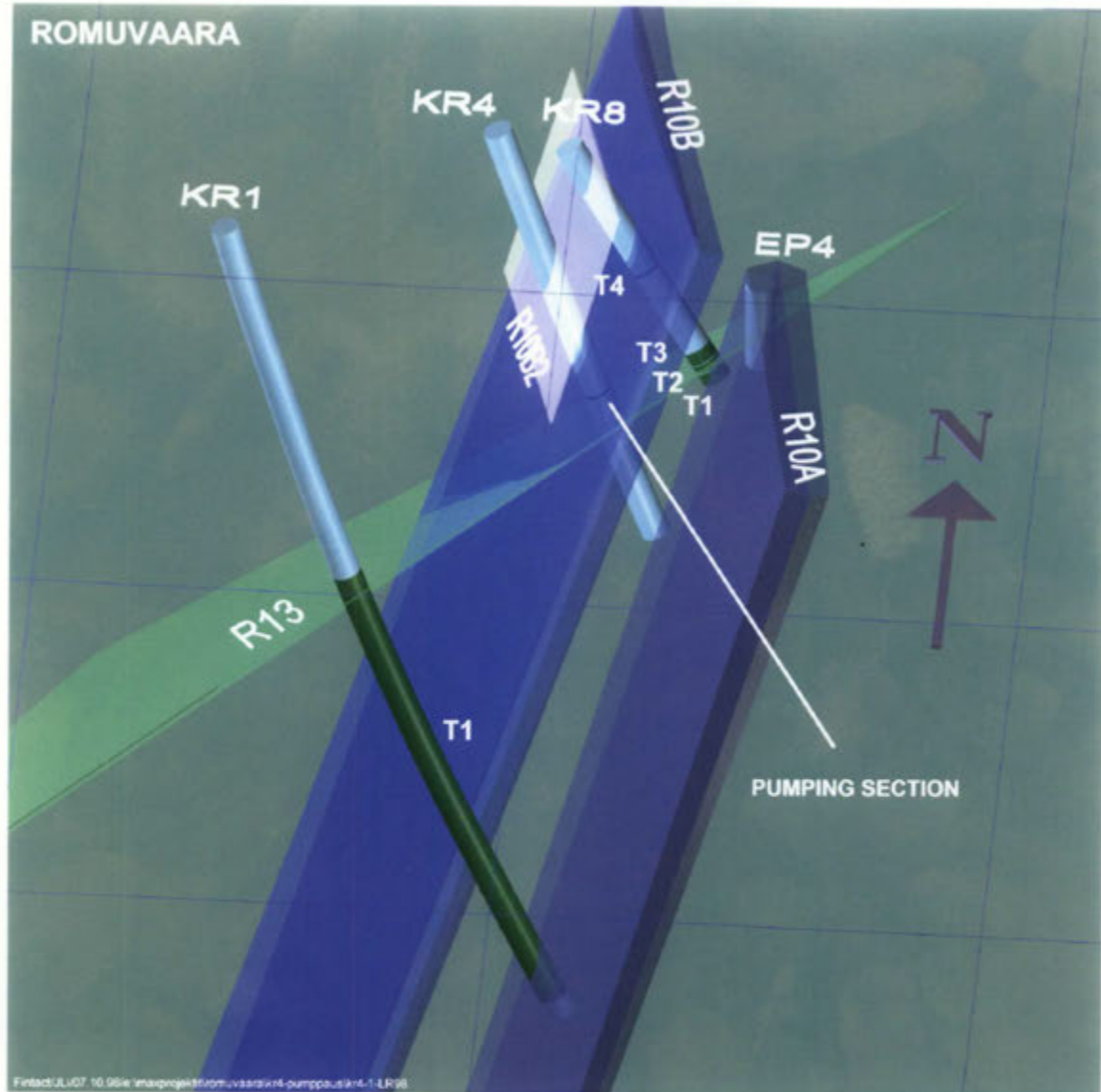


Figure 6.1-7. Pumping section in borehole KR4 and response intervals (T1 to T4) in boreholes KR1 and KR8 and in monitoring well EP4. Structures such as R10A, R10B, etc., which are assumed to be present and to influence the extent of drawdown, are also shown. Grid space in figure is 500 m.

It has been found that for structure R9, which is highly fractured in borehole KR1, the transmissivity determined from pumping test and flowmeter measurements is much smaller than the transmissivity determined from double-packer injection tests. The transmissivities determined using different types of measurement techniques are presented in Figure 6.1-8. It is possible that the relatively short duration of the double packer injection test measures properties of the rock only in the immediate vicinity of borehole, i.e. measured values of K are correct but they represent only the near-field around the borehole. In addition there is the possibility of injected water from the test section returning to the borehole, which would result in higher K values being calculated for the double-packer system than for the long-term pumping and flowmeter tests. On the basis of results to date it has been possible to provide better estimated values of transmissivity for the structure R9. Results from

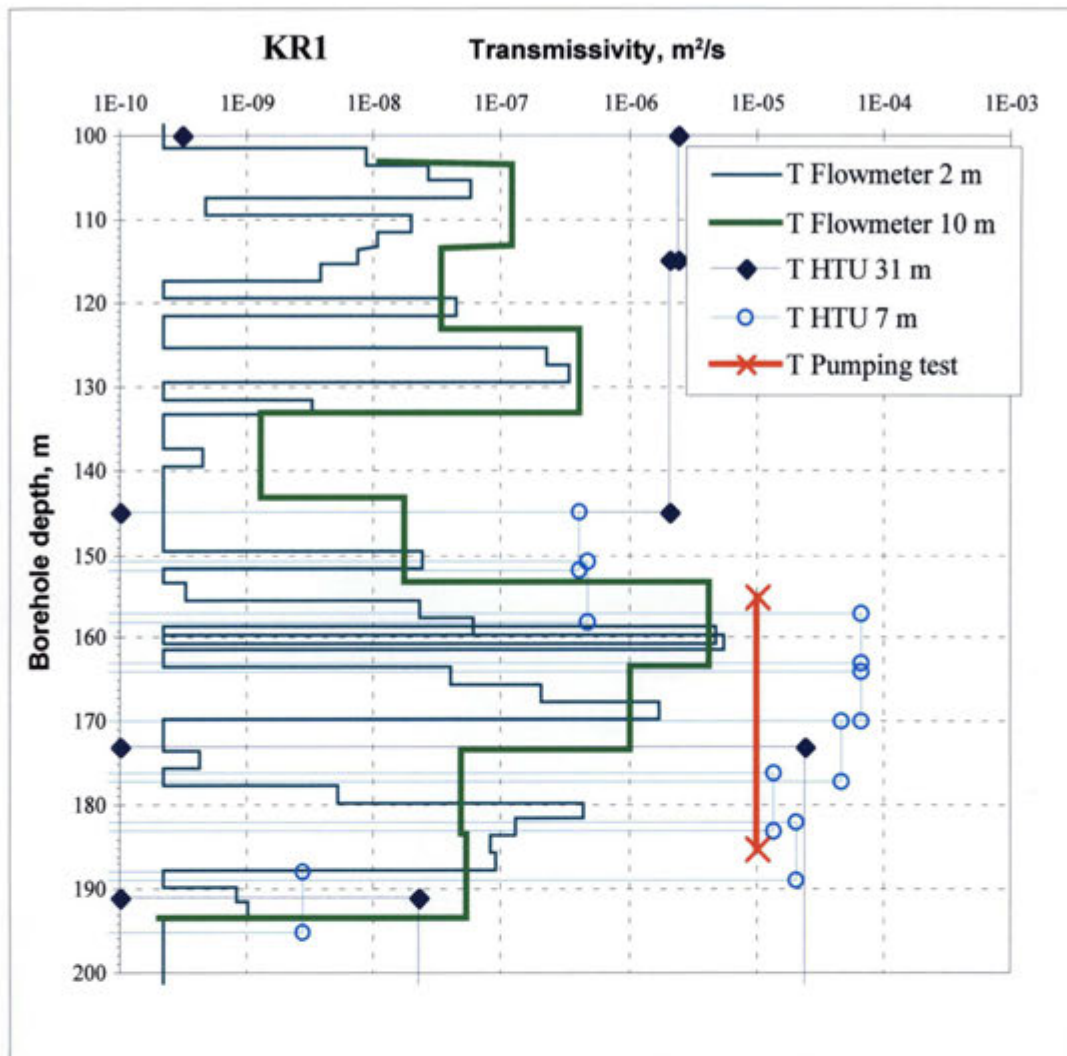


Figure 6.1-8. Transmissivities measured using the double-packer injection system (HTU), the flowmeter and one pumping test in structure R9 over a depth interval of 155 - 185 m in borehole KR1.

numerical groundwater simulations strengthen the conclusion that the transmissivity of structure R9 is lower than estimated from double-packer results (Taivassalo & Koskinen 1992).

The cross-hole transmissivity determined from the responses of interference tests, for some R-structures is, however greater than the transmissivity measured using double packers in a single borehole or using the flowmeter. This implies that the transmissivity of a conductive R-structure (or other kind of conductive feature) can be smaller in the immediate vicinity of a borehole than outside the borehole and also implies that the cross-hole transmissivity for such R-structures is higher than that determined from single-hole tests. As a general rule, it would appear that the results from interference tests are likely to be the most reliable. Unfortunately it has been possible to carry out only a limited number of interference tests, due to the distances between boreholes and the low transmissivity of most of the R-structures.

A new type of interference test has been tested at Romuvaara. Flow responses, i.e. differences in flow into or out of the borehole as well as across the borehole between natural and pumping conditions, have revealed hydraulic connections between adjacent boreholes (Niva & Rouhiainen 1996). On the basis of results it has been possible to estimate the likelihood of new connections between boreholes or describe the nature of conductive R-structures and their properties between boreholes.

6.2 Hydraulic Head in the Bedrock

Hydraulic heads at shallow depths have been measured in more than 30 shallow observation holes. Measurements have been carried out in about 20 holes at least once a month since 1987. These data have made it possible to study the relationship between the topography and the water table and to compile equipotentials for the water table, which are required for the definition of boundary conditions for numerical groundwater flow simulations. Equipotentials for the groundwater table are shown in Figure 6.2-1 (Ahokas et al. 1997).

Hydraulic head distributions at greater depths have been measured by several methods. The most reliable values are based on the long-term monitoring of water levels over several years in multi-packed boreholes. Estimates or calculated values from short duration double-packer tests and flow measurements have revealed some narrow sections in boreholes where hydraulic heads can differ markedly from values measured using multi-packer completions. Head measurements made in borehole KR3 are presented in Figure 6.2-2, where the differences in head determined from different measurement techniques is apparent. It is most unlikely that this kind of heterogeneity is a real phenomenon. However, some "anomalous" values are estimated to be real and have thus produced valuable information regarding the orientation of certain R-structures and have helped in the development of the structural and hydraulic models.

Head differences at shallow depths are clearly evident from Figure 6.2-1 and the horizontal hydraulic gradient can be calculated on the basis of equipotentials. To obtain an overall assessment of hydraulic heads and hydraulic gradients at greater depths, the most reliable values of hydraulic heads are presented in Figure 6.2-3. In general the hydraulic head is seen to decrease with increasing depth and the horizontal gradient is smaller at greater depths than at the surface. Some "anomalous" areas exist and they have been valuable for interpreting the presence of hydraulic connections and the orientations of certain R-structures, as well as for allowing the calibration of groundwater flow simulations or the estimation of the level of confidence (reliability) which could be ascribed to the results of such simulations (Taivassalo & Koskinen 1992).

6.3 Groundwater Flow

The amount of groundwater flow can be calculated based on values of measured transmissivity and estimations of hydraulic gradients presented earlier in this section. A direct method of measuring groundwater flow has been developed (Rouhiainen 1993) and results derived using this technique (Rouhiainen 1996c) are compared to calculated values in

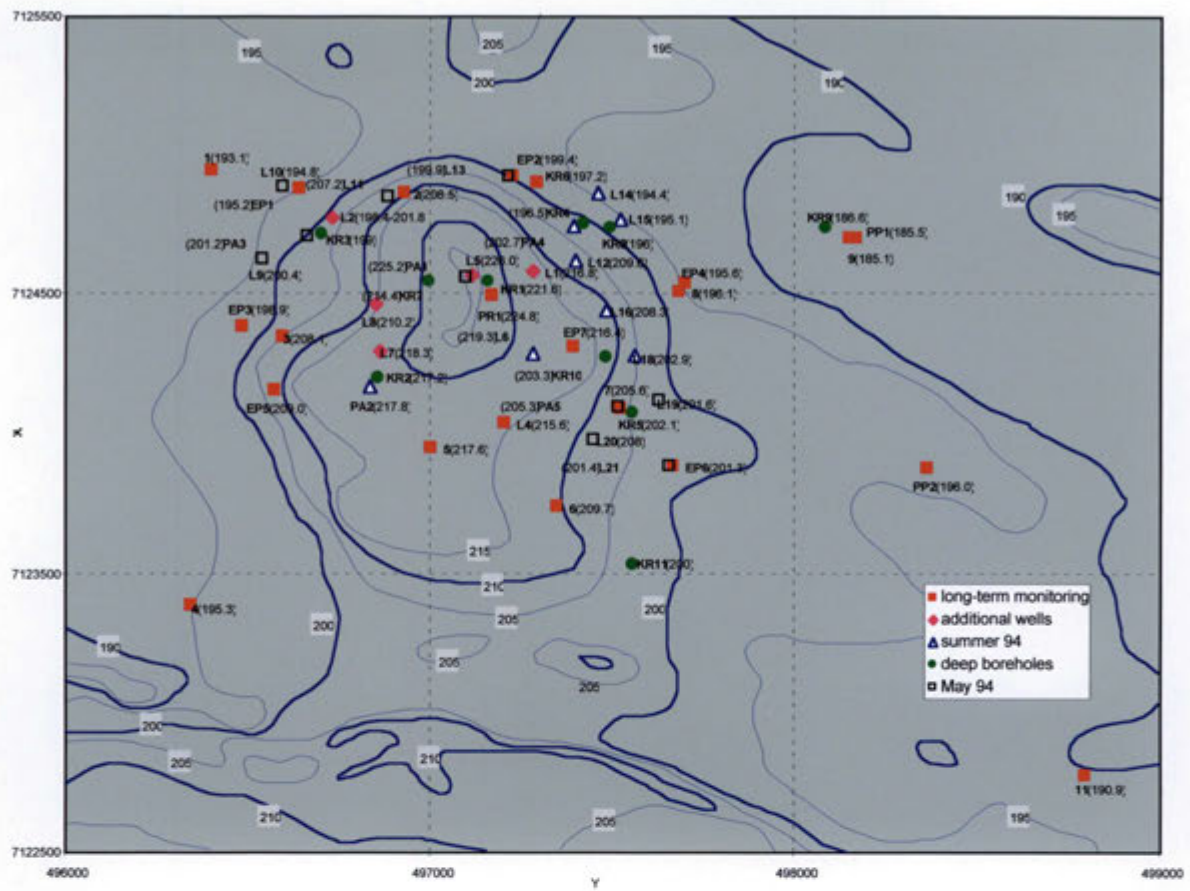


Figure 6.2-1. Measured means of hydraulic head in shallow boreholes and in the uppermost sections of permanent multi-level piezometers. Equipotentials for the ground-water-table are also shown (Ahokas et al. 1997).

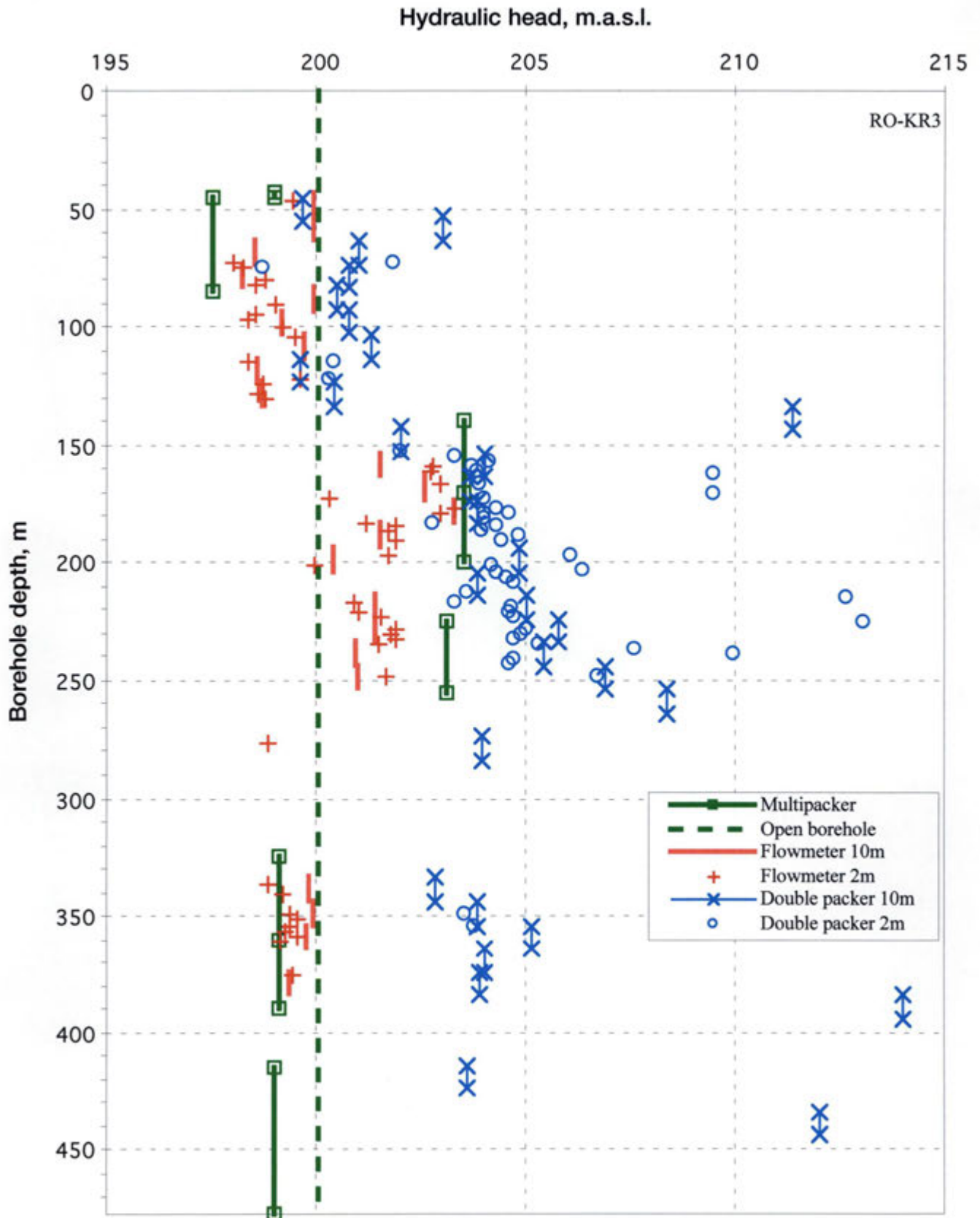


Figure 6.2-2. Hydraulic heads in borehole KR3 on the basis of long-term multi-packer observations and estimates or calculations from results of short-duration flowmeter and double-packer tests (Ahokas et al. 1997) (m.a.s.l. = meters above sea level).

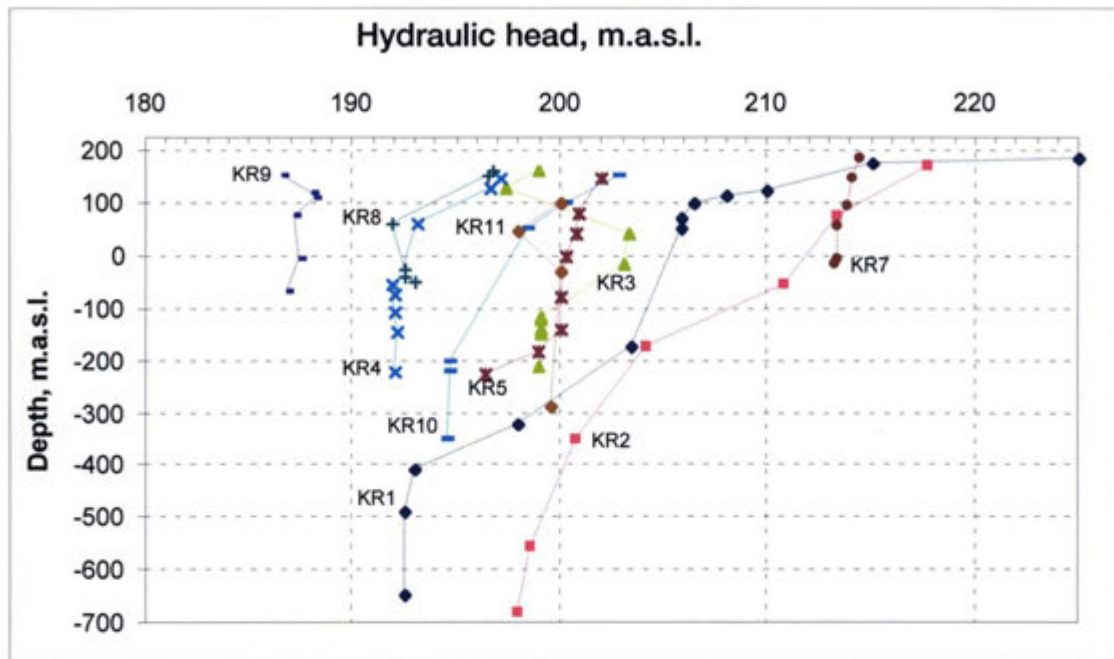


Figure 6.2-3. Hydraulic heads in deep boreholes at Romuvaara as a function of depth.

Figure 6.3-1. In the main only the most transmissive 2 m sections were chosen for practical reasons to be measured in each borehole. The results represent conductive features contained in both R-structures and in the intact rock. The range presented in Figure 6.3-1 is based on the assumption that the hydraulic gradient may vary between 0.5 - 6% and that the transmissivity may be as measured or ten times higher due to channelling within flowing fracture(s). About 20% of the measured values are higher than the upper limit of this estimated range. This may be an indication of a higher degree of channelling or a higher gradient, which may be caused by open-hole effects around the packed-off measuring sections. Some high values are thought to be caused by measuring errors, e.g. leaking flow guides in the flowmeter may have disturbed the measurements. In places where measured values are smaller than calculated ones, the heterogeneity of fracture(s) is the most probable explanation for any differences. In this case it implies that the measured transmissivity is determined by the presence of a narrow channel within the fracture or by the margin of a fracture which intersects only one side of the borehole wall, thereby preventing or severely reducing the potential for cross-flow. Additional investigations are required to find reasons for these incompatibilities and explanations for certain assumptions.

In conclusion, results from cross-flow (flowmeter) measurements (Fig. 2.3-1) have shown that groundwater flow can be measured directly and that flow takes place at several places within the rock mass. Thus assumptions and results from numerical calculations concerning the hydraulic gradient and the connectivity of transmissive fractures are often in harmony with measured values. Results also show that the heterogeneity of flow paths is often high and more detailed investigations concerning the nature of fractures and hydraulic properties are needed.

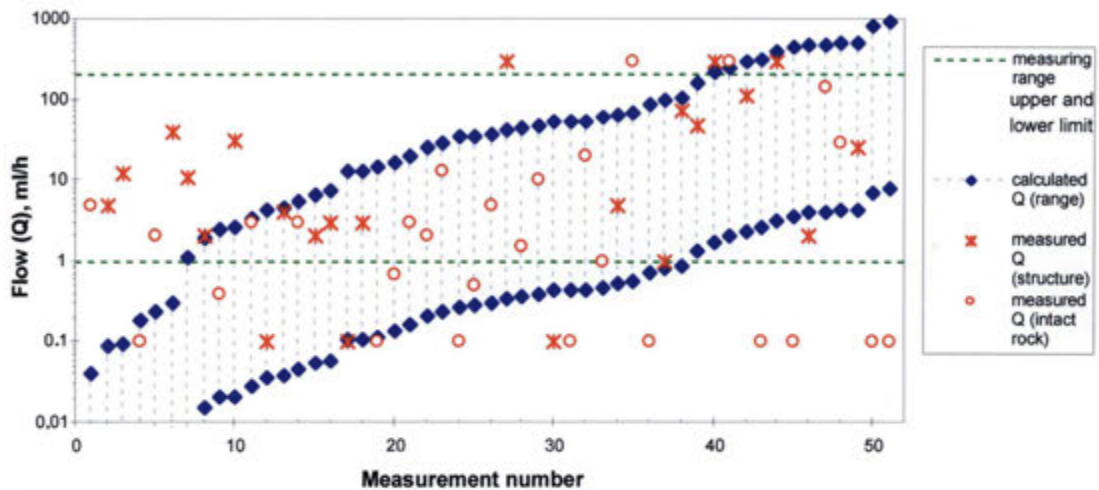


Figure 6.3-1. Measured and calculated groundwater flows (Q) in 51 different borehole sections.

6.4 Hydraulic Properties of the R-structures

The transmissivity of the R-structures (fracture zones) has been measured by several methods. Single-hole methods, such as constant head injection tests using a double packer system (HTU) and flow logging using the flowmeter, have proved to be the most useful in this regard. Cross-hole transmissivity has been measured for only a few fracture zones by the aid of interference tests. In total, 41 single-hole T values have been measured and they are presented in Figure 6.4-1 (13 of the R-structures have only one T value available). The maximum number of single-hole values for a single R-structure is three, and this situation exists for four R-structures. Unfortunately the variability in the measured transmissivities for some of these R-structures is very large and this makes it difficult to determine the values of their effective transmissivities.

R-structures are divided into four transmissivity classes for numerical flow modelling purposes and the depth-dependent curves of transmissivity for each class are presented in Figure 6.4-1 (Saksa et al. 1998). This classification is based on measured values or on the geological importance of R-structures for which no measured data are available. R-structures with a significant extension laterally or to depth are considered to be more transmissive than more local R-structures. The averaging process applied in order to place these zones into the different classes results in large uncertainties associated with this type of estimation. However, the significance associated with such uncertainties has been found to be small in characterising the groundwater flow regime for the site.

These values of T have been used as input values for numerical groundwater flow modelling (Kattilakoski & Koskinen 1999). Other input values, such as the location of the groundwater table, are presented in Figure 6.2-1 and the hydraulic conductivity of the intact rock in Ahokas (1999).

