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Summary report of the experiences from TVO´s site investigations

Antti Öhberg[1], Pauli Saksa[2], Henry Ahokas[2],
Paula Ruotsalainen[2], Margit Snellman[3]

1 Saanio & Reikkola Consulting Engineers,
Helsinki, Finland
2 Fintact Ky, Helsinki, Finland
3 Imatran Voima Oy, Helsinki, Finland

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SVENSK KÄRNBRÄNSLEHANTERING AB
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO

BOX 5864 S-102 40 STOCKHOLM
TEL. 08-665 28 00 TELEX 13108 SKB
TELEFAX 08-661 57 19

SUMMARY REPORT OF THE EXPERIENCES FROM TVO'S SITE INVESTIGATIONS

Antti Öhberg[1], *Pauli Saksa*[2], *Henry Ahokas*[2],
Paula Ruotsalainen[2], *Margit Snellman*[3]

1 **Saanio & Riekkola Consulting Engineers, Helsinki, Finland**
2 **Fintact Ky, Helsinki, Finland**
3 **Imatran Voima Oy, Helsinki, Finland**

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Antti Öhberg
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Pauli Saksa, Henry Ahokas,
Paula Ruotsalainen
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Margit Snellman
Imatran Voima Oy, Helsinki, Finland

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ABSTRACT

Teollisuuden Voima Oy (TVO) has completed preliminary site investigations at five sites in Finland. At the end of 1992 TVO presented the final report to the authorities. The preliminary site investigation phase 1986 - 1992 was conducted according to the investigation programme compiled by TVO.

The aim of this report was to compile a report on experiences from TVO´s site investigations. The main interest was focused on investigation strategies and the most important investigation methods for the conceptual modelling.

The objective of the preliminary site investigations was to obtain data on the bedrock properties in order to evaluate the areas. The programme was divided into four stages, each stage having its own subobjective. The site-specific investigation programme for each site included a large common part and a small site-specific part.

The strategies (objectives) and experiences from different disciplines, geology, hydrogeochemistry, geophysics and geohydrology, are presented in the report.

The conceptual modelling work procedure including both bedrock and groundwater modelling is described briefly using the Olkiluoto site as an example. Each of the other areas has undergone similar phases of work. The uncertainties associated with conceptual modelling are also discussed.

The usefulness of the investigation strategy and the investigation methods for conceptual modelling is discussed in the report.

Some new equipment, methods or enhancements that have not yet been used in TVO´s site investigations have become new tools in site characterisation and are briefly presented in the report.

ABSTRACT (SWEDISH)

Teollisuuden Voima Oy (TVO) har slutfört preliminära platsundersökningar på fem orter i Finland. I slutet av året 1992 presenterade TVO slutrapportet för myndigheterna. Den preliminära platsundersökningsperioden 1986 - 1992 utfördes enligt ett undersökningsprogram, som har utarbetats av TVO.

Syftet på denna rapport var att utarbeta en rapport om erfarenheter i TVO´s platsundersökningar. Huvudintresset riktade sig på undersökningsstrategier och på de väsentligaste undersökningsmetoderna för konceptualisk modellering.

Ändamålet för de preliminära platsundersökningarna var att få information om berggrundets egenskaper och därigenom få en uppfattning om området. Programmet delades i fyra skeden. Varje skede hade sitt eget ändamål. Det plats specifika undersökningprogrammet för varje plats, innehöll en omfattande allmän del och en mindre plats specifik del.

Strategier (ändamål) och erfarenheter från olika vetenskaper; geologi, hydrogeokemi, geofysik och geohydrologi har presenterats i denna rapport.

Den konceptualiska modellerings arbetsproceduren består både av berggrundets och grundvattnets modelleringar. Detta har beskrivits kort med hjälp av Olkiluoto som ett exempel. På varje plats har liknande arbetsskeden utförts. Osäkerheten beträffande konceptualisk modellering har också diskuterats.

Undersökningsstrategins och undersökningsmetodernas användbarhet för konceptualisk modellering har diskuterats i denna rapport.

I rapporten har kortfattat beskrivits några nya utrustningar, metoder och tillägg, som inte tidigare använts i TVO´s platsundersökningar och som har blivit nya verktyg innom platskarakteriseringen.

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SUMMARY

Teollisuuden Voima Oy (TVO) has successfully completed preliminary site investigation phase 1986 - 1992 during which five sites were characterised in Finland. At the end of 1992 TVO presented the final report to the authorities and selected three areas to the detailed site investigations.

The aim of this report was to compile a report on experiences from TVO´s site investigations. The main interest was focused on investigation strategies and the most important investigation methods for the conceptual modelling.

The objective of the preliminary site investigations was to obtain data on the bedrock properties in order to evaluate the areas. The investigation programme was divided into four stages, each stage having its own subobjective. The site-specific investigation programme for each site included a large common part and a small site-specific part.

The strategies (objectives) and experiences from different disciplines, geology, hydrogeochemistry, geophysics and geohydrology, are presented in the report.

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1 INTRODUCTION

1.1 GENERAL BACKGROUND

There are four nuclear power units in operation in Finland. At Olkiluoto, Eurajoki, Teollisuuden Voima Oy (TVO) owns two units (2 x 710 MW). Imatran Voima Oy (IVO) owns two (2 x 440 MW) units at Hästholmen, Loviisa. IVO returns the spent fuel of the Loviisa plant to Russia after approximately five years´ storage. The agreement between IVO and Techsnabexport (TSE) covers all the fuel delivered by TSE. Consequently, only TVO´s nuclear waste management programme will be discussed in this report.

The VLJ-Repository for low and intermediate level waste was put into operation in 1992 at Olkiluoto. The repository facilities lie at a depth of 70 - 100 metres in the bedrock. The total volume of the excavation work for the repository was 90,000 m^3. Investigations of the soil and bedrock of the Ulkopää cape at Olkiluoto were started in 1980. The investigations were aimed at finding bedrock suitable for the construction of the repository near the power plant. During construction, the site proved to conform to the preliminary investigation results. A discussion of experiences related to low and intermediate level waste management lies outside the main scope of this report and the presentation will therefore be very brief.

1.2 RESPONSIBILITIES AND REGULATORY FRAMEWORK

The Nuclear Energy Act, which came into force in 1988, defines the most important principles of nuclear waste management, such as responsibilities, licensing of the facilities and funding to meet future costs. Already in 1983, The Government defined objectives and time schedules for the implementation of waste management as well as for R&D work. In Fig. 1-1 the time schedule for TVO´s nuclear waste management is presented.

The utility, TVO, produces wastes and is therefore responsible for the safe management of the radioactive wastes generated by its power plant at Olkiluoto. According to present estimates, a total of 1840 t of spent fuel will accumulate during the projected 40 years´ lifetime of TVO´s units.

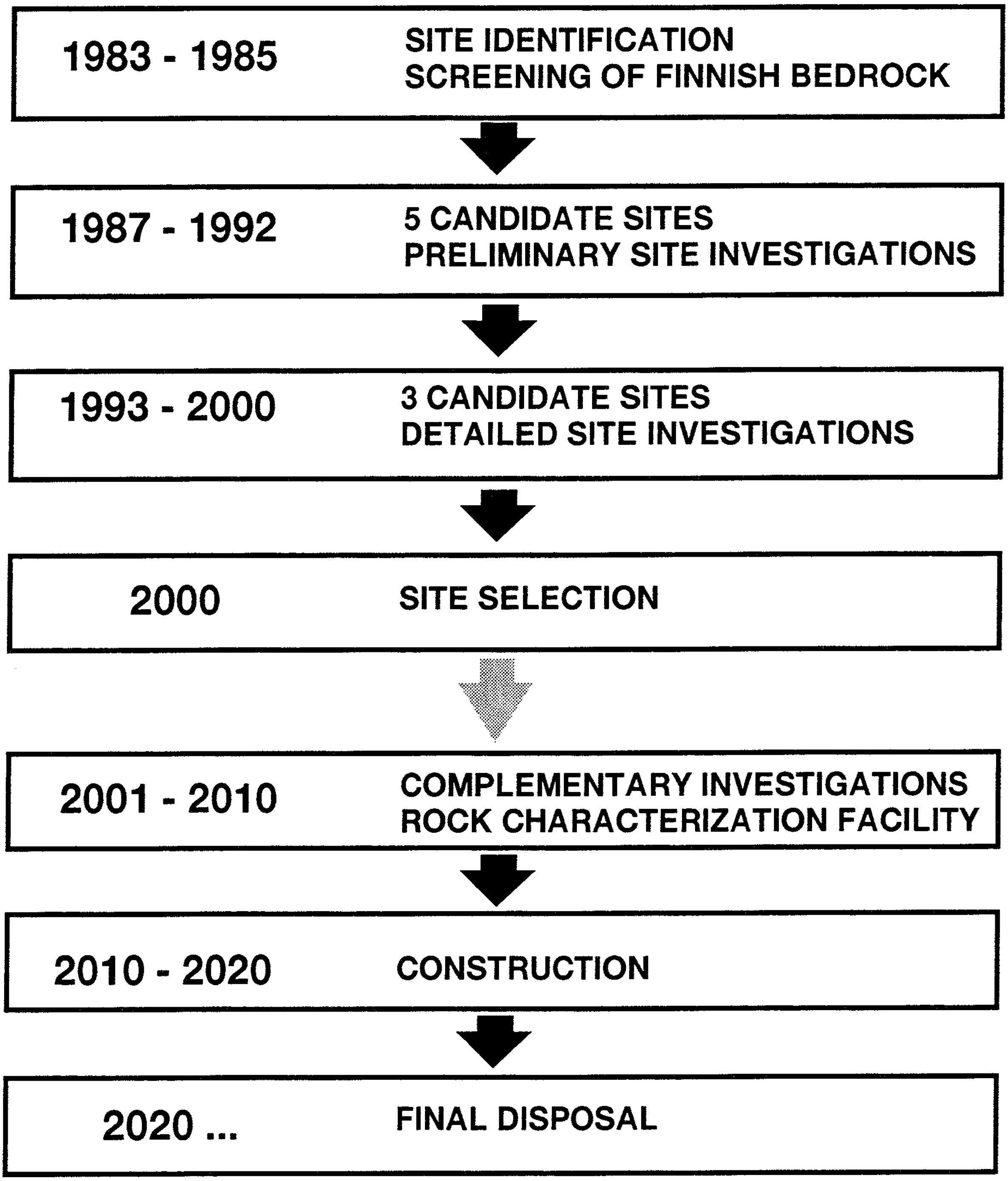


Figure 1-1. Time schedule for the spent fuel management of the Olkiluoto power plant.

Waste management cooperation between TVO and IVO is coordinated by their joint Nuclear Waste Commission (YJT).

The authorities regulate and supervise the progress of the programmes. The Ministry of Trade and Industry is responsible for licensing nuclear waste facilities and the Finnish Centre for Radiation and Nuclear Safety (STUK) for supervising safety. The organisation for nuclear waste management in Finland is shown in Fig. 1-2.

The authorities also define the necessary safety criteria for waste management. In 1991 the Finnish Government accepted the safety criteria for final disposal of low- and medium-level operating waste. The Nordic authorities have prepared joint recommendations for criteria covering high-level disposal. Furthermore, the authorities finance, to some extent, R&D work independent of the programme of the utilities /Ryhänen V et al, 1993/.

1.3 SITE SELECTION PROGRAMME

The site selection programme was started in 1983 and will last up to the year 2010. The selection and confirmation of the site comprises the following steps.

- 1983-1985: The recognition and selection of possible candidate areas for field investigations. Selection of several areas for preliminary site investigations.
- 1986-1992: Preliminary site investigations in several areas. Selection of the most suitable areas for detailed site investigations.
- 1993-2000: Detailed site investigations at a few sites. Selection of the site for final disposal by the end of 2000.
- 2001-2010: Complementary site investigations at the selected site. Construction of a pilot shaft. Construction of the repository is planned to start in 2010.

Before the start in 1983 fairly generic studies of the properties of the Finnish bedrock were carried out. The studies aimed at the development of a site selection approach and evaluation of the suitability of the bedrock for final disposal in general. In 1983 the geological studies advanced from generic studies to regional investigations and covered the whole of Finland and all rock types. The main idea was to localise large bedrock blocks, and by studying their properties to identify possible areas for field investigations. In addition to geological studies, environmental factors which would have an effect on the practical implementation of the final disposal and the field investigations were taken into consideration. The process of the selection has been presented in Fig. 1-3.

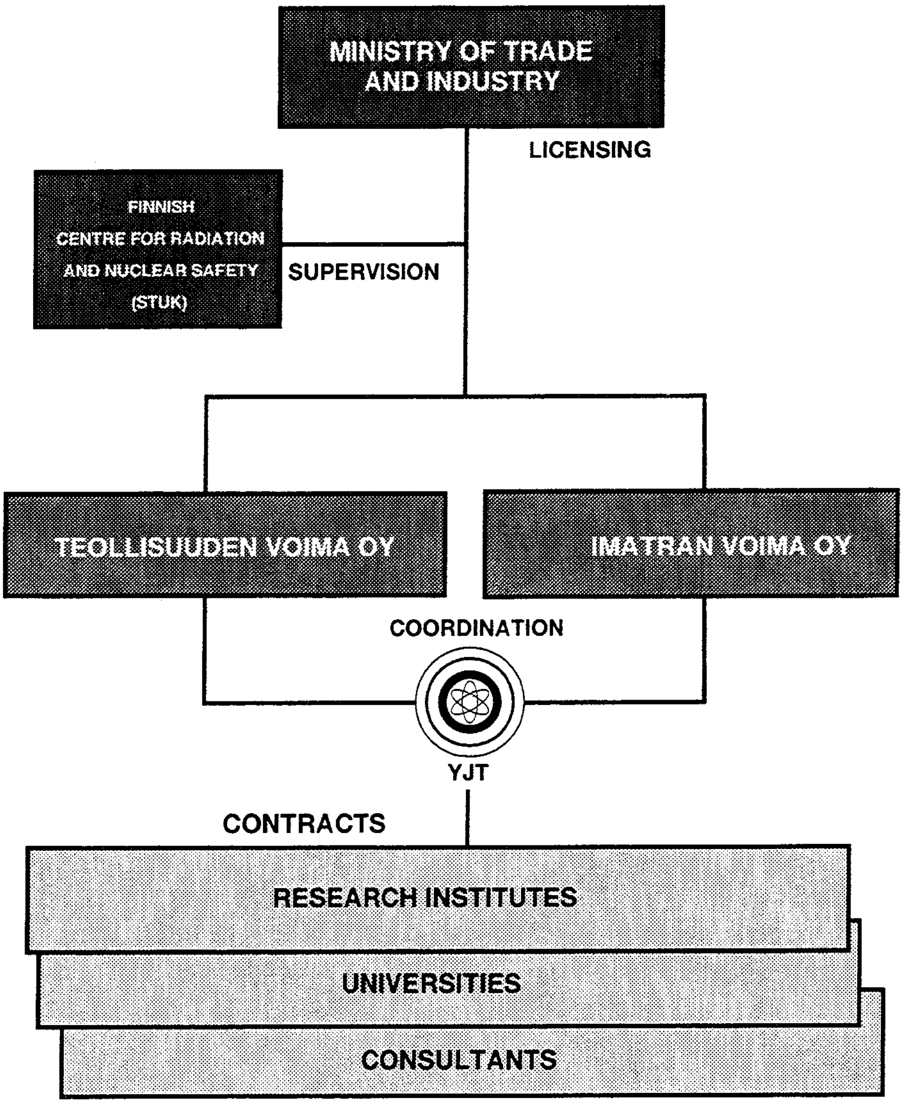


Figure 1-2. Nuclear Waste Management in Finland.

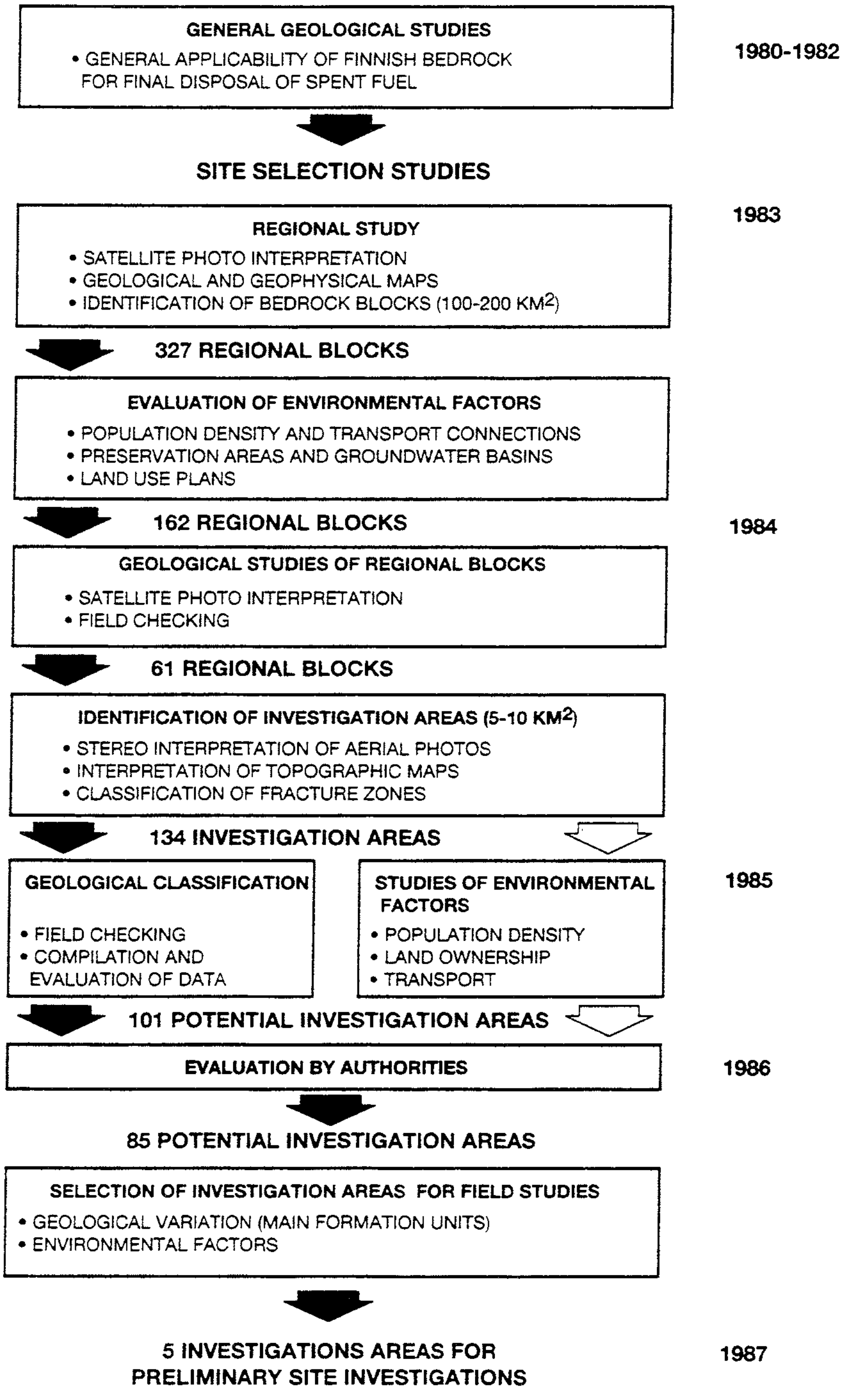


Figure 1-3. The process for the selection of investigation areas.

1.4 SITE SELECTION PHASE 1983 - 1985

The main goal of this phase was to identify areas that would be suitable for fieldwork and in which the bedrock provided sufficiently good conditions for safe disposal of spent fuel. As an outcome of the studies in this phase, 101 candidate areas were found to have potential for field investigations. In addition, a separate geological study /Hakkarainen, 1985; Kuivamäki and Vuorela, 1985/ was made of the Olkiluoto area, which has a special position in the programme due to its short transport distance from the power plants, for example.

The identification and selection was based on geological and environmental factors applied from the international guidelines existing at that time. The selection factors were:

- Topography
  Surficial landforms contributing to hydraulic gradients capable of giving rise to groundwater flow

- Stability
  General stability of the bedrock, which will ensure that the waste canisters remain in position deep in the bedrock. Any appreciable bedrock movements can be assumed to be concentrated primarily in the existing crush zones.

- Crush zones and fracturing
  Crush zones and fracturing are significant for the hydraulic conductivity of the bedrock unit and consequently for the magnitude of the groundwater flow and the routes followed by this flow. By means of investigations, crush zones are identified in order to avoid them when considering placement of the repository in the bedrock unit.

- Incidence of outcrops
  Incidence of outcrops affects the ease of investigation.

- Natural resources
  Natural resources could attract attention to the area in the future. Certain rocks occurring in Finland are more ore-critical than others and are thus potential objects of mineralogical research or mining activity. Comparable natural resources are groundwater reserves, which could be used in the future as water supplies for human communities.

- The size of the block
  Large-scale bedrock blocks (> 100 km^2) bounded by major crush zones were the target areas.

Preference was given to areas with the following attributes:

- The formation at the site should be sufficiently large so that the repository can be built at an adequate depth, i.e., a depth that will eliminate the effects of human interference and natural erosion factors. The area should be composed of ordinary, commonly encountered rock types which are highly unlikely to be considered for exploitation at any time in the future.
- The bedrock of the site should be free of structures belonging to tectonic systems in which appreciable movements could occur in the future, and the fractures and fracture zones commonly found in the bedrock should occur only rarely, so that the repository can be constructed by conventional methods and will be safe to work on.
- The surface topology of the site should be relatively gentle or smooth, thus minimising the hydraulic gradient and the turnover of groundwater in the bedrock. The bedrock should also be of a kind which will retard the movement of dissolved substances.
- The bedrock should be easy to study and its properties should be describable in a simple manner and predictable. This will be achieved most easily if the bedrock is homogeneous and observations can be made from outcrops.

The material concerning the site selection phase was submitted to the authorities in 1986 and 16 sites were removed from the list during the regulatory review. These areas comprised some planned protected areas.

1.5 PRELIMINARY SITE INVESTIGATION PHASE 1986 - 1992

During 1986 the regulating body did their review on the site selection material submitted by TVO. The review accepted TVO's approach and results presented. The recommendation for the further selection of areas was that these should represent geologically different sites.

TVO took notice of this recommendation, and selected in five out of 85 potential sites. The selected areas represented different granitic rock types, which were the major rock type within the areas. The preliminary site investigation phase was conducted according to the investigation programme compiled by TVO. At the end of 1992 TVO presented the final report /TVO, 1992/ to the authorities.

2 OVERVIEW OF THE TVO SITE INVESTIGATION PROGRAMME

2.1 SITE INVESTIGATION PROGRAMME

The site investigation programme was compiled in 1985. It gives the general objectives for the site investigations. The investigation methods, general studies to back up site-specific investigations and the R&D programme (development of field equipment, data management, hydrogeochemistry, tectonics etc.) are discussed in the programme report /Äikäs T, 1985/.

The screening of Finland and identification of bedrock blocks was based on remote sensing methods and terrain reconnaissance studies. The approach selected was based strongly on the conceptual assumption of mosaic structure in the Fennoscandian Shield. Since the work during 1983 - 1985 consisted of interpretation of existing data, the objective of the preliminary site investigations was to obtain data on the bedrock properties in order to evaluate the areas regarding their suitability to final disposal and further characterisation. The evaluation and comparison of the areas and their suitability were to be performed with the aid of different models.

In the programme of the active field investigation phase lasting about three years altogether, is divided into four stages (Fig. 2-1), each stage having its own subobjective. Dividing the investigation into several stages made it possible to evaluate the investigation results before the beginning of the next stage. A stepwise approach at each site also enabled an optimisation of investigation resources. Each stage complements the preceding stage, providing a good understanding of the credibility of the investigation results. Model calculations can already be performed in the course of the investigation phase. The suitability of the area for site characterisation in general can also be evaluated during the investigations and they can even be called off if this is found necessary.

The subobjectives and the contents for each stage were:

Stage 1: The aim of the general study and preliminary surface investigations was to produce data for the decision on a deep drilling. All existing geological and geophysical data was collected. After this study the first field work (geological mapping, ground geophysical survey) would be planned and implemented.

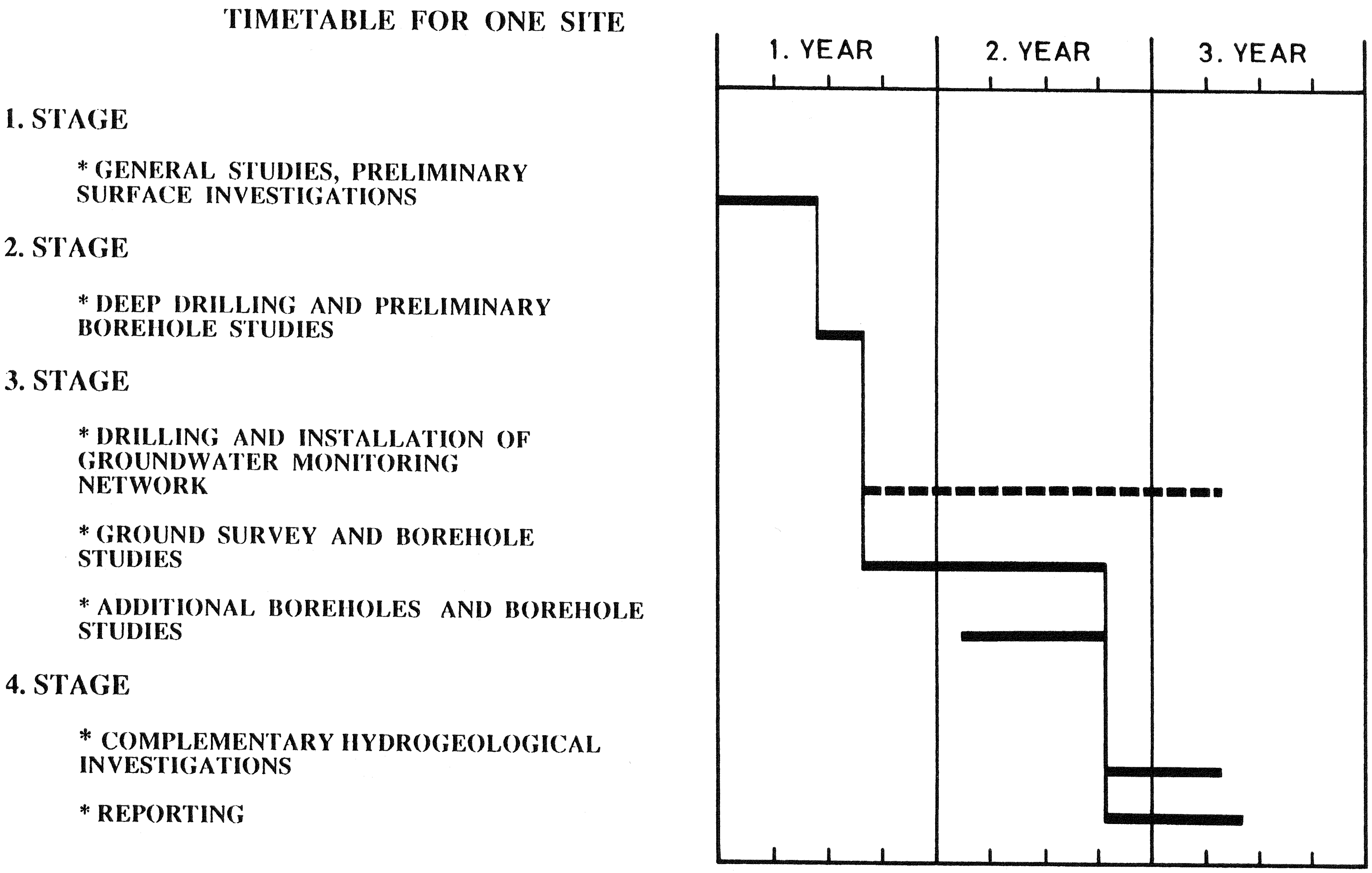


Figure 2-1. Timetable for one investigation area.

The aim of geological mapping was to obtain preliminary information on the rock types and crush zones. Geophysical survey was used to locate structural and lithological discontinuities as well as to locate possible ore mineralisations within the area.

The intact domain, which could be a possible site for a repository, was then determined by obtaining the relevant information. The location of the first deep (1000 m) borehole was determined with the guidance of the investigation results.