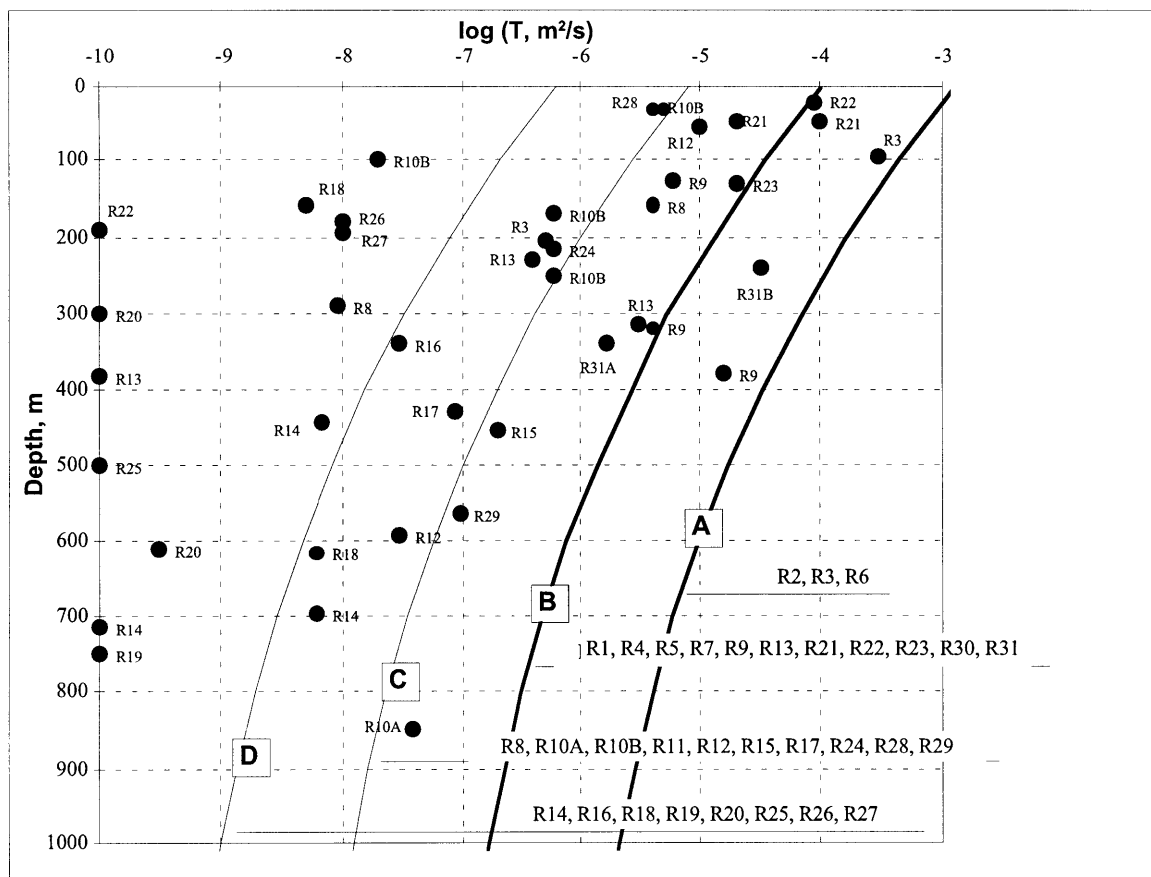


Figure 6.4-1. Measured transmissivities of R-structures and their classification into four depth-dependent transmissivity groups (curves A-D).

7 GEOCHEMISTRY

Hydrogeochemical studies were initiated at Romuvaara in 1987 during the preliminary investigation phase. Detailed investigations have been taking place since 1993, focusing mainly on a hydrogeochemical baseline characterisation of the site and aiming at mapping the natural groundwater conditions before the construction of any investigation shaft, which will inevitably introduce many changes in the groundwater flow system. The main goals of the studies are:

- the establishment of a representative data set for groundwater chemistry both laterally and with depth for the hydrochemical characterisation of local precipitation, and shallow and deep groundwaters,
- the evaluation of mean residence times and evolution of deep groundwaters, and
- the acquisition of input data for geochemical modelling and for performance assessment.

The later phase of the detailed site investigations, since 1997, has involved precision sampling of specific sections identified during the earlier phase, such as sampling of potential end-member groundwaters identified in geochemical modelling of the site. In addition there was a need for more information from deeper parts of the bedrock and generally for more representative samples to improve the understanding of the redox processes. It was also felt that the recharge conditions and groundwater chemistry in the upper part of the bedrock needed to be better known.

Since the late 1980s groundwater studies have involved sampling from deep boreholes (500 - 1 000 m), flushing water wells, shallow groundwaters, surface waters and from precipitation. The hydrogeochemistry, and especially the representativeness of the groundwater samples collected at Romuvaara area, has been discussed in several reports (Lampén & Snellman 1991, 1993, Pitkänen et al. 1993a, Tuominen 1994, Honkasalo 1995, Snellman et al. 1995, Pitkänen et al. 1996a, Ruotsalainen & Snellman 1996b, Helenius et al. 1998, Tuominen 1998). Detailed information on the sampling points, preparation of samples, analytical methods applied, as well as results on the water analyses and the characterisation of the local hydrogeochemical conditions are given in the summary reports by Lampén & Snellman (1993), and Ruotsalainen & Snellman (1996). The specific sampling methods and equipment used are given in reports by Rouhiainen et al. (1992), and Ruotsalainen et al. (1994, 1996, 1998).

A model for the hydrogeochemical evolution in different parts of the bedrock at Romuvaara area has been created and the significance of chemical reactions along different flowpaths has been calculated by Pitkänen et al. (1996a). The report summarizes probable processes and factors which control the hydrogeochemistry, such as pH and redox conditions in the bedrock. Also consistency between hydrogeochemistry and hydrogeological models and adjusted ^{14}C groundwater ages are considered.

This section summarizes the main hydrogeochemical results obtained during the period 1987 - 1997. Throughout this section, “depth” means borehole length.

7.1 Sampling and Chemical Analyses

Altogether 34 groundwater samples were taken in 1993 - 1994 from 6 - 7 isolated sections (section lengths generally 30 - 40 m, except for borehole KR1, where it was up to 115 m) in five deep boreholes KR1 - KR5 (Snellman et al. 1995). The extensive groundwater sampling intervals, especially that in borehole KR1, could have led to mixing of different types of groundwaters during sampling. However, according to the interpretation by Pitkänen et al. (1996a), groundwater flow is concentrated in a very limited number of fractures or fractured sections in the boreholes. The hydraulically conductive sections are narrow, only a couple of metres long, and usually occur alone in a single sampling interval, limiting any significant mixing of different water-types due to the straddle lengths.

In 1997 and 1998 groundwaters were sampled from shorter sections (3 - 9 m) from boreholes KR3 - KR4 and KR8 - KR11, in order to have more specific data on potential flow paths, discharge routes, end-member waters and also a better areal coverage of the site (Helenius et al. 1998). Sampling in 1997 also covered overburden (groundwater-pipes) and shallow percussion drilled wells at the site in order to obtain information on recharge conditions (Tuominen 1998).

Hydrogeochemical studies performed since the detailed site investigations have all been carried out according to the field manual for groundwater sampling (Ruotsalainen et al. 1994, 1998), which includes analytical programmes, protocols for the evaluation of the representativeness of the water samples, the use of sampling equipment, the handling and preparation of the water samples, field measurements and analyses. A good level of reproducibility for all samples at all sites has been achieved by following this manual. The progress of sampling and the representativeness of the samples were monitored by means of chemical field measurements (Rouhiainen et al. 1992, Ruotsalainen et al. 1994, 1998) which helped in making decisions regarding the most appropriate time for sampling. Pumped groundwater enters the combination of flow-through cells for measurement of O_2 (one separate small cell) and Eh, pH, EC (= Electrical conductivity) and temperature (another larger cell). This is performed on-line, and the measuring system has been N_2 -protected since 1997, thereby avoiding any contact with the atmosphere.

As groundwater is pumped from a borehole, the pressure decrease causes degassing, and this affects the contents of dissolved gases, some hydrogeochemical parameters, colloids and microbiology. Posiva has developed equipment for pressurized groundwater sampling (Ruotsalainen et al. 1996) known as PAVE (Fig. 7.1-1). The groundwater in the PAVE containers was analysed for dissolved gases and microbes, and isotope content (2H , ^{13}C , ^{18}O) of methane and carbon dioxide (Table 7.1-1). The recent sampling in 1997 - 1998 was performed with the PAVE sampler from double-packed sections of the deep boreholes.

The parameters analyzed in the water samples were selected with a view to the input data required for the hydrochemical characterisation, geochemical modelling, experimental studies (solubility, diffusion and sorption studies) and performance assessment. The number of parameters analyzed was very comprehensive (60 - 70 in total). Depending on the sampling location and method used, as well as the representativeness of the sample, the analyses were performed either according to the "standard" (baseline), "special" (evolu-

Table 7.1-1. Analytical programmes applied for the analysis of groundwater samples at Romuvaara.

Parameter	Standard programme	Special programme	Concise programme
Physicochemical variables	pH, EC (=Electrical Conductivity), density, alkalinity, acidity, DIC (= Dissolved Inorganic Carbon), KMnO_4 -consumption (= Chemical oxygen demand, COD), uranine (= tracer of the drilling water),	Standard	Standard
Anions	HCO_3 , CO_3 , Cl, Br, F, I, SO_4 , $\text{S}_{\text{tot}}^{2-}$, PO_4 , NO_3 , NO_2 , N_{tot} , P_{tot} , B_{tot} , S_{tot}	Standard	HCO_3 , CO_3 , Cl, Br, F, I, SO_4 , $\text{S}_{\text{tot}}^{2-}$, PO_4 , NO_3 , NO_2 , S_{tot}
Cations	Na, Ca, Mg, K, Al, Fe_{tot} , Fe^{2+} , Mn, SiO_2 , NH_4 , U^{4+} , U^{6+} *	Standard	Standard
Trace elements	Sr, Cs, Li, Ba, Rb, Zr	Standard + Lanthanides	
Organics	DOC (= Dissolved Organic Carbon), TOC (= Total Organic Carbon),	Standard	Standard
Isotopes	$\delta^2\text{H}(\text{H}_2\text{O})$, ^3H , $\delta^{18}\text{O}(\text{H}_2\text{O})$, ^{222}Rn , $\delta^{13}\text{C}(\text{DIC})$, $^{14}\text{C}(\text{DIC})$, $^{234}\text{U}/^{238}\text{U}$ and U_{tot} (in H_2O and particles)	Standard + USE (= ^{222}Rn , ^{232}Th , ^{228}Th , ^{30}Th , ^{226}Ra , ^{228}Ra , ^{234}U , ^{238}U), $\delta^{34}\text{S}(\text{SO}_4)$, $\delta^{34}\text{S}(\text{S}^{2-})$, $\delta^{18}\text{O}(\text{SO}_4)$, $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{13}\text{C}(\text{CO}_2, \text{CH}_4)$, $\delta^2\text{H}(\text{CH}_4)$, $\delta^{18}\text{O}(\text{CO}_2)$	$\delta^2\text{H}(\text{H}_2\text{O})$, ^3H , $\delta^{18}\text{O}(\text{H}_2\text{O})$, ^{222}Rn ,
Dissolved and evacuated gases	N_2 , O_2 , CO_2 , CO, CH_4 , C_2H_2 , C_2H_4 , C_2H_6 , C_3H_8 , H_2 , He	Standard PAVE in 1997 and 1998	
Microbes		PAVE: Total number of cells, autotrophic acetogens, heterotrophic acetogens, SRB (= sulphate reducers), IRB (= iron reducers), autotrophic methanogens, heterotrophic methanogens	

* for a few samples

tionary) or “concise” analytical programme. A summary of the analytical programme is shown in Table 7.1-1.

The general criteria used for the evaluation of the hydrogeochemical data are given in Table 7.1-2.

For the general evaluation of the hydrogeochemical system, 27 multi-packer samples (from boreholes KR1- KR5) and 9 shallow groundwaters, were used by Pitkänen et al. (1996a), in which report also the representativeness of the data is evaluated. The additional deep borehole samples and shallow groundwaters taken in 1997 - 1998 have been included in the evaluation of the hydrogeochemical system presented in this section.

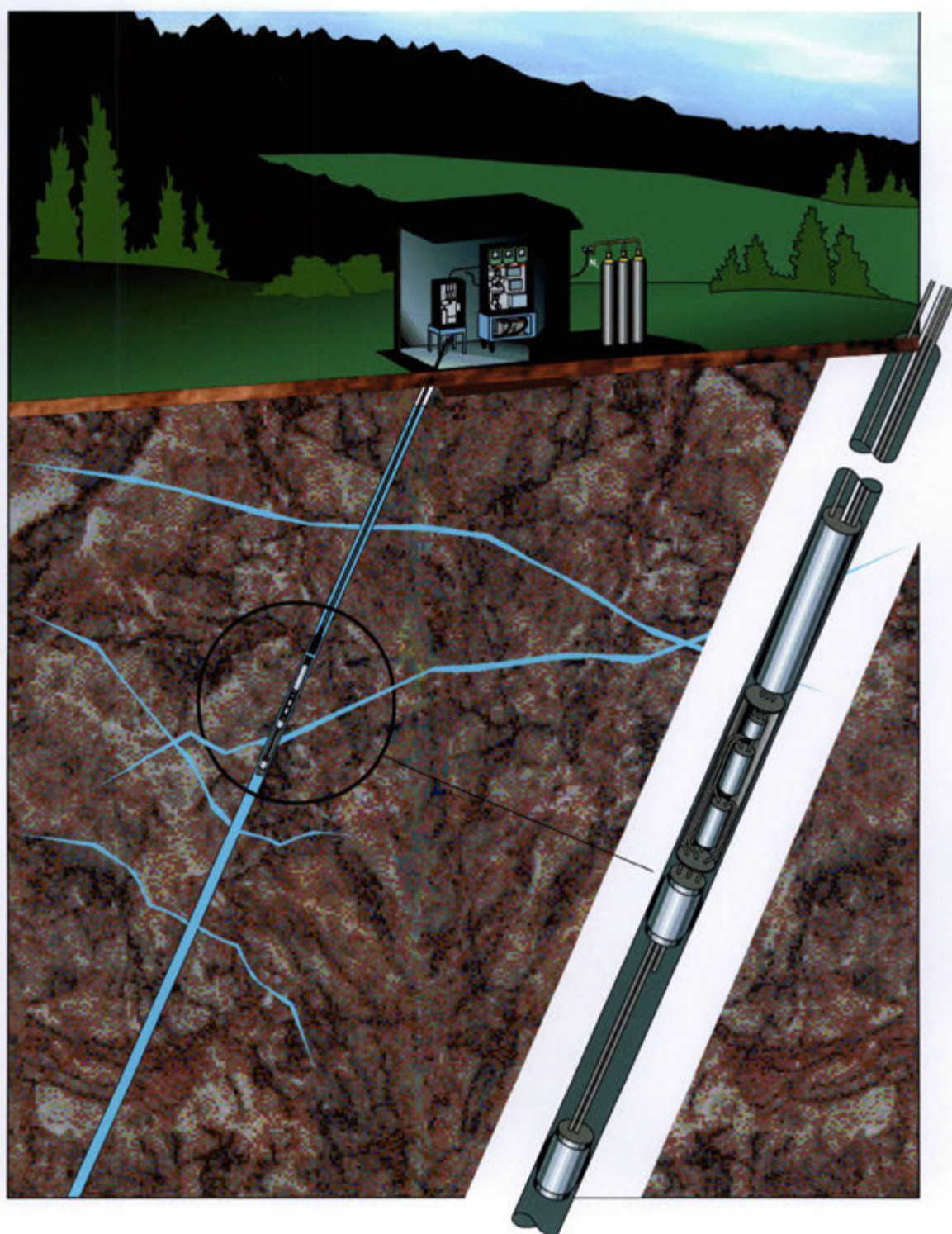


Figure 7.1-1. The pressurized groundwater sampling equipment (PAVE) developed by Posiva Oy.

Table 7.1-2. Criteria used in the classification of the hydrogeochemical data (from Ruotsalainen & Snellman 1996).

PARAMETERS	REPRESENTATIVE RESULTS, Boreholes	REPRESENTATIVE RESULTS, Shallow groundwaters
Technical effects	Samples with no obvious effects due to leakages from the multi-packer system or contamination by borehole stabilization cement	
Amount of remaining drilling water	< 2.5%	
pH, alkalinity, acidity	Field measurements	Field measurements
S^{2-}_{tot} , SO_4^{2-} , PO_4^{3-} , NH_4^+ , NO_2^- , NO_3^- , Cl^- , F^- , Br^- , Fe^{2+}	Field analyses	Laboratory analyses
Fe_{tot}	< 20 mg/l	< 20 mg/l
DOC	< 50 mg/l	< 50 mg/l
Charge balance	< $\pm 5\%$	< $\pm 5\%$

7.2 Basic Hydrogeochemical Features

All groundwater samples at Romuvaara are classified as fresh water, the Total Dissolved Solids (TDS) content being far below 1 000 mg/l (Davis 1964). The most evolved groundwaters ($Cl_{\text{max}} = 109 \text{ mg/l}$) are found at a depth of 415 - 500 m in borehole KR3 ($TDS_{\text{max}} = 265 \text{ mg/l}$), and the least evolved ones in borehole KR2 (TDS-values = 130 - 150 mg/l). TDS and generally also the chloride content (Fig. 7.2-1) increase with depth, but significant variations can be observed in a single borehole or between corresponding sampling levels in different boreholes, reflecting the importance of the local hydraulically conductive fracture zones in determining the spatial variability in water chemistry.

It was, therefore, felt appropriate to explain the evaluation of the hydrogeochemical features at Romuvaara with reference to the main fracture zones and the possible connections between the boreholes (KR1 to KR5), based on information from the hydraulic properties of these zones and from the groundwater flow and structural models. Three general flowpaths could be recognised (Fig. 7.2-2 and 7.2-3, Pitkänen et al. 1996a) as based on the hydrogeological concept and structural model of the area.

The general concept of groundwater flow has been taken from Taivassalo & Koskinen (1993), which is consistent with the recent updated model by Kattilakoski & Koskinen (1999). This model contains a few hydrogeological structures which are considered with reference to the hydrogeochemical data from Romuvaara. The three identified flowpaths are presented in Figures 7.2-2 and 7.2-3. All of these flowpaths are connected to the region of greatest topographic head on the top of the hill of Romuvaara, but are separated from each other downstream.

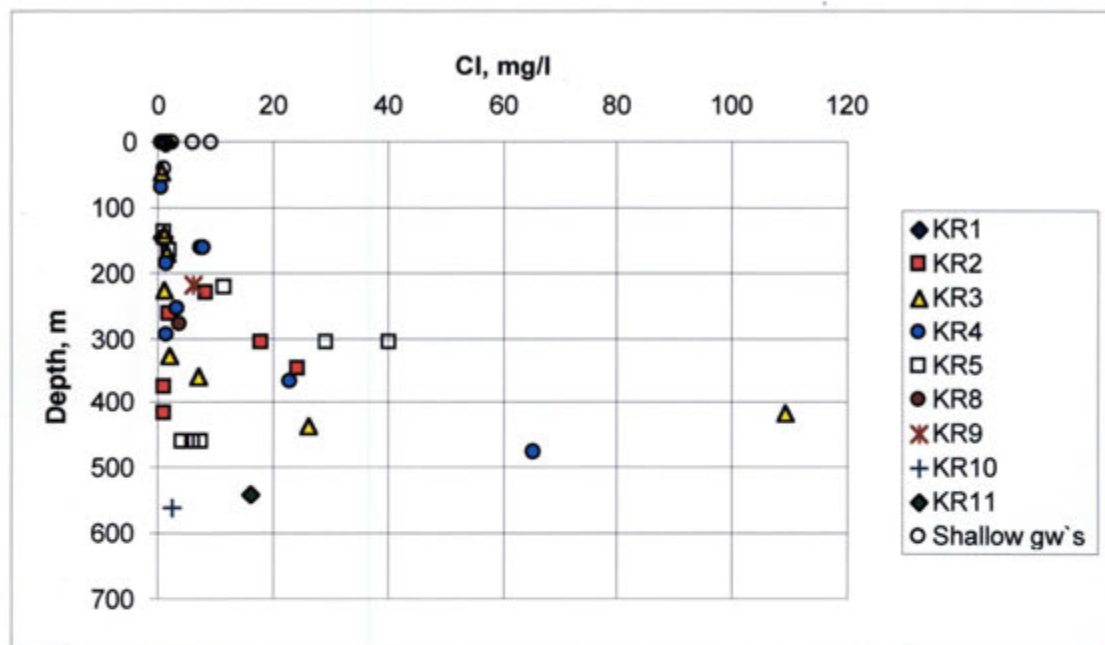


Figure 7.2-1. Chloride content as a function of depth. Shallow gw's represent shallow groundwaters from springs, groundwater pipes, wells and surface water.

Flowpath 1 commences at the top of the hill, which can be seen as a distinct recharge area (Fig. 7.2-2). Structure R9 is the main hydraulic conductor and transmits groundwaters from the surface to greater depths in the bedrock and towards where it is intersected by boreholes KR2 and KR3. The groundwater table within the structure R9 is assumed to reflect the local topography, and this structure is assumed to divide the groundwater flow at shallow depths into a western and an eastern component. Flowpath 1 considers the western component of the flow field and its discharge area is interpreted to be located to the west of boreholes KR2 and KR3. The modelled head field in structure R9 is shown in the reports by Taivassalo & Koskinen (1993) and Kattilakoski & Koskinen (1999).

Flowpath 2 describes groundwater being recharged from the eastern slope of the hill and flowing towards the northeast (Fig. 7.2-3). The groundwater flow is gently down dip from the area around borehole KR1, to the east or the southeast, according to the flow model (Taivassalo & Koskinen 1993, Kattilakoski & Koskinen 1999). Borehole KR4 is not directly connected by a single fracture zone to the area of highest head, but the flow simulations (Taivassalo & Koskinen 1993) support a gentle NE-dipping flow field from the top of hill towards borehole KR4 in the rock matrix (i.e. within the intact rock). A group of several intersecting structures, e.g. R9, R8, R10 and R13 (Fig. 7.2-3) may, however, connect borehole KR4 with the recharge area on the top of the hill.

Flowpath 3 considers recharge from the eastern slope of the hill towards the southeast (Fig. 7.2-2). Structure R8 is a subvertical diabase dyke contact zone which intersects the area in a NW-SE direction and cross-cuts borehole KR5 at quite a low angle. The zone itself and the subparallel flow in the adjacent rock matrix (i.e. within the intact rock) forms a plausible flowpath from the top of the hill of Romuvaara to the various groundwater sampling levels in borehole KR5 (Fig. 7.2-3).

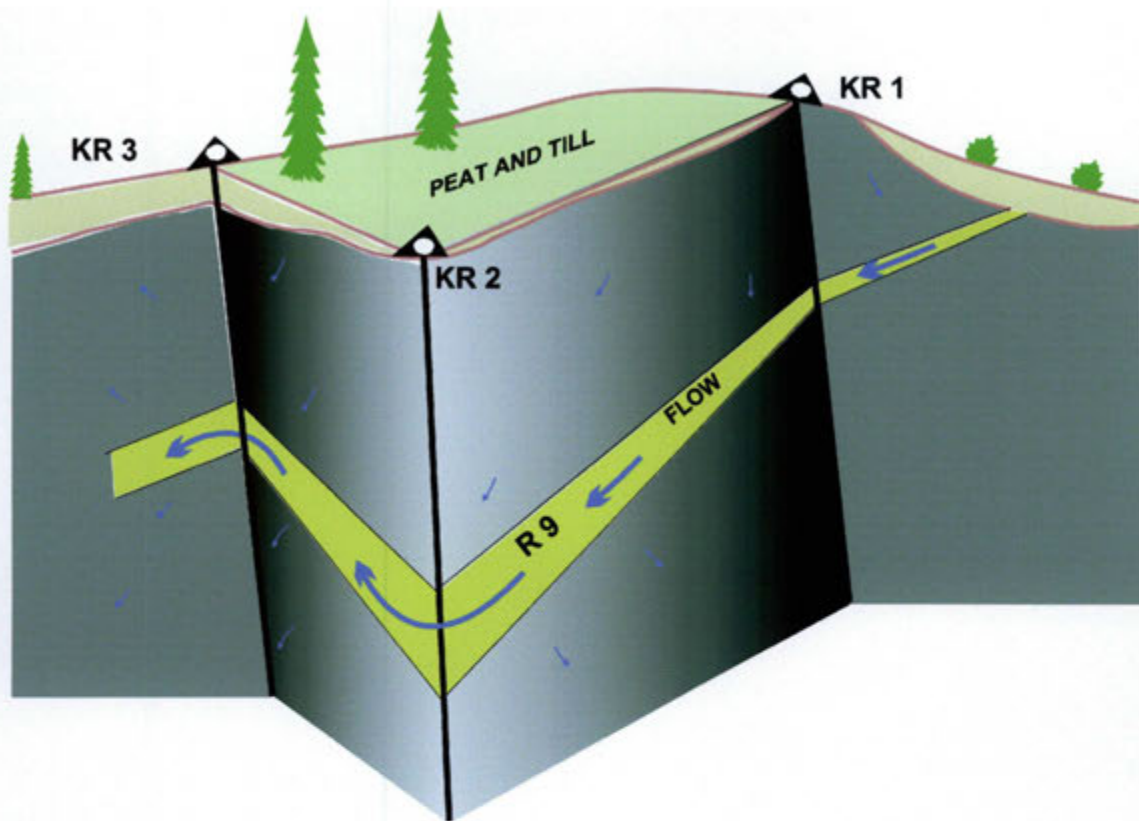


Figure 7.2-2. 3-D illustration of the conceptual hydrogeological model of *Flowpath 1* at the Romuvaara site according to Pitkänen et al. (1996a) (for actual location see Fig. 2.2-4). The model is limited to the main hydrogeological features of a block formed by boreholes KR1, KR2 and KR3. Structures are from Saksa et al. (1992, bedrock model version 1.0, and its updated version Saksa et al. (1998)) and flow directions (blue arrows) are modified according to Taivassalo & Koskinen (1993). Figure not to scale. View towards the north.

The chloride content is generally low in the main recharge zone R9, implying a relatively high conductivity for this zone (Fig. 7.2-1). Along Flowpath 1 (boreholes KR1, KR2, KR3) in both the hanging wall and footwall of R9, higher chloride values are observed in the bedrock. The enrichment of chloride with depth is comparable to that of Flowpath 2 (boreholes KR4, KR8 and KR9). Cl seems to show a slightly higher enrichment with depth in Flowpath 3 in the immediate vicinity of the metadiabase dyke than do the other two flowpaths, which are contained within the gneiss, and this could indicate an apparently longer residence time for Flowpath 3.