Stage 2: The purpose of deep drilling was to investigate the bedrock conditions at various depths, especially at the depth of final disposal. When deciding the depth, direction and inclination of the borehole, the goal was to obtain representative information on lithology, fracturing and tectonics. One borehole was drilled at this stage to a depth of 1000 metres.

If the prevailing conditions deep down were as expected on the basis of earlier conceptual assumption and observations, complementary investigations were launched.

Stage 3: The aim at this stage was to develop conceptual models and to determine input parameters for the groundwater modelling and safety assessment. Another goal was to develop the basis for the evaluation of different areas before undertaking detailed site investigations.

The main objective of the characterisations was to recognise and understand the regional bedrock properties that affect long-term safety in order to determine the location of the repository. The most essential factors investigated are the location and geometry of the hydrologically significant bedrock units, the hydraulic gradient, fracture system, fracture properties and the chemical properties of the groundwater.

The objective of fracture mapping was to achieve a statistically adequate description of the fracture frequency, orientation and lengths.

A geophysical ground survey was used to obtain information on the rock type distribution in the upper part of the bedrock and the occurrence of fracture zones in areas with overburden. Methods were chosen to complement the investigations carried out during the previous stage. Methods of studying a larger bedrock volume around the borehole were used in this stage.

The groundwater chemistry was perturbed by drilling of the boreholes and the investigations were carried out in the boreholes. Groundwater samples were taken after the other borehole investigations were completed, and again, after hydraulic head monitoring the following year. The objective was to gain an understanding of the extent to which flushing water affects the groundwater and to characterise the chemical composition of the groundwater at different depths. Later, when the disturbing effect of drilling has faded away, and an "equilibrium" has been established again, the chemical properties of groundwater are analysed. Groundwater samples taken from the boreholes are used in assessing the performance of different barriers (copper, bentonite), for example.

A deep borehole perturbs the hydraulic equilibrium prevailing in the bedrock by connecting borehole sections owing different hydraulic heads. The occurrence of these sections depends on the topographic and hydraulic properties of the bedrock. The flow along the borehole will change and balance the differences in the surrounding rock mass.

Hydraulic head monitoring in the deep borehole had two objectives:

- to prevent the groundwater flow along the borehole, which enables the restoration of the groundwater conditions close to a state that prevailed before drilling.
- to determine the vertical hydraulic gradient, which represents a potential field. The results can be used to verify the flow models.

After the hydraulic head monitoring and groundwater sampling, hydraulic measurements with fall-off method in packed-off sections were carried out in order to control the proper function of the multipacker system. Another objective of the fall-off tests was to determine hydraulic parameters deemed as important for later investigations as accurately as possible.

The objective of rock stress measurement was to obtain an understanding of the stress field in general, and for the design of a preliminary layout of the repository. The measurement was planned to be performed in a couple of boreholes.

A network for groundwater monitoring was built, comprising seven or eight multilevel piezometers (the boreholes were drilled with down-the-hole percussion drilling to a depth of 100 m), about 20 shallow (the boreholes were core drilled through the overburden into the bedrock to a rock depth of 10 metres) stand pipes for measuring the groundwater table, precipitation measurement and runoff measuring points. The results were used in adding the general understanding on the relationship between precipitation and infiltration and in the hydrogeological modelling.

The results from groundwater table observations and hydraulic head measurements in the boreholes were used to determine the horizontal hydraulic gradient in different parts of the investigation area. The infiltration rate into the bedrock together with the hydraulic gradient are crucial factors affecting the groundwater flow.

The bedrock units with significant hydraulic conductivity are normally associated with fracture zones. Ground surface measurements were used to locate fracture zones at the site. The purpose of additional core drillings was to verify the existence of fracture zones, their dimensions, hydraulic parameters and geological properties as well as to check how far the intact domain is extended.

When deciding on the depth, the place and the orientation of the additional boreholes, the results of the geological mapping and ground surveys were used. The geometry between the boreholes (four additional boreholes were drilled to a depth of about 500 m) should also provide probable cross-hole investigations in the future and the correlation of the rock mass properties met in the boreholes. The interpretation of cross-hole measurements are dependent on the geometry.

Stage 4: The objective was to verify the groundwater modelling by means of complementary hydraulic investigations. The groundwater potential field, groundwater flow velocity and flow rate are determined by means of modelling. On the basis of the results of the calculations, it is possible to determine the corresponding infiltration rate.

The hydraulic head distribution of the investigation area was determined by simultaneous hydraulic head measurements in several boreholes. The monitoring was started when there was no recharge in the area (early winter) and it was finished when the infiltration caused by melting snow started. The pumping test was carried out during the first part of the hydraulic head monitoring period. The pumping test was used to determine the hydraulic parameters in a larger rock volume. The hydraulic connections between the boreholes were estimated during the simultaneous hydraulic head monitoring and pumping test.

The timetable (Fig. 2-2) for the preliminary site investigations was originally drawn up for 5-10 areas, which was considered fully sufficient compared with the term "several areas" specified by the Council of State in its decision in principle /Council of State, 1983/.

A table of investigation methods, their objectives and the measures to be carried out is presented in the appendix to the programme /Äikäs T, 1985/.

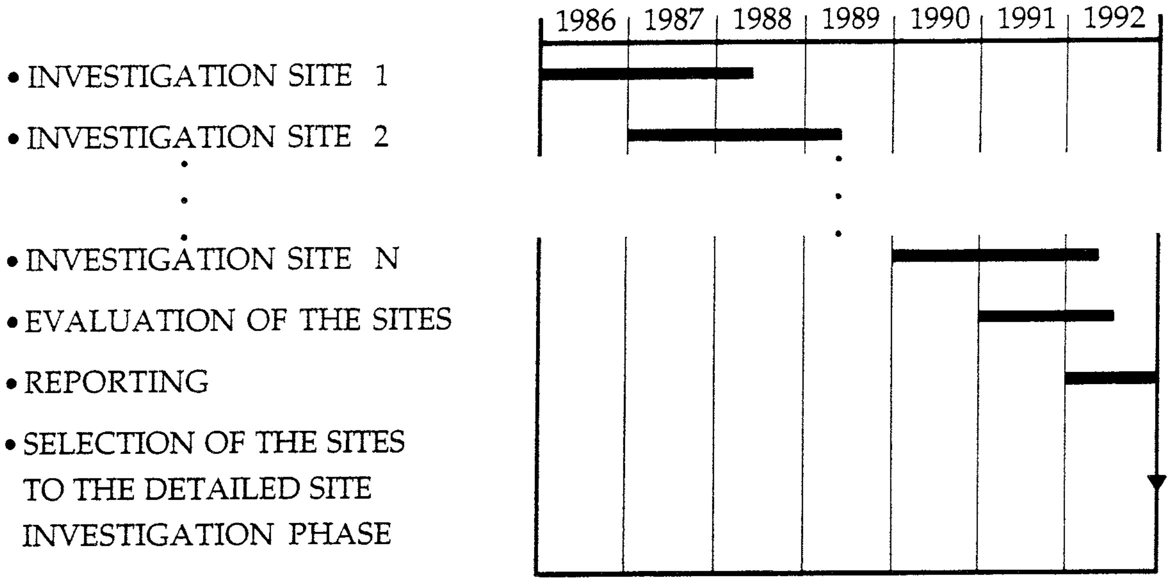


Figure 2-2. General timetable for the preliminary site investigations /Äikäs T, 1985/.

2.2 SITE-SPECIFIC CHARACTERISATION PROGRAMME

Since the screening process during 1983 - 1985 had eliminated the main differences already at the beginning, and produced at the end a shortlist of rather similar areas, the recommendation of authorities was not easy to fulfil. Although the five areas selected for field investigation in April 1987 represent different main rock types in Finland they were rather similar in their properties.

The information on these areas was gained from the ground surface, and only little or indirect information on the bedrock properties was available with increasing depth. Therefore the main goal of the preliminary site investigations was to characterise the areas and to find out if the conditions deep down were those anticipated. One of the main issues was to verify that no unexpected major feature will be encountered among the properties, which would jeopardise the safety of the final repository. Unexpected features might include very wide subhorizontal fracture zones, ore bodies, dramatic changes in the groundwater chemistry or rock types deeper down.

The main framework of the investigations is presented above in Chapter 2.1. To make it possible to evaluate the five areas (Kuhmo Romuvaara, Hyrynsalmi Veitsivaara, Konginkangas Kivetty, Sievi Syyry and Eurajoki Olkiluoto), a similar site-specific investigation programme was compiled for all the areas /Äikäs T, 1987a, 1987b, 1988a, 1988b, 1989/ before the preliminary site investigations were carried out.

The site-specific investigation programme includes a description of the investigation activities and timetable. Also, instructions on the data management, documentation and reporting are included in the programme. The generic studies and equipment development which proceed parallel with the site investigations are not discussed in the programme.

The site-specific investigation programme has the same structure as the site investigation programme, presenting the investigation methods and the rationale for each of the four stages more precisely.

Site characterisation programme has often been characterised as a programme that is standard and the same for all sites. It is standard in that the total amount and areal extent of the investigations is about the same at each site. The dominant factor is the number and length of the boreholes, with the associated borehole studies. The bulk of the programme for each site is common for all the sites but there is a minor site-specific part in each programme.

Site-specific studies were typically geophysical surveys which originated, for example, from the lithological or groundwater chemical differences that were found. Gravimetric surveys, for example, were conducted at Romuvaara to map weakly magnetised metadiabase dykes and at Syyry to map a heterogeneous mica gneiss formation boundary which dips towards the SW, and is situated below the target tonalite body. Another example is the geophysical electromagnetic sounding (AMT-method at Syyry and wide-band controlled source frequency soundings at Olkiluoto) used to delineate the location and extent of observed saline groundwater occurrences.

Seismic refraction soundings were made at four sites along three of the four lines located over anomalies detected in earlier investigations and considered to be possible indications of bedrock fracturing.

Differences in the geographical circumstances are a reason for site-specific studies, too. At the Olkiluoto site, two unique surveys were conducted: image processing for sea bottom and land area topography and Horizontal Seismic Profiling (HSP), i.e., Shallow Water Seismics. The basic reason for them was the almost totally lacking geoscientific information from the sea area. Both of the surveys were successful in providing additional data from the sea area which was further used in the conceptual modelling.

A standard programme is an aid to preserve comparability between the results and the rock models that are created for each site. In the chapter on the Olkiluoto conceptual modelling, the phenomenon of "model details vs. investigation density" is discussed.

An example of investigation sequence from the Olkiluoto site is presented in Fig. 2-3.

2.3 ANNUAL PROGRAMME

Power companies, that means TVO and IVO, have to submit annually their research programme for the entire nuclear waste management including the site investigations for the regulatory review. The programme has been commissioned by the Ministry of Trade and Industry.

Besides the site investigations, these programmes also cover equipment development and generic studies which are closely related to the site investigations.

The programmes follow the site-specific programmes closely. However, there has been a change in the programme that was introduced via the annual programme. Three-dimensional groundwater modelling was originally outside the scope of the project for preliminary site investigations since it belonged to another project but in the course of the investigations it was included in the site investigation programme.

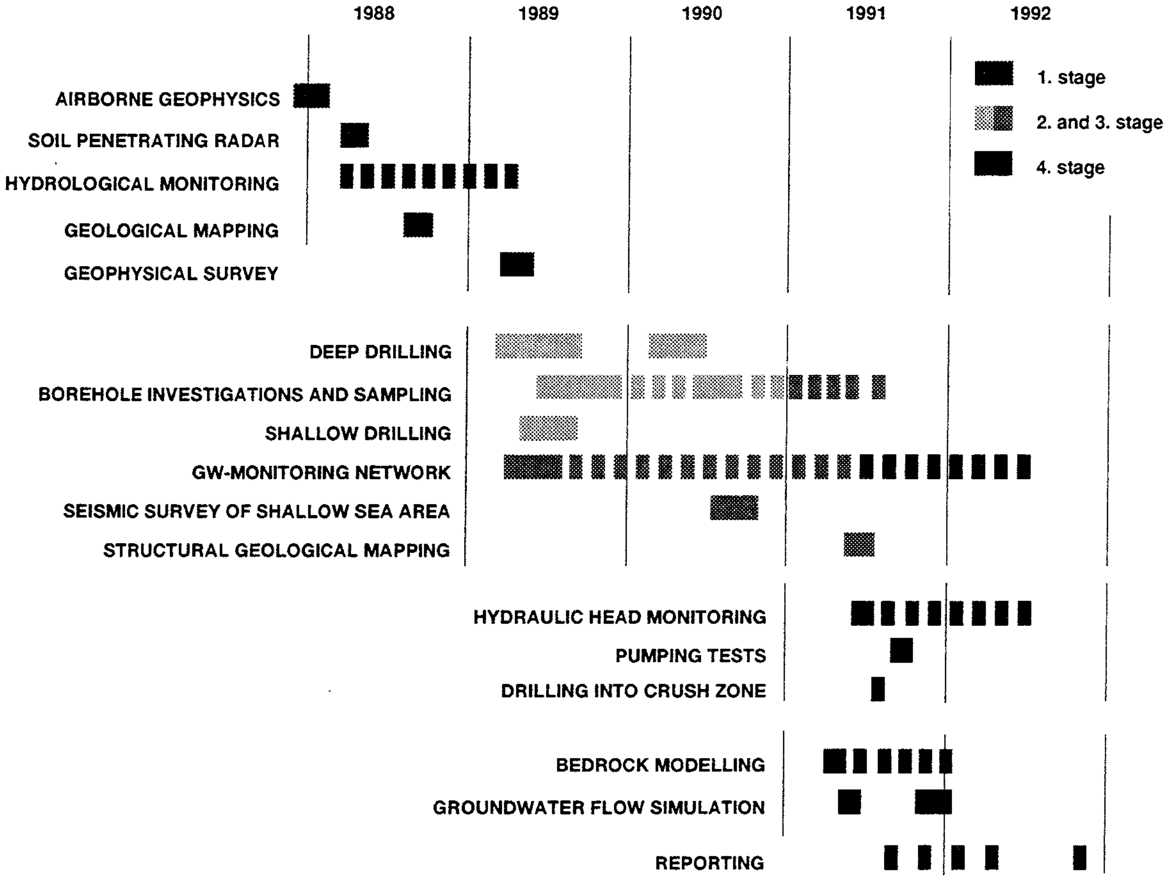


Figure 2-3. The investigation sequence that was carried out at the Olkiluoto site.

3 EXPERIENCES FROM DIFFERENT DISCIPLINES

3.1 GEOLOGY

The investigations were started with a general geological survey including a review of all the existing data available on the site.

The next task was to map the rock types and fracturing at the bedrock outcrops in the area as well as to determine the tectonic indices like schistosity, fold axis, linearity and fault planes. All features longer than a metre on the outcrops were also mapped (in terms of length, width, strike, dip and continuity), and fracture density was measured on the transects crossing the outcrops in a N-S and E-W direction. At the same time samples for laboratory examination was taken from the outcrops.

The geological mapping was supplemented with core drilling in places with no outcrops but also in places with anomalies in the geophysical survey.

A separate structural mapping of each area was also carried out in order to assess its tectonics and deformation.

The role of geological outcrop mapping was very important because it provided very valuable direct information for the structural model.

3.2 HYDROGEOCHEMISTRY

3.2.1 General

The main aims of the hydrogeochemical studies during the preliminary site investigations were:

- hydrogeochemical characterisation of the sites,
- classification of the water samples according to the water types,
- evaluation of the representativeness and
- production of input data for geochemical modelling and the performance assessment.

Water samples were taken not only from deep investigation boreholes, but also from a larger area surrounding the actual site. Surficial waters, such as rivers, brooks and lakes were sampled together with shallow groundwaters from natural springs and domestic bored wells. The monthly precipitation was collected for at least one year at each site. A snow sample profile was also taken at least once per year. These environmental water samples provided a large set of reference data for the interpretation.

Flushing water used in drilling was sampled frequently in order to characterise the water, and to monitor possible changes in the chemistry. The flushing water was labelled with two tracers - sodium fluorescein (uranine) and sodium iodide. The analytical determinations of these tracers were based in two different methods (fluorimetry and UV/VIS-spectroscopy) to avoid possible systematical errors.

Several deep (500 - 1000 m) boreholes were drilled at each site. Nearly all of the deepest boreholes were generally sampled from two levels. A presampling period with constant pumping took about 1-2 weeks. This was usually followed by 3-4 days (even 4 months) of pumping and monitoring the main hydrogeochemical parameters with the help of a system of flow-through cells. Then the pumped section was sampled. The pumping usually continued for another week with constant monitoring measurements at the same level, and finished with the second sampling.

Groundwater samples were also collected during the pumping tests performed in the deepest borehole at each site. There were usually two or three borehole sections that water was pumped from. During each pumping phase (borehole section) samples were taken. The amount of the hydrogeochemical parameters was not so extensive as during the actual groundwater samplings. Also, the multilevel piezometers built for the hydrological studies were sampled.

During the five years of the hydrogeochemical investigations at the five sites, about 340 water samples were collected. The results have been compiled in the hydrogeochemical summary report of TVO's preliminary site investigations /Lampén and Snellman, 1993/.

3.2.2 Planning of the studies

The sampling depths were usually chosen according to the indications of the hydraulically conductive fracture zones. The groundwater samples were frequently taken with the help of double packer equipment, the packer separation being 5 m. This rather narrow sampling range has been a benefit in the geochemical modelling, providing hydrogeochemical data from a rather limited amount of hydraulically conductive fractures. The mineralogical data of the core samples and the fracture coatings at the sampling depth can be dealt with in an efficient manner.

The programmes for laboratory analyses were planned according to the main goals presented above. During the entire preliminary site investigation project these programmes remained practically unchanged. This was according to the main features of the preliminary site investigations: all of the sites were studied according to the same programmes, providing equivalent raw data for interpretation. Even after the first groundwater sampling from the multilevel piezometers at Veitsivaara, which indicated local hydrogeochemical contamination caused by the construction materials, piezometers were sampled in a similar manner at all of the other sites. This was done with the aim of building hydrogeochemical confidence to the hydrological studies by the use of isotopical data.

The time schedules of the water sampling campaigns were planned according to the overall timetables of the site investigations. This did not always enable pumping periods long enough for getting representative groundwater samples. Also, on some occasions an early winter made it necessary to shorten the pumping periods.

3.2.3 **Instrumentation**

The original mobile field laboratory was planned and built in 1984 /Rouhiainen P et al, 1992, Öhberg A, 1991/. The cabin contained a refrigerator with a system of flow-though cells and the monitoring electrodes for continuous measurements of pH, electrical conductivity, redox potential, dissolved oxygen, temperature and pS. The cabin was quite small and lacked access to purified water as well as a hood which is needed especially in the field analyses of the iron species.

Groundwaters containing lots of dissolved gases, especially at Olkiluoto and Syyry, caused problems in the field measurements of conductivity. The originally horizontally installed flow-through cell was lifted in an upright position in 1991. This stabilised the measurements. The dissolved gases caused problems with pH measurements, too. The pH values measured on-site and off-site sometimes differed with many of the pH units. There was a systematic trend of higher field values. This was apparently caused by in-gassing of atmospheric CO_2 during transport and measurement in the laboratory.

The power generation with the help of a generator set was sometimes unsteady. Sharp variations in voltage were eliminated by introducing an UPS (Uninterrupted Power Supply) into the system. The insulation of the water sample hoses was a problem during the cold periods in winter.

The mobile field laboratory was renewed in 1987 with a new, bigger trailer providing better on-site facilities for preservation and analyses of the water samples. Small refrigerators maintained the bottled water samples at a suitable temperature before the transport to analysing laboratories.

Some problems during the interpretation phase were caused by the anomalously high TOC amounts of groundwater samples taken from the deepest sections with quite low pumping rates. This was especially true at Olkiluoto. These can be caused by organic material sticking to the inner surfaces of the hoses. A regular, through clean-up procedure is necessary to ensure the representativeness of the groundwater samples.

The disagreement of redox results obtained by platinum and glassy carbon electrodes has not yet been resolved. Apparently the measuring pairs are controlled by different redox pairs in groundwaters. In the results from the preliminary site investigations no clear trends, e.g., because of matrix effects or the sampling depth, could be noticed between the two measuring systems. In the hydrogeochemical literature platinum is most often used as the indicating electrode.

3.2.4 Field work of the hydrogeochemical studies

Uranine has been analysed in the field, either with a fluorimeter or a UV/VIS spectrophotometer. It was not until after the renovation of the field laboratory in 1987 that UV/VIS spectrophotometric determination of Fe^{2+} and $Fe_{(tot)}$ was carried out in the field. Alkalinity and acidity were determined by volumetrical methods in the field since 1990.

The water samples were not systematically filtered during the sampling or in the laboratories. Some of the analytical methods have included filtration. During the last few years of the preliminary site studies, many parallel groundwater samples were taken with on-line filtration (a series of 0.45, 0.22 and 0.05, 0.03 or 0.02 mm membranes). From both the filters and filtrates, Al, Ca, Fe, Mg, Mn, Si and S were analysed. The most prominent observations were that iron occurred to a fairly high percentage in the particle fraction (0.45 mm). In some samples most of the sulphur was found as particles, too. As the average amounts trapped by the filters were very low, the unfiltered and filtered water samples were considered to be practically parallel.

3.2.5 Analytical methods

Some problems were observed in the UV/VIS spectrophotometrical analysis of the tracer uranine added to the flushing water. The results have not always been in a good agreement with the fluorimetrical results. There may be some effects of the very saline matrix of the groundwaters of Syyry and Olkiluoto. In the detailed site investigations only sodium iodide will be used as a tracer in the flushing water during the drillings.

The determination of sulphide also caused some problems. This analysis was performed according to the Finnish SFS standard. Apparently the time delay between the moment of stabilising the S^{2-} ions by precipitation and that of the spectrophotometrical analysis is the most critical one. If the time schedule is very tight the sulphide particles have sometimes not been totally decanted and the particles thus cause erroneous results in the UV/VIS spectrophotometrical analysis.

Some problems have occurred in the determination of $KMnO_4$ consumption, especially when the amount of chemically oxidizable agents in the water sample has been high. The dilution of the sample has caused nearly unlimited amounts of $KMnO_4$ consumption.

When determining the total hardness of water samples, problems have occurred with the removal of disturbing ions according to the Finnish SFS standard. There seem to be trends depending on the chemicals used.

Aluminium is considered very important in geochemical modelling. Unfortunately it is quite likely that the groundwater samples have been contaminated already during the drilling operations. Also aluminium is present nearly everywhere as particles in the air. Therefore, as far as aluminium is concerned, the cleanliness of the field laboratory, equipment etc. is of extreme importance when considering the representativeness of samples.

The Fe^{2+} and $Fe_{(tot)}$ field analyses were performed according to the thioglycol- Ferrozine method /Dimmock et al, 1979/. The results indicate incomplete complexation of iron because the $Fe_{(tot)}$ results obtained with this method have often been lower than the AAS analyses in the laboratory. The thioglycol-Ferrozine method may encounter interference from the iron-containing mica particles in the water sample. This observation will be studied more thoroughly, too. Furthermore, the usage of a nitrogen atmosphere during sampling, preparation and analysis of ferrous iron will certainly help to diminish the oxidation risks.

3.2.6 Representativeness of the samples

The representativeness of the water samples gathered during the preliminary site investigations was evaluated during the processing of the raw data. A set of criteria was established for the evaluation /Lampén and Snellman, 1993; Laaksoharju et al, 1993/. Although the rather strict classification system considered that only a minority of the water samples were fully representative, the results can still be used for general hydrogeochemical characterisation and comparison between the different sites. Usually, Finnish groundwater investigations have so far not considered the question of representativeness serious.

3.2.7 Interpretation of the data

All of the about 340 water samples were classified according to the main cations and anions /Davis and De Wiest, 1967/. A general hydrogeochemical characterisation at each site was developed. Some clear trends were found for the different parameters according to their sampling depths or in graphical representations against, e.g., the chloride concentration. According to the main constituents, the most prominent differences were the occurrence of brackish and saline groundwaters at Syyry and Olkiluoto. Only fresh groundwaters were observed at Romuvaara, Veitsivaara and Kivetty.

The analysis programmes of the water samples in the preliminary site investigations were quite extensive. The most important physicochemical variables, main constituents and a large number of trace elements were analysed. Usually the concentrations of the trace elements were below the detection limits. The programme of the trace elements in the detailed site investigations will be more concentrated for those elements that meet the specific needs of geochemical modelling and the performance assessment.

Preliminary site investigations yielded interesting data on the evacuated gaseous constituents in the deep groundwaters in the boreholes. In many deep boreholes the occurrence of large proportions of methane and even hydrogen confirmed the field measurements of very negative Eh values and those of dissolved oxygen below the detection limit. The high $Fe^{2+}/Fe_{(tot)}$ ratios and the presence of sulphide confirmed these observations, too. The gas samples were collected at the surface. The instruments will be developed for the detailed site investigations in order to gather pressurised, in situ gas samples. The collected gaseous components will be analysed for the isotopes, too.

Discrepancies between the redox values and the measured iron contents (Fe^{2+}/Fe_{tot}), sulphide and oxygen levels were observed in some waters. The discrepancy might be due to the different analytical procedures applied as well as analytical and technical problems encountered in the oxygen measurements and the presence of gas bubbles in the samples. The simultaneous presence of Fe^{2+} and measurable amounts of oxygen is not likely in groundwaters with long residence times, and is rather an indication of the recent mixing of deep groundwater with oxygenated water (e.g. flushing water).

The number of isotopic analyses was quite limited during the preliminary site investigations. H-3, H-2, O-18 and Rn-222 were analysed from nearly all of the water samples, surficial waters and groundwaters. U-234/U-238, C-13(TIC) and C-14(TIC) were analysed only from selected samples. According to the H-3 and C-14 data, the longest mean residence times were observed in some groundwaters at Kivetty, Syyry and Olkiluoto. On the other hand, the hydrogeochemical data was collected from a rather limited amount of subsurface sampling points. Also, the usage of, e.g., Sr- and S-isotopes would have required sampling and analyses of the minerals, too. These analyses will be included in the hydrogeochemical programme of the detailed site investigations /TVO 1993, Smellie et al, 1993/. In order to evaluate the origin and mean residence time with more confidence, the detailed site investigations will include the study of both inorganic and organic C-13 and C-14 in aqueous, gaseous and solid phases.

The results and the conceptual models from the hydrological, geological and geophysical studies yielded structural bedrock models for each of the investigation sites /Saksa et al, 1991, 1992a, 1992b, 1992c, 1992d/. These and the results from the mineralogical studies were used in the process of interpreting the hydrogeochemical data. On many occasions the isotopes in particular confirmed the observations of other fields of investigation. In the detailed site investigations, one of the main goals will be to create site-specific hydrogeochemical models.

3.2.8 Modelling of the water-rock interaction

The goals for the geochemical modelling of the groundwater data were:

- hydrogeochemical interpretation of the data
- evaluation of the water-rock equilibrium
- further evaluation of the representativeness
- identification of the major processes controlling the groundwater chemistry

The hydrogeochemical interpretation of groundwaters at the Kivetty, Syyry and Olkiluoto sites was performed based on the groundwater chemistry and isotope data, mineralogical data, and the structure and hydrology of the bedrock, using correlation diagrams and thermodynamic calculations /Pitkänen et al, 1992/.

The salinity and chemistry of the waters were found to be affected by both local hydrology and geological events in the past, the evolution of the waters being a sum of different processes such as water-rock interaction, mixing of waters of different origin, water flow and the general geological history of the sites. Some processes identified were calcite dissolution and precipitation reactions and formation of ironoxyhydroxides consuming infiltrating oxygen in the upper part of the bedrock. Lower hydraulic gradients limit the occurrence of fresh water and ironoxyhydroxides at more shallow depths in Syyry and Olkiluoto. Brackish water at both Syyry and Olkiluoto are characterised by a relict of Baltic seawater, whereas saline waters contain a hydrothermal component.

The hydrogeochemical interpretation of the data was limited to the general lack of input data and the relatively few representative samples both due to hydrological conditions and contamination problems.

The pH and CO_2 problems encountered especially at Syyry and Olkiluoto influenced the interpretation of the carbonate minerals. Calcite is saturated or oversaturated in groundwater samples from Olkiluoto, the oversaturation probably being caused by CO_2 outgassing during sampling and too high carbonate values. The too high pH´s measured also have an especially strong effect on the redox calculations based on goethite and also to a smaller degree on the pyrite-based calculations. As most of the samples were not filtered, the iron content used for geochemical interpretation might be too high, too.

The wide scattering found in the SI values for gibbsite reflects the problems generally met in analysing the low alumina content of the waters.

The inadequate isotope data did not allow any extensive analyses of, e.g., the mean residence time of the waters and evolution aspects. An overall lack of detailed isotope data (C-13/C-14) from environmental reference samples was recognised. These have been taken into account in the detailed site investigation stage by including a large number of isotope analyses both from waters and minerals, from reference samples as well as from the deep boreholes.

The hydrogeochemical modelling is proceeding to a stage of quantification of the processes observed based on new hydrogeochemical data on the sites and by means of reaction path modelling. The aim is to develop a site-specific hydrogeochemical model.

3.3 GEOPHYSICS

3.3.1 High-resolution airborne geophysical survey vs. ground geophysical surveys

Investigations started at the Romuvaara and Veitsivaara sites during 1987. Among the first surveys carried out were ground geophysical magnetic and electromagnetic mappings, first by reconnaissance lines, later in a survey grid. The magnetic ground survey consisted of total field and vertical gradient recording. The electromagnetic measurements comprised VLF-magnetic field and VLF-resistivity. The grid was a one-directional line grid with 50-metre line spacing. The station intervals in the magnetic and VLF surveys were 5.0 m and 10.0 m, respectively.

During 1987 a low-altitude (40...45 m) helicopter-borne airborne survey was also carried out at all five sites. The survey specifications were of a very high resolution type - e.g. very sensitive instrumentation, high accuracy positioning, dense bi-directional grids and low altitude, low velocity flying. The instrumention used has been discussed in detail in the references /Suomen Malmi Oy Finnexploration, 1988; Saksa et al, 1991b/. The line spacing with bidirectional grids was 100 m and the station interval was 3.5 m on average.

The survey produced 25 thematic maps of each area. The electromagnetic results were converted to apparent resistivity maps using the pseudolayer method. In the magnetic data representation, both contour and grey shadow maps were compiled. A large number of stacked profiles were also compiled for quantitative interpretation. The high quality results obtained in 1988 made the evaluation between similar ground geophysical and airborne surveys possible. Especially, the Kivetty, Syyry and Olkiluoto areas were studied if the ground geophysics offered any advantages over airborne results or if airborne results could replace planned ground geophysical surveys.

The measurement results, detection and resolution aspects have been studied /Saksa P and Silvennoinen H, 1989/. High frequencies (>20 000 Hz) must be used to cover the resistivity range up to 30 - 50 000 Ωm that is typically encountered in crystalline bedrock areas with thin overburden and dilute groundwater conditions. The use of several frequencies in the band 1 000 - 100 000 Hz has enabled the required distinction between different anomaly sources. Aero-VLF modelling indicated that the detectability of typical structural conductors with the method is uncertain. Further findings from the Romuvaara and Veitsivaara areas are summarised in the following chapters.

3.3.2 Airborne and ground magnetics

The ground survey proton magnetometer had an absolute accuracy of about 1.0 nT in total field recording and about 1 - 2 nT/m with a vertical gradient. The critical factor for the airborne cesium magnetometer is the accuracy of compensation. This yielded an absolute accuracy of better than 0.08 nT for the total field and better than 0.02 nT/m for the vertical gradient at a flight elevation of 45 m. Hence, the sensitivity of the airborne instrument is much better than that of a ground magnetometer. On the other hand, anomalies are also much smaller in amplitude with an airborne survey.

Geological noise is an important factor when recorded values are to be interpreted /Saksa P and Silvennoinen H, 1989/, see Fig. 3-1. In practice interpretation deals with relative anomalies. The ground magnetic survey has a distinct geological noise component of a few nT originating near the surface soil and rock variations. This noise is almost completely absent in the airborne results. Figures 3-2...3-5 allow a comparison of two south-north oriented airborne profiles with corresponding ground magnetic profiles /Saksa P and Silvennoinen H, 1989/. The results from the Romuvaara site indicated the same character of the profiles with the Veitsivaara results.

This finding was also rather new to us since the ground magnetic surveys had been conducted using a very careful field work procedure. It is probably possible to find areas where the near-surface noise is even smaller than at Romuvaara and Veitsivaara, but if the small noise component (1 - 5 nT) is considered, this may be difficult to attain.

Comparison of the ground and airborne magnetic maps supports the high sensitivity of airborne magnetics. Furthermore, calculations with magnetised plate models gave supporting evidence. Airborne colour-shaded maps can show details similar to ground magnetic maps. This is partly due to the airborne bidirectional grid and the dense station interval.

Total magnetic field and vertical gradient measurements were carried out at Romuvaara, Veitsivaara and Olkiluoto, but not at Kivetty or Syyry, as comparison of the aeromagnetic and surface magnetic measurements at Romuvaara and Veitsivaara suggested that the sensitivity of the former was adequate for the purposes of interpreting the magnetic data.

Airborne work has, however, its inherent limitation in resolution. Anomaly sources adjacent to each other are summarised and cannot be differentiated during interpretation. As a rough rule, discriminating between adjacent, parallel bodies closer than the flight elevation (40 - 45 m) is difficult. So, if an anomaly from a dolerite dyke is recorded, it can be formed by a set of parallel thin veins instead of one thicker dyke. Also, local near-surface magnetised small 3-D bodies are better detected by ground survey lines which run over the bodies.

3.3.3 Airborne electromagnetic and ground VLF-measurements

Concerning the VLF-results from the Romuvaara and Veitsivaara areas it was found that the quite heavy damping applied with an airborne instrument caused some loss of sensitivity when compared to the ground survey results. However, the high-frequency electromagnetic system (Fig. 3-6) used gave much the same anomalies as the ground VLF-resistivity measurements /Saksa P and Silvennoinen H, 1989/. Nonetheless, the underlying theoretical basis is different with the methods and an absolute comparison should not be made. One advantage of the ground VLF-resistivity over the dipole-EM method is that higher absolute resistivity values can be mapped in practice.

MAGNETIC SURVEY NOISE

GROUND MAGNETIC SURVEY

CLASS	TOTAL FIELD	VERT. GRAD.
SWAMP AREAS	appr. 1 nT	1-2 nT/m
TILL AREAS	2-4 nT	2-5 nT/m
OUTCROPPED AREAS	locally > 5 nT	locally > 5nT/m

AIRBORNE MAGNETIC SURVEY

GEOLOGY	appr. 0.1 nT	appr. 0.02 nT/m
INSTRUMENT	< 0.08 nT	< 0.02 nT/m

NOISE = NON-INTERPRETABLE VARIATIONS IN SIGNAL WITH KNOWN GEOLOGY AT THE TIME OF CONSIDERATION

Figure 3-1. Analysed noise values from magnetic measurements from the Romuvaara and Veitsivaara /Saksa P and Silvennoinen H, 1989/.

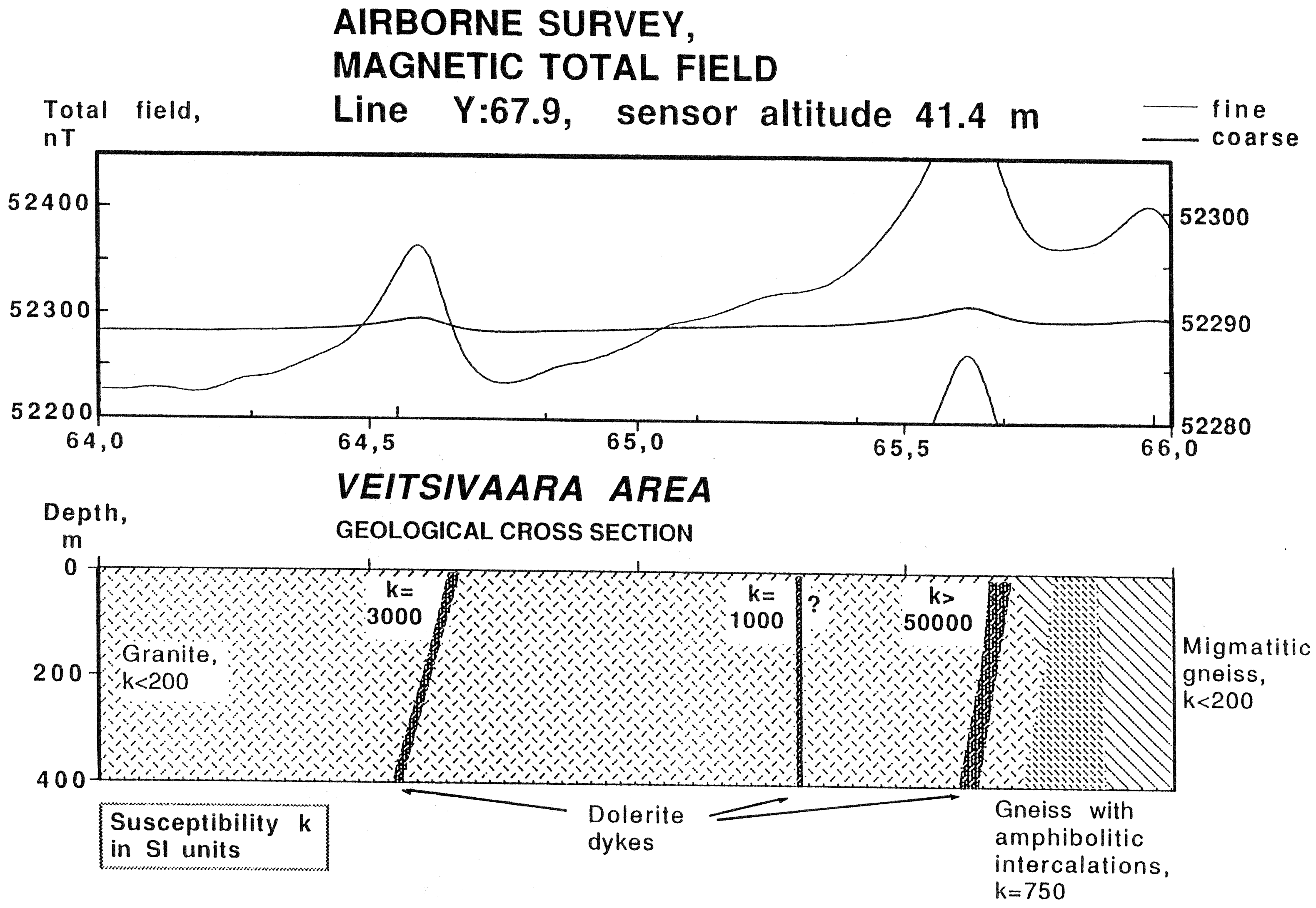


Figure 3-2. An airborne survey magnetic total field profile with a geological cross-section from Veitsivaara /Saksa P and Silvennoinen H, 1989/.

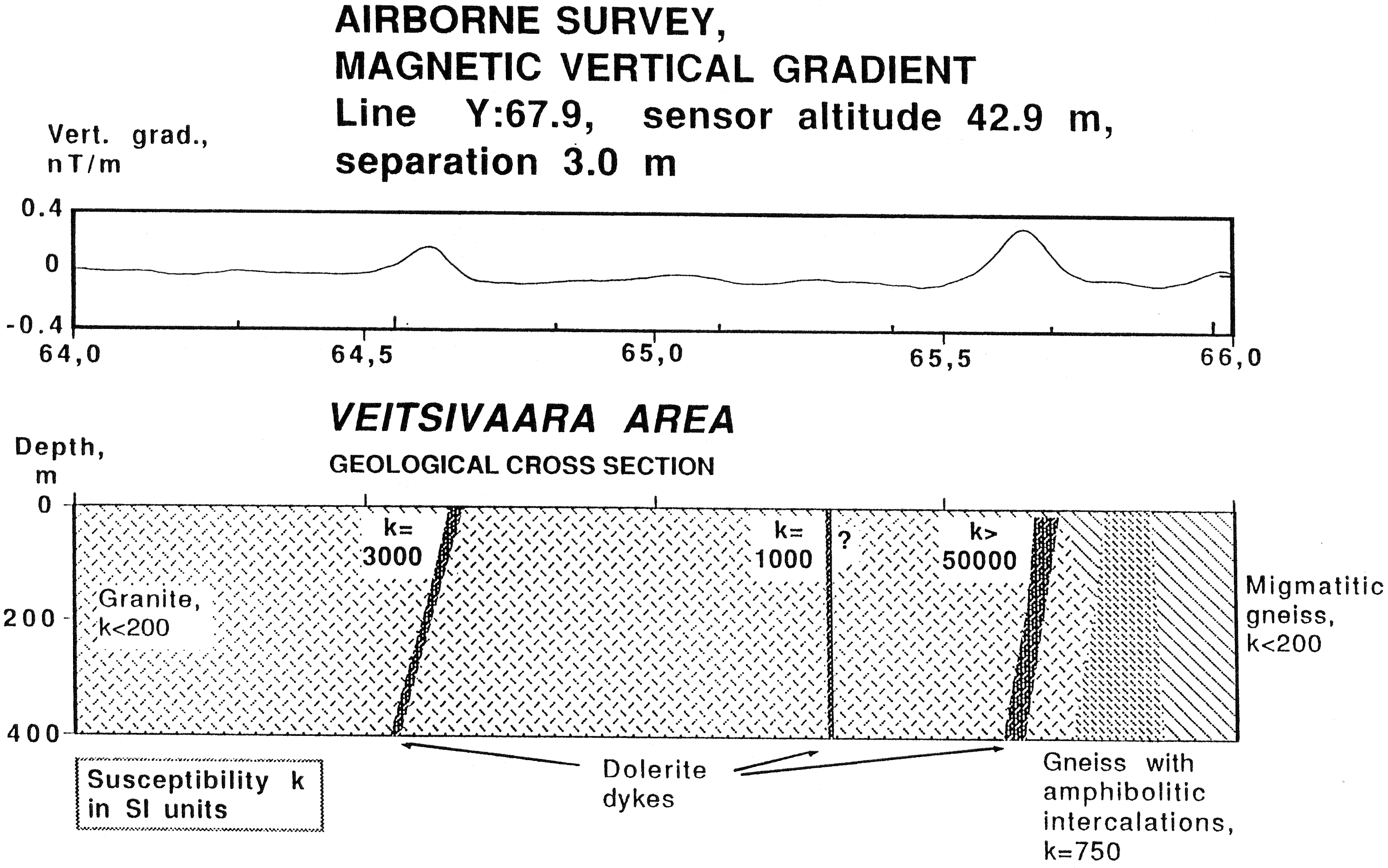


Figure 3-3. An airborne survey magnetic vertical gradient profile with a geological cross section from Veitsivaara / Saksa P and Silvennoinen H, 1989/.

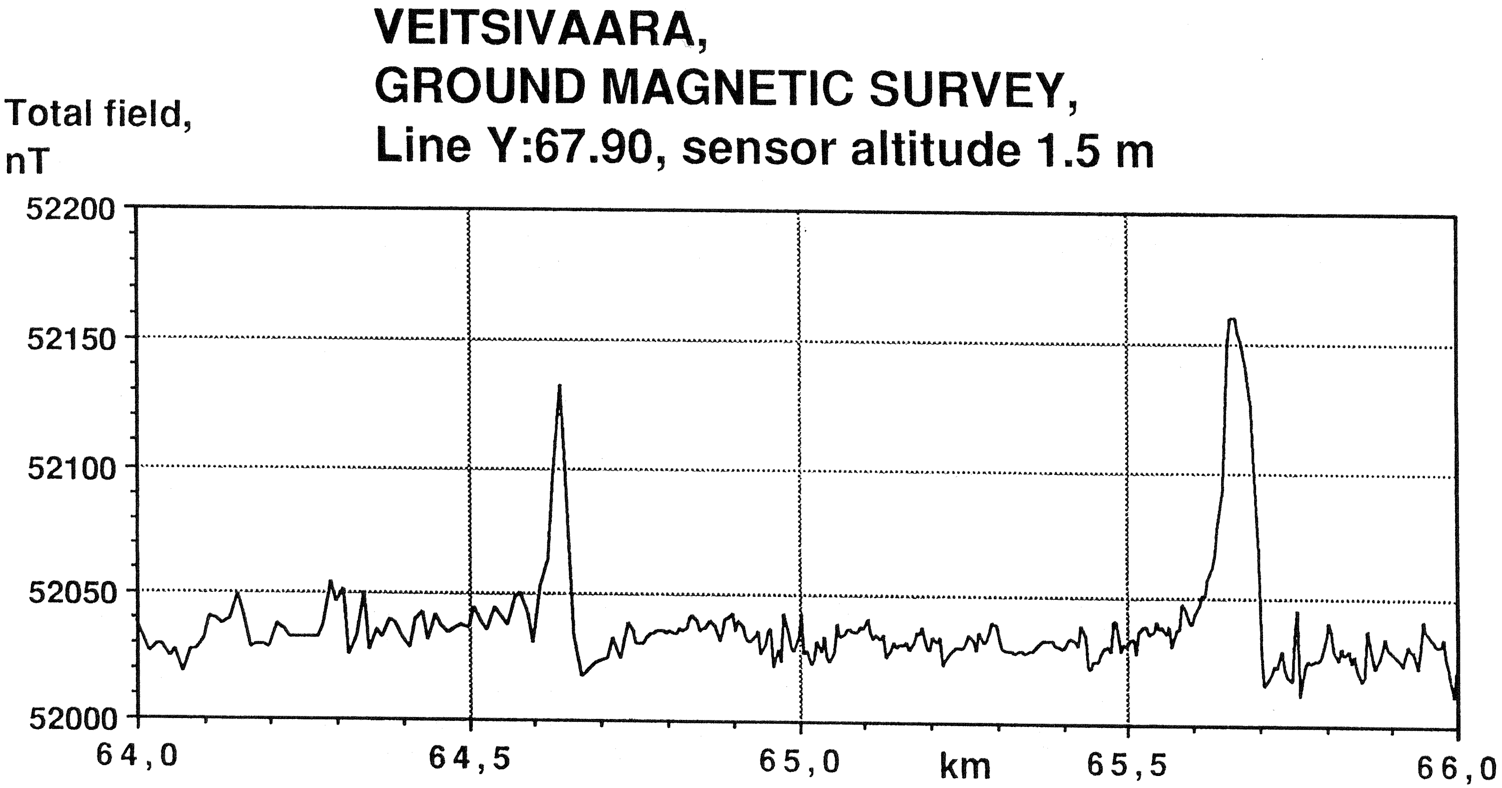


Figure 3-4. A ground survey magnetic total field profile from Veitsivaara /Saksa P and Silvennoinen H, 1989/.

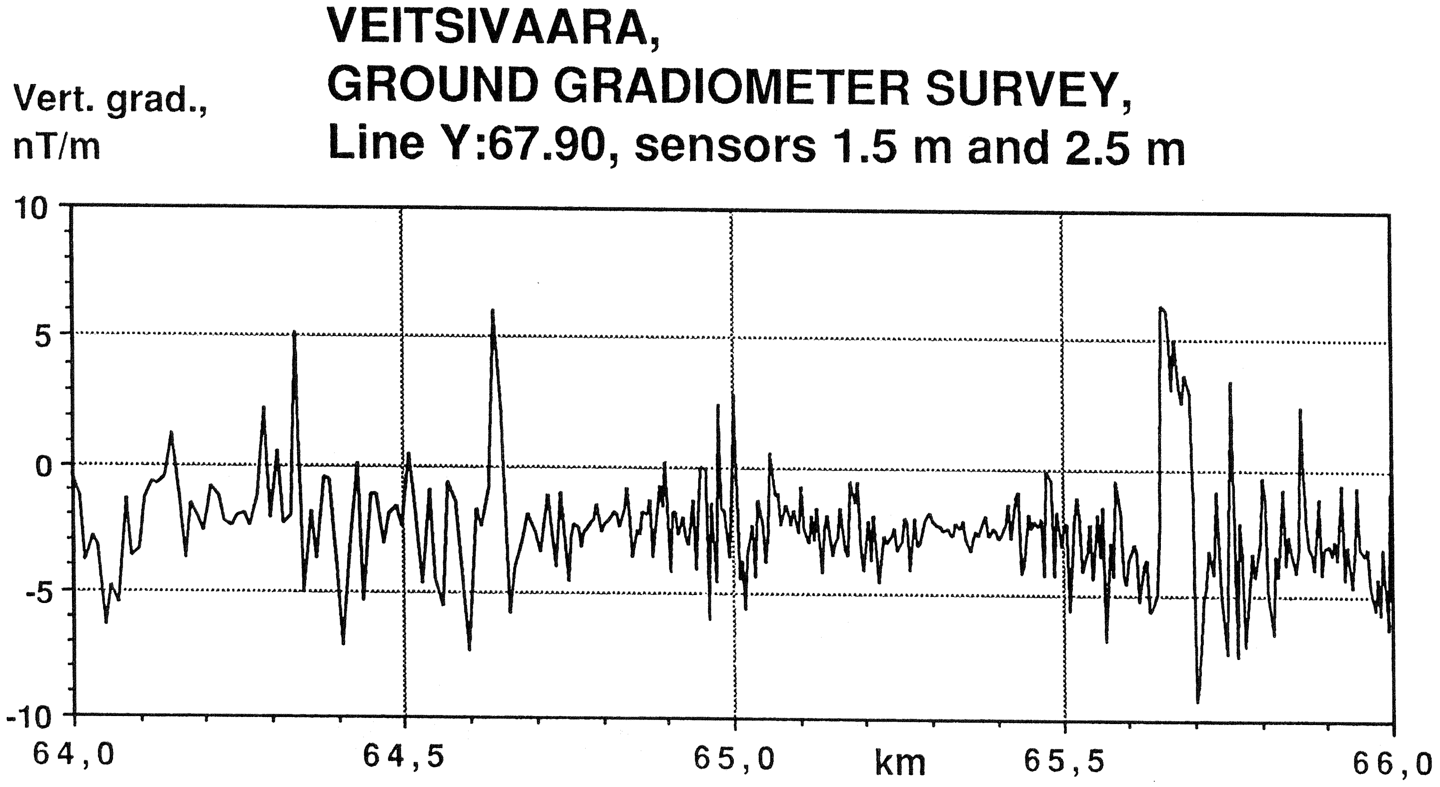


Figure 3-5. A ground survey magnetic total field vertical gradient profile from Veitsivaara /Saksa P and Silvennoinen H, 1989/.

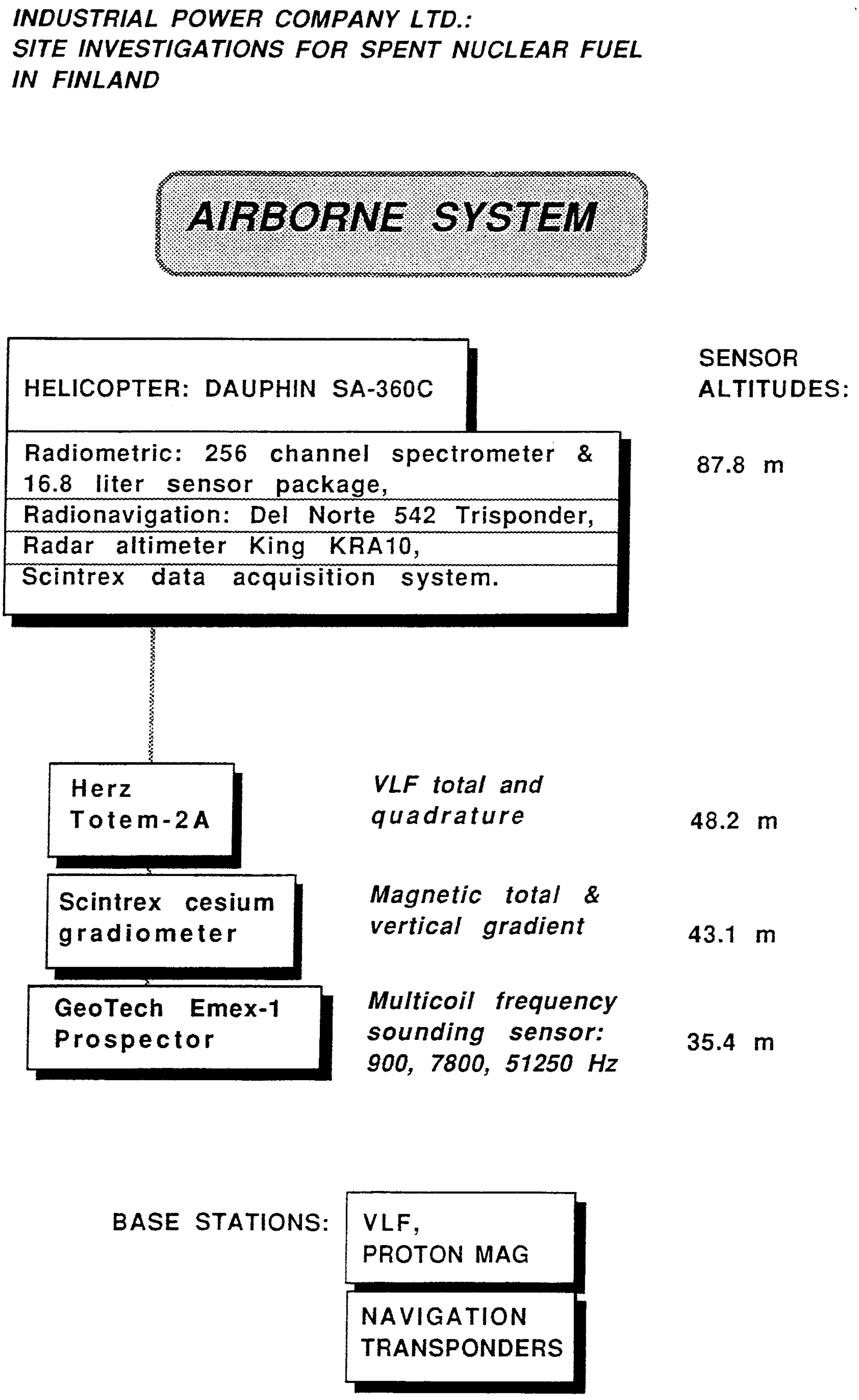


Figure 3-6. High-resolution airborne system instrumentation /Saksa P and Silvennoinen H, 1989/.

3.3.4 Topography image processing

A digital terrain image processing exercise /Autio H and Hakanen P, 1992/ was made during 1989...91. The purpose of the task was to develop computerised analysis methods for lineament interpretation and to reduce the effects of subjective/personal preference in the interpretation. It was also considered that it might be possible to make some kind of analysis of possible block elevations and surfaces of tectonic origin.

Veitsivaara was selected as a test site. The digital basic elevation data was received from National Land Survey of Finland and interpolated into a 25 • 25 m grid. The digital data was interpolated simply from the digitized map contour lines which have a contour interval of 2.5 m at the highest. The elevation values range from 188 m to 253 m in the area. The size of the processed area was 42 km^2.

Image processing typically produces a lot of pictures as a result of the different algorithms applied. At Veitsivaara colour contour maps, shaded relief maps, adaptive filtered maps, residual maps etc. were created. The best results were composite maps of various themes when joined together. Example is shown in Fig. 3-7 /Autio H and Hakanen P, 1992/. Its explanation is as follows:

The red colour represents adaptive filtering carried out by means of a 250 m calculation window, the intensity of the colour representing the deviation from the areal variation in elevation, i.e., ridges and depressions (e.g., the valleys of the Takkupuro and Varpujoki brooks in the northern part of the site). The green colour indicates an oblique illumination of the original material from the east, so that the wide low-lying areas in the western parts of the site appears as darker shades of green than the eastern parts. The blue colour represents oblique illumination from the north, in which the low-lying areas have been emphasised further. This makes the east-west structures stand out as possessing dark southern and illuminated northern slopes. The even peat bog areas are seen as continuous light and medium blue areas. The clearest topographical features visible in Fig. 3-7 are the network of vein-like strips of bog seen in red, the boundary between the light and dark areas running through the mid-part of the picture in an almost north-south direction, i.e., separating the low-lying western part from the eastern highlands, and the homogeneous flat areas seen in various shades of blue /Heikkinen et al, 1991/.

Fig. 3-7 indicates very well the small and faint existing topographical variations that can be found by fairly objective processing steps. The topographic details are limited by the available base map data density. The pixel size is 5.0 m.