Different evolutionary trends of chemical compositions along the flowpaths are observed. Typical of all trends is a first stage evolution from a Ca-Mg-HCO₃-type to a Ca-Na-HCO₃-type groundwater (classification according to Davis & DeWiest 1967), but then the composition along Flowpath 1 changes to a Na-Ca-Cl-type groundwater, whereas it alters to a Na-HCO₃-Cl-type groundwater along flowpaths 2 and 3. However, the relative content of calcium, increases along both flowpaths 1 and 2. Flowpaths 1 and 3 seem to represent the extreme evolutionary trends in Romuvaara. The trend of Flowpath 1 leads to a calcium-rich Na-Ca-Cl-type groundwater, which is typical of felsic rocks in Finland, and which would include tonalitic gneisses at Romuvaara. The trend towards a Na-Cl-type groundwater is typical of

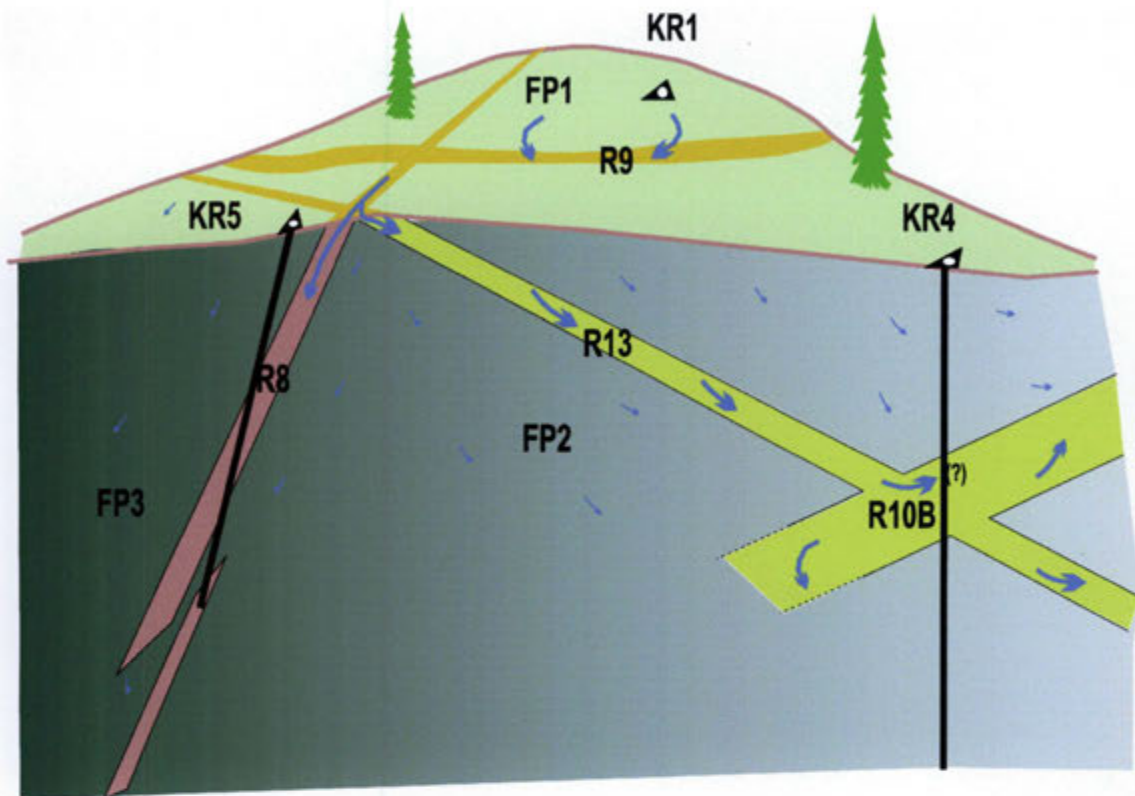


Figure 7.2-3. 3D-illustration of the rock mass between boreholes KR4 and KR5 showing the conceptual hydrogeological model of Flowpaths 2 (FP2) and 3 (FP3) according to Pitkänen et al. (1996a) at the Romuvaara site (for actual location see Fig. 2.2-4). The model is limited to the main hydrogeological features of a block formed by boreholes KR1, KR4 and KR5. Structures from Saksa et al. 1992 and flow directions (blue arrows) are modified according to Taivassalo & Koskinen (1993). Figure not to scale (from Pitkänen et al. 1996a). View towards the west.

mafic-ultramafic rock environments (e.g. Bottomley et al. 1990, Blomqvist et al. 1993b, Pitkänen et al. 1993a, Ruskeeniemi et al. 1996), which is typified by the metadiabase dykes at Romuvaara. Flowpath 2 has characteristics typical of both groundwater types. The reason for this may be the mixing of major groundwater types, e.g. during sampling, or possibly due to the fact that Flowpath 2 is open to interactions representing both major evolutionary trends, i.e. the groundwater has been in contact with both gneissic and metadiabase rock. The nearest metadiabase dyke to borehole KR4 is located downstream in structure R2/3, but groundwater may also flow from fracture zone R8 via fracture zone R13 to this borehole (see Fig. 7.2-3).

7.2.1 pH and Alkalinity

The pH value increases along all flowpaths from slightly acidic level near the ground surface as the groundwaters increase their salinity (Fig. 7.2-4). The highest (max. 10.3) pH values are observed in borehole KR5 (Flowpath 3), reflecting an interaction with the metadiabase dyke. High-pH waters with values of pH of 10 - 11 have been observed

typically in mafic-ultramafic rock environments according to Bottomley et al. (1990), Pitkänen et al. (1993b), Ruskeeniemi et al. (1996). A similar effect can also be seen along Flowpath 2, where groundwater in borehole KR4 has a maximum pH value of 9.4 and in borehole KR11, where the maximum pH value is 9.8, possibly due to the interaction with the amphibole-rich rock sections observed in boreholes (Gehör et al. 1997). The smallest increase in pH is observed along Flowpath 1 (boreholes KR1 - KR3), where the pH changes from a value of pH 7.0 - 7.5 to 8.9.

The trends in carbonate alkalinity are depicted in Figure 7.2-5. At low chloride contents the trend is similar to that observed at the other investigation sites of Kivetty, Olkiluoto and

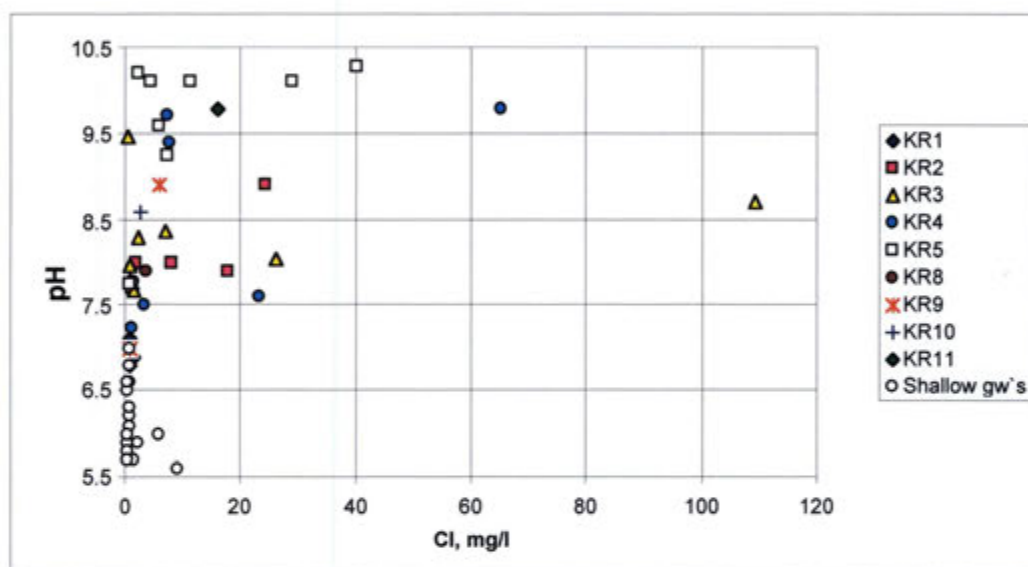


Figure 7.2-4. pH versus chloride content for Romuvaara groundwaters.

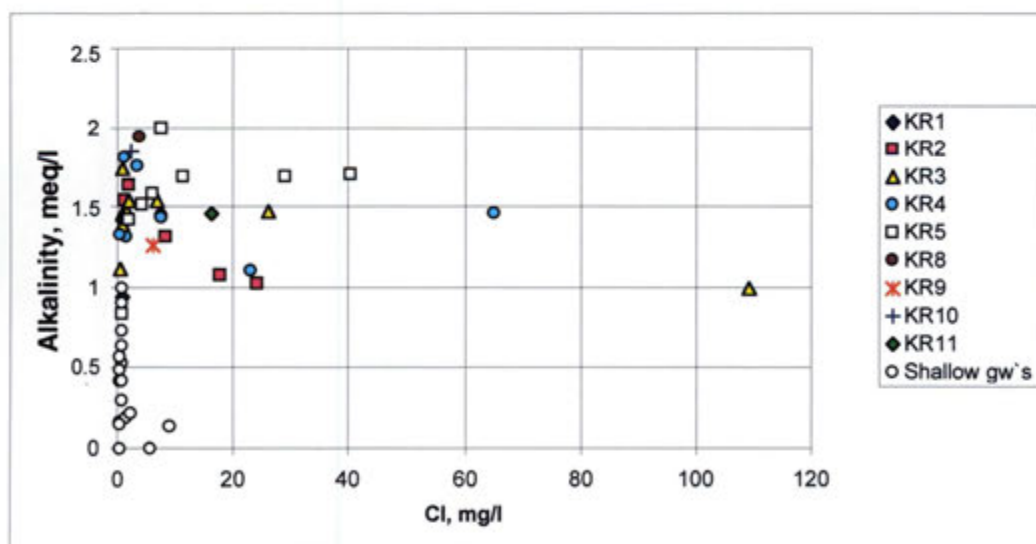


Figure 7.2-5. Alkalinity versus chloride content for Romuvaara groundwaters.

Hästholmen (Pitkänen et al. 1998, 1999, Snellman et al. 1998). There is an abrupt initial increase in alkalinity reaching a maximum value (< 2 meq/l) followed by a decrease, the steepest drop being along Flowpath 1 (samples from borehole KR1), whereas the alkalinity for Flowpath 3 (samples from borehole KR5) is fairly constant at a chloride content of about 10 mg/l. Some fluctuations in the carbonate alkalinity are found along Flowpath 2 (samples from borehole KR4, KR8 and KR9), the overall trend is, however, one of decrease.

Log $p\text{CO}_2$ values (calculated with EQ3NR) above the atmospheric partial pressure (log $p\text{CO}_2 = -3.5$) for the least evolved waters along all flowpaths indicate biochemical oxidation of organic carbon as a source for the carbonate in the water (Pitkänen et al. 1996a). The calculated log $p\text{CO}_2$ values decrease along the flowpaths to levels below -4.0 in Flowpath 1 and levels below -5.0 for the most evolved waters along Flowpaths 2 and 3 reflecting the high pH of these waters.

7.2.2 Redox Chemistry

The least disturbed redox measurements (with no major technical difficulties during field measurements or contradiction between concentrations of $\text{S}^{2-}_{\text{tot}}$ and measured Eh and dissolved oxygen) of the Romuvaara groundwaters suggest the prevalence of slightly reducing conditions in the boreholes (Eh 0...-400 mV, with a median value of -150 mV (Ruotsalainen & Snellman 1996b, Helenius et al. 1998)). The conditions are generally more reducing with increasing salinity, however, very low redox values (-400 mV) have been measured for samples with low salinity (Fig. 7.2-6).

Even though there are differences in the main compositional components and pH of the Romuvaara groundwaters, these represent fairly small variations in the concentrations of the redox-sensitive elements, except for that of sulphate (Fig. 7.2-7).

Samples with neutral pH and low chloride content show somewhat elevated values of iron.

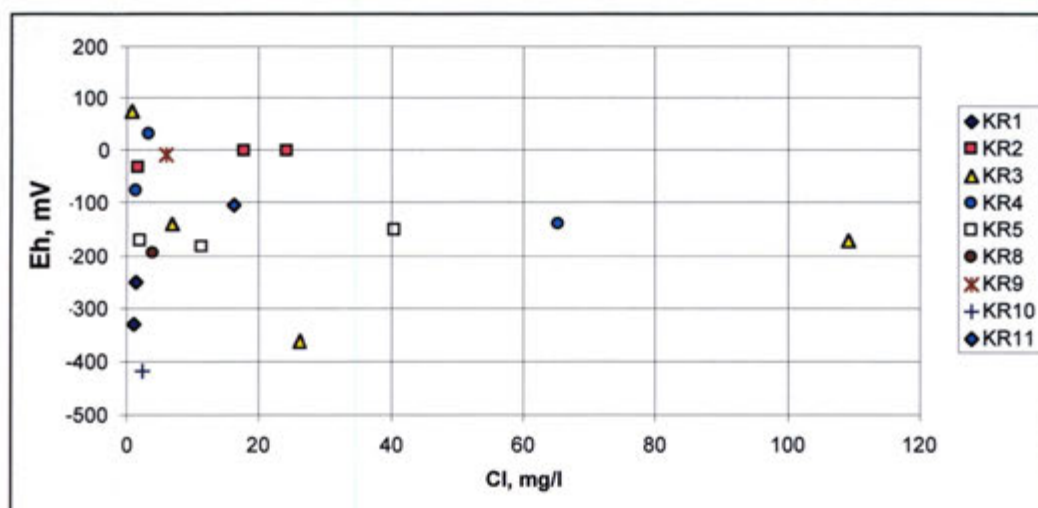


Figure 7.2-6. Eh versus chloride content for Romuvaara groundwaters.

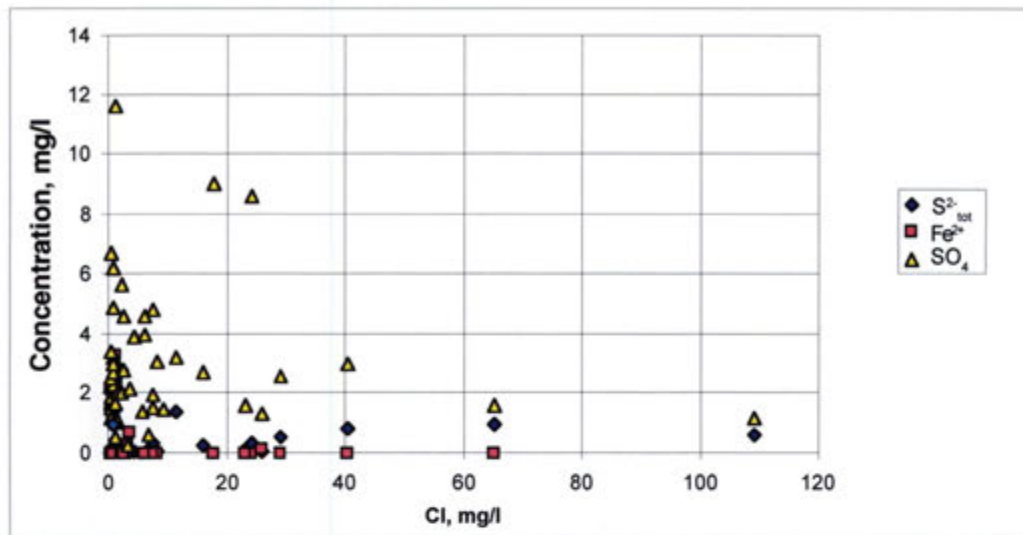


Figure 7.2-7. Redox parameters (Fe , SO_4 , S^{2-}_{tot}) in Romuvaara groundwaters.

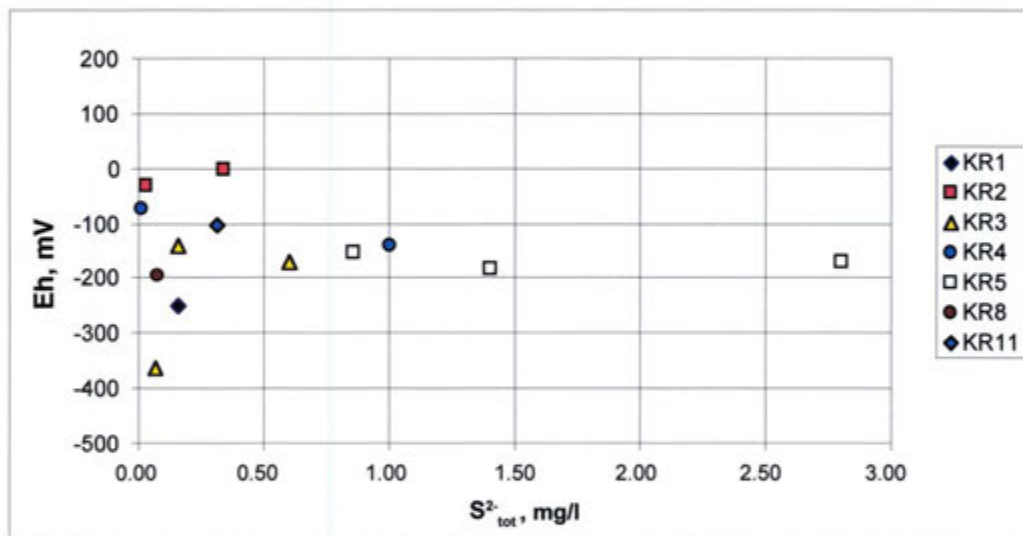


Figure 7.2-8. Measured Eh-values versus S^{2-}_{tot} in Romuvaara groundwaters.

Otherwise the iron content is low, and it exhibits a more or less constant level at higher chloride contents of the groundwaters (Fig. 7.2-7). The median value of Fe_{tot} of the Romuvaara groundwaters is 0.03 mg/l or $5.4 \cdot 10^{-7}$ mol/l, compared with a theoretical lower limit of 10^{-6} mol/l if Fe^{2+}/Fe^{3+} were the redox-controlling couple of iron required for successful Eh measurements (Grenthe et al. 1992). The iron pair is, therefore, not likely to be controlling Eh at Romuvaara. Iron oxides, rust, have been observed down to depths of 40 - 190 m. In these near-superficial conditions one likely redox buffer is the Fe^{2+} /goethite pair (Pitkänen et al. 1993a).

Groundwaters from boreholes KR3 and KR4, as well as from borehole KR5, with the lowest local Eh values, characteristically contained more sulphide than the others (Fig. 7.2-8). In these boreholes all samples containing a measured redox level of -100 to -250 mV and sulphide above 0.5 mg/l suggest reducing conditions. Some groundwaters with an appar-

ently lower sulphide content (0.09 - 0.15 mg/l) are also reducing, however the actual level of S^{2-}_{tot} is obviously greater than that observed due to technical problems during sampling (Ruotsalainen & Snellman 1996b).

Variable trends are seen in the sulphate content of the groundwaters along the flowpaths (Pitkänen et al. 1996a). However, the highest sulphate contents are found in the least evolved waters at low chloride contents and generally sulphate decreases with increasing chloride content (Fig. 7.2-7). The proportion of sulphide compared with sulphate increases with an increase in chloride content emphasizing the importance of the sulphur system as a redox buffer.

7.3 Fracture Mineralogy

Fracture mineralogy studies have focussed on existing (or geologically-recent) water-conducting fractures. Detailed fracture mineral investigations (Gehör et al. 1996a, b, 1997) have shown that low-temperature fracture mineral assemblages exhibit similar features in all drill core samples. The most common minerals are calcite, iron sulphides, ferrioxhydroxides and clay minerals. They can be classified into 12 assemblages as shown in Table 7.3-1 and Figure 7.3-1. The mineral assemblages represent group of minerals, which have been found on certain fracture surfaces of the drill core or consist of the fracture minerals found on adjacent fracture surfaces. The minerals belonging to the assemblage are not necessarily in contact or in chemical equilibrium with each other and they were not necessarily formed synchronously.

Table 7.3-1. The most common fracture mineral assemblages and their proportional distribution in drill core samples from Romuvaara boreholes KR1 - KR5, and KR7 - KR9 (Gehör et al. 1996a).

Fracture mineral assemblage	Proportional occurrence, %
Calcite-iron oxyhydroxides-clay minerals	39.2
Calcite-clay minerals	15.3
Calcite -iron sulphide-clay minerals	14.2
Iron sulphide-iron oxyhydroxides-clay minerals	9.9
Calcite	6.2
Iron sulphide-clay minerals	3.7
Iron oxyhydroxide-clay minerals	3.3
Calcite-iron sulphide	2.8
Iron sulphide-iron oxyhydroxide-clay minerals	2.7
Clay minerals	2.0
Iron sulphides	0.5
Iron oxyhydroxide	0.3

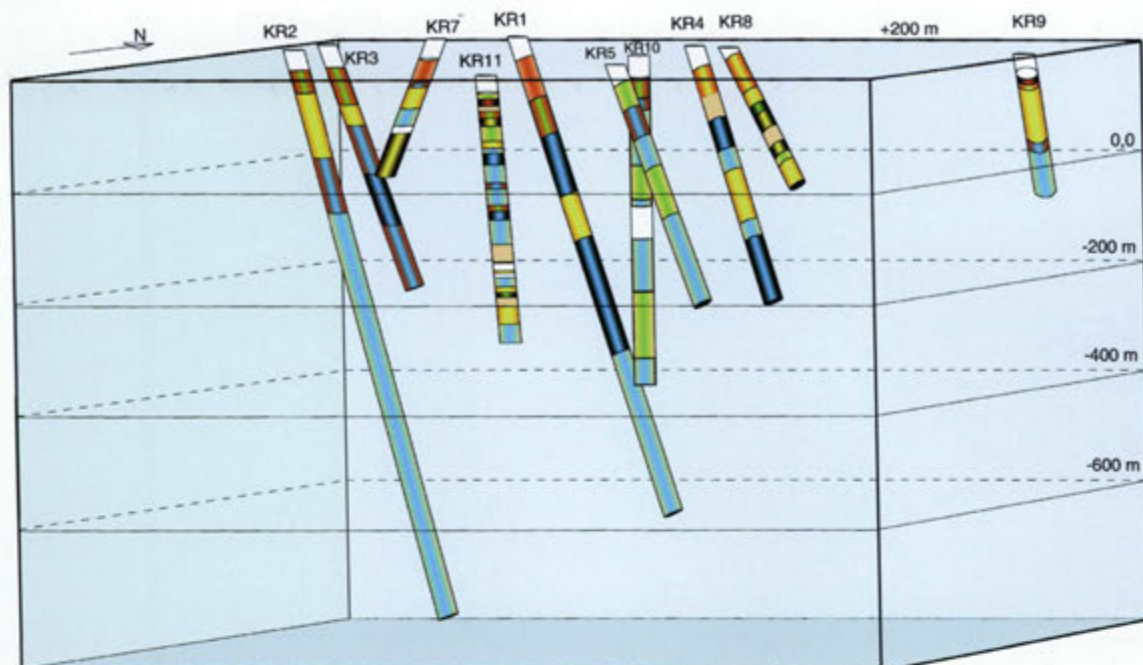


Figure 7.3-1. Occurrence of fracture mineral assemblages in the core samples from Romuvaara (Gehör et al. 1997).

The calcite-iron oxyhydroxide-clay mineral assemblage is the most abundant low-temperature fracture mineral assemblage in the area. Ferrihydroxides (goethite - limonite) are mainly observed down to about 150 m depth (except for some deeper observations from borehole KR3 and borehole KR11, at about 300 - 400 m). The most common fracture mineral, calcite, has rarely been found at shallower depths (down to 85 - 120 m). There are usually two generations of calcite coatings and sometimes small (2 - 3 mm) euhedral calcite crystals are also observed. Iron sulphides appear commonly below 100 m depth as small (< 1 mm) cubic crystals (pyrite) on the calcite, but thin pyrite films on calcite have also been observed. The most common clay minerals in the fractures are kaolinite, montmorillonite and other smectites. These can be observed in all drill cores and at every level. Laumontite is widely distributed in all of the fractures at Romuvaara regardless of depth (Gehör et al. 1996a).

7.4 Hydrogeochemical Evolution of Groundwater

The following model developed for the hydrogeochemical evolution of groundwater at Romuvaara by Pitkänen et al. (1996a) has been based on hydrogeochemistry, isotopic data and mineralogy, and mass balance modelling (NETPATH, Plummer et al. 1991) with an extensive use of carbon isotope data in conjunction with water chemistry and thermodynamic speciation calculations. There is a comprehensive hydrogeochemical dataset for the Romuvaara site and the modelling is believed to present a good general picture of the evolutionary processes prevailing in the upper 500 m of the rock mass since the last glaciation. The interpretation also support the concept of groundwater flow by Taivassalo & Koskinen (1993) and Kattilakoski & Koskinen (1999).

Figure 7.4-1 summarizes the general reactions occurring at Romuvaara and the carbon isotope evolution along Flowpath 1 (see Fig. 7.2-2). This interpretation is supported by observed $\delta^{13}\text{C}$ values of dissolved carbon and qualitatively also by the fracture mineralogy and by $\delta^{34}\text{S}(\text{SO}_4)$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in groundwaters. The hydrogeochemical evolution of the groundwater along Flowpath 2 was interpreted to be similar to that shown in Figure 7.4-1, however reaction paths deviate considerably along Flowpath 3 (Pitkänen et al. 1996a). The chemical processes leading to a different type of evolution between the end-member Flowpaths 1 and 3 seem to depend on the interaction between the host rock and the groundwater. The low $^{87}\text{Sr}/^{86}\text{Sr}$ ratio strongly corroborates mafic rock interaction along Flowpath 3, whereas higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the samples from Flowpath 1 indicate a more radiogenic signature and an input of strontium from Rb-bearing minerals such as biotite and feldspars, the dominant minerals of the felsic tonalitic gneisses of the Romuvaara site.

7.4.1 Recharge

The dominant groundwater processes during recharge into bedrock are organic carbon oxidation (a principal oxygen consumer) followed by calcite dissolution in the initial parts of the flowpaths, which results in an increase in pH to 8 - 9. Several studies (e.g. Nordstrom et al. 1985, Fritz et al. 1989, Banwart et al. 1994, Fontes 1994) based on $\delta^{13}\text{C}$ in dissolved inorganic carbon, have shown the importance of organic-derived carbonate as a source for dissolved inorganic carbon in addition to calcite dissolution.

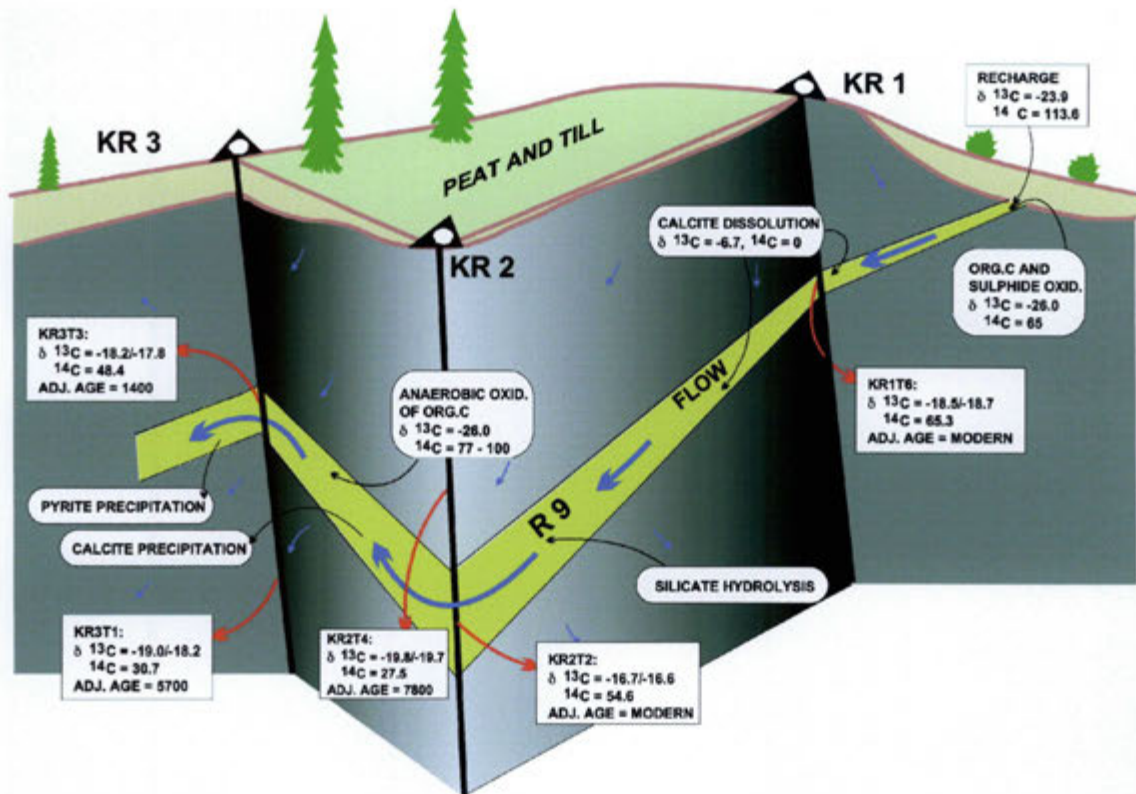


Figure 7.4-1. 3-D illustration of conceptual model of chemical and carbon isotopic evolution along Flowpath 1 at Romuvaara site. Structures from Saksa et al. (1992) (and the updated version Saksa et al. 1998) and flow directions (blue arrows) modified according to Taivassalo and Koskinen (1993). Rectangles contain carbon isotope data of modelled water sample; $\delta^{13}\text{C}$ (measured/calculated (‰ PDB); measured ^{14}C (% modern) and modelled adjusted ages (ADJ.AGE) in years. Rounded rectangles contain the main sources with estimated carbon isotope compositions and sinks along flowpath (from Pitkänen et al. 1996a). The code KR3TX refer to a sampling interval (T1...T7) in borehole KR3, for details see Pitkänen et al. (1996a). Figure not to scale. View towards the north.

During recharge, a semi-open system of “organic carbon”-derived dissolved carbonate is applied (Fig. 7.4-1). Oxidation of organic matter (peat and plant debris) by oxygen gas during recharge buffers carbon isotope composition of the dissolved CO_2 , which subsequently reacts with fracture calcite and silicates along the flowpath. This assumed process permitted an estimation of the average ^{14}C content of organic matter in peat bogs and depressions at the site. The mass transfer and carbon isotope data for the groundwater indicate -6.7‰ PDB of $\delta^{13}\text{C}$ in calcite, -26‰ PDB in organic carbon and 65% of modern ^{14}C content in organic matter.

Some minor silicate hydrolysis and limited sulphide oxidation are expected. Sulphide minerals in overburden (mainly glacial till) or in fractures may form a potential source for SO_4 . Sulphur isotope data from minerals potentially reveal the role of water-rock interaction in early SO_4 enrichment. Changes in concentrations and in cationic ratios of Ca and Na result in ion exchange reactions, that are particularly strong in mafic rocks (Flowpath 3).

7.4.2 pH and Carbonates

Geochemical evolution of the groundwaters at Romuvaara is characterised by increasing pH and decreasing $p\text{CO}_2$ driven by silicate hydrolysis reactions. Anaerobic respiration of dissolved organics combined with sulphate reduction may also increase alkalinity directly as methane-promoted reduction. Mafic minerals in the metadiabase dyke swarm are the probable reason for high pH values (about 10) in Flowpath 3, a conclusion which is also supported by an EQ6 model prediction (Pitkänen et al. 1996a).

Calcite is a common fracture mineral in the boreholes (Section 7.3) and, consequently, it should affect the water chemistry at the Romuvaara site. Calcite fillings are rare in the upper 100 - 200 m (depending on the boreholes and structures), and in the metadiabase-hosted sections of borehole KR5 (Flowpath 3). After an initial steep rise ($\text{Cl} < 2 \text{ mg/l}$) in dissolved carbonate concentration (mainly bicarbonate), groundwater is in principle saturated in respect of calcite ($| \text{SI} | < 0.3$) in all flowpaths, reflecting initial dissolution of calcite in the conductive upper parts of bedrock and later precipitation in the deep, more stagnant parts. The dissolution is confirmed by the immediate enrichment of dissolved carbonate and calcium and the increase in pH from recharge water to shallow groundwater (low-Cl concentration) and also by initial enrichment of $\delta^{13}\text{C}$ in the dissolved carbonate phase.

Following the calcite saturation, the chemical trends of the flowpaths deviate. In Flowpath 1, Ca, dissolved carbonate and $\delta^{13}\text{C}$ contents begin to decrease, which can be explained by calcite precipitation. Calcium decreases in Flowpath 3 even more than in Flowpath 1, but instead of decreasing, the amount of dissolved carbonate is fixed in Flowpath 3 and $\delta^{13}\text{C}$ continues to increase. These facts do not favour the role of calcite as the main controlling agent in carbonate hydrogeochemistry during the advanced evolution of Flowpath 3, which coincides with the rare occurrence of calcite in metadiabase dykes. The depletion of Ca may also be explained by Na ion exchange that has been proposed for the groundwater within the mafic East Bull Lake gabbro-anorthosite pluton in Canada (Bottomley et al. 1990), where the evolutionary trend from Ca-HCO_3 water to high-pH, Na-HCO_3 water is very similar to Flowpath 3. The continuing enrichment of $\delta^{13}\text{C}$ is not favoured by the fermentation of organic compounds, because the majority of $\delta^{13}\text{C}$ values of methane (-37 to -25‰ PDB) suggest a thermogenic source. Neither can the enrichment of $\delta^{13}\text{C}$ be explained by calcite dissolution, because the dissolved carbonate level is stable and the saturation of calcite does not favour dissolution. A stable carbonate content in groundwater prevents Ca/Na exchange-enabled calcite dissolution as a $\delta^{13}\text{C}$ source. Instead of calcite dissolution, calcite recrystallization, i.e. carbon isotope exchange, is considered the most obvious reason for $\delta^{13}\text{C}$ increase in the later stages of Flowpath 3, as is also the case in the most saline portion of Flowpath 1.

The samples of Flowpath 2 are mainly distributed according to the carbonate evolution type of Flowpath 1, reflecting water-gneiss interaction at the sampling location, although some samples show intermediate or even a Flowpath-3-type character for pH and Ca, indicating water-mafic rock interaction (with the metadiabase).

7.4.3 Salinity

Salinity and the degree of water-rock reaction remain at a low level in Romuvaara regardless of the advanced maturity of the groundwater in the evolved parts of the flowpaths, where moderate pH and fairly reducing conditions prevail and no reaction agents are left. Low salinity is considered to be typical for water-rock interaction in a cool climate – shield bedrock situation as none or only traces of fossil water, such as some palaeo seawater or residuals of ancient hydrothermal water are participating in the system.

The initial steep increase in major cations at the early stage of evolution may be best described as weathering, i.e. acidity-promoted hydrolysis in descending recharge water. During the next step Ca, Mg and K begin to decrease as Na continues increasing. Calcite precipitation acts as a sink for Ca in Flowpath 1. The process releases protons for silicate weathering, which acts as a source of sodium by plagioclase dissolution (Pitkänen et al. 1996a).

Calcite may be a possible sink to some extent for Mg, but probably the depletion of Mg and K is coupled with cation exchange. The depletion of Ca, Mg and K, and the enrichment of Na are stronger in Flowpath 3 than in Flowpath 1. The main sink for the three first mentioned ions has to be ion exchange or precipitation of secondary silicates during hydrolysis reactions, e.g. montmorillonites or some poorly crystallized alumino-silicate phases, because no anion depletion is observed to precipitate with these cations. The reaction system may be quite complicated. It may consist partly of pure cation exchange and partly of the weathering of primary silicates to clay minerals, simultaneously releasing Na and sorbing other cations, which can be also considered ion exchange in a broad sense, though irreversible, in nature. Na increases faster than Cl, supporting ion exchange in clay minerals, which is also indicated by activity diagrams (see Pitkänen et al. 1996a, ch.5.4). K exchange may lead later to illitization.

The salinity and chloride increase in the groundwaters of Romuvaara are quite small (max. TDS 265 mg/l, max. 109 mg/l Cl). Nevertheless, the complicated question of the origin of Cl as well as the enrichment of Ca at the end of Flowpath 1 needs an explanation. Chloride is not the main constituent of silicates, but the rocks contain chloride between 100 to 1 000 ppm (Table 4.1-1) (Lindberg & Kukkonen 1988, Lindberg & Paananen 1989, 1990, Gehör et al. 1996a, b, 1997), higher values belonging to mafic rocks. No evaporites have been observed, but secondary fluid inclusions are frequent (Melamed & Pirhonen 1994).

The salinity increase (cations and bicarbonate) of less than 2 mg/l (Pitkänen et al. 1996a) at shallow depth or in certain highly conductive structures (e.g. R9) shows to what extent it is possible to dissolve Cl from the rock by the incongruent dissolution of silicate during rapid recharge. According to Pitkänen et al. (1996a) sea water origin is not likely due to high Br/Cl and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in groundwaters. However, the comparable ratios of Br/Cl in most “saline” groundwater samples (about 0.01 using molar ratios) and bedrock (tonalite gneiss) strongly supports water-rock interaction as one source of salinity and excludes simple mixing of aqueous sources. Cl dissolution from the bedrock over the very long term at low temperature is according to Pitkänen et al. (1996a) reached already in groundwaters with chloride contents less than 3.5 mg/l Cl. A more plausible explanation for the origin of

salinity would be some leaching process of rock salts, fluid inclusions or grain boundary salts, as suggested for Stripa groundwaters (Nordstrom et al. 1989), Lac Du Bonnet (Gascoyne et al. 1992), and Syyry and Olkiluoto (Pitkänen et al. 1992, 1994, 1996b). Fluid inclusions in fracture calcites would form a potential source according to Frape et al. (1992). According to Pitkänen et al. (1996a) the origin of these salts at Romuvaara could be ancient hydrothermal activity, as based on evidence for fracture-controlled circulation of relic hydrothermal fluids observed in structures R2/3 and R10 (Saksa et al. 1992), the elevated Ca/Mg ratio in the most "saline" groundwater sample and the need to include remnants of hydrothermal fluid to account for the relative enrichments of Ca and Na in the most "saline" groundwater sample. The high Ca/Mg ratio may relate the origin of salinity even to Precambrian hydrothermal activity. It is also necessary to include remnants of hydrothermal fluid to account for the relative enrichments of Ca and Na in the most "saline" groundwater samples. Preliminary evaluation of the recent $\delta^{37}\text{Cl}$ isotope results (-0.16 and -0.21‰ SMOC) from the boreholes KR3 (depth 436 - 441 m) and KR10 (depth 561 - 566 m) suggest some salinity source related to the same salinity source as for water in the Baltic Basin, i.e. salt leaching from extensive Palaeozoic salt deposits south of the Baltic Sea according to Frape et al. (1996) ($\delta^{37}\text{Cl}$ ranging from -0.58 to 0‰ SMOC).

7.4.4 Redox

Due to problems with the interpretation of Eh measurements of natural groundwaters made by platinum electrodes Berner (1981) has proposed a classification of redox conditions in terms of "indicative redox species" or dominant electron accepting processes which usually form a reduction sequence with residence time and flow distance from the ground surface (Fig. 7.4-2).

Pitkänen et al. (1996a) have shown that the water chemistry, isotope data and mineralogy of the Romuvaara site contain imprints of progressive redox reactions representing the whole redox sequence in Fig. 7.4-2 down-gradient from the recharge zone.

Carbon and strontium isotope systematics emphasize the importance of organic matter and biotite in the consumption of dissolved oxygen during recharge. Aerobic respiration increases the partial pressure of CO_2 in water as calculated for groundwater samples from overburden and shallow groundwaters (Pitkänen et al. 1996a). In addition low $\delta^{34}\text{S}(\text{SO}_4)$ in "low saline" groundwater indicates the oxidation of sulphides, e.g. pyrite in fractures, to be a potential sink for oxygen and a source of sulphate. Elevated Fe^{2+} concentrations in shallow groundwaters indicate a shift from oxic to post-oxic conditions.

The general depletion of sulphate and enrichment of sulphide with chloride indicates that microbially-catalysed reduction of sulphate with increasing residence time (sulphidic zone, Fig. 7.4-2) has occurred, which is confirmed by the presence of dissolved sulphide, observations of SRB (Haveman et al. 1998) and by the increase of $\delta^{34}\text{S}(\text{SO}_4)$ with increasing chloride content and observations of cryptocrystalline pyrite on the fracture surfaces (Gehör et al. 1996a). Sulphate reduction is connected to organic carbon oxidation, and depletion of $\delta^{13}\text{C}$ of dissolved carbonate (Flowpaths 1 and 2), and if any reactive iron is present, iron sulphides will be formed (Drever 1997, Plummer et al. 1990, Appelo & Postma 1994).

However, the $\delta^{13}\text{C}$ depletion is not seen in Flowpath 3, explained initially by to calcite dissolution and later carbon isotope exchange during the recrystallization of calcite (Pitkänen et al. 1996a). The trends of sulphate and sulphide vary between flowpaths. The total sulphur content does not change much, but Flowpath 3 shows an immediate increase of sulphide in groundwaters of very low chloride content. The smoothly increasing sulphide trend in Flowpaths 1 and 2 suggests that the sulphide concentration is controlled by iron, which may reside in ferric oxyhydroxides on fracture walls (hematite and "rust"). Ferric oxyhydroxides are, however, absent in the metadiabase dyke of structure R8. Iron in silicates is bonded tightly and is released at a slower rate than from ferric oxyhydroxides. The release of iron from silicates may constrain sulphide precipitation and could be a possible explanation for the high sulphide contents in the groundwater samples of Flowpath 3, which decrease with increasing residence times.

The redox conditions at Romuvaara seem to be buffered mainly by the sulphur system. This is indicated by the sulphide content, as well by variations in the sulphate content of the groundwater, the Eh(measured) vs. sulphide correlation, $\delta^{34}\text{S}(\text{SO}_4)$ and SRB analyses and the occurrence of pyrite in the boreholes. Theoretically, according to the thermodynamic data of S-Fe-systems in the compilation of Brookings (1988), the expected Eh in a sulphidic zone is around -200 to -300 mV at a pH of 8.0 - 9.0, and in the high pH range measured in Romuvaara the expected redox level is even lower.

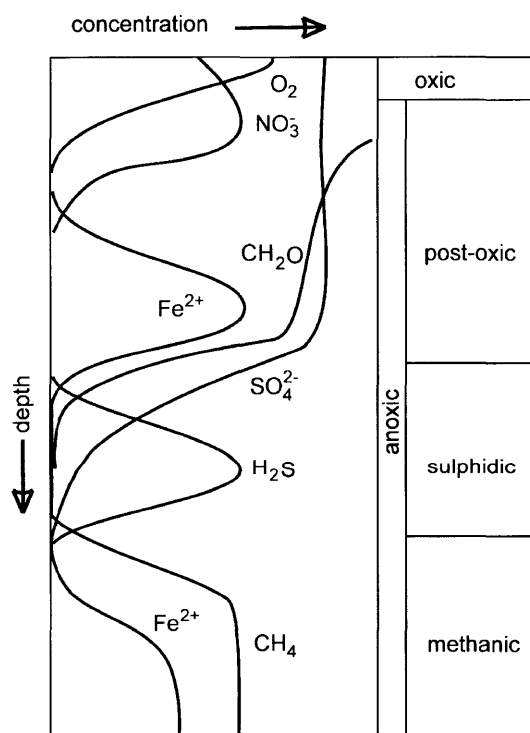


Figure 7.4-2. Sequence of reduction processes applicable to redox-sensitive species observed in groundwater at Romuvaara. Figure redrawn by Pitkänen et al. (1999) from Appelo and Postma (1994). Berner's (1981) classification of redox environments is shown on the right hand side.

7.4.5 Palaeohydrogeological Implications

The ^{14}C age data adjusted for the water-rock interactions at Romuvaara indicate that the dilution of the first "half-life" results from carbon reactions over a few decades. More advanced depletion requires radioactive decay. The adjusted ^{14}C ages cover virtually the time span since the site was released from the effects of glaciation 10 000 years ago (with an uncertainty of approximately 1 000 - 2 000 years). Young ^{14}C ages are typically connected to higher water conductivities and, for example, in borehole KR2 substantially higher ^{14}C ages are reached in the hanging wall side bedrock of R9 than in the highly conducting structure itself (Fig. 7.4-1).

The $\delta^{18}\text{O}$ contents of the old Romuvaara groundwater (adjusted ^{14}C age > 8 000 years) show only a slight depletion. Because the heavy oxygen isotope can generally be related to the temperature of condensation in the atmosphere (Fontes 1994), the temperature during the precipitation of the recharge waters at Romuvaara has been quite stable, assuming a non-mixed origin of the samples (Pitkänen et al. 1996a). There is no significant depletion of ^{18}O , although the adjusted ^{14}C age of the oldest samples may indicate mixtures of groundwaters containing meltwater from the last (Weichselian) glaciation, which theoretically should be lighter than modern recharge water. Pearson et al. (1991) present a similar problem for groundwaters in northern Switzerland.

The uncertainty in ^{14}C age calculations provides one explanation for the ^{18}O non-depletion problem, i.e. recharge occurred at late stages or after the Weichselian deglaciation (8 000 - 10 000 years ago) when the temperature was near modern values. It is also possible that the oldest water is a mixture of post-glacial recharge with much older waters, recharged during preglacial times. This is supported by the calcite recrystallization interpretation made by (Pitkänen et al. 1999) for samples from KR5, because the pressure and temperature changes connected to glaciation cycles may produce alternating dissolution and precipitation of calcite and carbon isotope exchange in fractures of closed/semi-closed systems (e.g. Blomqvist et al. 1993a). Evidence of light groundwaters with $\delta^{18}\text{O}$ contents varying between -17 and -16‰ SMOW has been observed in several localities in southern Finland, e.g. in Palmottu, Pori and the Outokumpu district (Blomqvist et al. 1994). Groundwaters from Olkiluoto and Hästholmen (Pitkänen et al. 1996b, 1998b, Snellman et al. 1998) have been interpreted to contain a significant glacial meltwater component, but when compared with Romuvaara, these sites have a different relationship with the glacial shoreline during the melting of the ice sheet, as they were below the highest shoreline whereas Romuvaara was above. The meltwater recharge is perhaps only a minor component of the groundwater due to the lack of cold water storage above the bedrock at Romuvaara and as a consequence of warmer precipitation reaching the groundwater table soon after the retreat of the ice sheet.

8 SUITABLE BEDROCK VOLUMES

8.1 Classification of the Rock Mass

The properties of the bedrock of Romuvaara have been evaluated according to the engineering rock mass classification developed for this work in order to define the bedrock volumes suitable for constructing a repository (Äikäs et al. 1999). The following properties of the rock mass have been considered to influence its constructability:

Rock quality

- determined by rock type, fracturing and hydrogeological properties. Rock type properties include mineralogy, texture, grain size, weathering, strength and deformation as well as thermal conductivity. Fracturing includes the number of fracture sets, frequency and length of fractures as well as their frictional properties. Hydrogeological properties include hydraulic conductivity and estimations of groutability and groundwater ingress.

Stress conditions

- magnitude and direction of in situ stresses and strength/stress ratio

Groundwater chemistry

- pH and concentration of sulphate, carbon dioxide, ammonium, magnesium, chloride and radon

Technical properties

- drilling, blasting, rock supporting and rock crushing properties.

All these rock properties have been classified into three classes depending on their influence on the construction of the repository. Although it is evident that methods for construction will develop in the future, the basis for the evaluation are the methods presently used in excavation and underground construction. The classes of constructability were determined as following:

Normal

- when construction of the repository can be carried out by applying conventional hard rock tunnelling techniques, working efficiency and materials, allowing for the high quality requirements for these kind of tunnels. Considering for example blasting and rock supporting properties this can mean that tunnels should be excavated using 4 - 5 m long blasting rounds and that rock supporting, which consists of rock bolts and shotcrete or wire mesh, can be done afterwards.

Demanding

- when construction of the repository needs more sophisticated and expensive construction methods or materials than in the normal class, rate of tunnelling is considerably lowered or much effort has to be put on safety at work. Considering for example blasting and rock supporting properties this can mean that tunnels should be excavated using 3 - 4 m long blasting rounds and supported temporarily with bolts and shotcrete or wire mesh after each round. Also pre-grouting may be needed. The final support can be done with rock bolts and fiber reinforced shotcrete.

Very demanding

- when construction of the repository needs much more sophisticated and expensive construction methods or materials than in the normal class, rate of tunnelling is very

much lowered or very much effort has to be put on safety at work. Considering for example blasting and rock supporting properties this can mean that tunnels should be excavated using 1 - 3 m long blasting rounds and supported temporarily with bolts and shotcrete after each round. Also spiling and pre-grouting are needed before excavation. The final support can be done using fiber reinforced shotcrete with reinforced ribs or cast concrete lining.

The classification of the rock mass has been carried out in the central part of the site, where most of the boreholes are located. Structures R1, R3, R4, R7 and R31 border the classification area which extends to the depth of 1 000 m. The surface and borehole investigations as well as the 3D bedrock model (see Section 5) have been used as input data for the classification.

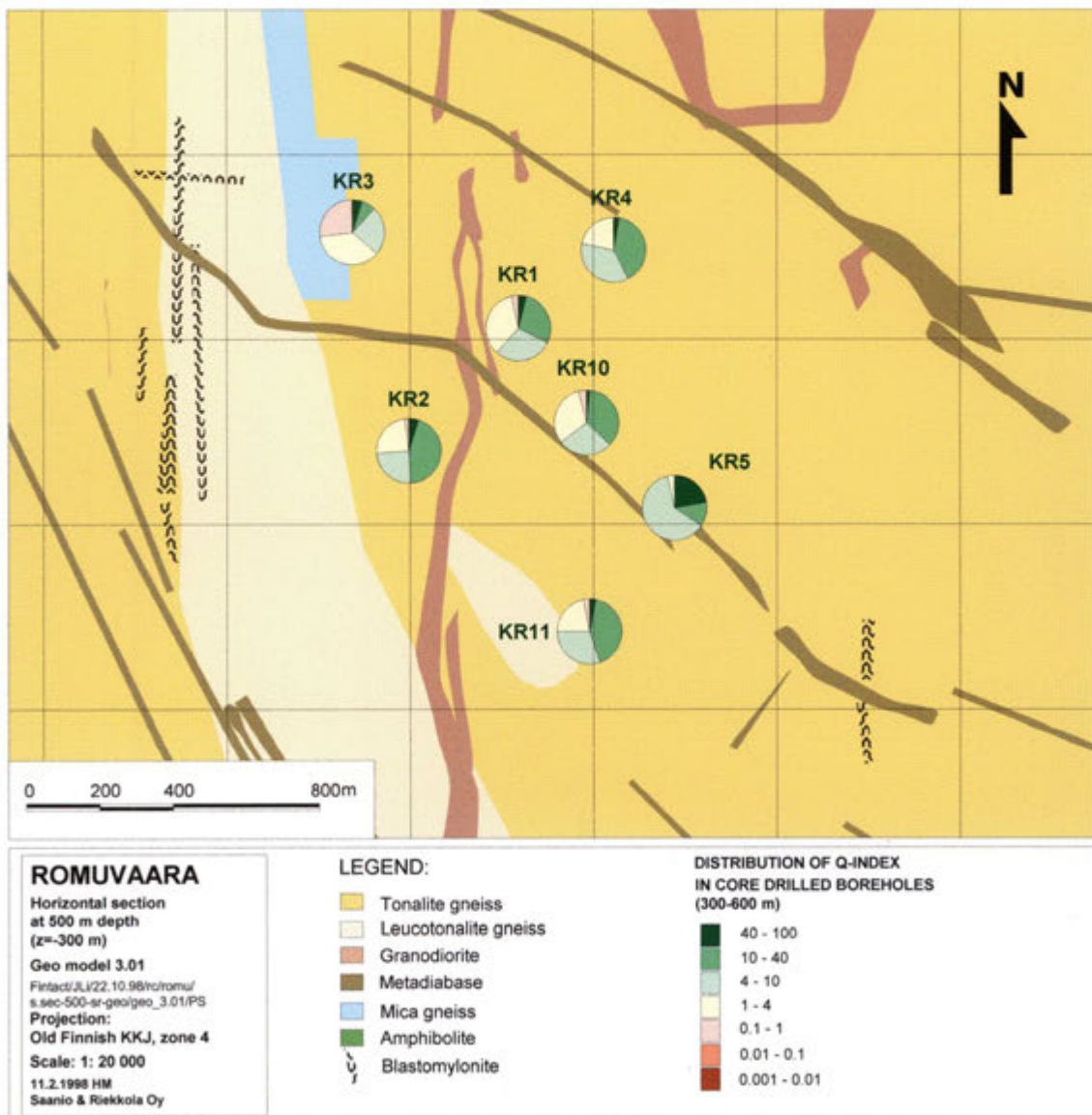


Figure 8.1-1. Average Q -values (geometric mean) of the investigation boreholes over the depth range of 300 - 600 m at the Romuvaara site (Äikäs et al. 1999).

In addition, the bedrock has been classified according to the empirical Q-system (Barton et al. 1974, Grimstad & Barton 1993) for the sake of comparison and for estimating the support measures at different depths and rock types (Fig. 8.1-1).

8.2 Evaluation of the Constructability

Evaluation of the constructability is at this stage based on the engineering rock mass classification and the Q-classification (Äikäs et al. 1999).

The aim is to construct as much of the repository as possible in volumes of rock which are classified as "normal". In practice this means that the construction should take place dominantly within intact rock and that major fracture zones (structures) should be avoided at the disposal depth. The majority of the rock mass at Romuvaara consists of intact rock and has generally been estimated as "normal" from the point of view of constructability. This means that excavation and rock support can be carried out using conventional methods and materials, as generally applicable to Finnish underground construction projects. This intact rock is typically hard and unaltered, the fracture frequency being quite low, in outcrops typically < 1 fracture/m and in rock cores 2 - 4 fractures/m. Local differences in the properties of intact rock within a single rock type were found to be small.

An important bedrock property that may limit the placement of the deposition tunnels and disposal holes at Romuvaara is the location of some fracture zones, which may prove to be difficult to seal against the ingress of groundwater and may also require extensive support. Structures R3, R9, R13, R14, R22 and R31 have been identified as "very demanding" from a constructability point of view for deposition tunnels. However, other tunnels (i.e. non deposition tunnels) and shafts could be excavated through these structures.

The suitable range of depth for repository construction may be reduced by the limited strength of some parts of the rock mass and by the values of the in situ stresses. Close to the maximum depth of 700 m, tonalite gneiss has been estimated to be "demanding" in terms of constructability because of the higher stress field ($\sigma_H \approx 40$ MPa at 700 m). Mica gneiss lies within the "demanding" category in depths greater than 400 m and "very demanding" in depths greater than 600 m. The classes "demanding" and "very demanding" mean that special methods and materials should be used when excavating and supporting the rock, which in turn, will result in more time and increased costs for the construction work (see Section 8.1).

The main conclusion of the evaluation based on classification work is that there seems to be no significant geotechnical constraints to repository construction within the depth range of 400 - 700 m, however, with increasing depth geotechnical factors do need to be given a higher priority.