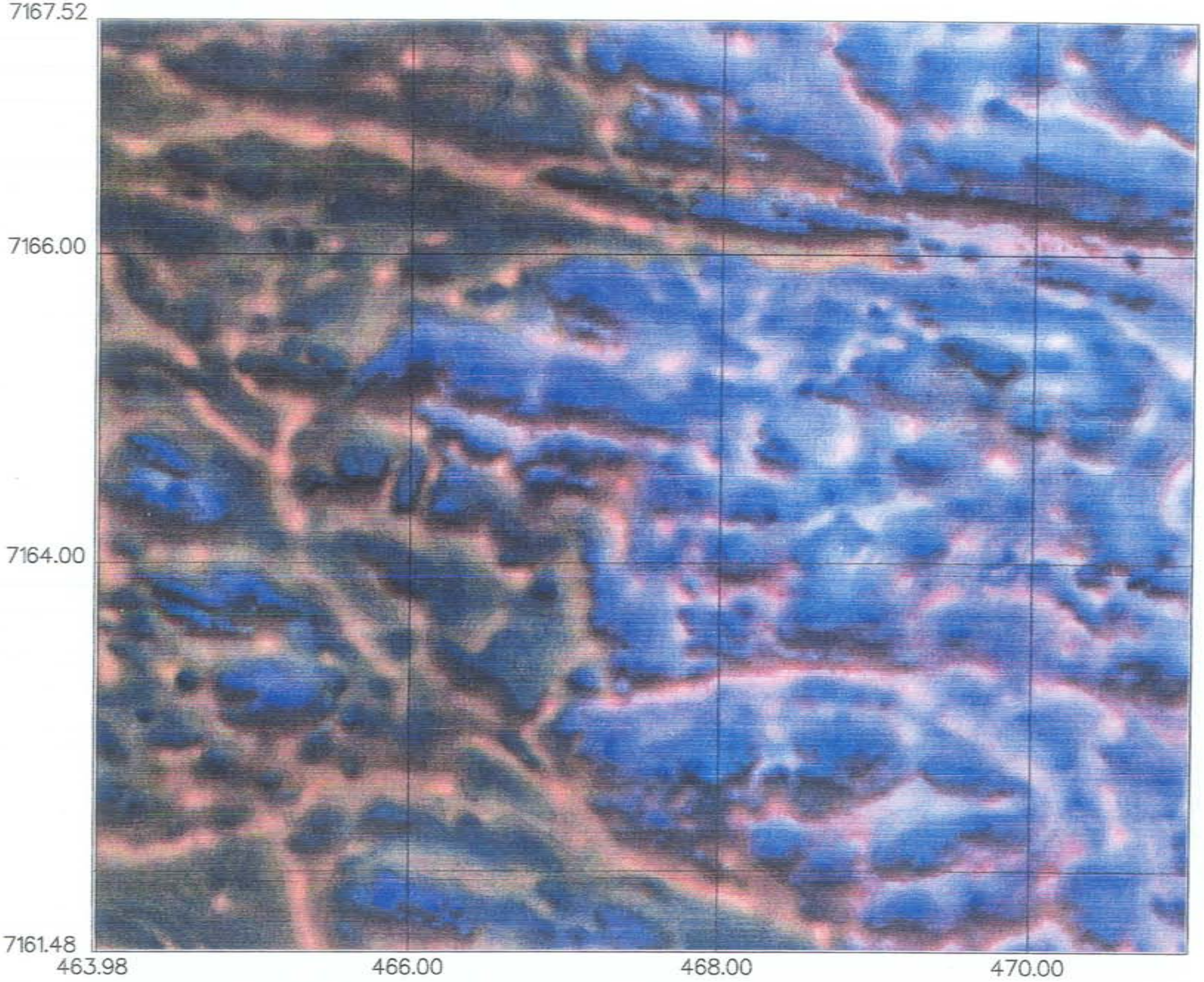
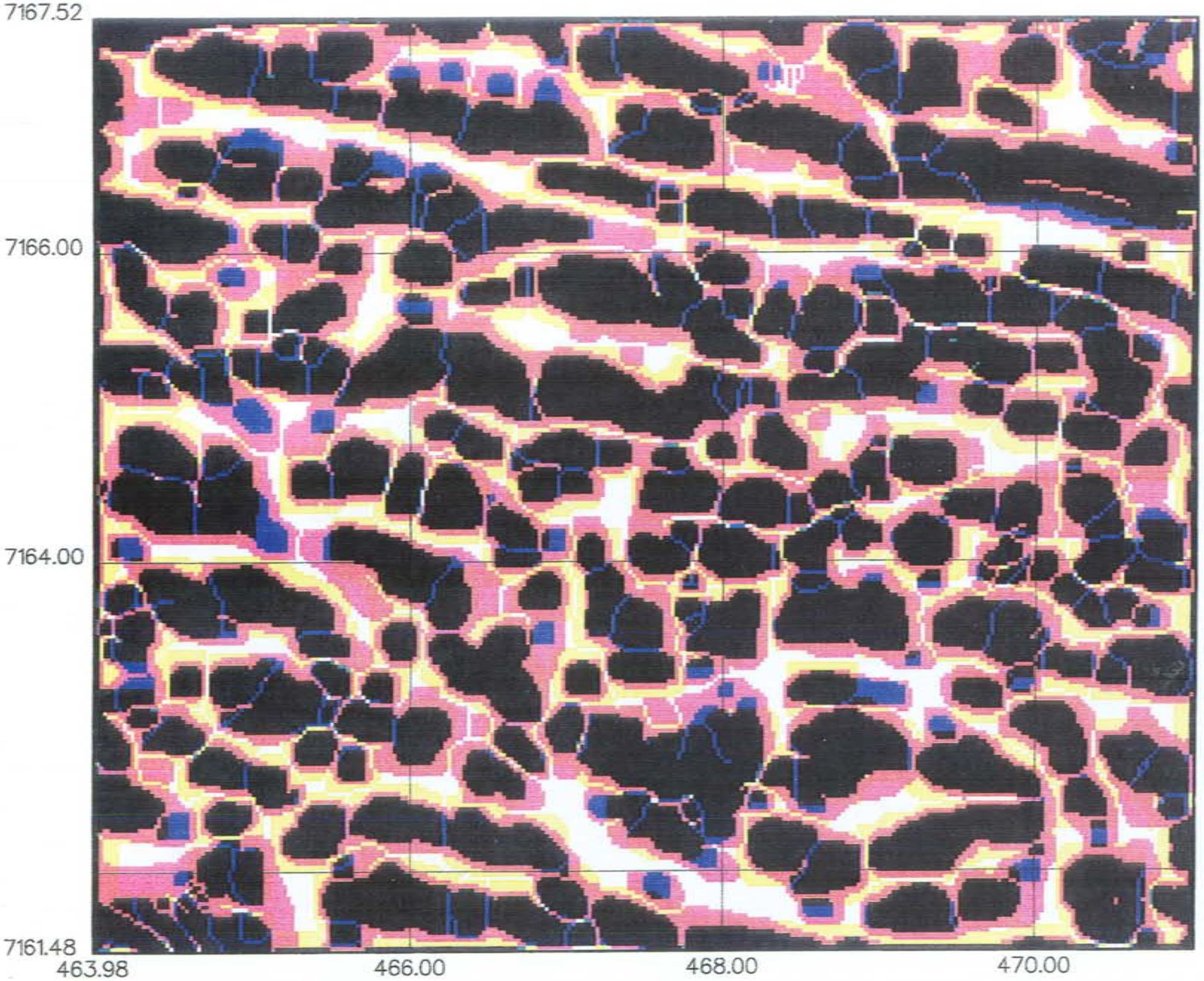


Figure 3-7. Combination of three themes from the digital image processing of ground surface elevations at the Veitsivaara site, reproduced from /Autio H and Hakanen P, 1992/.

The processing was continued experimentally to find continuous equielevation block areas at Veitsivaara. The processing was applied for adaptive filtered base data. Deutsch-filtering was used in region growing (pixel aggregation). A very tentative representation of the experiment is shown in Fig. 3-8. The black and white area indicates the more compact, even areas (like swamps). The other colours (grey shades) are transition areas. The picture is a supplement in the process aiming to achieve a more objective tectonic block classification. However, it is important to keep a feel for the original data values and their limitations and to understand the relationship between input and output values during the individual processing steps.

The Veitsivaara results were encouraging and later digital elevation data from the Olkiluoto area were processed, too /Autio H and Hakanen P, 1991/. The base map material was large, comprising land area base maps (partly on a scale of 1:4000) and sea bottom topography maps. The goals for the work were partly the same as at Veitsivaara but they also sought to cover the sea area, where the geoscientific data base is very sparse. The input data set was about 200 000 point (x,y,z)-values. The size of the area processed was 120 km^2 in an interpolated 10.0 m grid.

The results were good at Olkiluoto, providing many topographical new indications about the sea area and an omnidirectional, balanced indication set for land area. The basic grey-scale map is appended as Fig. 3-9 and the grey-shaded relief map as Fig. 3-10. Fig. 3-10 reveals many NE-SW features obscured by ancient ice sheet propagation in the NNW-ESE direction.



VEITSIVAARA/HYRYNSAL

DIGITAL TERRAIN IMAGE
GRID: 5 m x 5 m

ADAPTIVE FILTERING
AREA: 250 m x 250 m

INTERPRETATION OF ZONES
- BLACK, minimum areas
- BLUE, transition area
- RED, transition area
- YELLOW, transition area
- WHITE, maximum areas

Figure 3-8. Experimental plot of equielevation block analysis by region growing method (unpublished material, courtesy of Teollisuuden Voima Oy, processed by Tietokumpu Oy).

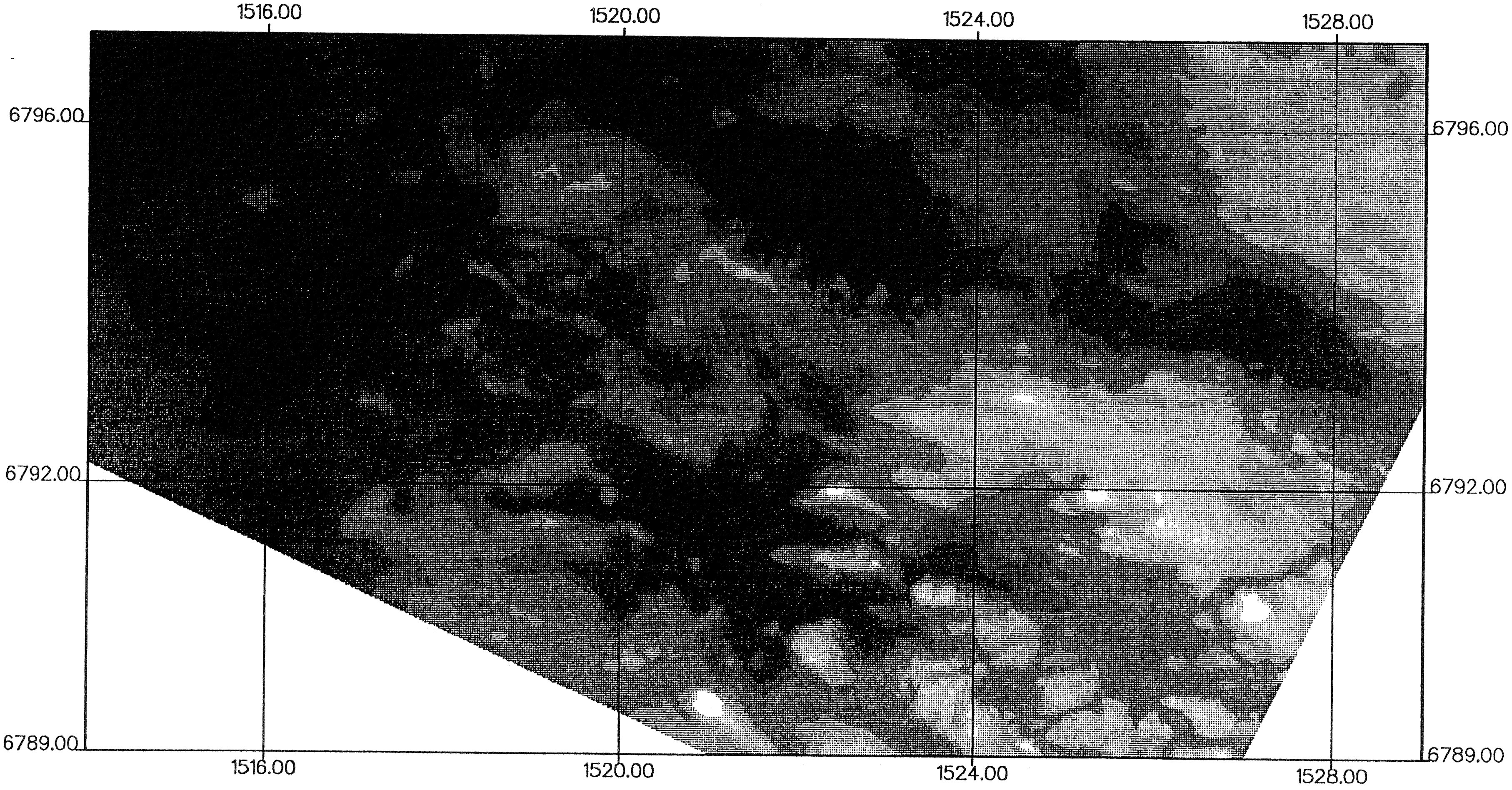


Figure 3-9. A digital grey-scale image of the Olkiluoto elevation data /Autio H and Hakanen P, 1991/. The scale is from -25.0 m (black) to +15.0 m (white).

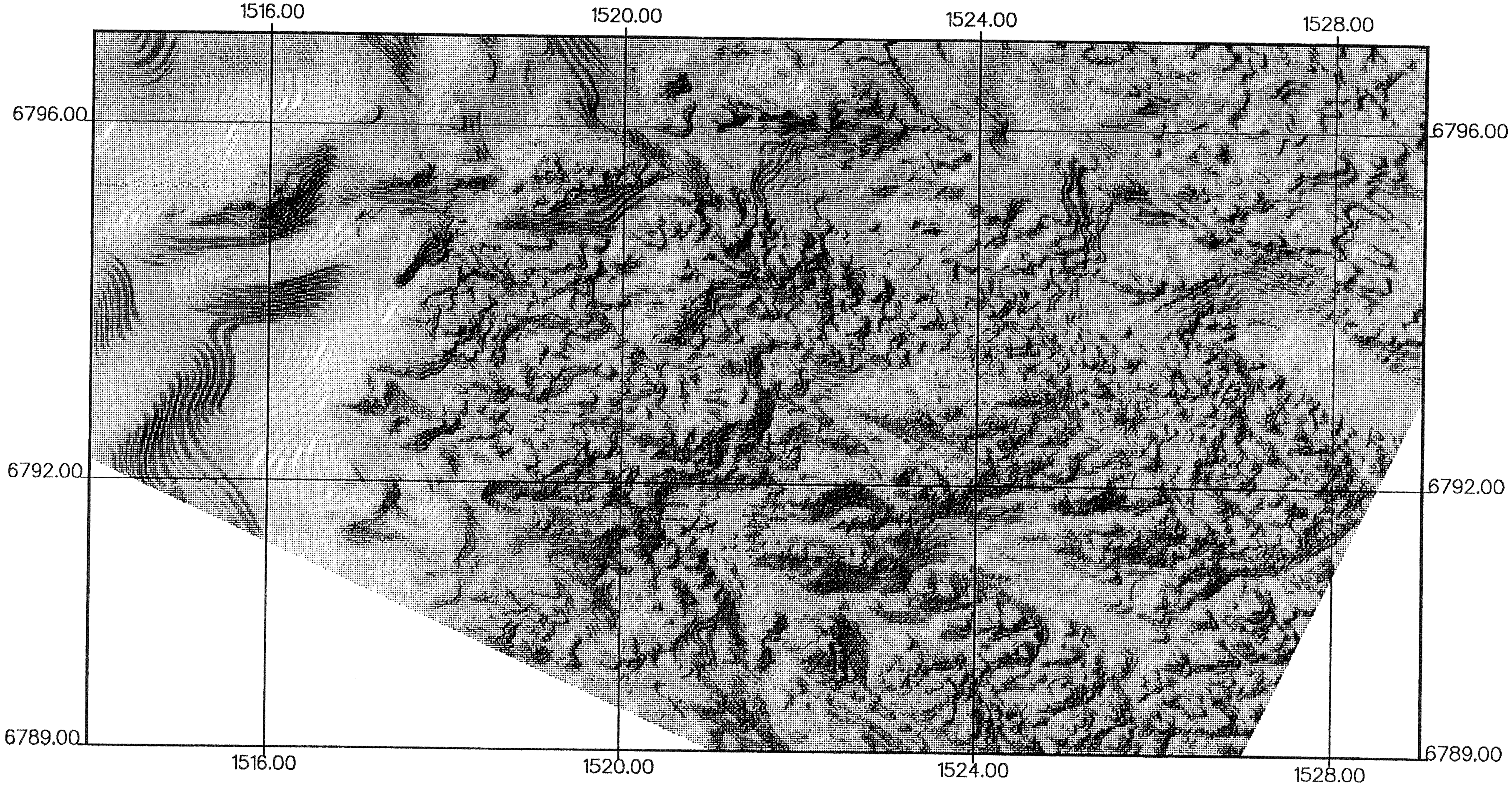


Figure 3-10. A grey-shade relief (gradient) image of the Olkiluoto elevation data /Autio H and Hakanen P, 1991/. The processing parameters are: illumination from 300° at an angle of 45°, pixel size 10.0 m, average filtered by a 11 • 11 pixel window.

3.3.5 Borehole loggings

The geophysical borehole loggings may be divided into those aimed at assessing local, small-scale variations and loggings directed at large bedrock volumes. Standard single hole loggings performed in all the boreholes comprised electrical earthing resistance and resistivity, the former as single point measurements and the latter employing a long normal array and either a short normal array or a Wenner array. Electrical potential, radiometric gamma-gamma scattering (density determination), the level of natural gamma radiation and magnetic susceptibility were also measured in all the holes, and radiometric neutron-neutron scattering (to study bedrock mineralogy and porosity), seismic P-wave velocity and borehole diameter (caliber) measurements in the 1000 m boreholes. The purpose of these was to obtain an impression of the variations in lithology and fracturing in the immediate vicinity of the boreholes, the short observation intervals enabling small-scale variations to be detected.

Geophysical borehole loggings which provide more oriented data (borehole TV, Televiewer, dipmeter) will be used in the next phase to supplement the results obtained during the preliminary site investigation phase.

Groundwater flow in the bedrock was monitored by fluid logging immediately on the completion of drilling. The method enabled the points to be identified at which water flowed in or out of the hole, as well as providing valuable data for water sampling sections. Due to the fact that only a short time had elapsed since the completion of drilling the directions of inflow and outflow were changed with the time. The drilling caused significant disturbances in the geohydrological regime close to the borehole. The fluid logging will be substituted with flow-meter in the next investigation phase with a longer period of time after drilling is completed /TVO, 1993/.

Vertical Seismic Profiling (VSP), a borehole application of seismic reflection sounding, was used together with single-hole borehole radar sounding and Vertical Radar Profiling (VRP) measurements to study wider bedrock volumes around the boreholes. The results were very useful as well as those obtained with borehole radar. Vertical Radar Profiling was carried out in the upper part of each borehole in order to map positions of electrically reflective contacts intersecting the hole. In the next investigation phase the radar device with directional antenna will be used in the old as well as new boreholes. Omnidirectional antenna providing longer reflection distances will be used in the new boreholes /TVO, 1993/.

3.4 HYDROLOGY

3.4.1 Surface hydrology

According to the investigation programme, the following parameters have been monitored:

- precipitation (one rain gauge per area)
- depth of the snow and water equivalency (about 2 km long snow course and two stake stations per area)
- runoff (about five selected points in streams in different parts of area)

The accumulated precipitation was measured irregularly from 1 to 10 times per month. One observation point and an irregular observation frequency were found adequate to characterise precipitation in the area. Daily observations from precipitation measurement stations of the National Board of Waters were used as a reference material. The closest reference point was most usually situated at a distance of 10 km from the area. Indications of the local nature of single rain showers and uncertainties caused by them were observed.

Depth of snow (about 40 reading points) and water equivalency (5...6 reading points) were measured regularly twice a month. Measurements at stake stations were made during snow melt once every five days. Observations from precipitation measurement stations or official regional mean values maintained by the National Board of Waters in the Monthly Hydrological Reports were used as a reference material. Measurements carried out at the sites completed and improved the accuracy of the "official" regional values, especially in those areas which are located higher than the surroundings. Inside the investigations site, local differences are large especially during snow melt. The phenomenon has been observed to alter the hydraulic heads in some of the boreholes in relation to time and place. Consequently, in some areas the observation network was made more complete by placing a stake close to some of the boreholes.

With the help of map material, watersheds were studied within the area and in the surroundings. The study enabled suitable boundary condition areas for groundwater modelling to be determined and an overall deduction of the regional flow directions to be made.

3.4.2 Geohydrology/Hydraulic conductivity

The measurements for hydraulic conductivity were aimed at:

- locating hydraulically conductive structures in general
- collecting input values for the flow modelling
- testing assumptions associated with the conceptual modelling

Locating hydraulically conductive borehole sections has partially dominated the development of a conceptual structural model. Sometimes it has been required to represent in the conceptual model sections that have been assumed to be local or small-featured on the basis of geology and geophysics. In the representation the sections are assumed to be continuous and several hundreds of meters wide due to the high hydraulic conductivity. It is also possible that very conductive sections are single fractures or fracture sets with hydraulic connections to an adjacent crush zone, which would mean that the measured values themselves do not characterise the crush zone itself. In some conductive sections the geophysical and geological anomalies have been minimal or there have not been any at all. In such cases the measured value of hydraulic conductivity has been left to represent intact rock and the variability in it.

The measured values of hydraulic conductivity determined according to /Moye, 1967/ in specific structures have been converted to transmissivities. With the help of statistical fitting, a curve or an approximation of the depth dependency has been attained and this has been used, as such or with minor modifications, as the reference dependency. These structures that have been tested in boreholes are classified in different transmissivity categories according to the measured values. Other structures have been classified according to their geological significance. The structures that have been assumed to be wide and continuous are considered to be conductive and the local noncontinuous structures are considered less conductive. One of the criteria in assessing the geological significance is the classification, where the structures interpreted as lineaments have been classified in four categories /Salmi M, Vuorela P, Kuivamäki A, 1985/. The depth dependency of the fitted linear and logarithmic approximation lines of the logarithmic values of the hydraulic conductivity in intact rock have been varied in order to avoid the effect of the values at the lower end of the measuring range (10^{-10} m/s).

The depth dependency and approximation of the hydraulic conductivity has been discussed in various reports during the characterisation phase. In the summary reports of bedrock models /Saksa et al, 1991, 1992a, 1992b, 1992c, 1992d/, hydraulic conductivity values are presented for each site by differentiating fracture zone values from intact rock values. A separate geostatistical analysis of the hydraulic conductivity is presented by (Niemi A and Kontio K, 1993/.

In Fig. 3-11 the hydraulic conductivities (Moye 31 m) are depicted as cumulative distribution functions for each site specified in five different depth classes. A theoretical curve with a normal distribution has been fitted for the data from every depth class. According to the figure, the data are normally distributed. Fig. 3-12 depicts a similar analysis for the data from the intact rock associated with the conceptual models. The values are normally distributed as well, although there are also indications of even distribution in some depth classes. Fig. 3-13 depicts analysis for the transmissivities of structures associated with the conceptual models.

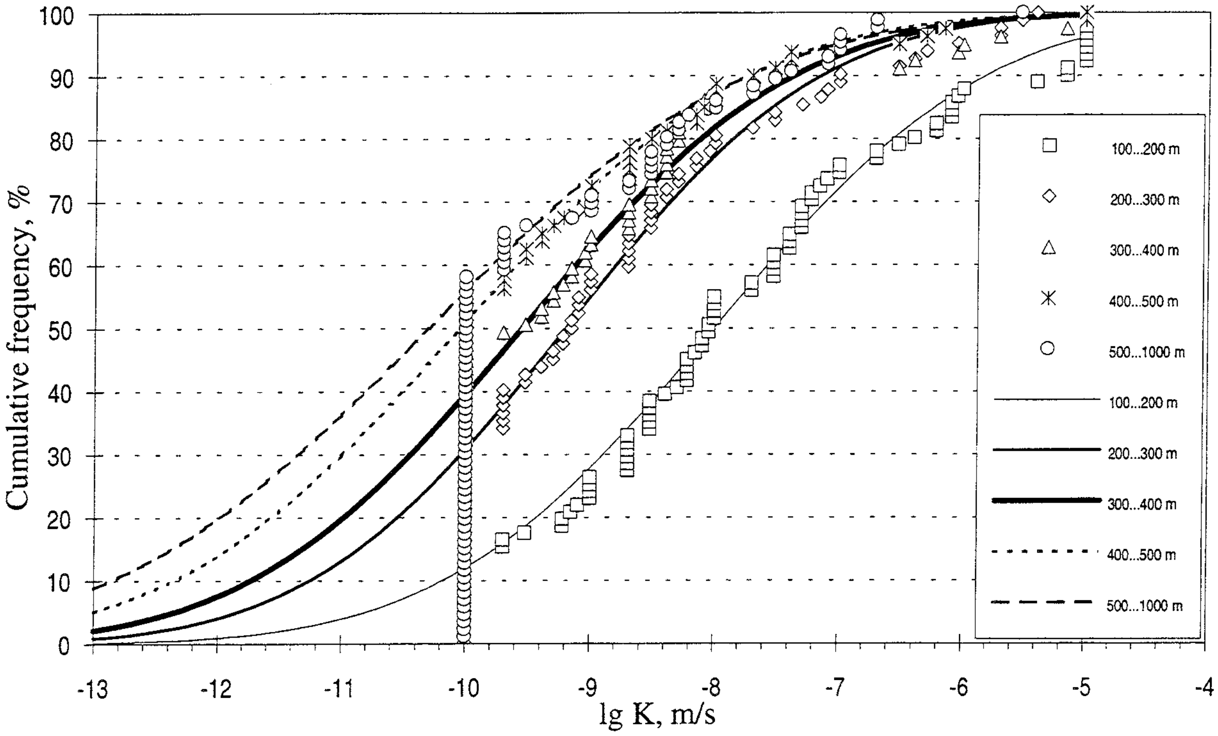


Figure 3-11. The measured hydraulic conductivity values (Moye 31 m) as cumulative distribution functions from each site specified in five depth classes. A theoretical curve with a normal distribution has been fitted for each set of depth data.

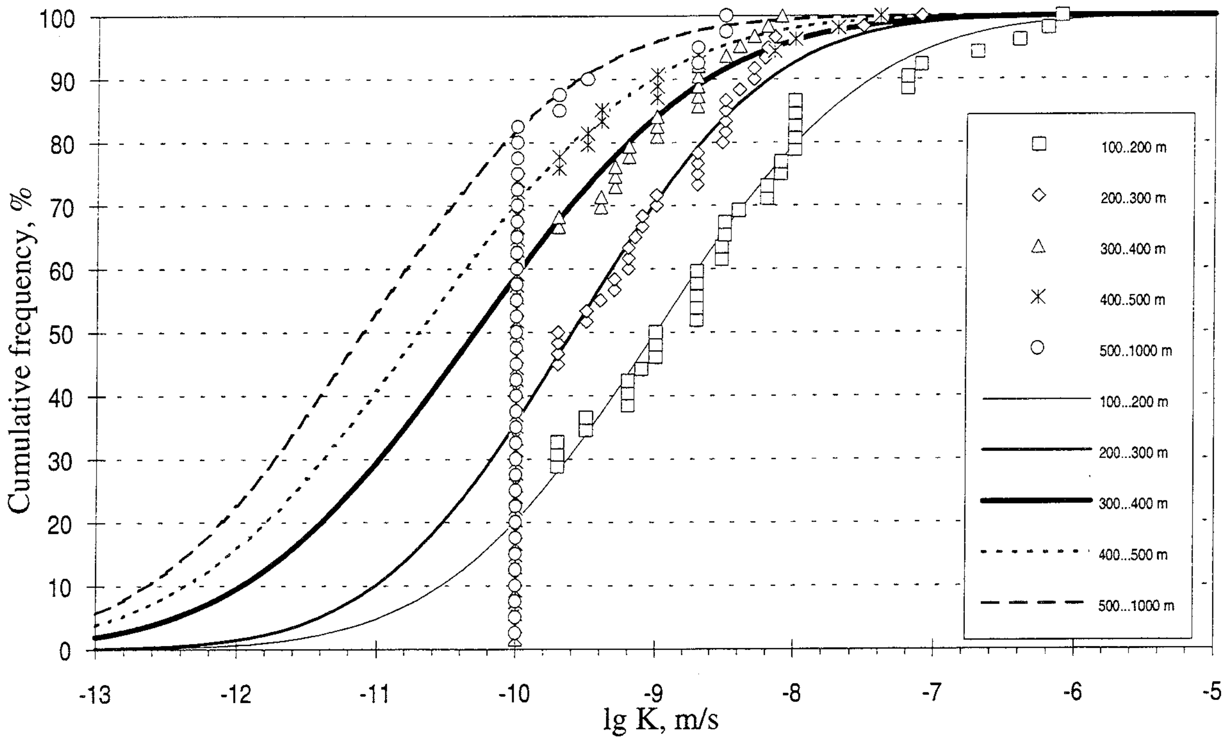


Figure 3-12. The hydraulic conductivities (Moye 31 m) in intact rock shown as cumulative distribution functions from each site specified in five depth classes. A theoretical curve with a normal distribution has been fitted for each set of depth data.

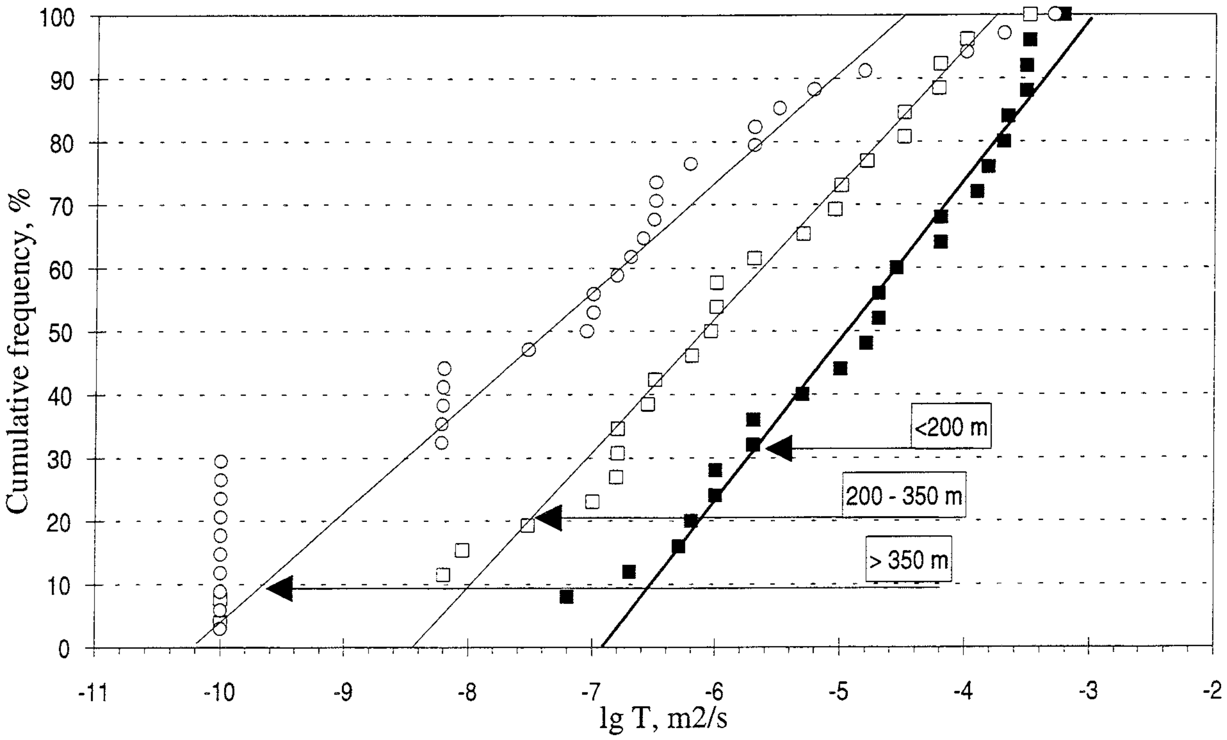


Figure 3-13. The transmissivities of structures shown as cumulative distribution functions from each site specified in three depth classes. A theoretical line with an even distribution has been fitted for each set of depth data.

The parameters determined by the above-mentioned examination are presented in Table 3-1.

Table 3-1. The mean and standard deviation of the logarithmic conductivity values in different depth classes on the assumption that the results presented in Figs 3-11 and 3-12 are normally distributed.

	All K-values		**Intact rock**	
Depth (m - m)	**mean value**	**standard deviation**	**mean value**	**standard deviation**
100 - 200	-8	1.7	-9	1.2
200 - 300	-9.2	1.6	-9.6	1.1
300 - 400	-9.6	1.7	-10.3	1.3
400 - 500	-10.1	1.8	-10.7	1.3
500 - 1000	-10.3	2	-11.1	1.2

The logarithmic fitting curves for the mean values are presented in Fig. 3-14. Two fitting curves have been used. The other curve also includes the values from the deepest class. In intact rock the fitting curve is in both cases nearly the same.

According to the measurements, the hydraulic conductivity shows a clear, probably linear depth dependency. It is possible that the dependency is not so strong below a depth of 500 meters. A phenomenon like this is best depicted with a logarithmic depth dependency or a combination of logarithmic and linear (uppermost 200 m) correlation.

By means of hydraulic interference tests, hydraulic connections between boreholes have been verified as well as the nonexistence or truncation of a potential connection. In the latter case the boundary conditions might have had some degree of influence. The transmissivities of some structures were specified and the storage coefficients were determined with the help of interference responses. The flow geometry was interpreted from the pressure responses. The geometry was usually found to be planar or in certain cases clearly tubular /Kuusela-Lahtinen A, 1992; Ylinen A et al, 1993/.

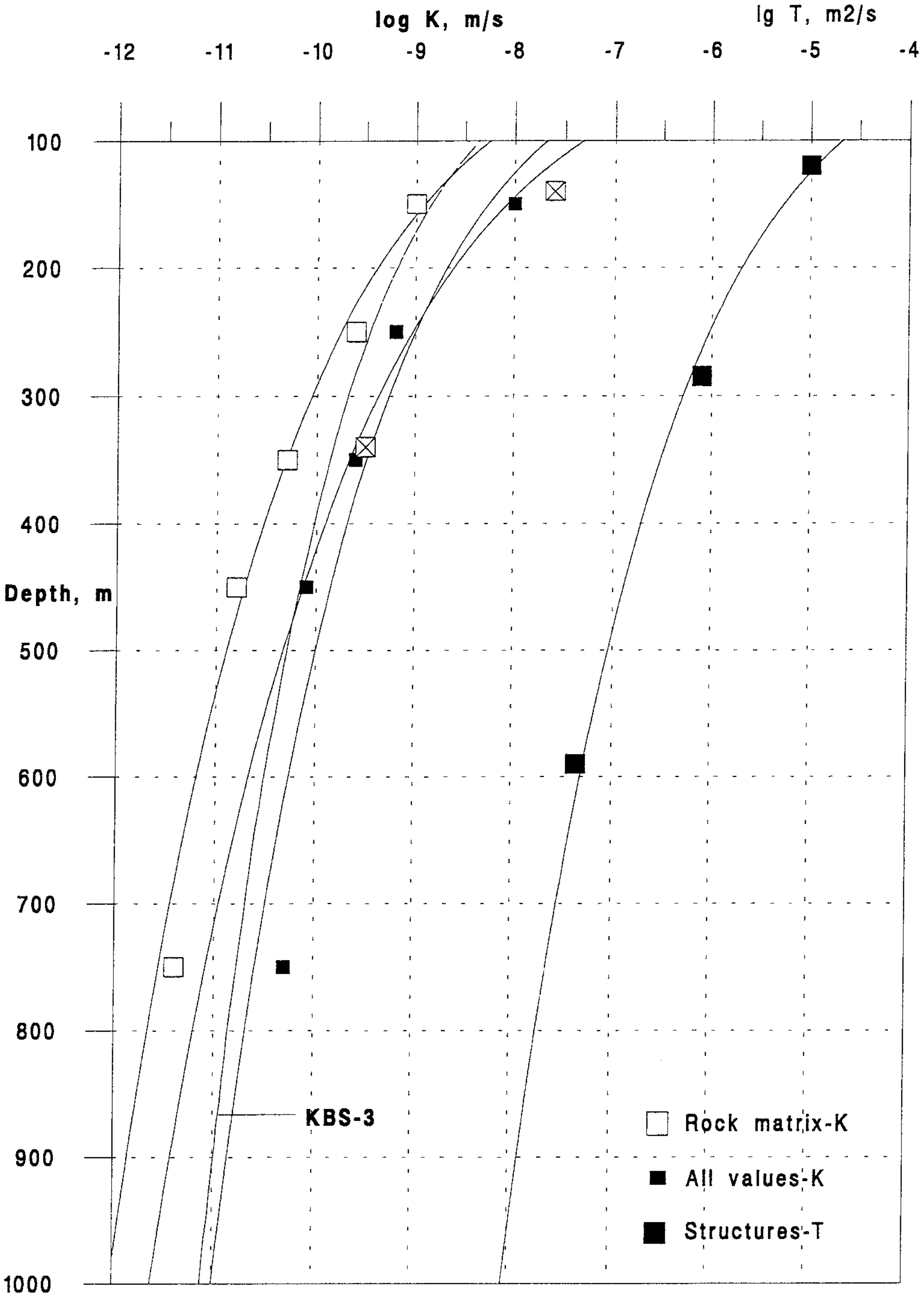


Figure 3-14. The mean values of different depth classes and the fitted logarithmic regression curves. Two curves have been fitted to the mean values. The other includes the four uppermost values and the other all five values. In intact rock the fitting curves are in both cases nearly the same. The open boxes represent so-called intact rock and the black boxes all the measured values. The open boxes containing a cross represent mean values of the entire data divided into two depth classes (< 200 m and 200 - 500 m) /Niemi A and Kontio K, 1991). In addition to the mean values and logarithmic fitting curves, a so-called KBS-3 fitting curve /KBS-3, 1983/ is also presented.

The hydraulic conductivity was measured with the constant head injection test principally from a depth of 100 meters to the bottom of the borehole (excluding the last 5...10 meters) with a 30.8 m packer interval, which was considered adequate considering the measuring time and resolution. The distribution and location of some (5...10 pcs) usually more conductive sections were remeasured with a 6.8 m packer interval. A section responsible for the transmissivity of the whole interval was often found. The quantity and quality of the results have generally been found to be good and adequate to characterise and approximate the intact rock in the flow model, in which intact rock was assumed to be based on the porous medium concept. The hydraulic conductivity results have preliminarily been used in fracture network model flow simulations. The results have been promising. A shorter packer interval combined with better fracture data would clearly decrease the impact of assumptions made in the simulation.

Passive fluid logging was used to locate inflow and outflow points in the borehole. The measurement was carried out by pumping deionised water into the borehole and by logging changes in the electric conductivity values in the borehole water. The results showed sections where water is flowing into the borehole or out of the borehole. Uncertainties were involved in interpretation of flow direction and location in some places, which decreased the reliability of results a little. In future, fluid logging will be replaced by a TVO-flowmeter, which can locate the flow points in the borehole. With the flowmeter it is possible to measure the hydraulic conductivity and estimate the hydraulic head by combining pumping of water from the borehole or injecting water into the hole with the flow measurement.

The hydraulic conductivity measurements by constant head injection have been interpreted using Moye´s equation for a stationary case. The results were on average 2...4 times higher than when using interpretation methods based on a transient case. Changing the injection time to one longer than one hour (used presently) would probably have decreased the difference between the two approaches because the flow rate at the end of the injection would have been slightly lower and consequently closer to real stationary conditions than in the present case. Taking into account the skin effect would have decreased the values with the Moye equation closer to the values with a transient approach. The average (median) skin apart from Kivetty area was in the range -1...-3. In Kivetty the average skin effect (median) was +1.

3.4.3 Hydraulic head

The hydraulic head was measured manually about once a week in 15...20 shallow boreholes at each site. The depth of the boreholes varied due to the overburden but the depth in bedrock was about 10 m. In reality the groundwater table might have been higher (recharge area) or lower (discharge area). By measuring the hydraulic head in boreholes and by a desk study of topographical maps, the isopotential maps of hydraulic head were compiled for each site and its surrounding. These were used as a boundary condition for the groundwater modelling. Mostly, a 2.5 meter interval in the isopotential maps was considered adequate. At Olkiluoto, where topographical relief is smoother than at the other sites, a 1.0 meter interval was chosen for the isopotential maps. In connection with groundwater modelling, some indications were discovered that in some central or essential areas the monitoring network was too sparse, or else determining the groundwater table by map study proved to be inadequate. The problem was emphasised in places where a major structure cuts the surface. If that particular place happens to be in an area higher than the surroundings, the impact of the structure may be several meters from the general correlation between the topography and the groundwater table.

Seven or eight multilevel piezometers were installed to monitor the hydraulic head in the upper part of the bedrock. The piezometers were about 100 m deep with three measuring sections. The sections were in the range of 5..10 meters long and they were backfilled with gravel. The sections were separated with cement packers. The lowermost section was placed at the bottom of the hole. The space between the uppermost packer and the casing created a fourth measuring section which complemented the data on the groundwater table. The measured values (the reading was carried out both with automatic device providing short reading intervals but also manually once per week enabling the control of the automatic reading) of the hydraulic head from the multilevel piezometers gave a good impression of the potential distribution and local deviations in the upper part of the bedrock.

The deep boreholes (500...1000 m) were packed off using inflatable rubber packers as planned. Water and nitrogen gas were used for inflating the packers. Only minor difficulties were encountered during the installation phase. Only in one borehole was the multipacker system left higher (about 30 m) than planned because the hole was jammed. Other problems related to installation and measurements were caused by measuring hoses in the upper part of the boreholes (leakage, cracks, flattening) and water used for inflating the packers (not enough water injected into the inflation hoses). The present measuring hoses will be replaced in future with smooth surface hoses made of polyamid. The inflation hoses (6/8 mm in diameter) will be replaced in future with larger diameter hoses which allow the amount of the water to be measured in the hose. In addition, it might be necessary to consider installing a one-way valve at the lower end of the inflation hose. The valve will control filling of the hose during the installation phase.

The results of the hydraulic head monitoring have already been used in some areas in conjunction with developing the conceptual structural model to verify the existence or nonexistence of a structure. The packed off boreholes have been used for monitoring purposes during the pumping test. They have also enabled groundwater sampling with much more representative samples than in the case of open boreholes. The results of the hydraulic head measurements have been of utmost importance when calibrating the groundwater flow model. The transmissivity of structures has been specified and changed in various cases. The consistency between the results from the groundwater flow model and the field data has enabled the evaluation of the representativeness and certainty of the conceptual structural model.

In addition to the problems related to the hydraulic head measurements mentioned above, there were some minor problems with malfunctioning of the automatic data loggers. The disturbances were mainly caused by humidity and probably by the stability problems with pressure transducers. Therefore the manual control measurements were of utmost importance.

4 OVERVIEW OF THE CONCEPTUAL MODELLING

4.1 BACKGROUND

Conceptual modelling in this context means the development of a set of geometric bedrock models and studies to derive the geological, hydrogeological, geochemical and rock mechanical properties of the structures in the models, all consistent with the data obtained. Modelling is based on interpretation of the different alternatives and expert judgment. A regional model describes the investigation site and its environment. The site model describes the site block in detail. The first conceptual models of the sites were compiled during the site selection phase in 1983-1985. During the preliminary site investigations the model was tested and more data has been collected for a true three dimensional model.

The modelling work procedure is described briefly here, using the Olkiluoto site as an example. Other areas have undergone similar work.

4.2 BEDROCK MODELLING

4.2.1 General

Bedrock models are generally free in their form and shape but here an approach was adapted that fracture zones and fractures are described as continuous, planar zones according to widely used principles. The starting point of the modelling of zones is that it can be approximated by a set of piecewise continuous planar zones. In the site scale where rock volumes are several cubic kilometers, the properties are averaged and they are assumed to be continuous to a certain extent.

A great number of structural details are typical to the models. The structures and rock types were divided into three categories (observed, probable, possible) according to their relative importance. The judgement of the importance is based on the likelihood of the existence, and the properties of the structures and rock types. This is why the conceptual structural models are complex. Modelling has consisted of combining complex geological, geophysical, hydrogeological and geochemical data. The data obtained in the work were evaluated, sorted and classified. Finally the goal was to achieve a wide understanding of the multidisciplinary data related to the models through discussions among the experts, thus arriving at a mutual understanding.

4.2.2 Modelling methods

Developing a structural model to describe the geometry of bedrock is mostly based on geophysical interpretation results. Various geophysical methods have been used to characterise the lithologic and structural units of the bedrock. Geophysical methods that are able to give information on a greater rock volume, such as Reflection Seismics, Vertical Seismic Profiling, single hole borehole radar, Vertical Radar Profiling, were systematically used to detect structures.

The most important three-dimensional geologic information was collected at outcrops and in boreholes. Observations were made on rock types, deformation and fracturing. Oriented core samples provide a valuable background information for a three-dimensional model development.

Other methods used in model development are:

- Combination of fracture data on the outcrops and boreholes. The errors in the distribution of the fractures caused by the observation geometry were corrected.
- Oriented core data were used to define the orientation of radar reflectors. It is assumed that most of the reflectors are consistent with the main fracture orientations.
- VSP and HSP reflectors are combined with other indications of fractured zones observed with other methods.
- The geohydrological properties of fracture zones were classified according to the results from constant head injection tests.
- The correlation between boreholes and the ground surface was established by means of comparing the characteristic features of the fractures and the geophysical anomalies.
- VRP reflectors were combined with the ground geophysical anomalies and crush zones observed in the boreholes and the VSP results.
- The three dimensions for hydraulically conducting borehole sections, and their connections to zones regarded as hydraulically significant, were studied, although information available is sparse. Specific lithologic, tectonic, geohydrological and geophysical features were used in the extrapolation of results between boreholes.

4.2.3 Modelling tools

Three-dimensional visualisation of the models to all the participants in a common form is an important task. For this purposes the ROCK CAD software was used. This three-dimensional method for presentation provided the modelling team with a shared view to each model and highlighted the details that called for complementary interpretation or further evaluation.

The structures of model were stored in a computerized system enabling display of the whole model or any part of it. Cross-sectional and perspective drawings were printed out for further use in conjunction with repository design, for example.

4.2.4 Bedrock modelling of the Olkiluoto site

4.2.4.1 Submodels

The conceptual three-dimensional rock model for the Olkiluoto site distinguishes between three types of submodels:
- lithology,
- fracture zones,
- rock matrix fracturing in general.

The fracture zone model and model rock matrix fracturing are overlapping by such a way that the rock matrix includes the fracturing not explicitly included in the fracture zone submodel.

4.2.4.2 Lithologic units

The rock types at Olkiluoto (Fig. 4-1) are migmatite which may be divided into mica gneiss and veined gneiss and also tonalite and coarse-grained migmatite granite (pegmatite). Tonalite and granodiorite are encountered in the gneiss as intrusions conforming to the direction of schistosity. The tonalite sequences are typically of medium or steep dip, the strike being to south and south-east. These sequences are also frequently gneissic. Diabase is encountered in a single narrow dike. Apart from the diabase, the rocks have undergone a polyphasic deformation.

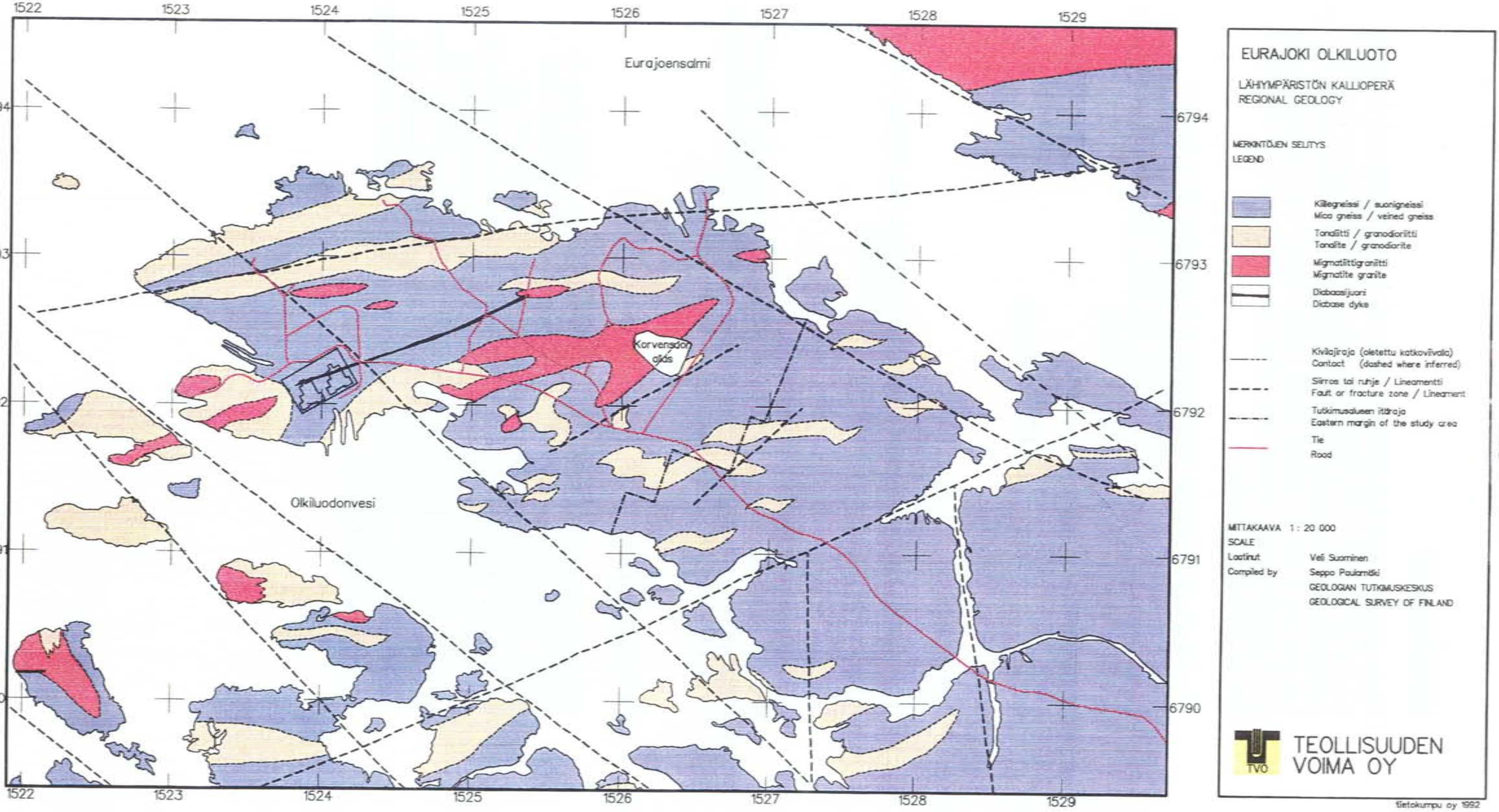


Figure 4-1. Regional geology at Olkiluoto /Anttila et al, 1992/.

The observed fractures are mainly tight and the mean fracture frequency varies in the range 0.6 ... 0.8 pcs/m on the outcrops and 1.0 ... 3.6 pcs/m in the boreholes. The highest fracture frequency occurs in the pegmatite of the surface parts of the bedrock. The fracturing is concentrated in five main orientations, two with a gentle dip and three with a steep dip, and these together account for over 50% of the total observed fracturing.

4.2.4.3 Structural units

The regional fracturing model (Fig. 4-2) is based on satellite images, aerial photographs, the basic maps and the ground level and airborne geophysical surveys. For the regional fracturing model it was assumed that the crush zones continued deep into the base of the model, i.e., to a depth of 1500 m. The dips of the structures are assumed to be vertical in case there is no information available.

The local fracturing model comprises the island of Olkiluoto and the archipelago in the immediate vicinity, and depicts the fracturing structures for which direct or indirect evidence was found in the fieldwork. The majority of the fracture structures were identified by direct observations in the field. The degree of fracturing in the local structures varied from stretches of bedrock with abundant fractures to significant crush zones.

The Olkiluoto model covers a bedrock volume of approx. 52 km^3, including about 27 km^3 of the island itself. It extends to a depth of 1500 m and contains 25 fracture structures (R1...R25). These occur mostly in zones, although with varying dimensions, particularly in terms of their width. The bedrock between these zones is regarded as intact. A three - dimensional illustration of the fracture zones at the surface and in the bedrock is shown in Fig. 4-3.

A summary of the fracture structures depicted in the bedrock model is given in Table 4-1. The model is mostly based on direct observations (combinations of drillings, surface and borehole geophysical measurements and hydraulic tests) with seven structures, R3, R4, R6, R7, R16, R24 and R25, derived from indirect evidence. These were not penetrated by the drillings but there are a number of other mutually corroborating pieces of evidence that confirm their existence. Only one structure classified as possible was included in the basic model.

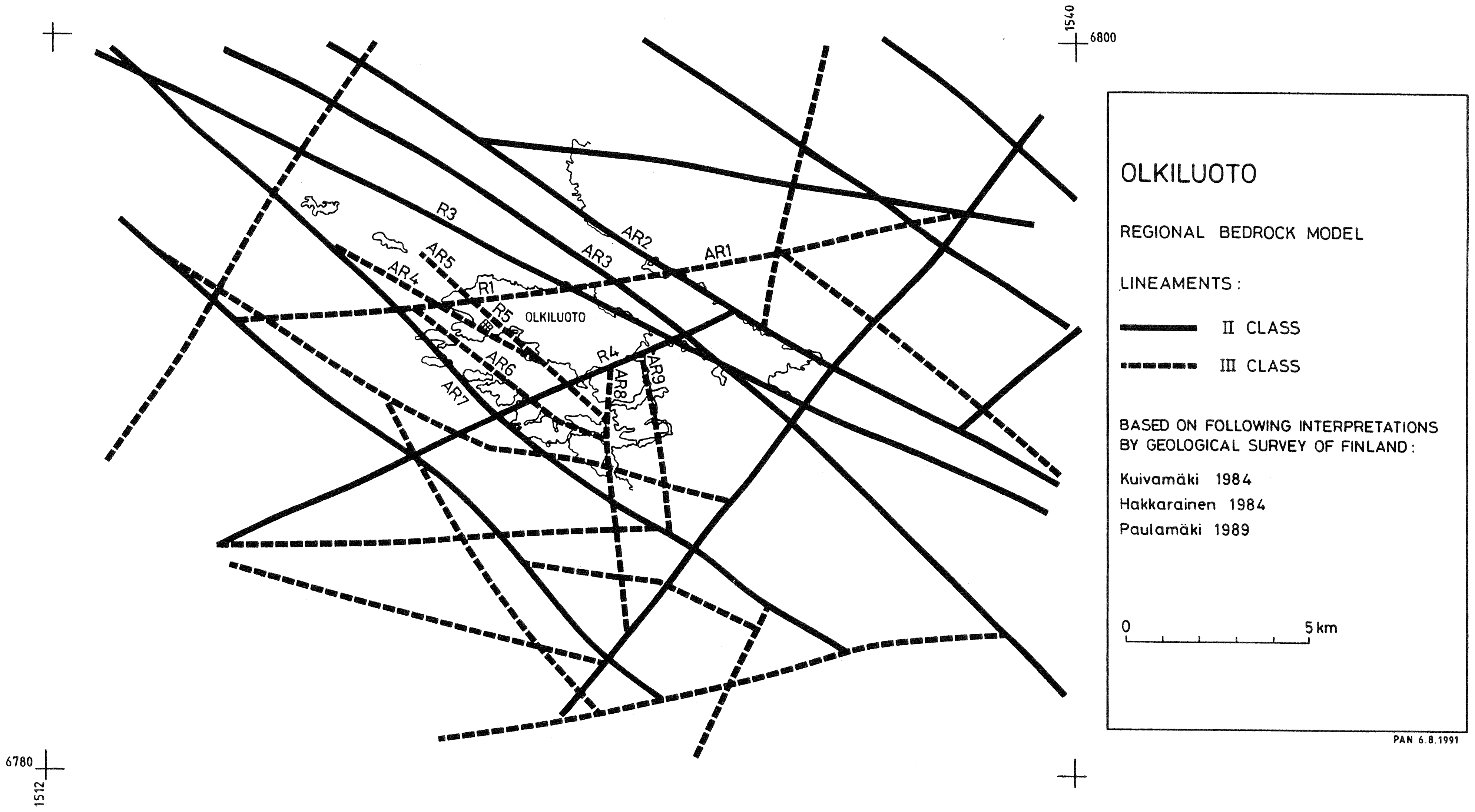


Figure 4-2. Regional fracturing model of the Olkiluoto site /Saksa et al, 1992c/.