Estimates of geotechnical behaviour based on empirical methods have been included in the engineering rock mass classification as well as in the Q-system (Fig. 8.2-1). The geotechnical behaviour of the repository during its construction phase has been analysed by numerical methods based on the geotechnical and geological information obtained in earlier

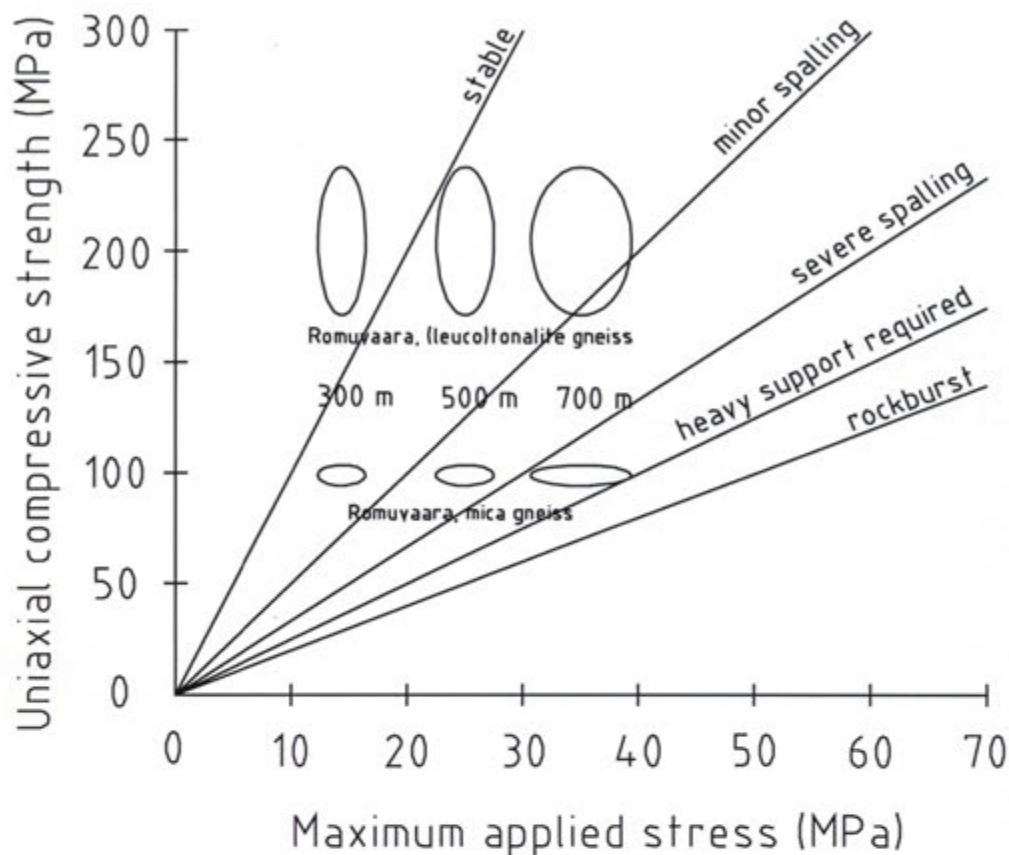


Figure 8.2-1. Empirical estimates of rock behaviour based on the strength / stress-ratio.

site investigation phases in 1987 - 1995. According to the results of 3D numerical modelling (Fig. 8.2-2), the maximum depths from a geotechnical point of view for constructing a repository at Romuvaara were estimated to be down to 700 m for tonalite gneiss and 350 m for mica gneiss (Tolppanen et al. 1995).

The requirements for rock support increase with the depth. Estimates of the average Q-number for intact tonalite gneiss suggest that tunnels can be supported with rock bolting over most of the considered depth range. Close to the lower depth limit the need for rock support increases and may call for rock bolts and fibre-reinforced shotcrete (Table 8.2-1). However, other types of support may also be used, such as rock bolts and wire mesh. The method for support will be selected based on the in situ geotechnical behaviour of the rock as well as on the suitability of the materials for the repository environment. Based on empirical estimates the tonalite gneiss remains stable at shallower depths and may be subject to minor spalling effects at depths close to 700 m. The scatter of compressive strength results is wide in tonalite gneiss, indicating a possible wide range in its geotechnical behaviour and in its support requirements. Mica gneiss may be subject to spalling effects at shallower depths than tonalite gneiss.

The extent of suitable rock at 500 m depth available for constructing the repository is shown in Figure 8.2-3. This potentially suitable area is limited by the presence of fracture zones and mica gneiss and, to some extent, by the size of the area characterised by borehole investigations.

The remaining uncertainty associated with the exact locations, dimensions and properties of the bedrock structures also results in uncertainty in the evaluation of the rock's constructability. It will be necessary to carry out investigations in situ at the proposed disposal depth in order to decide on exact locations for the deposition tunnels and disposal holes.

Table 8.2-1. Estimation of support methods in tonalite gneiss, leucotonalite gneiss and mica gneiss. Estimation is based on *Q*-classification (Äikäs et al. 1999).

Rock type	Support system		
	0 ... 300 m	Depth range 300 ... 600 m	600 ... 1000 m
Tonalite gneiss	Systematic rock bolting	Systematic rock bolting	Systematic rock bolting and fibre-reinforced shotcrete
Leucotonalite gneiss	Systematic rock bolting	Systematic rock bolting	Systematic rock bolting and fibre-reinforced shotcrete
Mica gneiss	Systematic rock bolting	Systematic rock bolting and fibre reinforced shotcrete	Systematic rock bolting and fibre-reinforced shotcrete

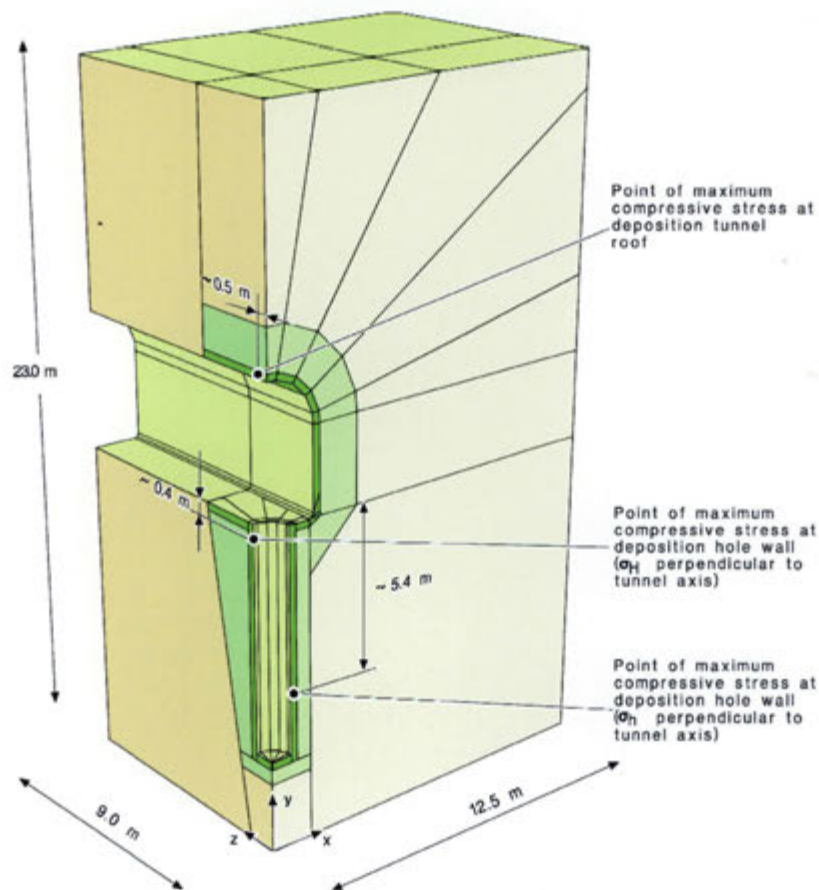


Figure 8.2-2. 3DEC model of deposition tunnel and deposition hole. Location of points of maximum compressive stress and dimension of the model (Tolppanen et al. 1995).

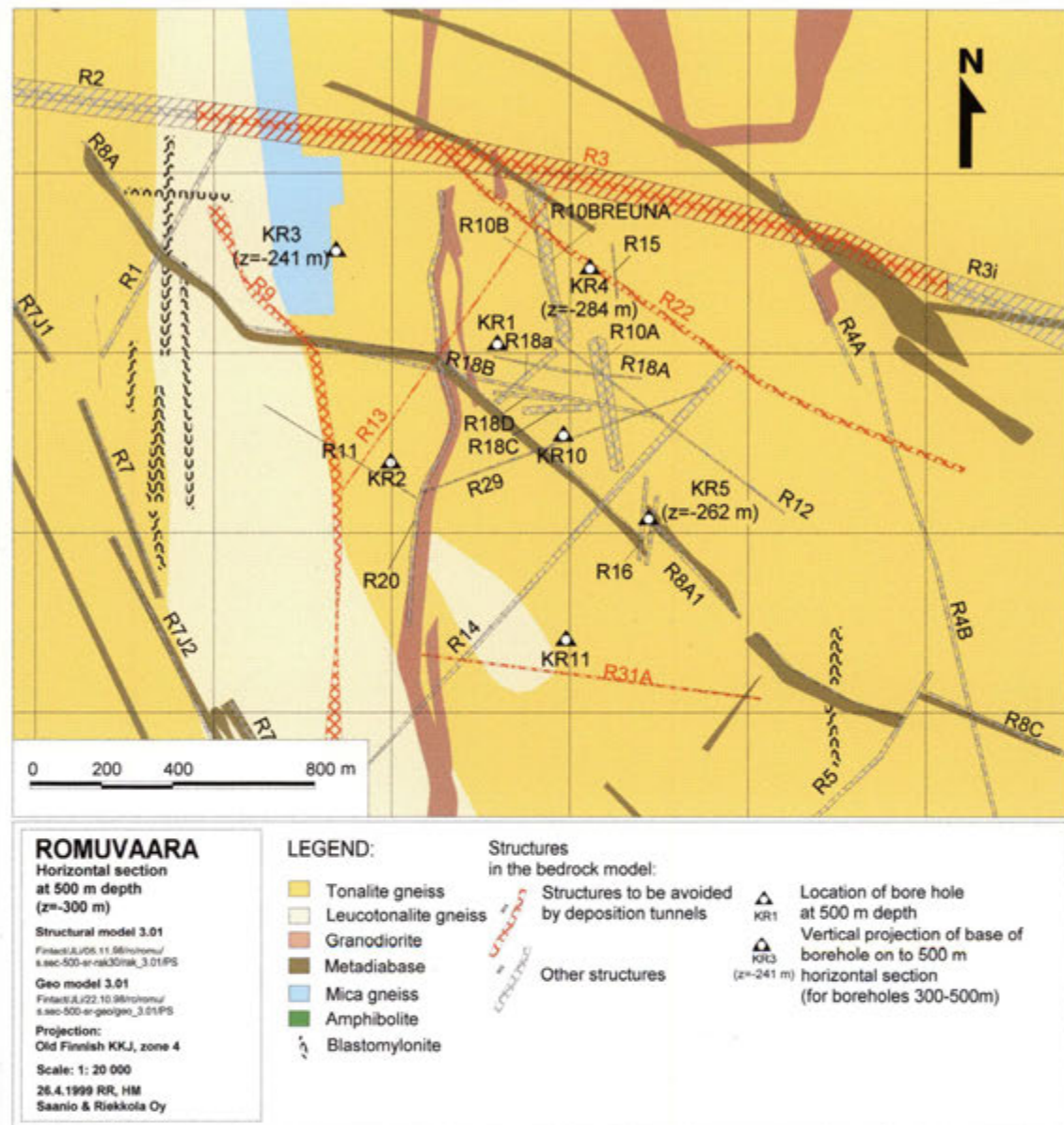


Figure 8.2-3. Areal extent of suitable rock for repository construction. Horizontal section at 500 m depth.

9 CONSTRUCTION OF THE REPOSITORY

9.1 Technical Description of the Repository

The basic concept for the disposal of spent fuel is based on its encapsulation and emplacement in crystalline bedrock at a depth between 400 to 700 m (Fig. 9.1-1). The selection of the final depth for the repository will be based on the site-specific properties and conditions of the bedrock.

The design of the basic concept is based on the use of the copper canisters. The diameter of the canister for BWR fuel from TVO is 1 052 mm and the length is 4 800 mm. The canister length for the VVER-440 type PWR fuel from IVO is 3 600 mm, the diameter of both canisters being the same.

The estimated total amount of spent fuel and the number of waste canisters corresponding to a 40 years operation time for the power plants is about 2 600 tU and 1 400 canisters respectively. The total excavated volume of the repository for this amount of spent fuel is estimated to be about 400 000 m³. If operation times were extended up to 60 years the corresponding amount of spent fuel would be about 4 000 tU and the number of canisters 2 200. Were two new nuclear power plants to be constructed the amount of spent fuel corresponding to 60 years operation times for all these power plants would be about 9 000 tU.

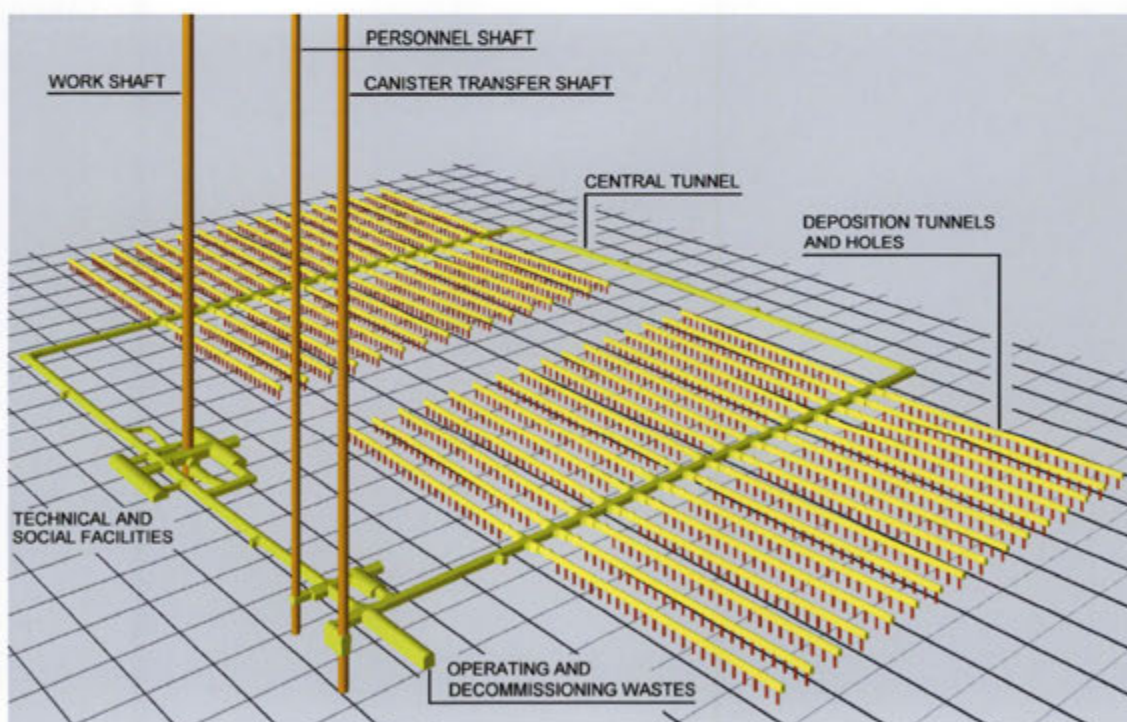


Figure 9.1-1. Basic design for the high level nuclear waste repository for 1 400 canisters assuming 40 years operating times for the current reactors.

In the reference design for the basic disposal concept the spent fuel canisters are emplaced in vertical holes which are excavated in the floor of the deposition tunnels (Fig. 9.1-2). The diameter of these disposal holes is 1 752 mm and their spacing is based on the site-specific thermal properties of the rock mass. The spacing of the tunnels is 25 m and at Romuvaara the current design intent spacing of the disposal holes is 8 m for 2 600 tU. The depth of the disposal holes is 7.8 m for the TVO type canisters and 6.6 m for the IVO type canisters. The deposition tunnels will subsequently be backfilled with a mixture of crushed rock and bentonite.

An encapsulation plant will be constructed at the surface where the spent fuel rod assemblies will be packaged in canisters. Access from the surface to the repository will be provided by three vertical shafts, a work shaft, a personnel shaft and a canister shaft, or by a combination of shafts and an inclined access tunnel.

9.2 Principles of Implementation

Before any construction of the actual repository commences a detailed characterisation of the selected site will be carried out. The purpose of this characterisation programme is to confirm the information obtained earlier and to acquire additional information for the detailed design and location of the repository at the site. To be able to obtain the relevant information it is planned to develop and operate an underground rock characterisation



Figure 9.1-2. Backfilled deposition tunnel with a canister in the disposal hole.

facility, which will initially involve the excavation of an investigation shaft or an access tunnel. During this phase of the investigations the in situ conditions at depth will be studied and exploratory galleries or tunnels will be constructed as and where required.

Construction of the repository is planned to start during the 2010s, after the characterisation has been completed and a permit for construction has been given by the Government. This will involve the construction of the remaining shafts, the central tunnel and the first part of the deposition tunnels, as well as other tunnels and surface facilities.

The operational phase is planned to start after 2020. The reference concept is based on an approach in which deposition tunnels are excavated stepwise during the operational phase, simultaneously with the installation of the waste canisters. The simultaneous excavation and installation of canisters appears to have advantages over the alternative approach, in which the whole repository is excavated before starting the operational phase. Figure 9.2-1 illustrates the steps from excavation to backfilling that are needed for simultaneous excavation and operation.

It is evident that the future development of techniques is likely for excavation, boring the deposition holes and backfilling the tunnels. In the current reference design, however, the central tunnel, deposition tunnels and other facilities will be excavated by a carefully controlled drill and blast technique. A smooth blasting technique will be employed and the blast design adjusted to the prevailing rock conditions and excavation disturbance constraints. The most advantageous method for the excavation of disposal holes is considered to be boring based on rotary crushing and vacuum dry suction of the crushed rock, a

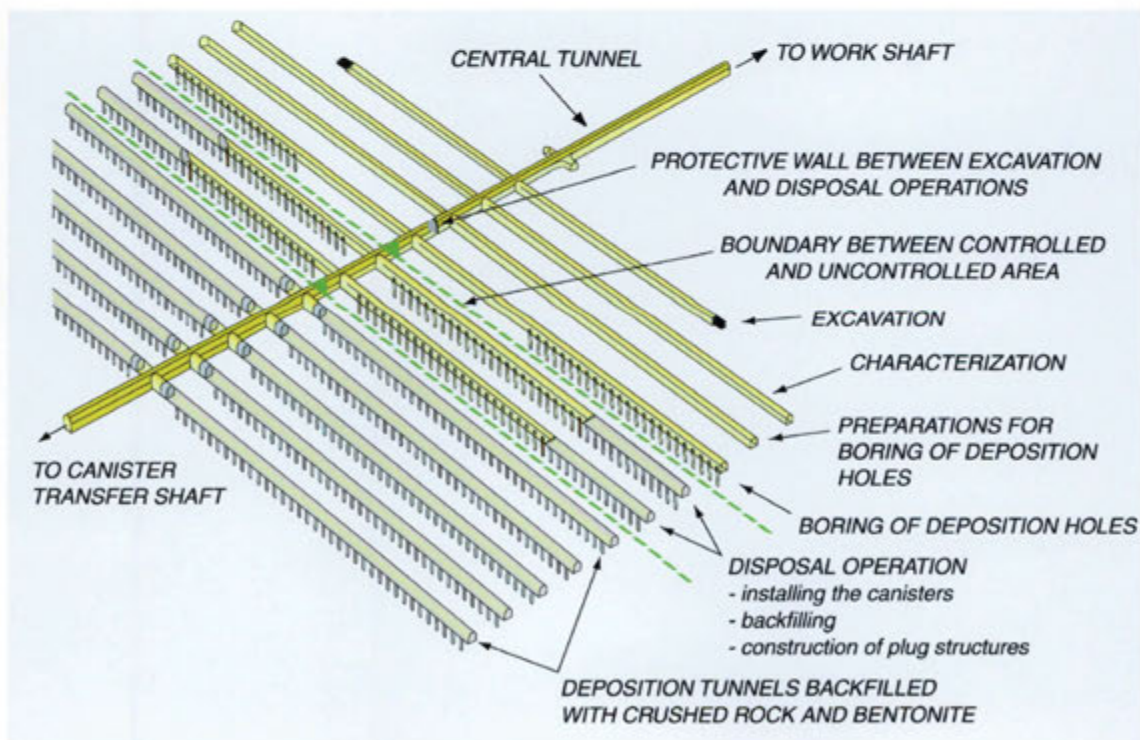


Figure 9.2-1. Principle of the stepwise construction of the repository.

technique demonstrated in the Research Tunnel at Olkiluoto (Autio & Kirkkomäki 1996). After the final disposal of the last canisters the encapsulation plant will be decommissioned, the remaining empty tunnels will be filled with bentonite and crushed rock and the access shafts will be sealed.

There remains uncertainty associated with the exact locations, dimensions and properties of bedrock structures and the repository layouts shown in Section 9.3 should, therefore, be considered to be only preliminary and illustrative. The details of the repository layout and the locations of the disposal holes will be determined using an observational method process during construction, which allows the repository layout to be refined and adjusted to the local structure of the bedrock as new data on the rock mass become available. The observational method is a continuous, managed and integrated process of design, construction control, monitoring and review which enables previously designed modifications to be incorporated during or after construction, as appropriate.

Information on in situ conditions will be obtained from investigations during excavation of the investigation shaft, during excavation of the central tunnel, in the construction phase of the repository, and during excavation of the deposition tunnels and boring of the disposal holes in the operational phase. Finally, the suitability of a potential location for a disposal hole may be assessed on the basis of information obtained from a small diameter pilot borehole, which it is proposed should be drilled in advance down the centre line of each disposal hole.

9.3 Preliminary Layouts

A preliminary adaptation of the repository layout to the site conditions has been carried out by Riekkola et al. (1996). In this study basic rock engineering principles were applied and used such a way that various factors having influence on the repository design with regards to site-specific conditions were recognized:

- Determining the location of the repository within a site is governed mainly by the location, geometry and transmissivity of the fracture zones, as well as, by the associated level of uncertainties in rock properties.
- Determining the orientation of the deposition tunnels is governed mainly by the direction of the maximum horizontal stress, by the orientation of the fracture sets and by the location of the fracture zones. The orientation selected is likely to be a compromise between the stress orientation and the various relevant properties of the rock mass.
- Determining the depth of the repository is governed mainly by the maximum horizontal stress, the strength of the rock, the location of the fracture zones and the groundwater chemistry, as well as by long-term safety aspects.

Based on the classification of the bedrock (Äikäs et al. 1999), which is discussed in Section 8, an illustrative example of the area needed for the construction of deposition tunnels for 2 200 canisters, corresponding to 4 000 tU, is shown in Figures 9.3-1, and 9.3-3. The intact rock within the area shown has been recognized as being potentially suitable for constructing the repository. It is located at a depth of 500 m in the central part of the borehole

investigation area and extends some hundreds of metres outside the area covered by the existing boreholes. This example is based on the assumption that the construction of deposition tunnels takes place in one storey exclusively in tonalite gneiss, leaving respect distances of 50 m to structures R3, R9, R13, R22 and R31.

Figures 9.3-2 and 9.3-3 show an illustrative example of the area needed for the construction of deposition tunnels representing the lower part of a two storey repository at the 600 m level. This lower storey is assumed to contain half of the 4 000 tU of the repository. The upper part of the repository would be situated at the 500 m level (Fig. 9.3-1). Both levels are assumed to be situated in intact rock leaving respect distances of 50 m to structures R3, R9, R13 and R22, and at the 600 m level also to the structure R14.

The volume of the rock modelled would, therefore, appear to be sufficient to host a repository for the larger amount of waste (4 000 tU) that will arise due to the longer anticipated life-times for the existing power plants. If still larger waste volumes need to be taken into account, the area covered by the detailed site characterisation programme would need to be enlarged. The potential rock volumes available allow flexibility in the location and construction of the repository, even for larger quantities of wastes than those from the present power plants.



Figure 9.3-1. Illustrative example of the area required by deposition tunnels at Romuvaara. Horizontal section at 500 m depth. Bedrock model version 3.01 used.

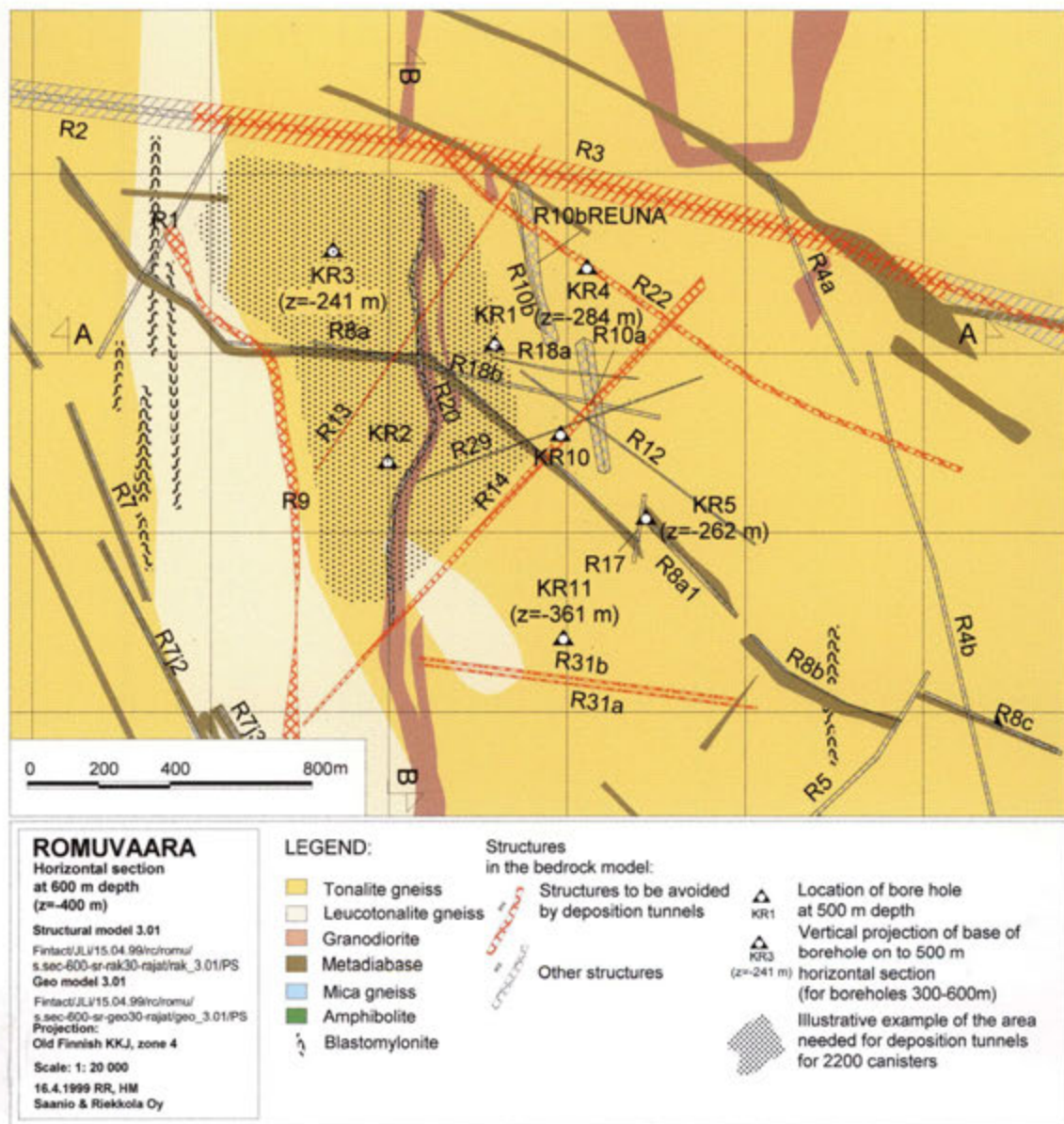


Figure 9.3-2. Illustrative example of the area required by deposition tunnels at Romuvaara. Horizontal section at 600 m depth. Bedrock model version 3.01 used.

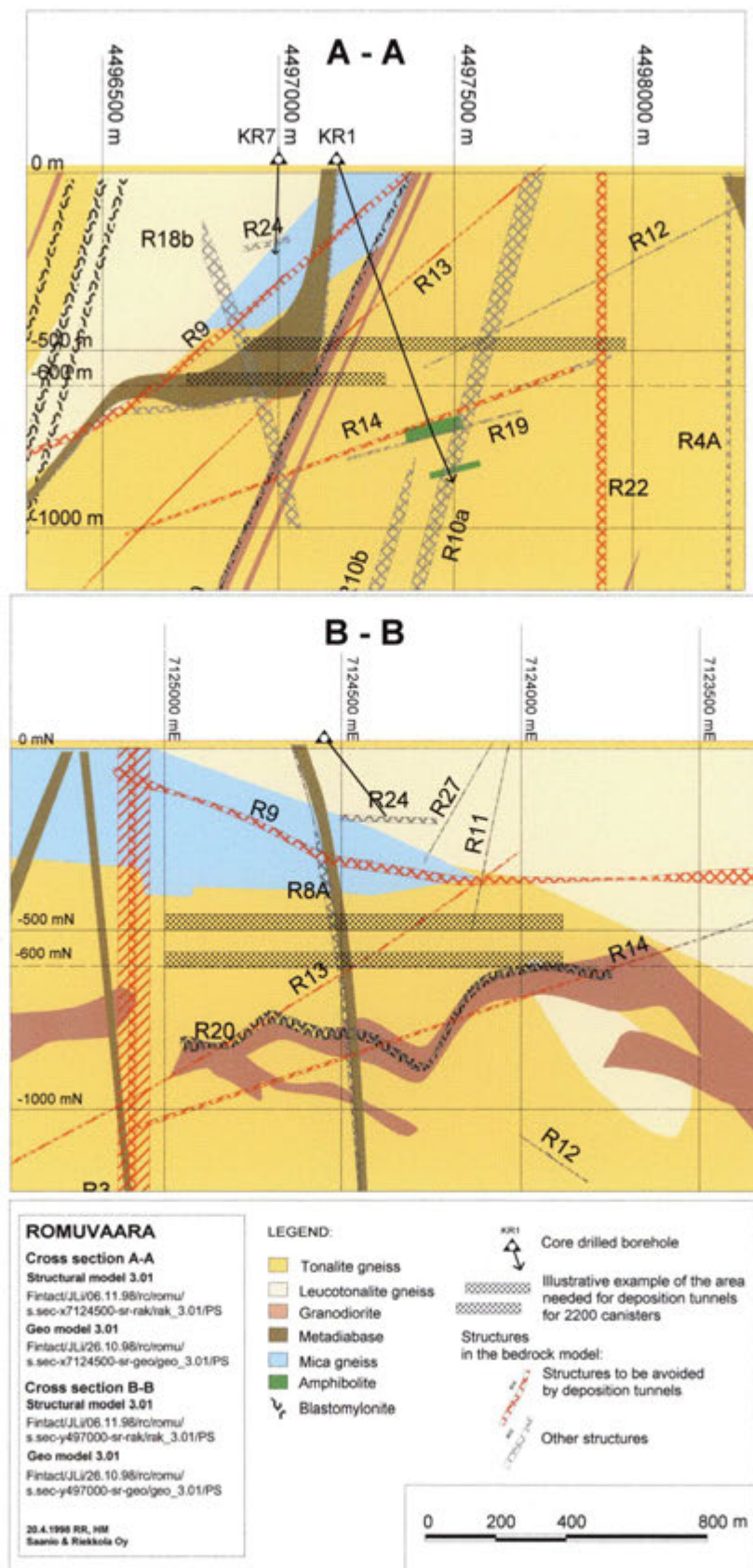


Figure 9.3-3. Illustrative example of a possible location of one (at 500 m depth) and two storey repositories (at 500 m and 600 m depth). Respect distances should be left to structures R9, R13, R14 and R22. Cross section A – A and B - B. Bedrock model version 3.01 used.

10 SUMMARY AND DISCUSSION

10.1 Particular Features of the Site

The Romuvaara and Kivetty sites are located inland, whereas Olkiluoto and Hästholmen lie on the coast, and both inland sites are also situated above the so called “highest shoreline” of the Baltic, and therefore have been in a supra-aquatic position since the last glaciation. This is reflected in a lack of fine-grained water-lain sediments at these inland sites and the presence of glacial till and a topography determined by moraine features. Another consequence of this supra-aquatic position is that the hydrogeochemical character of their groundwaters differs significantly from that found at the two coastal sites.

Glacial till, often overlain by peat bogs, almost completely obscures the bedrock of the Romuvaara site. Outcrops comprise only some 1% of the total area of the site and occur mainly in the western and southwestern part of the investigation area. The topography of the site is quite subdued, relative altitude differences being about 10 - 30 m, and the highest elevation being approx. 227 m. The main topographical features are due predominantly to the bedrock, but minor variations are often caused by the distribution and form of the moraines. In addition, an NW-SE trending esker (composed mainly of glaciofluvial gravel and sand) borders the site to the south. The peat bogs, as well as the few small lakes, indicate that the groundwater table lies very close to the ground surface in most parts of the area.

Since only a small portion of the bedrock is exposed, the airborne and ground geophysical measurements, in addition to the boreholes and drill core analyses, have been essential in the geological investigations. This has been especially so for the interpretation of different kind of dyke rocks and for the fracture zones on the site. Due to the limited number of outcrops, investigation trenches were excavated to supplement the information available from the rock surfaces.

The bedrock of Romuvaara belongs to the Archaean basement complex, which represents the oldest part of the Finnish crystalline bedrock, 3 100 - 2 500 million years in age. In this sense it differs considerably from the other three study sites, where the bedrock is geologically much younger. The most common rock type at the site is migmatitic tonalite gneiss, which is cut by Palaeoproterozoic metadiabase dykes (2 200 - 2 100 million years), trending NW-SE and representing a distinct rock unit in the otherwise Archaean felsic environment. Evidence from outcrops and core samples, shows that the contacts of the dykes with the country rocks are usually densely fractured, and thus probably represent hydraulically significant zones.

The granodiorite dykes differ markedly from the tonalite gneiss in the ground and airborne magnetic surveys, but are petrographically and geochemically close to the country rocks. Their contacts are, unlikely to be hydraulically significant, as observed on outcrops, since they have suffered the same Archaean ductile deformation history as the country rocks.

One of the most distinctive features on outcrops is the extent of the deformation of the bedrock, which, apart from the metadiabase, has suffered a complex, polyphase Archaean deformation history, including folding, faulting, metamorphism and igneous activity.

Based on refolding and cross-cutting relationships, six plastic deformation phases have been recognized. Because of the ductility of the deformation, the resulting structures are not hydraulically significant, however, they may have acted as mechanically weaker planes, along which fractures were preferentially formed during the later four brittle deformation phases.

One problem caused by this polyphase deformation is that any assessment of the dominant foliation directions and the extent of the rock units at depth is difficult. The cross-sections shown in Figures 4.1-4, 5.2-5, and 9.3-3 must, therefore, be considered as only tentative presentations of the mode of occurrence of the rock types. Only the metadiabase dykes, which have not been affected by the earlier deformations, can be located and interpolated to depth with reasonable confidence. The emplacement of the metadiabase dykes most likely represents a reactivation of the pre-existing Archaean zones of weakness, as interpreted for the Romuvaara area by Luukkonen (1988).

The particular features of the Romuvaara site, even though giving an impression of a complex geology, represent a typical geological environment for the Archaean basement. The rock types penetrated at depth in boreholes are the same as those that appear in outcrops, and there is no evidence of other geological formations or ore deposits in the area. The site is thus free from any geological resources that might have an economical value, either today or in the foreseeable future. The bedrock also cannot be regarded as constituting a groundwater resource and a more obvious source for groundwater extraction is provided by the esker south to the site. It can be concluded that no valuable natural resources are present and, in that sense, the site can be considered suitable for hosting a repository for spent nuclear fuel.

10.2 Suitability of the Site

10.2.1 Structure and Stability of the Bedrock

The regional bedrock structure of Romuvaara is characterised by a network of fracture zones reflecting the mosaic block structure typical of the Precambrian bedrock of Finland. These fracture zones are generally assumed to be steeply dipping and to continue to great depth, possibly several kilometres. Fracture zones trending NW-SE dominate the area, being longer than those with other orientations. This structural NW-SE orientation is emphasized by the metadiabase dykes which are often associated with these fracture zones. Another main structural trend is NE-SW, but these fracture zones are much shorter and less continuous. These major structural features had already been identified from aerial photographs and satellite imagery during the site selection phase in the 1980s, as is indicated in Figure 2.1-1. The Romuvaara site lies between two NW-SE trending regional fracture zones and the site investigations concentrated on determining the local structures of the bedrock block between these main zones.

Altogether 31 bedrock structures have been modelled at the site, as described in Section 5. The same structural trends, NW-SE and NE-SW, are repeated at the site scale. The majority (29) of the structures are evidenced from direct observations, mainly from borehole

intersections or from investigation trenches. Most of the structures represent steeply dipping (dip > 60°) fracture zones, typically dipping to the west, with only five gently dipping structures (< 30°). The intensity of fracturing and the degree of weathering, alteration and tectonization vary within the structures. Fracture zones are sometimes conformable with the metadiabase and granodiorite dykes or mylonitic zones. The presence of structures R1 - R31 can be used to explain 75% of the fractured sections in the boreholes.

The rock mass between the fracture zones (structures or R-structures) represents what is termed *intact rock*. This intact rock is typically hard and unaltered, the fracture frequency being quite low, in outcrops typically < 1 fracture/m and in rock cores 2 - 4 fractures/m. Occasionally the intact rock may include minor fracture zones which are not classified as structures in the bedrock model. In only 9% of the total length of the core samples (approximately 5.5 km in total) was the fracture frequency more than 10 fractures/m (representing broken rock quality), and this gives a general impression of the level of rock quality at the site, which is generally good. The majority of the fractures are steeply dipping. Their strikes vary somewhat in different rock types, but the general structural trends of NW-SE (NNW-SSE) and NE-SW (ENE-WSW) seen in the structures are repeated in the smaller scale fractures.

The structural features of the bedrock, especially with reference to the number of modelled structures and the intensity of fracturing, are quite similar to those at the other study sites. This overall similarity might be a reflection of a gross structural homogeneity of the Precambrian crystalline rocks in Finland.

The structure of the bedrock has been studied and modelled more accurately in the central part of the site, where most of the boreholes are located, and where the proposed area for repository development lies (see Fig. 9.3-1). The suitability of the bedrock from a constructional point of view was discussed in Section 8. The general conclusion of this analysis was that there were no significant geotechnical constraints to repository construction over the depth interval considered. Most parts of the rock mass are composed of intact rock, consisting of typical hard Precambrian crystalline bedrock with favourable constructional properties. The fracture zones which will affect the location of the repository are not sufficiently frequent in the area of interest to cause too many problems regarding construction of the repository. Although the exact locations and geometries of these fracture zones are not known over their entire lengths, their characteristic variabilities are generally well understood, both in terms of their hydraulic properties and from a constructional point of view.

The seismicity of the area is very low, as discussed in Section 3.5, and any displacements associated with earthquakes are assumed to occur along existing fracture or fault zones. The nearest earthquake (1971, $M_L = 2.4$) was located some 35 km west of the site, and was probably related to the N-S trending Kuhmo greenstone belt. In general terms, the seismicity of Finland is not regarded as a key factor when the future stability of bedrock structures is being considered.

Slow movements of the bedrock have been measured at Romuvaara using GPS since 1996. The data obtained to date are too limited to make any specific conclusions, but there are

indications of an E-W trending horizontal compression, probably due to the spreading of the Mid-Atlantic ridge, causing a slight (<1 mm/year) movement in the rock mass (Chen & Kakkuri 1998). These preliminary results correlate very well with GPS observations made elsewhere in Finland. The measured in situ stress field, which is influenced by this oceanic spreading, indicates conditions (e.g. $\text{Sig-H} \approx 30$ MPa at 500 m depth) which are typical for Finnish Precambrian bedrock. Another relatively slow process taking place at the site is the postglacial uplift, the rate of which is currently about 6 mm/year. These slow bedrock movements, like the earthquakes, are not likely to have much significance regarding constructional and operational safety. Their influence will, however, need to be considered in terms of their possible effects on the long term post-closure behaviour of the repository.

As far as the structure and stability of the bedrock are concerned, the Romuvaara site can be regarded as being suitable for repository development. The volume of potentially suitable rock for hosting the repository does not include any regional major fracture zones, and the local bedrock structures are not too frequent to prevent from being located entirely within the intact rock. The Romuvaara site lies in a region of low seismic and tectonic activity, and no anomalous uplift or subsidence is expected before the onset of the next glaciation. In addition, the in situ stresses are considered normal for this type of geological environment. There are, therefore, no indications of phenomena that might modify the hydrogeological regime or the mechanical stability of the rock mass over the long term in a manner that might be deleterious for repository safety.

10.2.2 Hydrogeology

The hydrogeological conditions of the Romuvaara bedrock have been studied by using double-packer injection tests, groundwater flow measurements, long-term pumping tests and monitoring of the hydraulic head. The hydrogeological information has been used as input data to groundwater flow modelling and for evaluating the constructability of the rock mass.

The results clearly indicate that the hydraulic properties of the uppermost 100 - 200 m of the bedrock are distinct from those at greater depth, i.e. hydraulically conductive fractures are more frequent and several very high transmissivities (T) exist in this near-surface zone. It is also evident that there is a clear decrease with depth in the hydraulic conductivity of both the intact rock and the modelled structures (R-structures).

The R-structures are generally hydraulically more conductive than the intact rock, even in situations in which several hydraulically non-conductive R-structures are present and where several very conductive fractures and minor fracture zones exist outside known structures, i.e. in the intact rock. The mean value of transmissivity (T) of the R-structures is $1.6 \cdot 10^{-7} \text{ m}^2/\text{s}$. The corresponding mean of the hydraulic conductivity for the intact rock measured using a 2 m packer interval is $8 \cdot 10^{-12} \text{ m/s}$, if a lognormal distribution for all measured values is assumed.

The measured transmissivities of several R-structures are very low ($T < 10^{-9} \text{ m}^2/\text{s}$) and this may indicate that R-structures are generally less conductive at Romuvaara than at the other

investigation areas. Romuvaara, however, was the first area where structural modelling was carried out and more non-conductive or sparsely fractured sections might have been included within R-structures than at the other sites, perhaps due to the way in which such structures were modelled. In groundwater flow modelling exercises some of these sparsely fractured R-structures were subsequently assumed to be a part of the intact rock.

The variability of measured transmissivities within an R-structure is sometimes very large. This spatial variability may be real and may provide a true picture of the structure but, in some cases, this variability may be an artefact. This could be the case if there were errors in the interpretation of the position of the structures, with the possibility of the measured transmissivities being related to different structures.

There are few measured hydraulic conductivities at depth and unfortunately the number of such data is much smaller at Romuvaara than at the other sites. One reason for this is that values of hydraulic conductivity obtained from borehole KR2 were assumed not to be representative, due to the presence of cement grout which was used for stabilizing a fracture zone at a depth of 400 m. There are indications, however, based on other investigation methods, e.g. borehole TV, that the hydraulic conductivity of the intact rock of Romuvaara could actually be lower than at the other sites.

Measured hydraulic heads indicate that groundwater flow is controlled by local gradients. There is no regional groundwater flow from south to north, which would be the expected direction from a study of the topography and from the gradient of the groundwater table. It is evident, from head measurements in boreholes, that the hill of Romuvaara has a rather strong effect on the hydraulic heads at depth, causing variable directions of groundwater flow, and the results of the groundwater flow modelling strengthen this assumption (Kattilakoski & Koskinen 1999). The measured directions of groundwater flow also indicate that the possibility of a systematic regional flow at depth is unlikely. Measured directions of groundwater flow are, however, in many places counter to the flow directions estimated from the groundwater table gradient or from the results of the groundwater flow modelling. It is evident that the flow directions at the borehole scale are very irregular, due to heterogeneities in the properties of the fractures, which are caused by the variability of fracture orientations and fracture connectivities and by the channelling within individual fractures.

The hydrogeological studies show that groundwater flow conditions in the rock mass are generally favourable for hosting a repository. The hydraulic conductivity of the intact rock, in which any repository would be located, is rather low, and it seems likely that groundwater flow will mainly occur in the more conductive fracture zones. It is concluded that certain structures need definitely to be avoided when locating a repository, but that minor structures can be safely sealed by grouting during construction. The results of hydraulic tests indicate that fractures down to depths of approximately 200 m are hydraulically more conductive than those at greater depth, and this is one good reason for locating a repository at depths of greater than 200 m. Highly transmissive structures, however, also exist at greater depths and any repository needs to be located carefully with respect to these.

10.2.3 Hydrogeochemistry

Evolution trends

The hydrogeochemical interpretation and modelling of groundwater at Romuvaara reported by Pitkänen et al. (1996a) and at Kivetty (Pitkänen et al. 1998) indicate that similar reactions have occurred in the evolution of groundwater types at these sites as at those sites with saline groundwater, e.g. Olkiluoto (Pitkänen et al. 1999). The major reactions at Romuvaara are related to the oxidation of organics with contemporaneous CO₂ production, and silicate weathering during recharge. Some oxidation of ferrous minerals (sulphides and silicates) is also evident. Subsequent dissolution of calcite is evident at shallow depths and/or in dynamic flow systems as suggested by, for example, variations in $\delta^{13}\text{C}(\text{DIC})$. At greater depths, the precipitation of calcite promotes an equivalent amount of silicate hydrolysis, which usually stabilizes pH to 8 - 9. Water-rock interaction with mafic rocks such as metadiabase dykes is a probable reason for high pH (up to 10) ground waters. The change in cationic ratios and concentrations results partly in ion exchange of Ca (Mg, K) for Na, a process that seems to be particularly strong in mafic rocks. Groundwater evolves from Ca-Mg-HCO₃-type to Ca-Na-HCO₃-type at shallow depths, but at greater depths and with longer residence times the relative composition of the groundwater changes either towards a Na-Ca-Cl-type, or a Na-Cl-type endmember. The trend to more Ca-rich Na-Ca-Cl-type groundwater is typical of felsic rock sites in Finland such as Kivetty, Olkiluoto and Hästholmen. The evolutionary trend towards a Na-Cl-type high-pH groundwater corresponds to the interaction of mafic-ultramafic rocks with groundwater, a process which appears to be common in both the Fennoscandian shield (Blomqvist et al. 1993b, Pitkänen et al. 1993b, Ruskeeniemi et al. 1996) and the Canadian shield (Bottomley et al. 1990).

The least disturbed redox measurements on deep Romuvaara groundwater suggests the prevalence of slightly to fairly reducing conditions at depth (Eh 0 to -400 mV, with a median value of -150 mV (Ruotsalainen & Snellman 1996b, Helenius et al. 1998). Anaerobic oxidation of organic carbon, with sulphate reduction as the predominant electron acceptor, is expected to be the main redox-controlling process in groundwater over long residence times at depth. This process is also indicated by the occurrence of sulphide, by the decreasing sulphate content of groundwater with increasing Cl, by the decreasing trend of Eh (measured) versus increasing sulphide, by the occurrence of sulphate reducing bacteria, and by the increase in $\delta^{34}\text{S}(\text{SO}_4)$ with increasing Cl. Pyrite precipitation would seem to be a plausible sink for part of the reduced SO₄ according to fracture mineral observations (Gehör et al. 1996a). Theoretically, according to the thermodynamic data of S-Fe-systems in the compilation of Brookings (1988), the expected Eh in a sulphidic zone is around -200 to -300 mV at a pH of 8.0 - 9.0, and in the high pH range measured at Romuvaara the expected redox level is even lower.

Salinity and the extent of calculated geochemical reactions remain at a low level at Romuvaara, regardless of the maturity of the most evolved groundwater. A low salinity is considered to be typical of the interaction between crystalline bedrock and groundwater in a cold climate, with limited or no input of fossil water, such as palaeo sea water or residuals of ancient hydrothermal water, being leached into the system.

The TDS and also the chloride content increase with increasing depth, but significant variations can be observed for a single borehole or between corresponding sampling levels in different boreholes, reflecting the importance of the local hydraulically-conductive fracture zones in controlling the spatial variabilities in groundwater chemistry.

The palaeohydrogeology of the four investigation sites, particularly their relation to the Weichselian glaciation and to the palaeo-Baltic stages varies, and is reflected in the chemistry of the groundwater. Romuvaara has clearly been in a supra-aquatic position since the last glaciation. The groundwater ^{14}C ages at Romuvaara (adjusted for interaction by the calculated mass-balance models) cover virtually the whole period of time since the retreat of the ice sheet about 10 000 years ago, with young groundwater ages being typically connected with higher hydraulic conductivities in the bedrock. However, no cold water signature is observable in the stable isotope data of old groundwater samples at Romuvaara, whereas these are frequent at the other sites. The storage of glacial meltwater above the bedrock would have been limited due to the supra-aquatic location of Romuvaara and the small amounts of recharged glacial meltwater were probably either rapidly and efficiently flushed out of the system or the ice sheet was possibly cold base and permafrost prevented glacial meltwater intrusion. There is no evidence of oxygen intrusion to great depth, since observations of iron oxyhydroxide in fractures are generally limited to the upper 200 m of the bedrock.

There is a comprehensive dataset for the Romuvaara site and the geochemical modelling (Pitkänen et al. 1996a) is considered to produce a good general picture of the evolutionary processes prevailing in the upper 500 m since the last glaciation. Isotope data on groundwaters are already extensive, but specific analyses are still needed to augment conclusions drawn from the hydrogeochemical interpretation of Romuvaara (Pitkänen et al. 1996a). Carbon isotope analyses of calcite, gases and organic matter are needed, for example, to check the reaction models themselves, and extensive ^{34}S and ^{18}O analyses of sulphur species are also required for computing the extent of actual sulphide production through water-rock interaction.

Some important identified processes affecting the present geochemical conditions at Romuvaara with respect to hosting of a repository for spent nuclear fuel are given in Table 10.2-1. Favourable anoxic reducing conditions buffered by anaerobic oxidation of organic carbon, with simultaneous sulphate reduction prevail at depth. The sulphide concentration is expected to be controlled by iron, eg. hematite on the fracture walls, for pyrite precipitation. The higher sulphide level associated with mafic rocks could be explained by the slower release rate of iron from iron in silicates, which thus may constrain pyrite precipitation. Calcite precipitation and silicate hydrolysis buffer pH to slightly basic pH values (8 - 9) at depth. Exceptionally high pH levels (about 10) are associated with mafic rocks. The salinity and extent of geochemical reactions at Romuvaara remain at a low level. Below 500 m processes, such as those that determine the increase in salinity, are less well understood and require further study.

Table 10.2-1. Summary of important processes affecting geochemical conditions at Romuvaara.

Processes and indicators	
<u>pH</u> Shallow groundwater, 5.5 - 7 Deep groundwater, 8 - 9 9 - 10	Organic respiration, Silicate weathering , Calcite dissolution $\log p\text{CO}_2$ -2.0...-3.0 Calcite precipitation, $\log p\text{CO}_2 < -4.0$ Silicate hydrolysis Mafic rocks, equilibrium with laumontite, $\log p\text{CO}_2 \approx -5.0$
<u>Eh</u> Shallow groundwater, Postoxic Deep groundwater, Sulphidic <-200 mV Mafic rocks	Organic respiration Oxidative weathering of Fe and S bearing minerals e.g. biotite, pyrite Microbial sulphate reduction (SRB), increase in $\delta^{34}\text{S}(\text{SO}_4)$, anaerobic organic respiration Sulphide concentration control by Fe e.g. hematite Pyrite coatings Higher sulphide, Fe controlled by silicates
<u>Alkalinity</u> Shallow groundwater, < 1 meq/l Max. 2 meq/l Deep groundwater, decreasing trend	Organic respiration, Calcite dissolution Calcite precipitation at $\text{Cl} < 2 \text{ mg/l}$. Silicate hydrolysis Anaerobic organic respiration
<u>Salinity</u> Shallow groundwater Deep groundwater, TDS max. 265 mg/l Cl max. 109 mg/l	Precipitation Weathering (acidity promoted hydrolysis) Silicate hydrolysis, leaching of fossil salts: Hydrothermal water-rock interaction, high Ca/Mg and evidence of fracture-controlled circulation of hydrothermal fluids in the past e.g. R2/3, R10. $\delta^{37}\text{Cl}$ suggest some salinity source related to the same salinity source as for waters in the Baltic Basin, i.e. salt leachate from extensive Palaeozoic salt deposits south of the Baltic Sea.
Chemistry vs. flow	Consistent with local hydraulically conductive fractures ^3H anomalies can be explained with observed fracture zones Longer ^{14}C-residence times in more intact rock above and below conductive fractures
Rock-specific features	Metadiabase veins: high pH and Na groundwaters Relatively higher Cl-content in water High $^{87}\text{Sr}/^{86}\text{Sr}$ signature in water corresponds with Rb-rich minerals, biotite and feldspars in the gneissic rocks of Romuvaara
Origin of water types, residence time & indicators of oxygen	$\delta^{18}\text{O}$ fairly constant-> mainly non-mixed meteoric origin for the groundwaters. No depletion in $\delta^{18}\text{O}$ at adjusted ^{14}C age < 8 000 BP ^{14}C ages cover range from release of ice sheet 10 000 BP - present. At depth a mixture of older pre-glacial water and young recharge. Iron oxyhydroxide observations at depths above 40 - 190 m
Chemical reactions and mass transfer	Low overall mass transfers - of the order of few mmol/l.