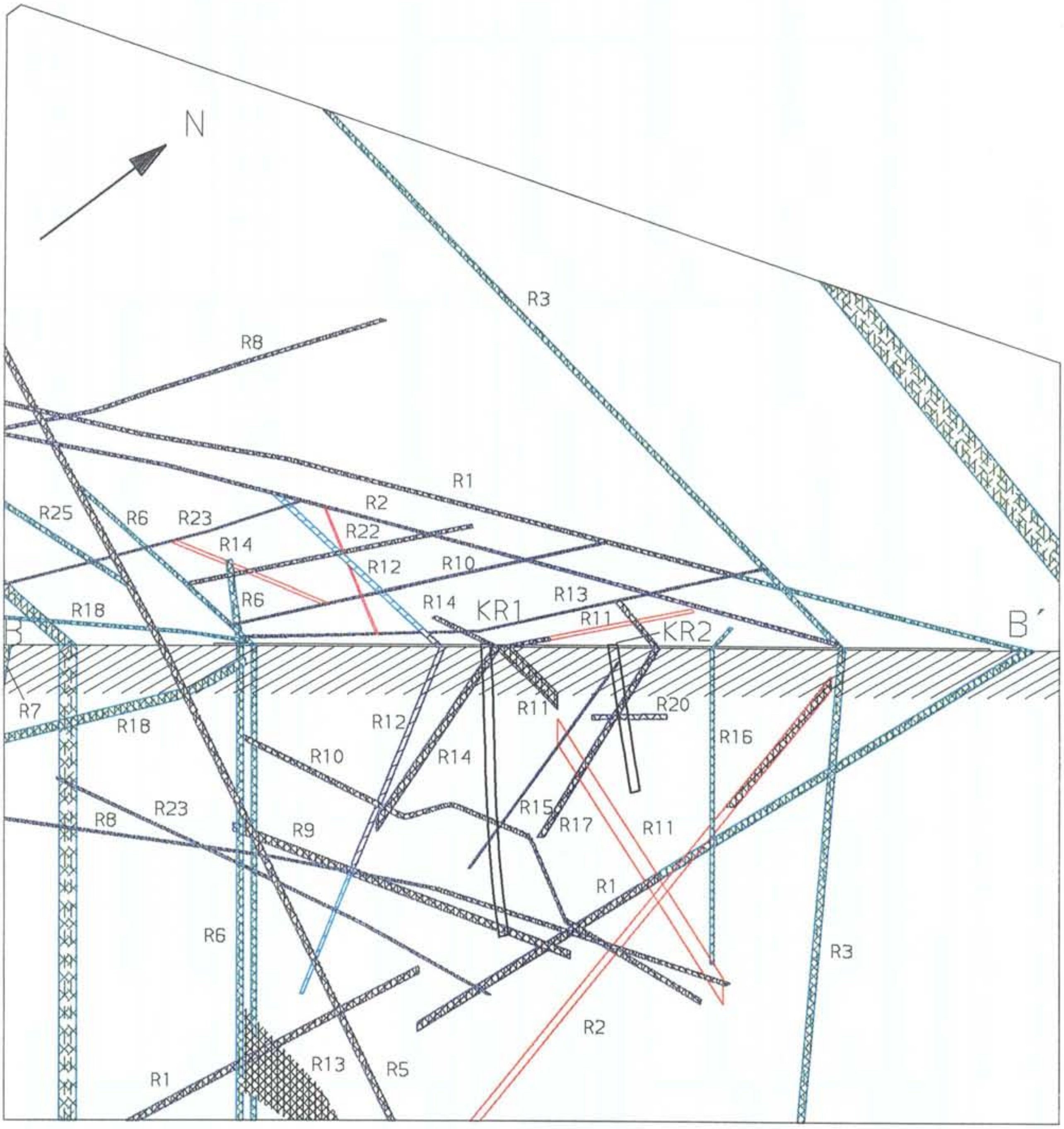


Figure. 4-3. Three-dimensional representation of the structures at the surface and in the bedrock /TVO, 1992/.

Table 4-1. Summary of the properties of the fracture zones in the bedrock model /Saksa P at al, 1992c/.

NOTATION: * = observed or deduced property of the structure

STRUCTURE PROPERTY, CHARACTER AND SPECIAL FEATURES	*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**
Extension at the ground surface																									
- 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	*	*																							
Continuous, compact structure /	*	*	*		*	*		*	*		*	*	*		*	*						*	*	*	*
Discontinuous structure				*			*			*				*			*	*	*	*	*				
Tectonized, mylonitized	*					*				*															
Knowledge level																									
- based on direct observations	*	*			*			*	*	*	*	*	*	*	*		*	*	*	*	*		*		
- based on several indirect interpretations and estimations of different types			*	*		*	*									*								*	*
- based on one indirect interpretation or uncertain in other respects																						*			
Weathering degree: Rp0 - Rp3	0-2	0-1						0	0	0-2	0-1	0	0-1	0-1	0-1		0	0-1	0-2	0	0-2		0-2		
Fracturing degree: Ri I - Ri V	III-IV	II-III						III	III	II-IV	II-III	II	III	II-III	III-IV		III	II-III	II-III	III-IV	III-IV		III-IV		
Structures deemed most important for rock engineering	*		*	*	*					*					*					*	*		*		
Structures deemed most important for groundwater hydraulics			*	*	*							*		*	*			*							
Observations in deep boreholes KR-KR6, ( )=indirect observation	KR1 KR6	KR5						KR1	KR1 KR3	KR1 KR3 KR5	KR1	KR4	KR1	KR1	KR1 KR2 KR4		KR2 (KR5)	KR4	KR4	KR2 (KR5)	KR5				

4.2.4.4 Description of interpretation procedure

The first interpretation phase (covering tasks like borehole-by-borehole evaluation or ground and airborne geophysics interpretation) preceded the modelling work. Hence, all surface and borehole plots, maps and summarising tables etc. were compiled and reported in TVO´s work report series.

The 3-D interpretation and outlining of a tentative model was outsourced as a first step to three different groups of specialists. Organisations, tasks and contents of the working groups are summarised in Table 4-2 below.

Table 4-2. Organisations, tasks and compositions of the 3-D interpretation and model outlining works.

Organisation	**Task / Report code**	**Specialist(s) involved**	**Focused on**
Geological Survey of Finland; Nuclear Waste Disposal Research	Characterisation of bedrock structures at the Olkiluoto study site, Eurajoki, western Finland / Work Report 91-33	Geologist, Geophysicist	- lithology and fracture zones, - also regional coverage
Technical Research Center of Finland; Road, Traffic and Geotechnical Laboratory	Characterisation of bedrock structures at Olkiluoto test site, Eurajoki, SW Finland / Work Report 91-31	Geologist-geochemist, Geologist, Geophysicist	- fracture and hydraulic zones, volume delimited by borehole studies
Saanio & Riekkola Oy	Interpretation of fracture zones using site investigations of TVO I and TVO II and VLJ-site Work Report 91-42	Engineering geologist	- Olkiluoto island western half, - other than SITU-project geoinvestigations

The work was done during the first half of 1991. Each group used approximately 2 ... 5 man-hour months. Each group also focused on some part or discipline they were most familiar with. As final products they produced surface maps of inferred fracture zone locations, as well as cross-sections along predetermined cut lines. Surface maps of these models developed are reproduced in Figs 4-4...4-6. Each working group used its own classification criteria. One of these was the Engineering Geological classification adopted in Finland. The purpose was to take notice of as many structures and indications of fractured zones as the modelling groups could find and justify. The maps in Figs 4-4...4-6 are to some extent in a good agreement but also indicate diverging and contradictory results. This could also be expected due to the partly differing input material and the complex nature of the anomalies to be interpreted.

After this tentative modelling work phase the modelling group of TVO´s project organisation was assigned for next phase (Table 4-3). The group assessed the three previous submodels, collected common, correlating interpretations and made further interpretations and studies concerning open issues (such as unsolved fracture zone sections in the boreholes). Submodels were coded and listed in the ROCK-CAD system, including a small set of the most important borehole reference data. Cross-sections were drawn by ROCK-CAD, studied and some iterative adjustment was done for the bedrock structures.

After the structural model was mainly fixed, an assessment of the hydraulic properties of the zones was made. The indications of the saline groundwater were discussed in relation to the structural model developed. The geometry of the fracture zone structural submodel was converted in digital form to a groundwater flow simulation. A surface map of the fracture zone submodel from this phase is reproduced in Fig. 4-7. This work phase was at the end of 1991.

The final modelling phase consisted of expert meetings and writing the bedrock modelling report. Three expert meetings were arranged during March-April 1992. The participants were the same as involved in the previous modelling tasks. The report of the geometrical model was reviewed, an attempt was made to resolve open issues (for example, the seismic interpretation workstation was on hand for the meeting). If two or more possible alternatives were noted, one was selected as more probable for the structural model and others documented as an alternative solution. Lithology (such as rock type names), most recent data (e.g., head value recordings and tectonic borehole KR6 results) were discussed and their influences in the corresponding submodels were incorporated into the model. Supplementary interpretations were documented in the form of internal memoranda.

A description of the three-dimensional rock matrix fracturing was written after fracture zone structures were fixed. This is documented and illustrated in detail in the bedrock modelling report /Saksa et al, 1992c/.

The surface maps of the final structural and lithologic submodel that were obtained are presented in Figs 4-8 and 4-9. A careful comparison of Figs 4-7 and 4-8 shows that several changes were made during the final modelling stage. A fairly large number of small changes were made to the surface extent, depth extent, dip values, and "certainty" degree of the structures. It is important to note, and understand that the fine-tuning did not seek to achieve one realistic detailed model of the site. The purpose was to construct mutually correct evaluations between the structural submodel components and to achieve the best-estimate result. Fig. 4-8 reveals the fact that model is more detailed ("structure density") where the data are available for interpretation. This implies that the investigation programme, i.e., the methods selected, largely regulates - and well before the modelling even is carried out - the type of models developed and the degree of detail they will have.

Table 4-3. The work phases within TVO´s own project organisation

Organisation	**Task/ Report code**	**Specialist(s) involved**	**Focused on**
Saanio & Riekkola Oy Imatran Voima Oy	Geometrical model of the fracture zone structures of the Olkiluoto site, Eurajoki /Work Report 91-52	Geologist, Geophysicist, Hydrologist, CAD-engineer	- combined interpretations, - regional and local coverage, - hydraulic assessment, - CAD modelling, - GW salinity

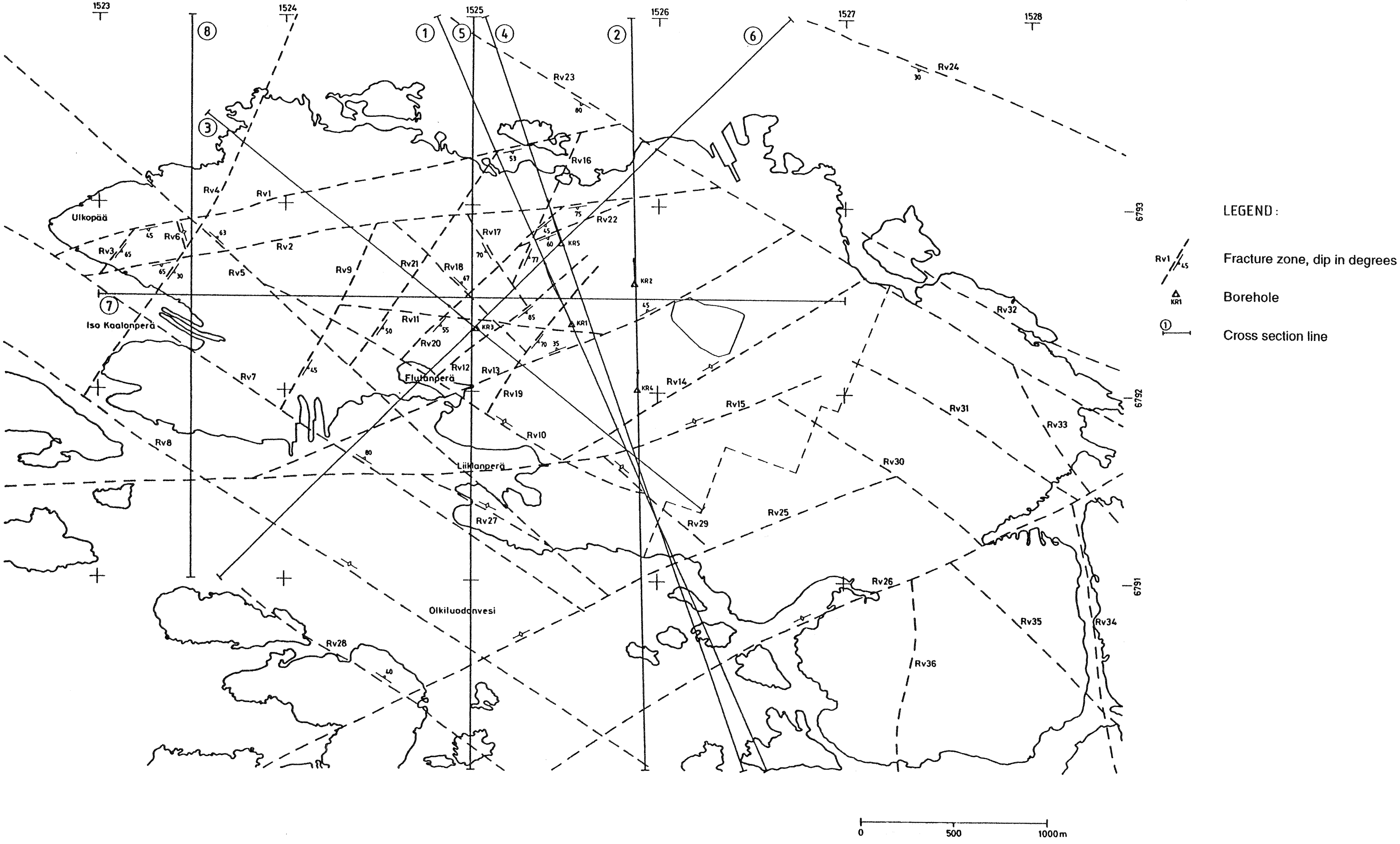
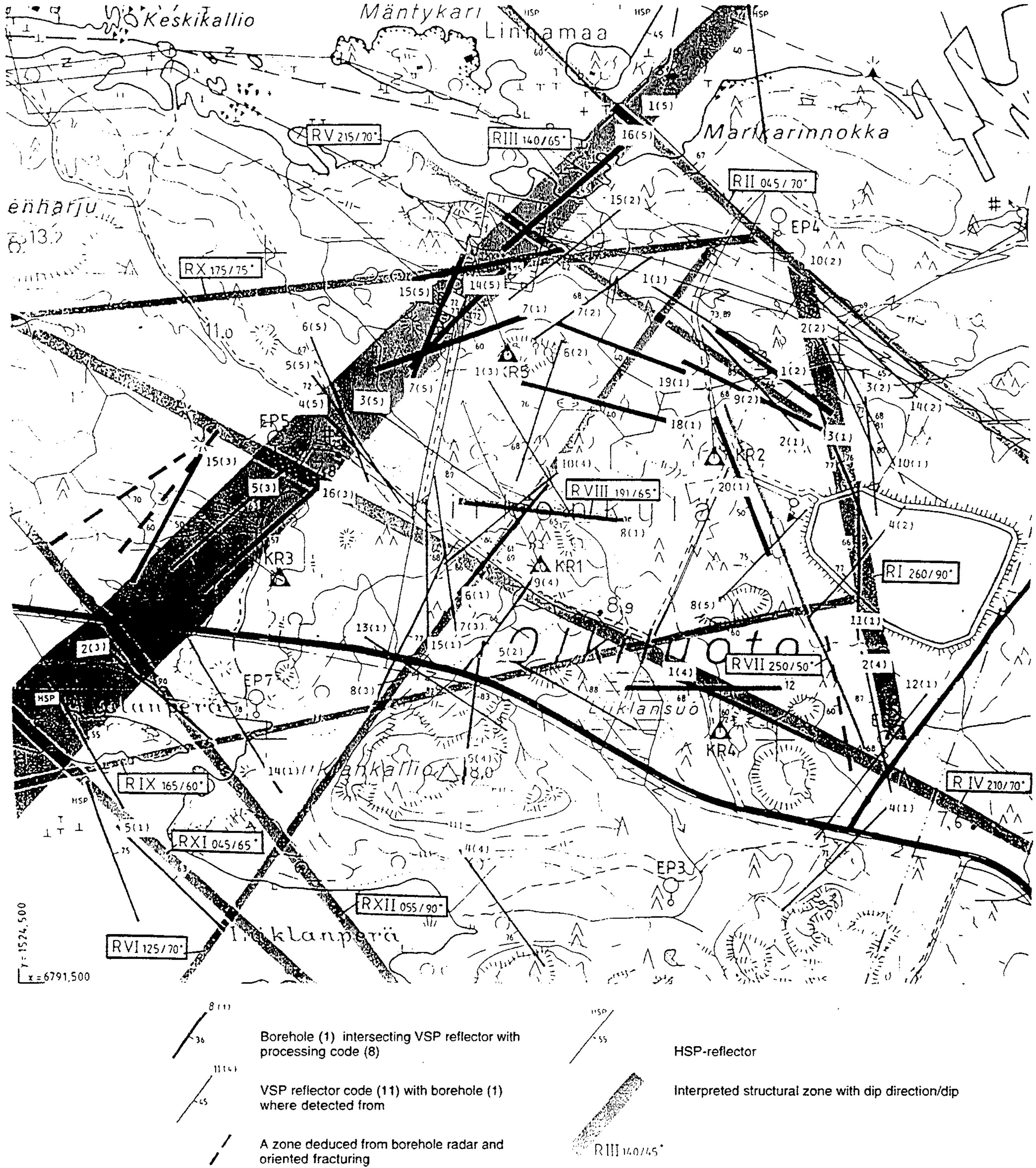


Figure 4-4. Surface map of one realisation of the fracture zones at the Olkiluoto area /Paulamäki S and Paananen M, 1991/.



Technical Research Centre of Finland
Road, Traffic and Geotechnical Laboratory

Figure 4-5. An interpretation of the locations of fracture zone structures at the primary, borehole covered area /Pitkänen et al, 1991/.

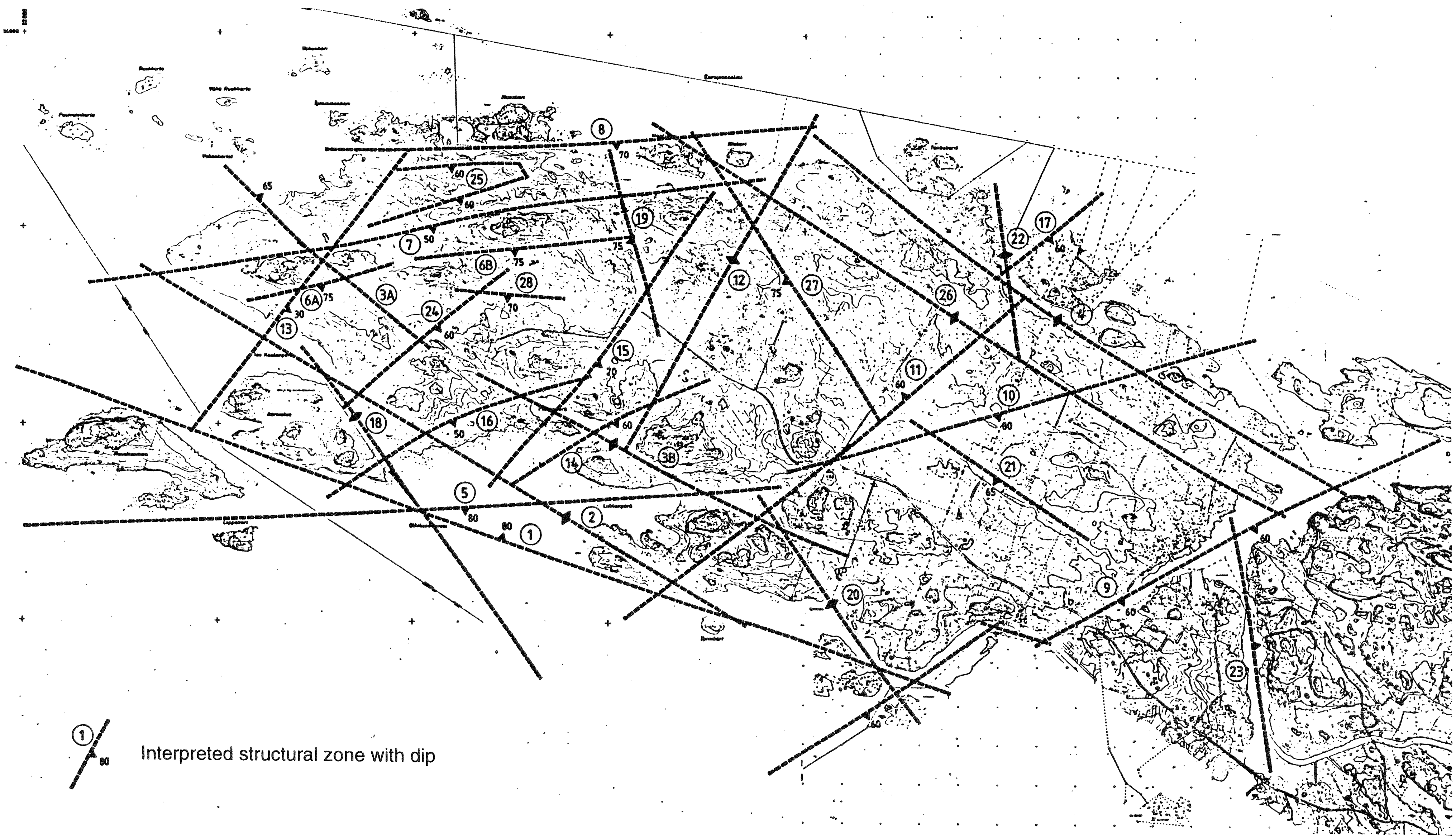


Figure 4-6. A surface map of the power plant and VLJ investigations based on a realisation of the fracture zones in the Olkiluoto area /Äikäs K, 1991/.

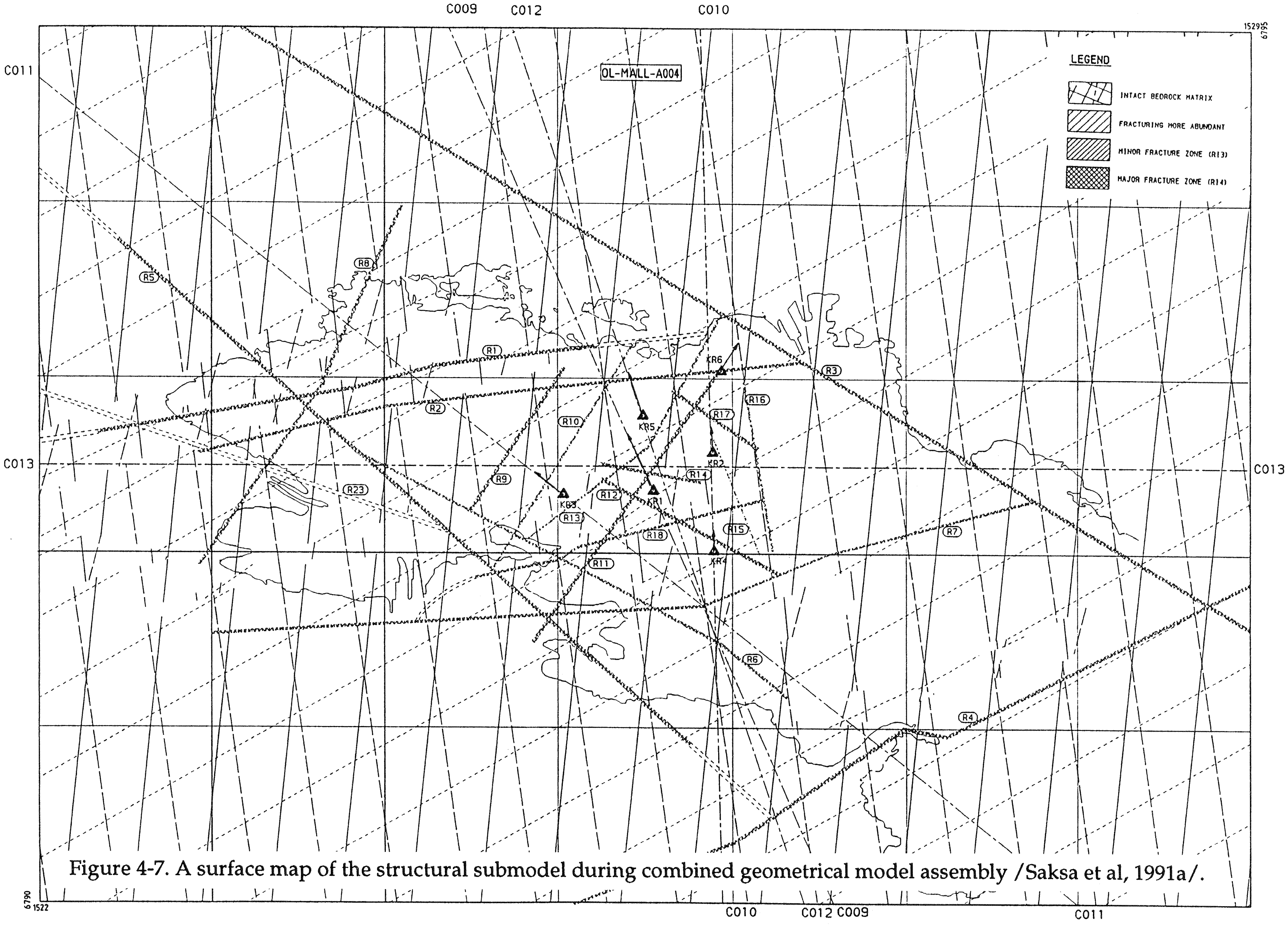


Figure 4-7. A surface map of the structural submodel during combined geometrical model assembly /Saksa et al, 1991a/.

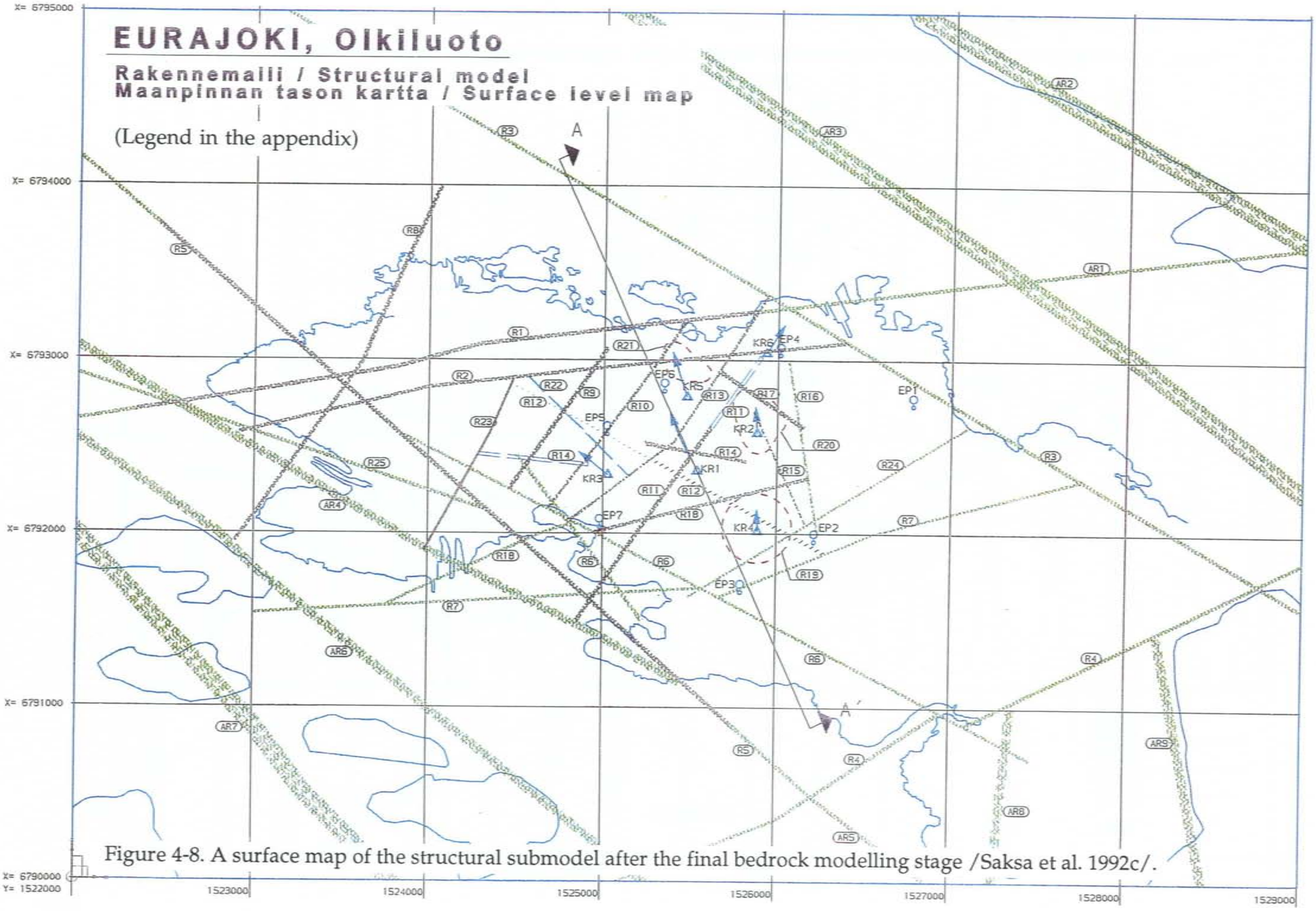


Figure 4-8. A surface map of the structural submodel after the final bedrock modelling stage /Saksa et al. 1992c/.