Importance for corrosion, buffer, solubility and transport

The anoxic reducing conditions at depth at Romuvaara are expected to be favourable for limiting *the corrosion rate of canisters*. In oxygen-free water, sulphide is the most corrosive agent for the Cu canister, and the most important corrosion products are cuprous sulphides Cu_{2-x}S , corresponding to the mineral phases, chalcocite, anilite and djurleite (Ahonen 1995). Cupric sulphides such as covellite are also likely admixtures. The sulphide content in the gneissic rock groundwater at Romuvaara appears to be constrained by the availability of dissolved Fe from iron oxyhydroxides present. In mafic rocks (which are present at Romuvaara but only to a limited extent) dissolved sulphide is less limited due to the probable control of dissolved iron by iron silicate. This explanation is believed also to be applicable for the situation at Olkiluoto, where groundwater with elevated dissolved sulphide content is present (Pitkänen et al. 1994).

Favourable conditions are expected to exist for the stability of the *bentonite buffer* at Romuvaara as well as at Kivetty, although ion exchange with clay minerals is favoured where Ca, Mg and K is exchanged for Na, according to thermodynamic calculations by Pitkänen et al. (1996a), and this is supposed to be the case also for Na-montmorillonite. The overall mass and mole transfer in this process is expected to be low, but will need to be evaluated more precisely.

The most important groundwater parameters that affect *radionuclide solubility* are pH, the carbonate content and Eh, with salinity also being important for certain elements. Temperature has a strong effect on pH and hence on the solubilities of elements that can be hydrolysed. The temperature at depth is somewhat higher at Hästholmen and Kivetty compared to Romuvaara and Olkiluoto, apparently due to the more radiogenic bedrock (elevated levels of U, He, Rn, Ra and Th) of Hästholmen (rapakivi granite) and Kivetty (granodiorite). However, the difference is not so large as to affect the solubilities to any significant. The temperature in the near-field of the spent fuel repository will rise to a maximum of about 100°C within a few decades and will then gradually decrease towards the ambient temperature of about 15°C within a few thousands of years (Raiko 1996). The probability of the corrosion-resistant canister allowing any release of radionuclides during this thermal phase is, however, very low. In addition to carbonates, strong complexing agents in the groundwater such as hydroxide, chloride, sulphate, sulphide, and phosphate may be of importance if their concentrations become high enough. At Romuvaara, however, the content of these ligands is low compared with the dominant dissolved carbonate ions, even for the high pH water associated with the mafic rock.

In natural groundwater systems one of the most important factors defining the pH level is the amount of dissolved CO_2 . The dissolved carbonate contents at the four sites range from less than 0.1 meq/l to 7 meq/l. The lowest values are exhibited in the most saline groundwaters at Olkiluoto and Hästholmen. The highest values are observed in the brackish HCO_3^- -rich waters at shallow depths at Olkiluoto (Pitkänen et al. 1999). The pH values of groundwater at the sites range generally from about 7 to 9, apart from certain locations at Romuvaara, where the variation is from 7 to 10, reflecting the influence of more variable mineralogy, the high pH values being found in boreholes which intersect metadiabase dykes. High pH groundwater are potentially unfavourable with respect to some nuclides by increasing their solubility and is an aspect which has to be evaluated.

Many organic ligands are known to have a strong complexing affinity, but at present specific knowledge of the amount and the nature of organic complexing agents present in the groundwaters at these sites is scarce. Organic ligands, such as humic and fulvic acids, have not been discussed or considered in this report. Data on such species are available only from one location at Olkiluoto indicating relatively low concentration (0.01-0.02 mg/l) of humic acids (Laaksoharju et al. 1994).

Reducing conditions, which are favourable for low radionuclide solubility and slow canister corrosion, are expected to exist at depth at all the sites. The main redox reactions at depth in groundwater are related to anaerobic oxidation of organics, in parallel with SO_4 reduction, according to evidence from enriched $\delta^{34}\text{S}(\text{SO}_4)$, dissolved sulphides and pyrite precipitates on calcite fillings (e.g. Pitkänen et al. 1994, 1996a,b 1998, 1999). Depending on the pH, the redox level is generally interpreted to be buffered from -200 to -300 mV at all sites. But at Romuvaara, in particular, groundwater in the mafic host rock with high pH is expected to be buffered towards a lower Eh as compared with the lower pH groundwater in the gneisses.

The *sorption properties* of the rocks at the sites can be estimated on the basis of their cation exchange capacities (CEC), the amount of Fe oxides, their degree of alteration and their porosity, which are all related to the mineral composition and microstructure of the rock (Huitti et al. 1996). The CEC's of the rocks are generally fairly similar for all sites, although mica gneiss, especially that at Olkiluoto, seems to have the best sorption properties for elements such as Cs, which sorbs by ion exchange. The CEC of the altered rapakivi granite at Hästholmen is reported to slightly higher than the tonalites at Romuvaara and only slightly lower than that of mica gneiss at Olkiluoto (Huitti et al. 1996). The mica gneiss and tonalites at Romuvaara have higher percentages of minerals with larger sorption capacities, such as biotite, chlorite and hornblende, than do granitic rocks in general. The easily accessible biotite of the Romuvaara gneiss is expected also to have a buffering capacity against ingress of oxygenated groundwater, such as glacial meltwater.

In addition to sorption properties, the minerals possess reduction capacities, which could be expressed from their Fe(II) content. The mica gneisses and granodiorites at Olkiluoto contain more of such minerals with Fe(II) contents (biotite, chlorite, hornblende) than do granitic rock types. However, at Hästholmen the chlorite content of unaltered rapakivi granite is higher than generally found in granite and increases with the alteration degree of the rock (altered, weathered rapakivi). Of the rocks studied the Olkiluoto mica gneiss has the highest chlorite content, whereas biotite is very common in the gneisses both at Romuvaara and Kivetty.

However, the differences attributed to the groundwater composition, such as redox conditions (reducing vs. oxidising) and salinity (fresh vs. saline), are considered to be of greater importance for sorption than the differences attributed to the rock type (Hakanen & Hölttä 1992). The low ionic strength of water (TDS max. 265 mg/l) is expected to be favourable for sorption both at Kivetty as well as at Romuvaara. The brackish and saline groundwater types at Olkiluoto and Hästholmen (TDS max. 69 g/l) are expected to be less favourable for elements sorbing by ion exchange, e.g. alkaline- and alkaline-earth elements Cs, Ra and Sr, as compared with fresh water.

Colloidal forms of radionuclides may significantly affect their rate of transport in groundwater, if the sorption of radionuclides on colloids is irreversible. However, bentonite in the near-field is expected to act as a filter for possible colloidal forms. Furthermore, the available data on inorganic colloids (less than ≈ 360 ppb) and humic acids (≈ 10 ppb) in Finnish groundwater (Laaksoharju et al. 1994) as well as the data on the properties of Swedish groundwater colloids (Laaksoharju et al. 1995) indicate low colloid concentrations.

The hydrogeochemical characteristics of the Romuvaara site show that the conditions are generally favourable for the stability of the buffer, slow copper corrosion rate, low solubility and slow transport of radionuclides, i.e. low salinity, anoxic reducing conditions, pH in neutral or slightly basic range, and low sulphide content. However, the role of high pH of mafic rocks need to be evaluated further.

10.2.4 Construction

The bedrock of Romuvaara has been characterised and classified in order to assess the suitability of the rock mass for locating and constructing the repository, as described in Section 8.1. The expected range of disposal depths is from 400 to 700 m. Estimates regarding a suitable range of depths for the repository are mainly influenced by the hydrogeological properties (minimum depth) and the strength and in situ stress of the rock (maximum depth). The positioning of the repository within the rock mass is determined primarily by the location and geometry of the major fracture zones. From a rock engineering point of view, the constructability is affected by the lithology and the fracturing of the bedrock, and its engineering properties by the magnitude and orientation of the in situ stress, as well as by the hydrogeological and hydrogeochemical environments. It is important to consider the prevailing groundwater conditions, i.e. the hydrogeology and hydrochemistry, when assessing the need for sealing fractures prior to rock excavation, and in the choice of constructional materials to be used.

The constructability of the bedrock at Romuvaara has been estimated to depend mainly on the depth and lithology and on whether construction takes place in intact rock or in fracture zones. Local differences in the properties of intact rock within a single rock type were found to be small, but more variation can be found between different rock types. Mica gneiss seems to be the weakest rock type at the site, however, the volume of the rock mass that consists exclusively of mica gneiss is quite limited, and it typically exists as interlayers within the tonalite gneiss mass, thereby somewhat reducing this rock's strength.

The main conclusion from the evaluation is that there seems to be no significant constraints in constructing a repository within the depth range of 400 to 700 m. The major part of the intact rock volume has been estimated as "normal" from the point of view of its constructability. This means, in practice, that the excavation and rock support can be carried out using conventional methods and materials, as generally applicable to Finnish underground construction projects. Close to the maximum depth of 700 m, tonalite gneiss has been estimated to be "demanding" or "very demanding" in terms of its constructability because of the higher stress field ($\sigma_H \approx 40$ MPa at 700 m). Mica gneiss lies within the "demanding"

category from depths greater than 400 m. The classes "demanding" and "very demanding" mean that special methods and materials should be used when excavating and supporting the rock, which in turn, will result in more time and increased costs for the construction work.

Although all the fracture zones encountered at the site could be excavated and supported in an appropriate manner, it is proposed that certain structures should be avoided, at least when locating the deposition tunnels and disposal holes. Structures R3, R9, R13, R14, R21, R22 and R31 (see Fig. 8.2-3) are expected to prove difficult to seal against ingress of groundwater and may also require extensive support.

There are still considerable uncertainties concerning the exact locations, dimensions and properties of the bedrock structures. It is very probable, anyhow, that bedrock volumes suitable for repository construction can be found. The repository layouts developed at this stage in the programme should be considered to be only illustrative in nature, such as that presented in Fig. 9.3-1, which indicates the area needed for the construction of deposition tunnels for 2200 canisters. The details of the repository layout and the locations of the deposition holes will be determined in a design-as-you-go process, in which the repository concept will be adjusted to the in situ conditions during construction.

11 CONCLUDING REMARKS

An extensive characterisation of the Romuvaara site has been carried out over a period of more than 10 years. The area, originally selected as a fairly large block of bedrock, has been investigated from the air, from the surface and with the help of deep boreholes. The investigations have demonstrated that the area can indeed be modelled as a large block, the definition of such a block, however, being a matter of definition. The characterisation programme, thanks to the sophisticated methods used, has identified more than 30 features which can be regarded as structural zones. In the course of this programme it has become apparent that the detection of such zones is a matter not only of the resolution of the investigation techniques applied, but also of the methods that can be used to provide a classification of the rock mass. The bedrock lying between these zones is considered to be of sufficiently good quality to satisfy the requirements of long-term safety and of locating and constructing a repository.

The main structural properties and the variation in the hydraulic parameters at Romuvaara are similar to those found at the other three study sites of Kivetty, Olkiluoto and Hästholmen, as well as those found earlier at Syry and Veitsivaara. Evidence from studies on comparable rock types in Sweden also give rather similar results (Saksa & Nummela 1998). This overall similarity may reflect a general consistency in the properties prevailing in the Fennoscandian Shield, and thus the Romuvaara site could be considered to represent a typical geological environment. In addition, Romuvaara has no potentially valuable natural resources.

According to published recommendations for siting a deep repository (e.g. IAEA 1994), the site should be located within an tectonically stable area. Studies of the seismicity and the present tectonic movements in Finland demonstrate that the Fennoscandian Shield is very stable. The recommendations also emphasise the necessity of selecting a site that is amenable to investigation. The characterisation programme at Romuvaara has evolved in a step-wise fashion, and the conceptual models of the site have not changed markedly as the programme has proceeded, suggesting that the site is suitable in this regard. An important factor affecting the ease of investigation is that the rock in both the outcrops and at depth is similar, which makes for the easier development of geological models.

The number of boreholes drilled from the surface has to be limited so that the containment properties of the rock mass are not jeopardised. There are, therefore, uncertainties associated with the exact geometry, location and properties of the fracture zones and the extent of volumes of intact rock. As a consequence of these uncertainties, it is not possible to develop detailed repository designs at this stage, however, volumes of bedrock which are considered to be potentially suitable for hosting a repository can be defined. An evaluation of the constructability of the rock mass has demonstrated that a repository could be constructed at the site, although with some restrictions. Factors such as this will have to be taken into account in designing the detailed characterisation programme which is planned in conjunction with the construction of the investigation shaft.

Along with the tectonic and rock mechanical characteristics the hydrogeological and hydrochemical properties of the bedrock are considered most important in terms of their

impact on the long-term safety of the disposal system. Based on the information obtained from borehole studies there seems to be fairly good consistency between the structure of the bedrock, its hydrogeological properties and the hydrochemical environment at depth. The hydrogeological and hydrogeochemical conditions are considered to be favourable for low radionuclide solubility, slow canister corrosion and for the stability of the bentonite buffer, as well as for the slow transport of radionuclides. The high pH of the groundwater where mafic dykes are present, however, needs to be studied further.

The evaluation of the available data suggests that the Romuvaara site has the potential to host the repository and provide the conditions for safe, long-term disposal based on the current reference disposal concept. The development of a repository at the site would, however, require additional investigations, preferably underground, to evaluate the importance of the uncertainties regarding the structural zones and to examine the impact of future natural evolution on the properties of the site in greater detail.

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SITE INVESTIGATIONS AT ROMUVAARA
GROUND AND AIRBORNE SURVEYS
STUDIES IN BOREHOLES OTHER THAN KR1...KR11

APPENDIX 1
1(4)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
GEOLOGICAL MAPPINGS AND SAMPLINGS	PRE, Phase	Geological generic study	Complementing of former studies for identification of areas	87-24
	PRE, Phase 1	Geological mapping	Mapping of rock types, fracturing and tectonic parameters	87-24
	PRE, Phase 1	Development of line grid	Line grid for linking different measurements to national coordinate system	87-30
	PRE, Phase 1	Bedrock sampling	Determination of rock types and fracturing in areas covered with overburden, determination of sources for geophysical anomalies	87-19
	PRE, Phase 3	Mapping of geological structures	Complementing of former mappings, definition of the deformation history and fracturing	90-02
	DET, Phase 1/C	Repair work of the line grid	Line grid for linking different measurements to national coordinate system	94-01
	DET, Phase 1/C	Geological mapping of the investigation trenches TK1 and TK2	Complementing of former mappings of rock types, fracturing and structures	95-14 95-64
GEOPHYSICS	PRE, Phase 1	Geophysical reconnaissance surveys (magnetic, VLF electromagnetic)	Mapping of fracture zones, mapping of rock types, definition of methods and directions for surveys along the line grid	87-30 88-10
	PRE, Phase 1	Ground radar survey, larger area	Mapping of soil types and fracture zones	87-02
	PRE, Phase 1	Geophysical surveys (magnetic, VLF electromagnetic)	Mapping of soil types and surficial rock, mapping of rock types	87-30 88-10
	PRE, Phase 1	Detailed ground radar survey	Study of surface fracturing, additional fracture mapping	88-01
	PRE, Phase 1	Airborne survey (magnetic, VLF electromagnetic, dipole electromagnetic, radiation)	Mapping of rock types and structures of bedrock at the site	88-22 89-14
	PRE, Phase 1	Gravity survey	Delimitation of fracture zones, diabase dykes and other rock types	88-31
	PRE, Phase 1	Seismic refraction survey	Checking the location of fracture zones	88-45 89-03

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APPENDIX 1
2(4)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
	DET, Phase 1/C	Aerial photography	Maps for varying site investigations	95-04
	DET, Phase 1/C	Electromagnetic frequency soundings	Survey of variation in resistivity of the bedrock, to obtain information about fracture zones	94-13 94-45
	DET, Phase 2	Borehole TV-monitoring, EP8 and EP9	Determination of fracture zones and packer positions for hydraulic head monitoring	98-04
HYDROLOGICAL MEASUREMENTS	PRE, Phase 1	Drilling and installation of network of multilevel piezometers	Network for monitoring of hydraulic head in the upper part of bedrock	87-25
	PRE, Phase 3 ->	Measuring of hydraulic heads	Monitoring of hydraulic head and its fluctuation in the upper part of bedrock	88-64 92-02
	PRE, Phase 3->	Measuring of groundwater table	Monitoring of groundwater table and its fluctuation in the upper part of bedrock	88-64 92-02
	PRE, Phase 3->	Measuring of snow depth and water equivalent of snow	Determination of precipitation of the investigation area	88-64 92-02 96-62
	PRE, Phase 3	Measuring of discharge in brooks by current meter or weir	Determination of runoff of different parts of the investigation area, determination of runoff of minimum runoff period	88-64 92-02
	PRE, Phase 3->	Measuring of precipitation	Determination of precipitation of the investigation area	88-64 92-02 96-62
	PRE, Phase 3	Fall off tests in multilevel piezometers	Determination of hydraulic conductivity of the upper part of bedrock	89-86 90-56
	DET, Phase 1/C	Manual measurement of water tables	Monitoring of gw-table and hydraulic head in wells, open boreholes and packed-off sections	96-62
	DET, Phase 1/C	Pumping test at Särkkäharju	Determination of yield at the Särkkäharju esker	***)
	DET, Phase 2	Constant head injection tests, EP8 and EP9	Determination of hydraulic conductivity and locations of measuring sections for installation of packers	98-58
GROUNDWATER CHEMISTRY	PRE, Phase 1	Groundwater sampling, surrounding area	Gathering of reference samples from the surrounding area	88-13

SITE INVESTIGATIONS AT ROMUVAARA
GROUND AND AIRBORNE SURVEYS
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APPENDIX 1
3(4)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
	PRE, Phase 1	Groundwater sampling from PR1 and KA1	Determination of the quality of the groundwater in the upper part of bedrock, the influence of the drilling, the influence of the pumping from the borehole well and the spreading of the labeled flushing water	88-13 88-15
	PRE, Phase 1	Percussion drilling of PR1	Determination of the quality of the groundwater in the upper part of bedrock and the influence of the drilling	87-27
	PRE, Phase 2	Groundwater sampling from KA2	Determination of the quality of the groundwater in the upper part of bedrock and the influence of the pumping from the borehole well	88-13 88-15
	PRE, Phase 3	Groundwater sampling from KA2	Determination of the quality of the groundwater in the upper part of bedrock and the influence of the pumping from the borehole well	89-07
	PRE, Phase 3 DET, Phase 1/B	Snow sampling	Determination of the chemistry of snow	89-07 92-54 95-32
	PRE, Phase 3	Groundwater sampling from KA3	Determination of the quality of the groundwater in the upper part of bedrock and the influence of the pumping from the borehole well	89-07
	PRE, Phase 4	Groundwater sampling, multilevel piezometers	Determination of the quality of the groundwater in the upper part of bedrock, estimation of groundwater residence time in bedrock with the aid of changes in chemical quality	89-87
	PRE, Phase 4	Rain water sampling	Determination of the chemical composition of the water infiltrating to groundwater from rain	92-54
	DET, Phase 1/B	Rain water sampling	Local hydrogeochemical characterization and geochemical modelling	94-49
	DET, Phase 1/B	Groundwater sampling from KA2 and KA3	Local hydrogeochemical characterization and geochemical modelling	94-49
	DET, Phase 1/B	Environmental reference samples	Hydrogeochemical reference data from a larger area	94-49
	DET, Phase 2	Groundwater sampling from PR2, PR3, PVP1 and PVP15	Local hydrogeochemical characterization and geochemical modelling	98-16

SITE INVESTIGATIONS AT ROMUVAARA
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APPENDIX 1
4(4)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
OTHER MEASUREMENTS	DET, Phase 1/C	Stability	Monitoring of stability of the bedrock	96-07e 96-65e 98-08e
	DET, Phase 2	Bird study	Primary study for environmental impact assessment	97-44
	DET, Phase 2	Ecological survey	Primary study for environmental impact assessment	97-65

*) PRE = Preliminary investigations, DET = Detailed investigations,
Phases are referring to the figure 2.2-2.

B = Baseline investigations

C = Complementary characterization

T = Testing of results and assumptions

**) Ref. = reference to the work report

***) The work and results presented in the thesis for M.Sc. by Jari Pöllänen

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR1

APPENDIX 2
1(3)

Investigation	Phase*)	Method	Purpose	Ref. **)
DRILLING	PRE, Phase 2	Core drilling (979 m)	Determination of rock types, fracturing and bedrock structures in the place estimated as intact bedrock	87-27
GEOPHYSICS	PRE, Phase 2	Geophysical standard borehole logging: Fluid resistivity and temperature, resist. (normal 1.6 m and 0.4 m, single point), natural gamma, gamma-gamma density, neutron-neutron, self potential, 1-arm caliper, P-wave velocity susceptibility	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	88-04
	PRE, Phase 2	Vertical seismic profiling (VSP)	Mapping of fracture zones and contacts between rock types	88-05
	PRE, Phase 2	Seismic tube-wave survey	Localization of water bearing or hydraulically conductive fractures	88-02
	PRE, Phase 2	Borehole radar	Mapping of position of fractures and fracture zones	88-46
	DET, Phase 1/C	Borehole-TV measurements (40-940 m)	Interprete and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation. Interpreted sections: 139-200 m, 290-441 m and 539-940 m	96-58e
	DET, Phase 1/C	Galvanic charged potential measurements	Verification the connection of the interpreted fracture zone R9 in the bedrock, completion of interrupted work in 1994	95-74 96-04
	DET, Phase 1/C	Directional borehole radar	Mapping of position and direction of fractures and fracture zones	95-11e
	DET, Phase 1/C	Dipmeter	Localization, orientation and statistical analysis of fractures and fracture zones in the borehole.	96-37e
HYDROGEOLOGY	PRE, Phase 2	Constant head injection test	Determination of hydraulic properties of bedrock, localization of hydraulically conductive zones	88-11 88-20 89-17

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR1

APPENDIX 2
2(3)

Investigation	Phase*)	Method	Purpose	Ref. **)
	PRE, Phase 4	Installation of multipacker system	Returning of the natural hydraulic heads, prevention of groundwater flow along the hole	90-11
	PRE, Phase 4	Pumping test	Determination of hydraulic conductivity of the bedrock, localizing of the rapid flow paths and general determination of their properties, comparison with the bedrock model	90-30 91-27 ***)
	PRE, Phase 4	Measuring of hydraulic heads in several borehole sections	Monitoring of hydraulic head and its variations in bedrock, estimation of hydraulic gradient	92-02
	PRE, Phase 4	Fall off test	Determination of hydraulic conductivity of bedrock, checking of the tightness of the packers of the multipacker equipment	92-02
	DET, Phase 1/C	Slug and bail test	Controlling of multipacker equipments and determination of transmissivities in packed-off sections	94-14
	DET, Phase 1/C	Measuring of hydraulic heads in packed-off sections during water sampling	Controlling of multipacker equipment and localization of hydraulic connections between different sections in the borehole	94-52
	DET, Phase 1/C	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of their hydraulic properties	95-35e
	DET, Phase 1/C	Flowmeter / groundwater flow measurements	Measuring of (natural) groundwater flow across the borehole (or along the fracture(s))	95-38e
	DET, Phase 1/C	Installation of multipacker system,	Determination of hydraulic heads in the packed-off sections, head monitoring during pumping test in KR4	96-78
	PRE, Phase 2	Groundwater sampling with double packer method	Determination of the quality of the groundwater deep in bedrock	88-13 88-15
GROUNDWATER CHEMISTRY	PRE, Phase 3	Groundwater sampling from groundwater during the pumping test	Determination of the quality of the groundwater in different depths, influence of the great pumping volumes on the chemical composition of the groundwater	90-31
	DET, Phase 1/B	Groundwater sampling from packed-off sections	Local hydrogeochemical characterization of groundwaters at various depths; production of in-put data for geochemical modelling and performance assessment	95-55

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR1

APPENDIX 2
3(3)

Investigation	Phase*)	Method	Purpose	Ref. **)
OTHER MEASUREMENTS	PRE, Phase 4	Rock stress measurements with hydraulic fracturing method	General direction and magnitude of stress field in bedrock	90-09
LABORATORY TESTS	PRE, Phase 2	Petrographic, litho-geochemical and petrophysical studies	Determination of rock types, fracture fillings, geochemical properties, petrophysical parameters of borehole samples for evaluation of chemical conditions and interpretation of geophysical measurements	88-07
	PRE, Phase 3	Study of rock mechanical properties	Determination of rock mechanical properties of the investigation areas, comparison of laboratory and field tests	92-36
	PRE, Phase 3	Study of thermal properties of rock	Determination of the thermal properties of the most common rock types of the investigation area	92-56
	DET, Phase 1/C	Fracture mineral mapping/study	Determination of low temperature fracture minerals for examination of qualitative properties	95-87

*) PRE = Preliminary investigations, DET = Detailed investigations,
Phases are referring to the figure 2.2-2.
B = Baseline investigations
C = Complementary characterization
T = Testing of results and assumptions

**) Ref. = reference to the work report

***) See also report YJT-93-10

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR2

APPENDIX 3

1(3)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	PRE, Phase 3	Core drilling (0-500 m)	Determination of rock types, fracturing and bedrock structure, determination of orientation and continuity of fracture zones, determination of extent of intact bedrock area, penetration of schistosity and fracturing in optimized orientation	87-29
	DET, Phase 1/C	Core drilling (500-1100 m)	Obtaining bedrock data, checking of bedrock data	94-20 94-37
GEOPHYSICS	PRE, Phase 3	Geophysical standard borehole logging (0-500 m): Fluid resistivity and temp. resistivity (normal 1.6 m and Wenner 0.3, single point), susceptibility, gamma-gamma density, self potential, natural gamma	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	88-18
	PRE, Phase 3	Tube-wave measurement	Localization of water bearing or hydraulically conductive fractures	88-02
	PRE, Phase 3	VSP measurement	Mapping of fracture zones and contacts between rock types	88-05
	PRE, Phase 3	Borehole radar, singlehole and VRP measurement	Mapping of position of fractures and fracture zones	88-46
	DET, Phase 1/C	Geophysical standard borehole logging (500-1100 m): Fluid resistivity and temp. resistivity (normal 1.6 m and 0.3 m, single point), susceptibility, gamma-gamma density, natural gamma, sonic full wave form (40-1100 m), 3-arm caliper (40-1100 m)	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	95-70 95-88
	DET, Phase 1/C	Directional borehole radar	Mapping of position and direction of fractures and fracture zones	95-11e
	DET, Phase 1/C	Borehole-TV measurements	Demonstrate the tool and processing, produce data for method comparison	95-34e