4.3 GROUNDWATER FLOW MODELLING

4.3.1 General

The objective of groundwater flow modelling is to simulate groundwater flow at the investigation site. Three-dimensional groundwater flow modelling is based on a conceptual bedrock model, interpretation of the hydraulic bedrock units and the elevation of the water table.

The main stages in the modelling of the groundwater flow are presented in simplified form in Fig. 4-9.

The work was carried out in two phases. The first phase includes developing a conceptual flow model, a simplified bedrock model. The second phase comprises the calibration of the flow model. The objective of these phases is to model the flow as realistically as possible. The main aim is to understand the flow pattern within the area and quantify the amount of groundwater moving in the bedrock. The choice of the modelling method is governed both by the purposes for which the model is intended and also by the extent of the area to be studied, and of course, the nature and quantity of the data available. The numerical simulation method is based on the continuous porous medium approach and the finite element method.

The first step included preliminary modelling with the tentative results. The modelling area was expanded outside the borders of the investigation area to the boundaries where no-flow boundary conditions were assumed to be prevailing.

As the second step the model was updated and adjusted to match the final version of structural model and the measured values of the hydraulic head in the boreholes. Both the undisturbed situation and the pumping test were modelled. The computed infiltration rate was examined, too. In the calibration process, the boundary condition for the surface that is groundwater table, was modified. On the surface the piezometric head field was assumed to follow the elevation of the water table. Sensitivity and uncertainty analyses were also included in these calculations in order to assess the significance of the uncertainties contained in the initial data for the results.

The results of hydraulic conductivity measurements with constant head measurements as well as pumping tests have been valuable for the groundwater flow modelling. A hydraulic head monitoring system is compulsory in order to establish the hydraulic head distribution in the bedrock.

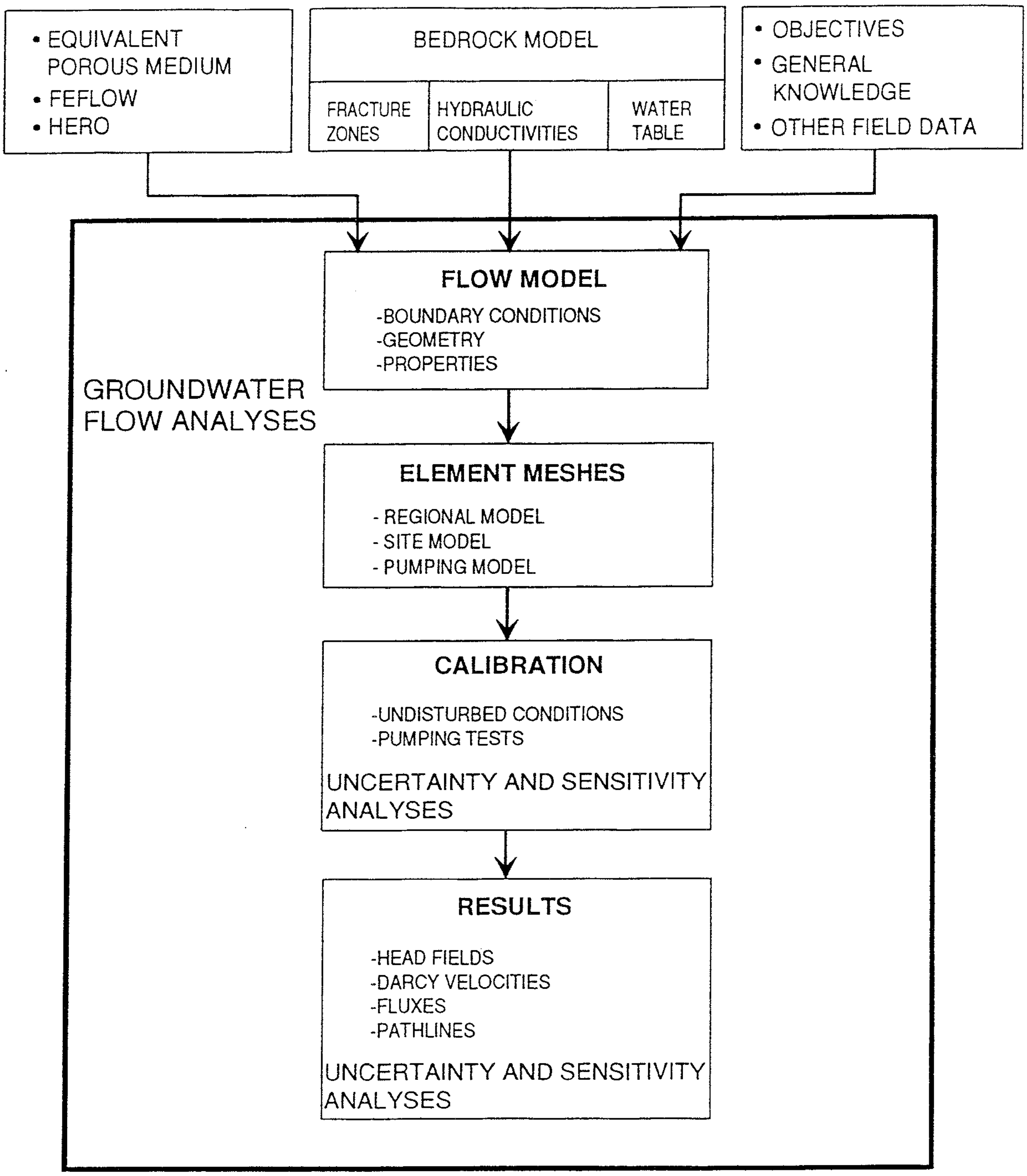


Figure 4-9. The main stages in the modelling of groundwater flow /Taivassalo et al, 1994/.

4.3.2 Modelling tools

Groundwater flows was calculated using the FEFLOW software developed for the three-dimensional simulation of groundwater flow in a continuous porous medium. The program also uses two- and one-dimensional elements to represent fracture zones, for example. The software allows the continuity of the hydraulic head to be resolved, as well as the flow field, the flux with respect to an arbitrary surface, and the groundwater flow paths in terms of pathlines with flow distances and times.

The commercial PATRAN program was to first used to generate the element mesh required for the FEFLOW software, and later for the presentation of the results. This is an interactive pre-treatment and post-treatment tool for the analysis programs based on the finite element method. The program accepts the geometry developed for a bedrock model to be transferred directly from the ROCK CAD software in digital form as an initial database for groundwater modelling. The benefit of this procedure is that when developing a conceptual flow model, and its structure, the orientation, location and size can be kept exactly similar to conceptual bedrock models. This is especially important when calibrating the calculations by flow model to measured head values, for example. If boreholes and structures do not exist in the same location in the both models adjustment of flow simulation becomes more complicated.

The operation of the sub-programs POMO, PAAWI, ELMO and ONNI in conjunction with PATRAN is depicted in Fig. 4-10.

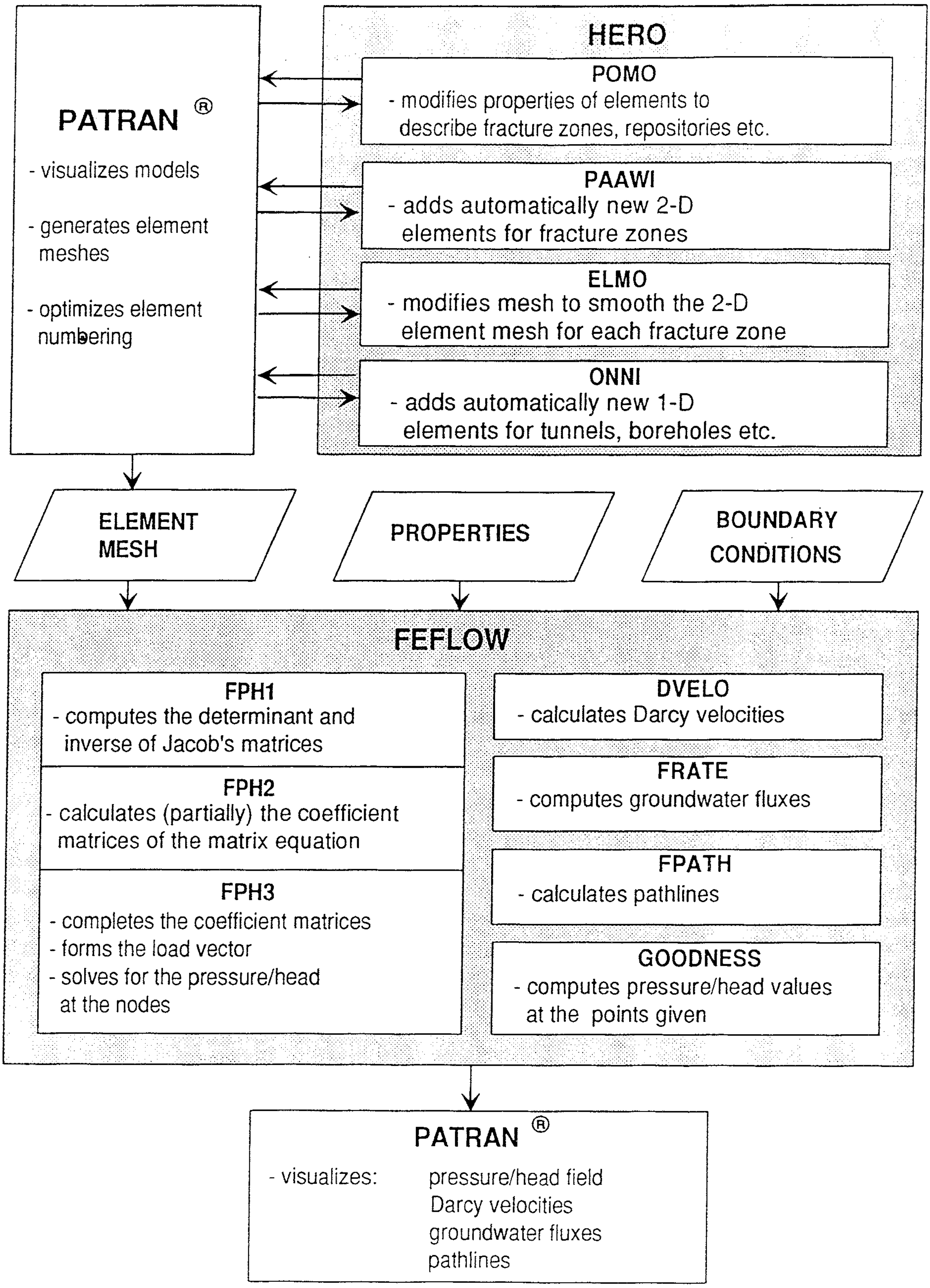


Figure 4-10. Software used in the modelling of groundwater flow /Taivassalo et al, 1994/.

4.3.3 Groundwater flow modelling of the Olkiluoto site

4.3.3.1 Initial model

The conceptual bedrock models were used to produce conceptual flow models to represent the groundwater flow and enable an examination to be made of these, and the amount of water flowing in the intact bedrock. Modelling of the groundwater flow requires the definition of initial hydrogeological data for the fracture zones and intact bedrock separately, and this was also done for the regional and local models separately.

The fracture zones at Olkiluoto were divided into four classes (sensitivity analysis was carried out with a different number of classes) as presented with calculated hydraulic conductivities. The geologically significant crush zones in the regional model (AR2, AR3, AR6 and AR7) were calculated to have conductivities equal to the most conductive fracture zone in the local structure model detected by the field measurements, R18 (class A in Fig. 4-11). The measurement results placed structures R12, R14 and R15 in class B, and the local structures R3, R4 and R5 and the remaining zones in the regional model attained comparable values. All the other local structures belong to classes C and D, or under an alternative classification scheme to a single class E.

The intact bedrock of the regional model is estimated to have a slightly higher hydraulic conductivity than that in the local model because it includes local fracture zones which are treated separately in the local model. Two linear averagings were fitted to the logarithmic hydraulic conductivity values obtained for the fractured intact bedrock one of which, line H, is derived from data in which some of the values at the lower limit of sensitivity are reduced to correspond to the actual low hydraulic conductivities.

The conceptual bedrock model was the basis for the conceptual flow model. The aim was that it should be as nearly identical in its hydrogeological properties to the bedrock model as possible and should conform to it particularly as far as the connections between the structures were concerned. Each structure and each stretch of intervening bedrock was assumed to alter with depth. The initial values were obtained mainly from the bedrock model, and the upper boundary of the model was taken to consist of watersheds or regional crush zones where possible, the other boundaries being assumed to be closed to groundwater flow. The initial hydraulic conductivities were defined on the basis of the values assigned to the fracture zones and intact bedrock in the bedrock model, and the final values were presented after adjustment. Since the flow model extends to the depth of 2000 m, extrapolations were made from the conductivity values assigned in the bedrock down to 1000 m.

The finite element meshes were constructed for the numerical simulation of the groundwater flow. The larger of these covered the whole block in which the Olkiluoto site is situated, an area of approx. 15 km^2, and was used to calculate the boundary conditions for the smaller one, the actual site model, applying to an area of about 7 km^2 and containing about 36 000 elements. The most significant bedrock crush zones in the areal model were described by means of two-dimensional elements.

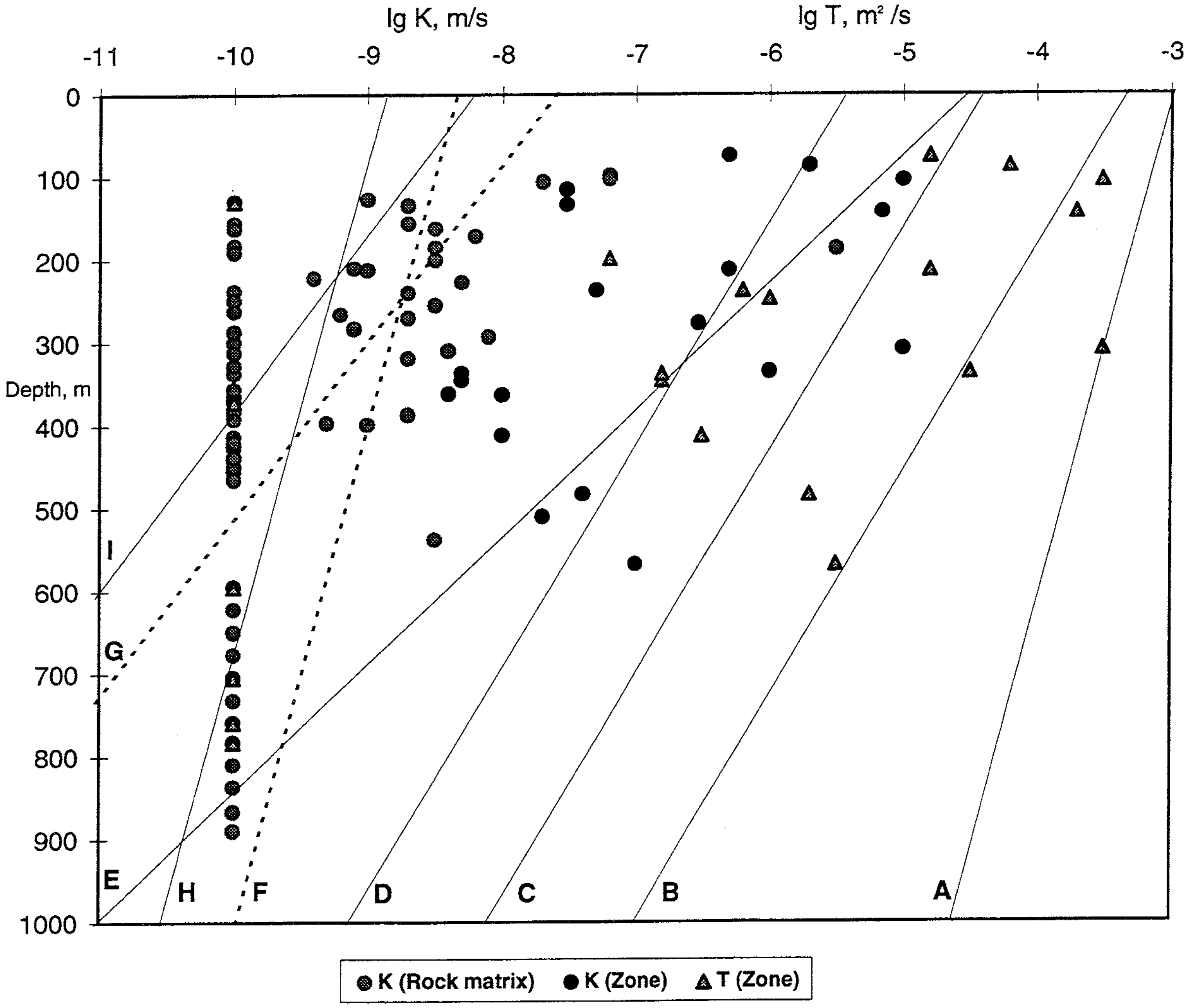


Figure 4-11. Transmissivity of fracture zones (T;m^2/s) and mean hydraulic conductivity of intact bedrock (K;m/s) at Olkiluoto. A = main regional fracture zones and local zone of highest conductivity (T), B-E = other fracture zones (T), F and G = regional intact bedrock (K) and H and I = local intact bedrock (K) /TVO, 1992/.

The site model was delimited in such a way as to ensure that its boundaries were sufficiently far away from the area characterised by the boreholes and located in intact bedrock beyond the crush zones surrounding this area. This enables boundary values to be transferred more reliably from the larger areal model. The position of the groundwater table used as the upper boundary for the model is depicted in Fig. 4-12. The depth of the model was then set at 2000 m, i.e., sufficiently deep that this dimension would no longer affect the results at around 500 m, the depth of maximum interest.

For the sake of simplification it was assumed that the groundwater density is constant, although saline water (< 28 g/l) has been encountered at Olkiluoto.

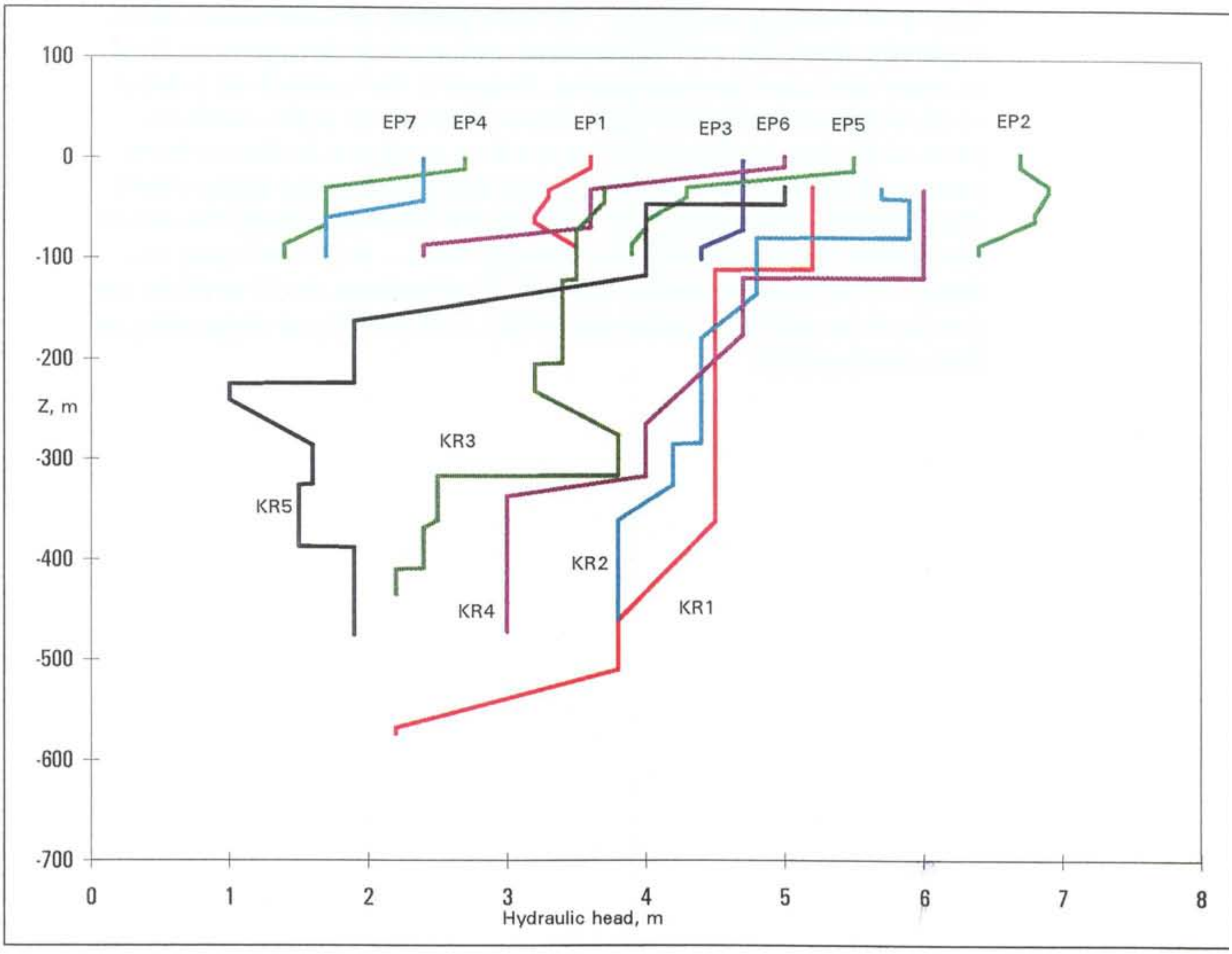


Figure 4-12. Hydraulic head in packed off boreholes and multilevel piezometers as a function of depth /TVO, 1992/.

4.3.3.2 Calibrated model

The flow model was then used to solve the groundwater head field, so that the result could be compared with the borehole measurements, after which the flow model could be adjusted by making alterations to the hydraulic conductivities of the fracture zones and intact bedrock in an attempt to find values which would best correspond to the measurements and the estimated infiltration rate. No adjustments were made to the structure of the flow model.

For adjustment purposes a use was also made of the pumping tests carried out in various sections of the deepest borehole, since the responses of the pumpings had been observed in the surrounding holes. The calculated hydraulic heads are presented for horizontal planes at the surface and at a depth of 500 m in Fig. 4-13. The crucial parts of the site are located in the centre of the island, where from the groundwater flows to the north and south on either side of the practically E-W-oriented watershed. The flow pattern is nevertheless interrupted by local hills and depressions which cause deviations in flow in many directions at some points. Deeper in the bedrock (at a depth of about 500 m) the water again flows southwards in the southern parts of the area and towards the north or northeast in the northern parts, and the various deviations from this found at the surface have disappeared. The groundwater flow in the bedrock outside the actual conductive structure varies in the range 0.001 ... 0.01 $l/m^2/year$ at a depth of 500 m. If we assume that all the structures are 10 m thick, the flow in them will vary in the range 0.01 ... 30 $l/m^2/year$ depending on their conductivity.

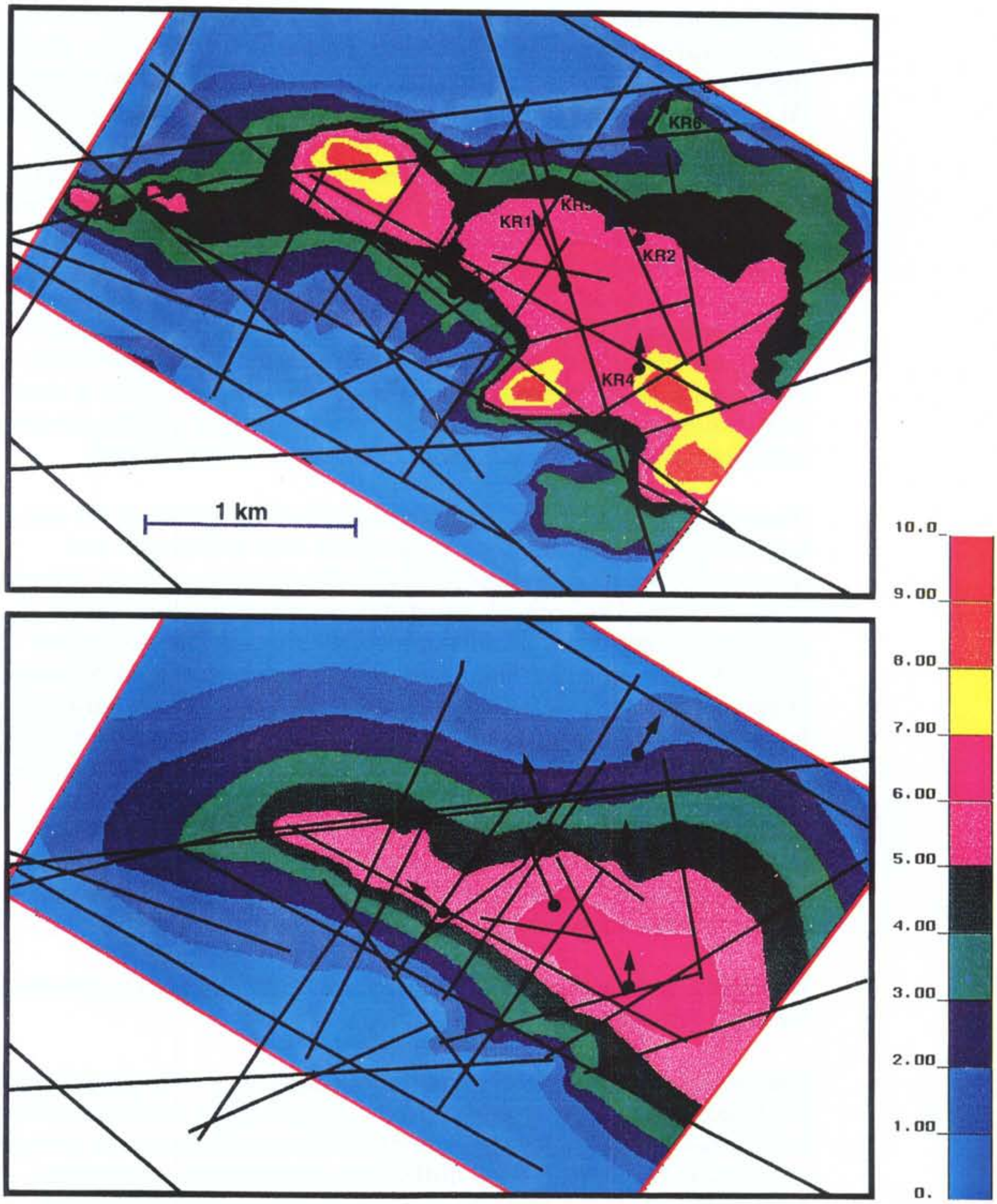


Figure 4-13. Calculated hydraulic head and structures recognised in the flow model, at the surface (above) and at a depth of 500 m (below).