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR2

APPENDIX 3

2(3)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
HYDROGEOLOGY	DET, Phase 1/C	VSP (3D) measurement (380-1100 m)	Mapping of position and orientation of seismic reflections from fracture zones and possibly from contacts between rock types	95-72e
	DET, Phase 1/C	Dual neutron logging	Provide data for analysis of rock types and porosity in the rock close to borehole	96-33e
	DET, Phase 1/C	Dipmeter	Localization, orientation and statistical analysis of fractures and fracture zones in the borehole.	96-37e
	PRE, Phase 3	Constant head injection test	Determination of hydraulic properties of bedrock, localization of hydraulically conductive zones	88-11 88-20
	PRE, Phase 4	Installation of multipacker system	Returning of the natural hydraulic heads, prevention of groundwater flow along the hole	90-11
	PRE, Phase 4	Measuring of hydraulic heads in several different measuring sections	Monitoring of hydraulic head and its variations in bedrock, estimation of hydraulic gradient	92-02
	PRE, Phase 4	Fall off test	Determination of hydraulic conductivity of bedrock, checking of the tightness of the packers of the multipacker equipment	92-02
	DET, Phase 1/C	Slug and bail test	Controlling of multipacker equipment and determination of transmissivities in packed-off sections	94-14
	DET, Phase 1/C	Measuring of hydraulic heads in packed-off sections during water sampling	Controlling of multipacker equipment and localization of hydraulic connections between different sections in the borehole	94-52
	DET, Phase 1/C	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of their hydraulic properties	95-35e
	DET, Phase 1/C	Flowmeter / groundwater flow measurements	Measuring of (natural) groundwater flow across the borehole (or along the fracture(s))	95-38e
	DET, Phase 1/C	Installation of multipacker system	Determination of hydraulic heads in the packed-off sections, head monitoring during pumping test in KR4	96-78
GROUNDWATER CHEMISTRY	DET, Phase 1/B	Groundwater sampling	Local hydrogeochemical characterization of groundwaters at various depths; production of in-put data for geochemical modelling and performance assessment	95-55

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR2

APPENDIX 3
3(3)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
OTHER MEASUREMENTS	DET, Phase 1/B	Rock stress measurements with hydraulic fracturing method	Obtaining the horizontal stress field	96-26e
LABORATORY TESTS	PRE, Phase 3	Petrographic, lithogeochemical and petrophysical studies	Determination of rock types, fracture fillings, geochemical properties, petrophysical parameters of borehole samples for evaluation of chemical conditions and interpretation of geophysical measurements	88-07
	PRE, Phase 3	Study of rock mechanical properties	Determination of rock mechanical properties of the investigation areas, comparison of laboratory and field tests	92-36
	DET, Phase 1/C	Fracture mineral mapping / study	Determination of low temperature fracture minerals for examination of qualitative properties	95-87
	DET, Phase 1/C	Petrographic and lithogeochemical studies (499 - 1100 m)	Determination of rock types and geochemical properties to complement earlier studies	95-87

- *) PRE = Preliminary investigations, DET = Detailed investigations,
Phases are referring to the figure 2.2-2.
B = Baseline investigations,
C = Complementary characterization,
T = Testing of results and assumptions

- ***) Ref. = reference to the work report

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR3

APPENDIX 4
1(3)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	PRE, Phase 3	Core drilling (476 m)	Determination of rock types, fracturing and bedrock structure, determination of orientation and continuity of fracture zones, determination of extent of intact bedrock area, penetration of a diabase dyke, study on the geometry and properties of this structure	88-26
GEOPHYSICS	PRE, Phase 3	Geophysical standard borehole logging: Fluid resistivity and temp. resistivity (normal 1.6 m and Wenner 0.3, single point), susceptibility, gamma-gamma density, self potential, natural gamma	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	88-57
	PRE, Phase 3	Borehole radar, singlehole and VRP measurement	Mapping of position of fractures and fracture zones	88-46
	PRE, Phase 3	Tube-wave measurement	Localization of water bearing or hydraulically conductive fractures	88-38
	PRE, Phase 3	VSP measurement	Mapping of fracture zones and contacts between rock types	88-05
	DET, Phase 1/C	Galvanic charged potential measurements	Verification of the connection of the interpreted fracture zones in the bedrock	94-42 95-06
	DET, Phase 1/C	Geophysical borehole logging (neutron-neutron, caliper, sonic (full wave form))	Detailed mapping of fracture zones, fractures, water bearing sections and rock types	94-47e 95-15
	DET, Phase 1/C	Directional borehole radar	Mapping of position and direction of fractures and fracture zones	95-11e
	DET, Phase 1/C	Dipmeter	Localization and orientation of fractures	95-07e
	DET, Phase 1/C	Acoustic borehole televiewer test	Localization and orientation of fractures	95-09e
	DET, Phase 1/C	Borehole-TV measurements	Demonstrate the tool and processing, produce data for method comparison, interpret and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation	95-90e

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR3

APPENDIX 4
2(3)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
HYDROGEOLOGY	PRE, Phase 3	Constant head injection test	Determination of hydraulic properties of bedrock, localization of hydraulically conductive zones	89-17 89-30
	PRE, Phase 4	Installation of multipacker system	Returning of the natural hydraulic heads, prevention of groundwater flow along the hole	90-11
	PRE, Phase 4	Measuring of hydraulic heads in several different measuring sections	Monitoring of hydraulic head and its variations in bedrock, estimation of hydraulic gradient	92-02
	PRE, Phase 4	Fall off test	Determination of hydraulic conductivity of bedrock, checking of the tightness of the packers of the multipacker equipment	92-02
	DET, Phase 1/C	Slug and bail test	Controlling of multipacker equipment and determination of transmissivities in packed-off sections	94-14
	DET, Phase 1/C	Measuring of hydraulic heads in packed-off sections during water sampling	Controlling of multipacker equipment and localization of hydraulic connections between different sections in the borehole	94-52
	DET, Phase 1/C	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of hydraulic properties of them	95-35e
	DET, Phase 1/C	Flowmeter / groundwater flow measurements	Measuring of (natural) groundwater flow across the borehole (or along the fracture(s))	95-38e
	DET, Phase 1/C	Installation of multipacker system	Determination of hydraulic heads in the packed-off sections, head monitoring during pumping test in KR4	96-78
	DET, Phase 1/C	Constant head injection test	Determination of hydraulic properties of bedrock, localization of hydraulically conductive zones	95.84 96-72 96-12e
GROUNDWATER CHEMISTRY	DET, Phase 1/B	Groundwater sampling	Local hydrogeochemical characterization of groundwaters at various depths; production of in-put data for geochemical modelling and performance assessment	95-55
	DET, Phase 2	Groundwater sampling	Local hydrogeochemical characterization and geochemical modelling	98-45
OTHER MEASUREMENTS	DET, Phase 1/B	Rock stress measurements with hydraulic fracturing methods	Obtaining the horizontal stress field	96-26e

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR3

APPENDIX 4
3(3)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
LABORATORY TESTS	PRE, Phase 3	Petrographic, lithogeochemical and petrophysical studies	Determination of rock types, fracture fillings, geochemical properties, petrophysical parameters of borehole samples for evaluation of chemical conditions and interpretation of geophysical measurements	89-26
	PRE, Phase 3	Study of rock mechanical properties	Determination of rock mechanical properties of the investigation areas, comparison of laboratory and field tests	92-36
	DET, Phase 1/C	Fracture mineral mapping / study	Determination of low temperature fracture minerals for examination of qualitative properties	95-87

- *) PRE = Preliminary investigations, DET = Detailed investigations,
Phases are referring to the figure 2.2-2.
B = Baseline investigations
C = Complementary characterization
T = Testing of results and assumptions

- **) Ref. = reference to the work report

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR4

APPENDIX 5

1(3)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. (**)
DRILLING	PRE, Phase 3	Core drilling (508 m)	Determination of rock types, fracturing and bedrock structure, determination of orientation and continuity of fracture zones, determination of extent of intact bedrock area penetration of a significant fracture zone	88-49
GEOPHYSICS	PRE, Phase 3	Geophysical standard borehole logging: Fluid resistivity and temp. resistivity (normal 1.6 m and Wenner 0.3, single point), susceptibility, gamma-gamma density, self potential, natural gamma	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	88-57
	PRE, Phase 3	Tube-wave measurement	Localization of water bearing or hydraulically conductive fractures	88-38
	PRE, Phase 3	VSP measurement	Mapping of fracture zones and contacts between rock types	88-41
	PRE, Phase 3	Borehole radar, singlehole and VRP measurement	Mapping of position of fractures and fracture zones	89-18
	DET, Phase 1/C	Galvanic charged potential measurements * KR4 * KR4 <-> KR8	Verification of the connection of the interpreted fracture zones in the bedrock	94-42 95-06
	DET, Phase 1/C	Directional borehole radar	Mapping of position and direction of fractures and fracture zones	95-11e
	DET, Phase 1/C	Geophysical standard borehole logging (caliper, sonic full wave form)	Detailed mapping of fracture zones, fractures, water bearing sections and rock types	94-47e 95-15
	DET, Phase 1/C	Dipmeter	Localization and orientation of fractures	95-07e
	DET, Phase 1/C	Tomographic cross-hole radar test between KR4 and KR8	Study of fracture structures in the vicinity of the boreholes and determination of properties and orientation of the identified structures	96-52e
HYDROGEOLOGY	PRE, Phase 3	Constant head injection test	Determination of hydraulic properties of bedrock, localization of hydraulically conductive zones	89-17 89-80

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR4

APPENDIX 5
2(3)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
	PRE, Phase 4	Installation of multipacker system	Returning of the natural hydraulic heads, prevention of groundwater flow along the hole, equipment of the borehole for groundwater sampling from KR5	90-11
	PRE, Phase 4	Measuring of hydraulic heads	Monitoring of hydraulic head and its variations in bedrock, estimation of hydraulic gradient	92-02
	PRE, Phase 4	Fall off test	Determination of hydraulic conductivity of bedrock, checking of the tightness of the packers of the multipacker equipment	92-02
	DET, Phase 1/C	Slug and bail test	Controlling of multipacker equipment and determination of transmissivities in packed-off sections	94-14
	DET, Phase 1/C	Measuring of hydraulic heads in packed-off sections	Controlling of multipacker equipment and localization of hydraulic connections between different sections in the borehole	94-52
	DET, Phase 1/C	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of hydraulic properties of them	95-35e
	DET, Phase 1/C	Flowmeter / groundwater flow measurements	Measuring of (natural) groundwater flow across the borehole (or along the fracture(s))	95-38e
	DET, Phase 1/C	Constant head injection test	Determination of hydraulic properties of bedrock, localization of hydraulically conductive zones	95-85 96-72 96-12e
	DET, Phase 1/C	Pumping test	Localization of hydraulic connections between boreholes and determination of their hydraulic properties	96-06 95-52
	DET, Phase 1/C	Installation of multipacker system,	Determination of hydraulic heads in the packed-off sections, head monitoring during pumping test in KR4	96-78
	DET, Phase 2	Pumping test	Determination of hydraulic connections of fracture zones (R13, R10B and potentially R12) with other boreholes	97-20
GROUNDWATER CHEMISTRY	DET, Phase 1/B	Groundwater sampling	Local hydrogeochemical characterization of groundwaters at various depths; production of in-put data for geochemical modelling and performance assessment	95-55
	DET, Phase 2	Groundwater sampling	Sampling for sorption tests	98-45

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR4

APPENDIX 5
3(3)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
LABORATORY TESTS	PRE, Phase 3	Petrographic, lithogeochemical and petrophysical studies	Determination of rock types, fracture fillings, geochemical properties, petrophysical parameters of borehole samples for evaluation of chemical conditions and interpretation of geophysical measurements	90-13
	PRE, Phase 3	Study of rock mechanical properties	Determination of rock mechanical properties of the investigation areas, comparison of laboratory and field tests	92-36
	PRE, Phase 3	Study of thermal properties of rock	Determination of the thermal properties of the most common rock types of the investigation area	92-56
	DET, Phase 1/C	Fracture mineral mapping / study	Determination of low temperature fracture minerals for examination of qualitative properties	95-87

*) PRE = Preliminary investigations, DET = Detailed investigations,
Phases are referring to the figure 2.2-2.

B = Baseline investigations

C = Complementary characterization

T = Testing of results and assumptions

**) Ref. = reference to the work report

**SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR5**

**APPENDIX 6
1(2)**

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	PRE, Phase 3	Core drilling (502 m)	Determination of rock types, fracturing and bedrock structure, determination of orientation and continuity of fracture zones and their dimensionality, determination of extent of intact bedrock area	88-55
GEOPHYSICS	PRE, Phase 3	Geophysical standard borehole logging: Fluid resistivity and temp. resistivity (normal 1.6 m and Wenner 0.3, single point), susceptibility, gamma-gamma density, self potential, natural gamma	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	88-57
	PRE, Phase 3	Tube-wave measurement	Localization of water bearing or hydraulically conductive fractures	88-38
	PRE, Phase 3	VSP measurement	Mapping of fracture zones and contacts between rock types	88-41
	PRE, Phase 3	Borehole radar and VRP measurement	Mapping of position of fractures and fracture zones	89-18
HYDROGEOLOGY	PRE, Phase 3	Constant head injection test	Determination of hydraulic properties of bedrock, localization of hydraulically conductive zones	89-17 89-81
	PRE, Phase 4	Installation of multipacker system	Returning of the natural hydraulic heads, prevention of groundwater flow along the hole, equipment of the borehole for groundwater sampling from KR5	90-11
	PRE, Phase 4	Measuring of hydraulic heads	Monitoring of hydraulic head and its variations in bedrock, estimation of hydraulic gradient	92-02
	PRE, Phase 4	Fall off test	Determination of hydraulic conductivity of bedrock, checking of the tightness of the packers of the multipacker equipment	92-02
	DET, Phase 1/C	Slug and bail test	Controlling of multipacker equipment and determination of transmissivities in packed-off sections	94-14
	DET, Phase 1/C	Measuring of hydraulic heads in packed-off sections	Controlling of multipacker equipment and localization of hydraulic connections between different sections in the borehole	94-52

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR5

APPENDIX 6
2(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
GROUNDWATER CHEMISTRY	PRE, Phase 4	Groundwater sampling	Determination of the quality of the groundwater deep in bedrock	91-22
	DET, Phase 1/B	Groundwater sampling	Local hydrogeochemical characterization of groundwaters at various depths; production of in-put data for geochemical modelling and performance assessment	95-55
	DET, Phase 1/C	Groundwater sampling	Sampling for sorption tests	96-21
LABORATORY TESTS	PRE, Phase 3	Petrographic, lithogeochemical and petrophysical studies	Determination of rock types, fracture fillings, geochemical properties, petrophysical parameters of borehole samples for evaluation of chemical conditions and interpretation of geophysical measurements	90-13
	PRE, Phase 3	Study of rock mechanical properties	Determination of rock mechanical properties of the investigation areas, comparison of laboratory and field tests	92-36
	PRE, Phase 3	Study of thermal properties of rock	Determination of the thermal properties of the most common rock types of the investigation area	92-56
	DET, Phase 1/C	Fracture mineral mapping / study	Determination of low temperature fracture minerals for examination of qualitative properties	95-87

- *) PRE = Preliminary investigations, DET = Detailed investigations,
Phases are referring to the figure 2.2-2.
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C = Complementary characterization
T = Testing of results and assumptions

- **) Ref. = reference to the work report

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR6

APPENDIX 7
1(1)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	PRE, Phase 3	Core drilling (299 m)	Penetration of a significant crush zone bordering the site and indicated by geophysical anomalies, study on its internal structure and hydraulic conductivity	90-43
GEOPHYSICS	DET, Phase 1/C	Geophysical borehole logging (long normal resistivity)	Planning of galvanic charged potential measurements	94-41
	DET, Phase 1/C	Galvanic charged potential measurements	Verification of the connection of the interpreted fracture zones in the bedrock	94-42 95-96
LABORATORY TESTS	PRE, Phase 3	Petrographic, lithogeochemical and petrophysical studies	Determination of rock types, fracture fillings, geochemical properties, petrophysical parameters of borehole samples for evaluation of chemical conditions	91-26

*) PRE = Preliminary investigations, DET = Detailed investigations,
Phases are referring to the figure 2.2-2.

B = Baseline investigations

C = Complementary characterization

T = Testing of results and assumptions

**) Ref. = reference to the work report

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR7

APPENDIX 8
1(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. (**)
DRILLING	DET, Phase 1/C	Core drilling (301 m)	Checking of structure R18 and a potential lineament, acquiring more data about fracturing	94-10
GEOPHYSICS	DET, Phase 1/C	Geophysical standard borehole logging: Fluid resistivity and temp. resistivity (normal 1.6 m and 0.4 m, single point), susceptibility, gamma-gamma density, self potential, natural gamma	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	94-41 95-15
	DET, Phase 1/C	VSP (3D) measurement	Mapping of position and orientation of fracture zones and contacts between rock types	95-13e
	DET, Phase 1/C	Tube-wave measurement	Localization of water bearing or hydraulically conductive fractures	94-46e
	DET, Phase 1/C	Directional borehole radar	Mapping of position and direction of fractures and fracture zones	95-11e
HYDROGEOLOGY	DET, Phase 1/C	Constant head injection test	Determination of hydraulic properties of bedrock, localization of hydraulically conductive zones	95-59 96-70 95-78e
	DET, Phase 1/C	Pumping test	Localization of hydraulic connections between boreholes and determination of their hydraulic properties	95-01
	DET, Phase 1/C	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of their hydraulic properties	95-35e
	DET, Phase 1/C	Flowmeter / groundwater flow measurements	measuring of (natural) groundwater flow across the borehole (or along the fracture(s))	95-38e
	DET, Phase 1/C	Installation of multipacker system	Determination of hydraulic heads in the packed-off sections, head monitoring during pumping test in KR4	96-78
GROUNDWATER CHEMISTRY	DET, Phase 1/B	Groundwater sampling	Local hydrogeochemical characterization and geochemical modelling	94-49
LABORATORY TESTS	DET, Phase 1/C	Fracture mineral mapping / study	Determination of low temperature fracture minerals for examination of qualitative properties	95-87
	DET, Phase 1/C	Petrographic and lithogeochemical studies	Determination of rock types and geochemical properties to complement earlier studies	95-87

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR7

APPENDIX 8
2(2)

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- *) PRE = Preliminary investigations, DET = Detailed investigations,
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C = Complementary characterization
T = Testing of results and assumptions
**) Ref. = reference to the work report

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR8

APPENDIX 9
1(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET, Phase 1/C	Core drilling (301 m)	Checking the continuity of structures R10A, R10B, R12, R13 and R15 and dip direction of structure R3, obtaining additional data from the foot wall side of structure R9, provide the cross-hole investigations between boreholes KR8 and KR4	94-17
GEOPHYSICS	DET, Phase 1/C	Geophysical standard borehole logging: Fluid resistivity and temp. resistivity (normal 1.6 m and 0.4 m, single point), susceptibility, gamma-gamma density, self potential, natural gamma	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	94-41 95-15
	DET, Phase 1/C	Galvanic charged potential measurements between KR4 and KR8	Verification of the connection of the interpreted fracture zones in the bedrock	94-42 95-06
	DET, Phase 1/C	Directional borehole radar	Mapping of position and direction of fractures and fracture zones	95-11e
	DET, Phase 1/C	Geophysical standard borehole logging (sonic full wave form)	Detailed mapping of fracture zones, fractures, water bearing sections and rock types	94-47e
	DET, Phase 1/C	Borehole-TV measurements	Interprete and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation	96-58e
	DET, Phase 1/C	VSP (3D) measurement	Mapping of position and orientation of seismic reflections from fracture zones and possibly from contacts between rock types	95-72e
	DET, Phase 1/C	Tomographic cross-hole radar test between KR4 and KR8	Study of fracture structures in the vicinity of the boreholes and determination of properties and orientation of the identified structures	96-52e
HYDROGEOLOGY	DET, Phase 1/C	Constant head injection test	Determination of hydraulic properties of bedrock, localization of hydraulically conductive zones	95-60 96-71 96-12e
	DET, Phase 1/C	Pumping test	Localization of hydraulic connections between boreholes and determination of their hydraulic properties	95-01
	DET,	Flowmeter / difference	Localization of hydraulically conductive	95-35e

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR8

APPENDIX 9
2(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
	Phase 1/C	flow measurements	fractures and determination of their hydraulic properties	
	DET, Phase 1/C	Flowmeter / groundwater flow measurements	Measuring of (natural) groundwater flow across the borehole (or along the fracture(s))	95-38e
	DET, Phase 1/C	Installation of multipacker system	Determination of hydraulic heads in the packed-off sections, head monitoring during pumping test in KR4	96-78
GROUNDWATER CHEMISTRY	DET, Phase 1/B	Groundwater sampling	Local hydrogeochemical characterization and geochemical modelling	94-49 98-45
LABORATORY TESTS	DET, Phase 1/C	Fracture mineral mapping / study	Determination of low temperature fracture minerals for examination of qualitative properties	95-87
	DET, Phase 1/C	Petrographic and lithogeochemical studies	Determination of rock types and geochemical properties to complement earlier studies	95-87

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Phases are referring to the figure 2.2-2.
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T = Testing of results and assumptions

- **) Ref. = reference to the work report

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR9

APPENDIX 10
1(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET, Phase 1/C	Core drilling (300 m)	Checking of structure R23, study of discharge area in the flow model	94-18
GEOPHYSICS	DET, Phase 1/C	Geophysical standard borehole logging: Fluid resistivity and temp. resistivity (normal 1.6 m and 0.4 m, single point), susceptibility, gamma-gamma density, self potential, natural gamma	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	94-41 95-15
	DET, Phase 1/C	Directional borehole radar	Mapping of position and direction of fractures and fracture zones	95-11e
	DET, Phase 1/C	Geophysical borehole logging, (sonic full wave form)	Detailed mapping of fracture zones, fractures, water bearing sections and rock types	94-47e
	DET, Phase 1/C	VSP (3D) measurement	Mapping of position and orientation of seismic reflections from fracture zones and possibly from contacts between rock types	95-72e
	DET, Phase 1/C	Constant head injection test	Determination of hydraulic properties of bedrock, localization of hydraulically conductive zones	95-83 96-71 96-12e
HYDROGEOLOGY	DET, Phase 1/C	Pumping test	Localization of hydraulic connections between boreholes and determination of hydraulic properties of them	95-01
	DET, Phase 1/C	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of their hydraulic properties	95-35e
	DET, Phase 1/C	Flowmeter / groundwater flow measurements	Measuring of (natural) groundwater flow across the borehole (or along the fracture(s))	95-38e
	DET, Phase 1/C	Installation of multipacker system	Determination of hydraulic heads in the packed-off sections, head monitoring during pumping test in KR4	96-78
	DET, Phase 1/C	Groundwater sampling	Local hydrogeochemical characterization and geochemical modelling	94-49
GROUNDWATER CHEMISTRY	DET, Phase 1/C	Groundwater sampling	Local hydrogeochemical characterization and geochemical modelling	***)
LABORATORY TESTS	DET, Phase 1/C	Fracture mineral mapping / study	Determination of low temperature fracture minerals for examination of qualitative properties	95-87

SITE INVESTIGATIONS AT ROMUVAARA
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APPENDIX 10
2(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
	DET, Phase 1/C	Petrographic and lithogeochemical studies	Determination of rock types and geochemical properties to complement earlier studies	95-87

*) PRE = Preliminary investigations, DET = Detailed investigations,
Phases are referring to the figure 2.2-2.

B = Baseline investigations

C = Complementary characterization

T = Testing of results and assumptions

**) Ref. = reference to the work report

**) Will be reported later

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR10

APPENDIX 11
1(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET, Phase 1/T	Core drilling (618 m)	Checking previous assumptions in the central area of the site covered with borehole investigations, stress measurements with overcoring method, potential place for a shaft	95-73
GEOPHYSICS	DET, Phase 1/T	Geophysical standard borehole logging: Fluid resistivity and temp. resistivity (normal 1.6 m and Wenner 0.3 m), single point resistivity, susceptibility, natural gamma, gamma-gamma density, sonic full wave form, 3-arm caliper	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	96-16 97-18
	DET, Phase 1/T	Dual neutron logging	Provide data for analysis of rock types and porosity in the rock close to borehole	96-33e
	DET, Phase 1/T	Directional borehole radar	Mapping of position and direction of fractures and fracture zones	96-52e
	DET, Phase 1/T	Dipmeter	Localization, orientation and statistical analysis of fractures and fracture zones in the borehole.	96-37e
	DET, Phase 1/T	Borehole-TV measurements	Produce data for method comparison, interpret and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation	96-58e
	DET, Phase 1/T	VSP (3D) measurement	Mapping of position and orientation of seismic reflections from fracture zones and possibly from contacts between rock types	96-56e
HYDROGEOLOGY	DET, Phase 1/T	Flowmeter / difference flow and cross flow measurements	Localization of hydraulically conductive fractures and determination of their hydraulic properties, determination of natural gw-flow along fractures	96-18e
	DET, Phase 1/T	Installation of multipacker system	Determination of hydraulic heads in the packed-off sections, head monitoring during pumping test in KR4	96-78
	DET, Phase 2	Constant head injection test	Determination of hydraulic properties of bedrock	98-20
GROUNDWATER CHEMISTRY	DET, Phase 2	Groundwater sampling	Local hydrogeochemical characterization and geochemical modelling	98-45

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BOREHOLE KR10

APPENDIX 11
2(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. (**)
OTHER MEASUREMENTS	DET, Phase 1/B	Rock stress measurements	Obtaining the magnitudes and the directions of the 3-D principal stress field	96-26e
	DET, Phase 1/B	Rock stress measurements with hydraulic fracturing method	Obtaining the horizontal stress field	96-26e
LABORATORY TESTS	DET, Phase 1/C	Petrographic and lithogeochemical studies	Determination of rock types and geochemical properties to complement earlier studies	96-30
	DET, Phase 1/C	Fracture mineral mapping/study	Determination of low temperature fracture minerals for examination of qualitative properties	96-30
	DET, Phase 2	Study of rock mechanical properties	Determination of rock mechanical properties of tonalite gneiss	98-06e

*) PRE = Preliminary investigations, DET = Detailed investigations,
Phases are referring to the figure 2.2-2.

B = Baseline investigations

C = Complementary characterization

T = Testing of results and assumptions

**) Ref. = reference to the work report

SITE INVESTIGATIONS AT ROMUVAARA
BOREHOLE KR11

APPENDIX 12
1(1)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET, Phase 1/T	Core drilling (603 m)	Checking previous assumptions in the area without any borehole investigations, characterization of potential repository extension area	96-25
GEOPHYSICS	DET, Phase 1/T	Geophysical standard borehole logging: Fluid resistivity and temp. resistivity (normal 1.6 m and 0.4 m), single point resistivity, susceptibility, natural gamma, gamma-gamma density, sonic full wave form, 3-arm caliper	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	96-39 97-18
	DET, Phase 1/T	VSP (3D) measurement	Mapping of position and orientation of seismic reflections from fracture zones and possibly from contacts between rock types	96-56e
HYDROGEOLOGY	DET, Phase 1/T	Flowmeter / difference flow and cross flow measurements	Localization of hydraulically conductive fractures and determination of their hydraulic properties, determination of natural gw-flow along fractures	96-68e
	DET, Phase 2	Constant head injection test	Determination of hydraulic properties of bedrock	98-11
GROUNDWATER CHEMISTRY	DET, Phase 2	Groundwater sampling	Local hydrogeochemical characterization and geochemical modelling	***)
LABORATORY TESTS	DET, Phase 2	Petrographic and lithogeochemical studies	Determination of rock types and geochemical properties to complement earlier studies	97-19

*) PRE = Preliminary investigations, DET = Detailed investigations,
Phases are referring to the figure 2.2-2.

B = Baseline investigations

C = Complementary characterization

T = Testing of results and assumptions

**) Ref. = reference to the work report

***) Will be reported later

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