4.4 ASSOCIATED UNCERTAINTIES

4.4.1 Bedrock modelling

To draw up a conceptual structural model, various measurements and interpretations were used. The description of rock types, fracturing and fracture zones for a model was based on several work stages. At the end of the process three-dimensional interpretation, screening and combination of the results from various measurements were carried out. All stages include uncertainty which is either conseptual in nature or relatd to amount of data available. In the modelling work assumptions and simplifications are made to develop the model. These assumptions introduce conceptual uncertainty into models. The approach to select planar representation for crush zones carries uncertainty, especially regarding their dimensions, into models. The depth, for example, is assumed to be the same as the length unless direct or indirect observations prove otherwise. The depths of structures bound to certain rock types are interpreted on genetic grounds, and often as continuing deep into the bedrock (over 1500 m).

Amount of available data is in the key role when deciding the existence of structures. Classification was one way to describe and manage the uncertainties associated to the model in general (see also Chapter 4.2.1). The bedrock structures were classified into three categories of certainty: verified, probable and possible. A verified structure is the one identified by a direct observation at an outcrop or by core sample at least in one location. Its geometric extensions, however, are still, at least partly, based on interpretations and estimates. A probable structure is the one that has been observed by two or more indirect methods, and the possible one by one indirect method. Where special reasons and observations indicate the existence of a structure observed only indirectly, and statements by experts agree, the structure is assigned to the ´verified´ category. No attempts were made to assess the classification.

An example of a summary of the elements contained in the structural model is presented in Table 4-1.

The dimensions of the zones in different directions vary greatly and their deduced character ranges from local groups of separate fractures to regional altered crush zones. Some of the structures in the interpretation material also included indications of alternative geometries, the most probable ones having been selected for the structural model.

4.4.2 Flow modelling

Sensitivity and uncertainty analyses in the groundwater flow modelling phase are discussed by /Taivassalo V et al, 1994/. Uncertainties in the flow model were estimated in terms of variation in input parameters. The input parameters that were studied are: transmissivities of the fracture zones including their depth dependences, the hydraulic conductivity of the matrix, depth of fresh water system and high salt content of the groundwater.

5 USEFULNESS OF THE INVESTIGATION STRATEGY AND INVESTIGATION METHODS FOR CONCEPTUAL MODELLING

5.1 MAIN STRATEGY OF THE INVESTIGATION PROGRAMME

It is a requirement for the long-term safety that the bedrock provides adequate properties for the safe isolation of spent fuel and also maintains those properties over long periods of time. The need to locate and characterise the so-called "best" site for final disposal is thus unnecessary. The feasibility study in 1982 and safety analysis in 1985 showed that the concept of safe disposal can be achieved in the geological conditions typical for Finnish bedrock. A major objective in the site selection programme, and especially in the preliminary site investigations, was to demonstrate that bedrock conditions favorable for final disposal prevail to a large extent and that those conditions can be determined in the selected areas.

The main strategy /Äikäs T, 1993/ was:
- to locate possible main discontinuities and homogenous bedrock areas by geophysical airborne, ground surface methods and shallow drillings
- to determine the distribution of rock types and fracturing by geological mapping from outcrops and by shallow drillings
- based on the results obtained, to localise an area having no major fracture zones and consisting mainly of intact rock quality, and by drilling a deep borehole to determine the conditions by geophysical, hydrological and hydrogeochemical borehole studies
- by drilling four other deep holes, to check the extent of the bedrock conditions characterised by the first borehole and further determination of bedrock conditions by borehole studies
- to develop a conceptual geometrical model of the site, testing of the model parts by additional geophysical surface measurements and drillings
- to obtain parameters for developing boundary conditions to be used in groundwater flow modelling by monitoring the groundwater table and acquiring data for testing and calibration of those models by measuring the hydraulic head distribution and by large-scale hydraulic interference tests
- to develop a conceptual flow model based on the conceptual geometrical model and to study the head distribution and flow rate especially at a depth of several hundred meters in the bedrock
- to determine the characteristic chemical quality of the deep groundwater

Other important objectives were to collect data, to model the areas and to evaluate their properties against the suitability for final disposal and for further selection, and to collect field data for the safety assessment TVO-92 and technical planning of the repository system. The previous assessments were conducted with field data taken from the literature and they concentrated mostly on the feasibility, safety and costs of final disposal. The results revealed, however, that the only way the radionuclides can escape from the repository is by dissolution and migration along with the groundwater.

5.2 DISCUSSION OF THE USEFULNESS OF THE INVESTIGATION STRATEGY AND METHODS

A variety of methods were used systematically in all the areas. The different investigation methods belonging to the various disciplines used at the Olkiluoto site are summarised in Table 5-1.

It is clear that a typical standard programme is comprised of studies whose importance is weighted differently. However, the effect on the costs of the investigation programme by leaving out some individual methods (examples might be borehole geophysical SP measurement or perhaps some laboratory core sample studies) giving secondary or minor information is marginal. In addition, it is often opposed and there is always an expert who is of the opinion that "the method gave useful results in certain places".

Boreholes play an important role since they make it possible to examine factors against the depth and provide valuable direct information. They also determine the area where more data is available. Another question is how many boreholes per site are enough? In the TVO's site characterisation programme, five deep boreholes were considered enough at this stage. One of the boreholes was about 1000 m deep and the other holes about 500 m deep. The principal factors influencing the choice of location and direction of the boreholes are presented in /TVO, 1992/. By five boreholes it has been possible, however, to cover a fairly large bedrock volume. The volume is many times larger than needed in TVO's repository consept.

Although the majority of the geophysical methods employed in studying the bedrock and surficial deposits were generally well-established ones, a wide range of applied geophysical techniques were used. One of the aims of the measurements was to characterise the rock types present and to support the geological mapping so that the magnetic and gravitational measurements were clearly directed towards the needs of lithologic mapping. At the same time a variety of electromagnetic and seismic measurements were made in order to identify and characterise crush zones or fractured zones in the bedrock, the fracturing in general and its extent in the bedrock blocks. For this purpose it was essential to select both high-sensitivity methods and methods applicable to larger bodies of material.

The geohydraulic tests and geophysical soundings carried out in the boreholes formed an important part of the geohydraulic and hydrogeological investigations. They provided information on variations of hydraulic conductivity in the immediate vicinity of the boreholes, while the other geophysical measurements yielded indirect or detailed data on the small-scale variations in the structural properties of the bedrock.

The purpose of the hydraulic borehole measurements was to acquire information on the hydraulic conductivity of the bedrock as initial data for the groundwater modelling. The method chosen for this purpose was a constant head injection test. The grounds for this choice were its technical simplicity, ease of control and the comprehensiveness of the area covered.

The hydraulic head measurements were performed in order to determine the hydraulic gradient in the bedrock and to obtain reference values for calibrating the groundwater model. Measurements were made at three levels: in a number of shallow boreholes, in multilevel piezometers and in the deep boreholes The measurements provided valuable information in general on the spatial distribution of hydraulic head in bedrock. The number of piezometers in the recharge areas was found to be too small in some connections. The results from piezometers were used only to a small extent in groundwater modelling due to the low depth of the piezometers.

Pumping tests were used to investigate the hydraulic connections between the boreholes and test the conceptual assumptions incorporated in the structural model. The main focus of interest was on hydraulic importance the structures of the conceptual model, which was possible to be confirmed by means of the pumping tests.

Hydrogeochemistry provided information on the chemical nature of the groundwater for the evaluation of the behaviour of technical barriers as well as the spent fuel itself. The representativeness of the samples proved to be problematic despite the efforts in careful sampling. The parameters analysed were chosen with the input data required by the various safety models under consideration.

The preliminary site investigations produced hydrogeochemical data on surficial and groundwaters from five sites. The water samples were evaluated for their representativeness and classified according to the main water types. The most prominent differences were the occurrence of brackish and saline groundwaters at Syyry and Olkiluoto. Only fresh groundwaters were observed at Romuvaara, Veitsivaara and Kivetty. The results of the shallower samples (max.

depth about 250 m) were in good agreement with those of the earlier Finnish studies /Rönkä E, 1983; Lahermo P W et al, 1990; Lampén et al, 1992/.

The deeper groundwaters showed trends which have also been observed in other hydrogeochemical studies in crystalline bedrocks. The ionic strengths and pH values usually increase with depth and the measured redox potentials together with observations of sulphide, methane and hydrogen point to to highly reducing conditions. The comparison of the results from the deeper groundwaters was more complicated because the results of the TVO site investigations represent areas without ore potential, unlike many of the Finnish and foreign studies. According to the isotopic data (H-3 and C-14) the longest mean residence times were observed in some groundwaters at Kivetty, Syyry and Olkiluoto.

The preliminary site investigations gave a valuable set of data on the hydrogeochemical features of deep groundwaters in fractured, crystalline bedrock in areas without any ore potential. This background reference data and the development of instruments and interpretation processes will form a solid basis for the detailed site investigations at Romuvaara, Kivetty and Olkiluoto. The future investigations will concentrate more on revealing the processes of water-rock interaction and the evolution of different groundwaters through an increased use of isotopic studies on both the aqueous and the solid phases. Emphasis will also be placed on studies of those trace elements that are especially needed for the performance assessment.

Airborne geophysical methods provide some advantages compared with a ground geophysical survey. Better sensitivity and lower noise level are features that can be associated with airborne methods.

The borehole radar technique (reflection with omnidirectional radar, Vertical Radar Profiling) developed for the Stripa project was employed as a standard procedure after the initial good experiences with it. Another method that proved to be indispensable in the borehole studies was Vertical Seismic Profiling, allowing reflectors to be interpreted from a few hundred meters from a borehole with a sufficiently good resolution.

In general it can be stated that characterisation of five areas by selected approach has been successful and has served well the objective for narrowing the number of sites. Deciding the scope of the programme is always a compromise between objectives of the research, time available and resources. The strategy of TVO's programme has the elements for continued efforts in site characterisation which have been limited by time, for example. During the years 1987 - 1992 the drilling of five 1000 m deep boreholes instead of selected set would have required not only the doubled time but even more. Also the amount of information to be processed and interpreted would have been significantly larger. The reduction of uncertainties, especially conceptual ones, would have been marginal.

In the further study it is easier to judge the need for additional information and extend existing boreholes deeper into bedrock and place some new boreholes to complement the bedrock volume already studied and understood.

Table 5-1. The different investigation methods employed at the Olkiluoto site during the preliminary site investigations.

GEOLOGY

MAPPINGS
- ☐ Rock Types
- ☐ Fracturing
- ☐ Structures

BEDROCK SAMPLES
- ☐ Petrography
- ☐ Fracture Minerals
- ☐ Petrophysics

SHALLOW DRILLINGS
- ☐ 30-35 Boreholes

CORE DRILLING
- ☐ KR1 (1000 m)
- ☐ KR2 (500 m)
- ☐ KR3 (500 m)
- ☐ KR4 (500 m)
- ☐ KR5 (500 m)
- ☐ KR6 (300 m)

GEOPHYSICS

SURFACE SURVEYS
- ☐ Ground Radar
- ☐ Magnetometric
- ☐ VLF, VLF-R (test measurement)
- ☐ Shallow Water Seismics
- ☐ Resistivity
- ☐ Electromagnetic
- ☐ Slingram

AIRBORNE GEOPHYSICS
- ☐ Low Altitude Survey

BOREHOLE STUDIES
- ☐ Fluid Logging (passive)
- ☐ Resisistivity
- ☐ Point Resistivity
- ☐ Natural Gamma
- ☐ Gamma-gamma
- ☐ Neutron-neutron
- ☐ Self Potential
- ☐ Caliper
- ☐ Acoustic
- ☐ Susceptibility
- ☐ Tube Wave
- ☐ Offset VSP
- ☐ Borehole Radar

HYDROLOGY

- ☐ Discharge
- ☐ Precipitation

HYDRAULIC CONDUCTIVITY
- ☐ KR1
- ☐ KR2
- ☐ KR3
- ☐ KR4
- ☐ KR5
- ☐ Tests / Multipiezometers

GROUNDWATER TABLE
- ☐ Multilevel Piezometers
- ☐ 10 Standpipes

HYDRAULIC HEAD
- ☐ Monitoring Instruments

PUMPING TEST
- ☐ Pumping test / KR1

ROCK MECHANICS
- ☐ Rock Stress Measurement-KR1
- ☐ Rock Sample Studies

HYDROGEOCHEMISTRY
- ☐ Sampling in Environment
- ☐ Sampling / Drilling Water
- ☐ Sampling KR1
- ☐ Sampling / Multipiezometers
- ☐ Sampling / Pumping Test
- ☐ Sampling / Head Monitoring Borehole

INTERPRETATION AND MODELLING

HYDRAULIC CONDUCTIVITY
- ☐ KR1
- ☐ KR2
- ☐ KR3
- ☐ KR4
- ☐ KR5

- ☐ SURFACE AND AIRBORNE GEOPHYSICS

BOREHOLE GEOPHYSICS
- ☐ KR1
- ☐ KR2
- ☐ KR3
- ☐ KR4
- ☐ KR5

MODELLING
- ☐ Geological Model-Preliminary
- ☐ Geological Model-Detailed
- ☐ Structural Model-Preliminary
- ☐ Structural Model-Detailed
- ☐ Head Data / Distribution
- ☐ Interference Tests
- ☐ Preliminary Groundwater Simulation
- ☐ Calibrated Groundwater Simulation

6 RECENT DEVELOPMENTS

6.1 TVO-FLOWMETER

Computer modelling has commonly been used to study flow conditions. A great deal of information has been gathered for the modelling, comprising information on the structure of the bedrock, hydraulic conductivity and hydraulic head. Very little is, however, known by the existing groundwater simulation techniques on the flow velocity and flow paths. These are needed in the future for the analyses of the transport.

There is a need to assess the results of modelling with direct field observations. In the phase of detailed investigations, more detailed information will be needed for site-specific safety analysis and technical planning. This includes estimating the distribution of the flow velocity in fractures. With the newly developed TVO-flowmeter (Fig. 6-1) it is possible to acquire information on the volumetric flow and its direction in boreholes in relatively intact bedrock.

The flowmeter with some minor modifications could also be used to measure the hydraulic conductivity with a constant pressure test. The method would give directional information on the hydraulic conductivity. The transmissivity range is estimated to be $2 \times 10^{-10} \ldots 2 \times 10^{-6} m^2/s$. The potential of the flow-meter equipment have been discussed in greater detail by /Rouhiainen P, 1993a/.

A new type of method and a flow guide (Fig. 6-2) have been developed, constructed and tested. Flow into or out of the borehole can be measured with the flow guide. The measurements can be performed with or without pumping water from the borehole. The hydraulic conductivities and hydraulic heads of individual fractures or fractured zones can be solved from the results. The new flow guide enables logging of a borehole much faster than the one described above and therefore could be used in localising the fractures or fracture zones of greater interest. Another advantage with the new method is a good depth resolution.

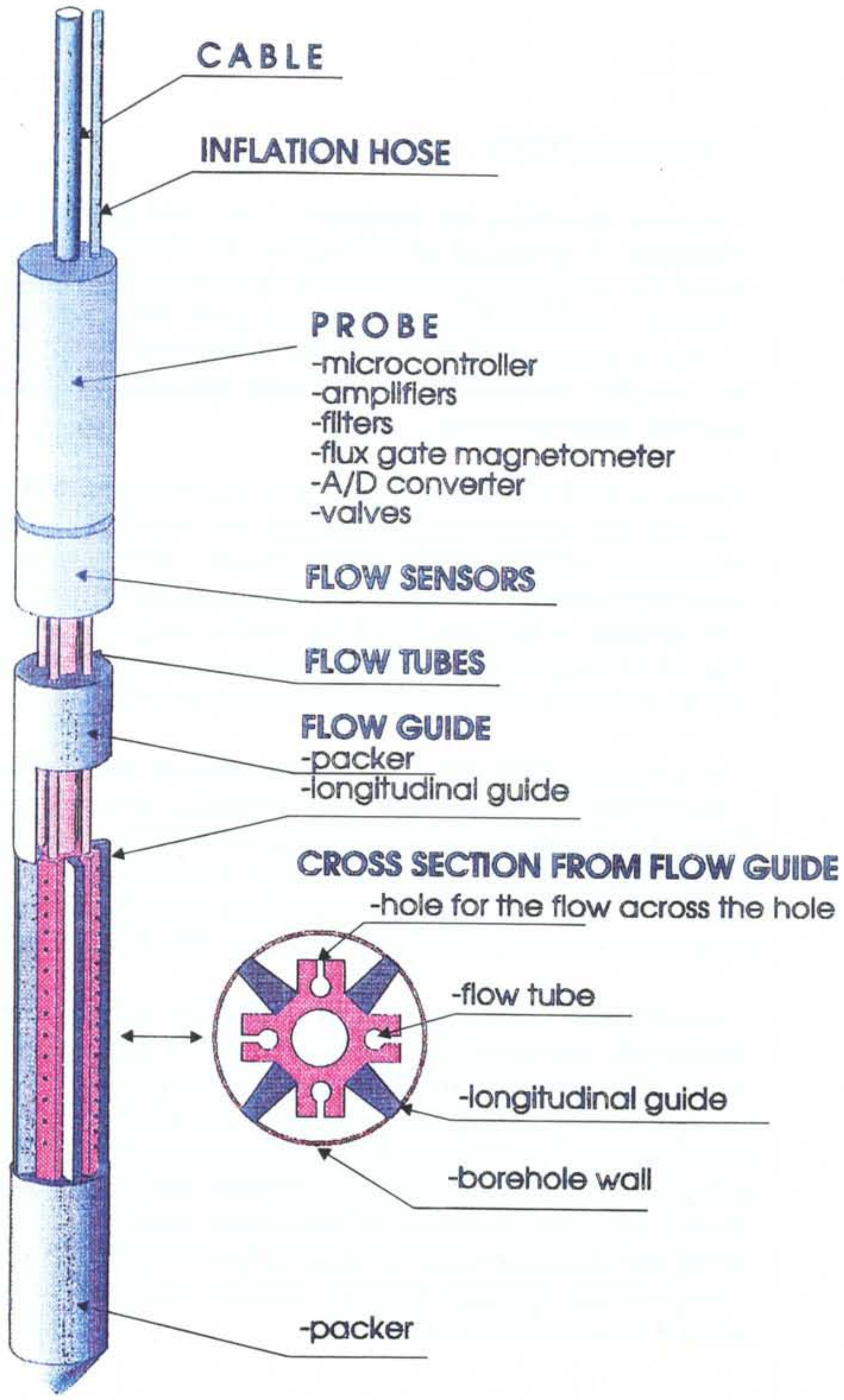


Figure 6-1. TVO-flowmeter /Rouhiainen P, 1993b/.

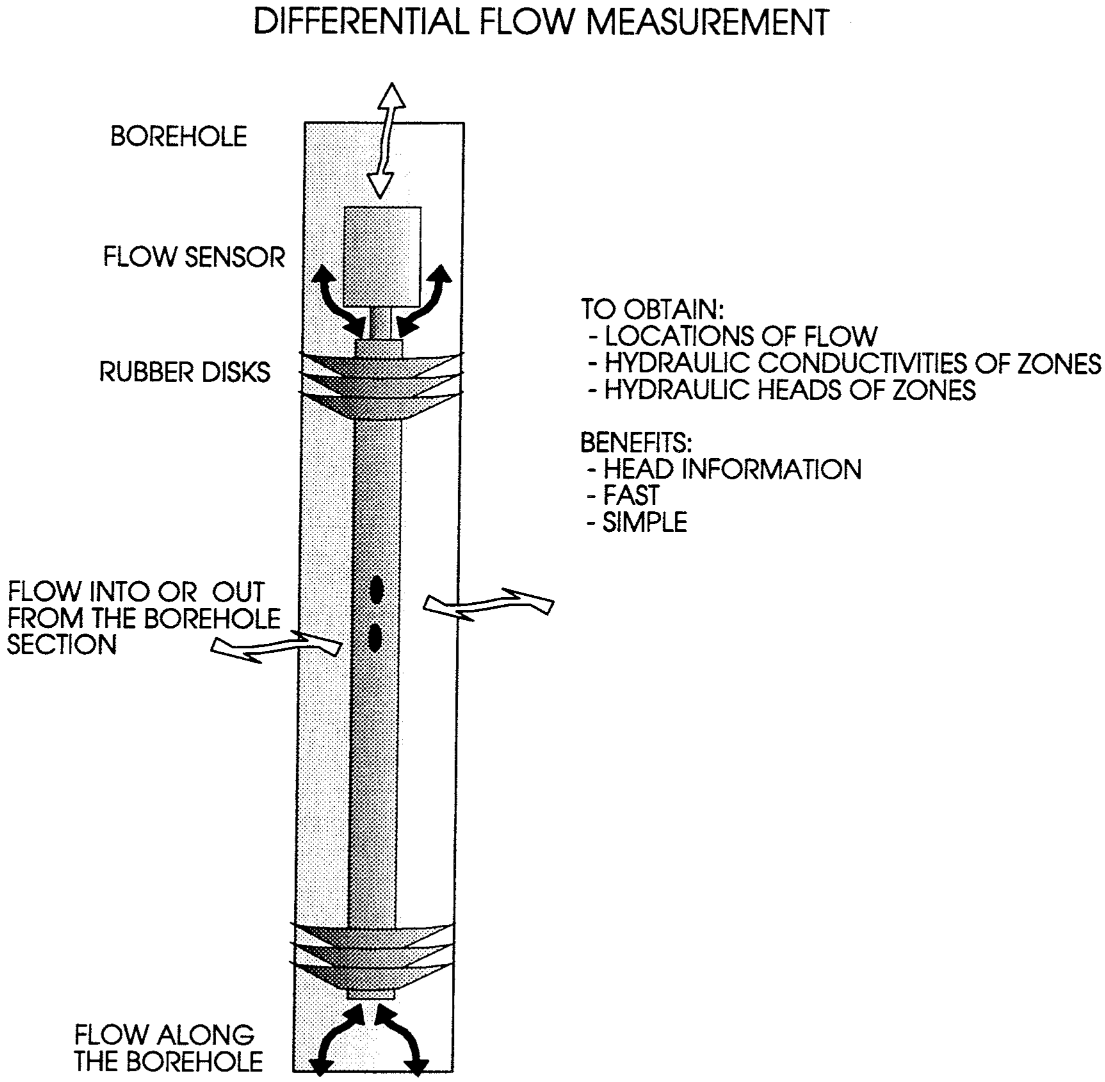


Figure 6-2. A new type of flow guide.

6.2 NEW METHODS IN WATER SAMPLING

Some efforts have been directed towards studying the possibility of taking pressurised groundwater samples separately as well as in conjunction with determination of the hydraulic conductivity by the flowmeter. A preliminary study /Rouhiainen P, 1993a/, made on the subject reveals that in the case of groundwater flow across the borehole it is theoretically possible to take oriented water samples - i.e. from the direction where the water is coming from.

Pressurised water samples will be provided in the future with the aid of pressure bottles and slim membrane pumps. The pumps have already undergone some tests. The idea is to use the bottles eventually in conjunction with the flowmeter, drilling and a standard water sampling equipment.

The representativeness of groundwater samples is significant for the success of a hydrogeochemical interpretation. In order to enhance the future interpretation, groundwater samples will be taken at the beginning of the detailed investigation phase. The results will establish base-line information after the investigations are initiated. Another way to enhance the representativeness of water samples during the detailed investigation phase is new drilling techniques, e.g., air-lift pumping enabling a better recovery of flushing water. In future, water samples will also be taken during the drilling phase right after penetration of a conductive zone with the same objective as above.

6.3 GROUNDWATER FLOW MODELLING WITH THE FEFLOW-CODE

Features of the FEFLOW package have been presented by /Taivassalo V et al, 1994/. The code is a package including several programs. The code is used in performing the numerical three dimensional simulations and the routines applied in creating finite element meshes.

In groundwater flow modelling, density variations of the groundwater can nowadays be included in the FEFLOW-code as a function of the time and location. The enhancement of the code has been reported by /Löfman J and Taivassalo V, 1993/. The variation in the groundwater density has been included in the flow equation with the help of pressure. Due to the fact that the salinity and/or temperature is not known at every point, they have to be calculated from the boundary conditions. Consequently, the simulation of the two parameters was added to the code as well as the parts of equations that solve for the flow, heat transport and migration. The newly enhanced FEFLOW-code makes it possible to discretise the structure of the model in a way that is easier and more versatile than other similar modelling codes.

Only a few of the new features of the code have been applied in the modelling cases related to the preliminary site investigations. In connection with the calibration phase of the model, the pressure field was calculated assuming a simple salinity distribution if saline groundwater was encountered in the area. Also, the natural groundwater conditions around Äspö island have been simulated with the enhanced code by taking into consideration the coupling of the salinity and the flow field.

6.4 ROCK-CAD MODELLING SYSTEM

ROCK-CAD has been in use since 1989. Experiences from many investigation sites indicate that the ROCK-CAD system is necessary if complex geological conditions are to be studied and illustrated in detail.

Participants in modelling team, for example, will get a common and shared view into the "3-D world" by using the same software in the work. Time-consuming pseudo-3-D and error-prone manual compilation of drawings has been supplanted by systematic work at workstations. The documentation of the geological interpretations and conclusions has been improved by coding the results into ROCK-CAD. The models have furthermore been transferred to other purposes. The most important one is the groundwater flow simulation. The ROCK-CAD model also forms the basis of small-volume 3-D rock mechanical calculations. Because the creation of three-dimensional geometry is a complicated task in general, links and standards to ease the transfer of 3-D CAD model between different computer systems are required and have been developed, too.

It is important to note a difference between 3-D interpretation and 3-D modelling. Interpretation and data analysis is an extensive phase of work that precedes the creation of a 3-D model. Multidisciplinary interpretation within geosciences results in lithologic and structural indications, estimations and concepts differing in their detail and accuracy. These interpretations are transferred to 3-D modelling. Further study of bedrock structures can be conducted with 3-D views from the modelling system by means of expert discussions and the use of judgment. This often leads iteratively back to interpretation and 3-D model revisions. Typically after two-three cycles, a relatively "stable" conceptual model will be developed. It is important to understand that a 3-D subsurface model cannot be any better than the interpretations, data quality or subsurface understanding it is based on. Modelling is representation of interpreted results using conceptual assumptions agreed within the group. The assumptions and models developed can be well managed by a CAD system. This is easily forgotten because 3-D graphics are generally convincing and impressive. ROCK-CAD is also tuned to take care of some uncertainties related to modelling facts.

The ROCK-CAD software used for geometrical modelling of a site has been developed further. A software module that incorporates geotechnical and geophysical logs into 3-D models was programmed. Also, the implementation of the Medusa Full Featured Shader provides an opportunity to get both vector and raster images of the rock models. Full interactivity in 3-D object shape design will be achieved by means of the CV Design 4.0 module, which is currently being developed/implemented.

6.5 FORWARD 3-D MODELLING OF WEAK ELECTRICAL CONDUCTORS FOR AN AIRBORNE GEOPHYSICAL ELECTROMAGNETIC SYSTEM

Recently the Helsinki University of Technology /Peltoniemi et al, 1993/ carried out an extensive theoretical modelling of airborne electromagnetic anomaly responses. The focus was on anomalies related to fractured bedrock and overburden and forward 3-D modelling was applied. The calculations were performed for an airborne system used in TVO's previous site investigation programme.

In summary, the study indicated that an anomaly from a steeply dipping electrical plate conductor will decrease significantly when the conductor is embedded in a weakly conductive host rock and is overlain by an electrically conductive overburden. Changes in the overburden conductivity will also cause the plate-anomaly values and shape to change markedly /Peltoniemi et al, 1993/. The lateral resolution was found to be about 50 m (eight times the coil spacing) for two adjacent conductors. The resolution aspects are similar to those for airborne magnetic measurements discussed in Chapter 3 in the section "High-resolution airborne geophysical survey vs. ground geophysical surveys".

6.6 VSP AND REFLECTION SEISMIC 3-D PROCESSING AND ANALYSIS

A new development project has started for high-resolution VSP and reflection seismics. The assignment has been given to Vibrometric Oy and it is coordinated by SKB and TVO. The key areas of the development project are:

- The first task consists of reprocessing existing Romuvaara site borehole KR2 data (as an example) and assessing its spatial coverage. A new 3-D interpretation will be made. A 2-D Image Point transform will be carried out for all shot points and for several dip directions at approximately 15° intervals. Ray tracing and a velocity model will be used. Data from Romuvaara borehole KR2 will be used for testing, and further information on medium dipping (dip 40 - 45°) major fracture zone R9 will also be produced.

- The location of the reflecting elements will be defined separately for all the shot points. All sections will be migrated. After reprocessing, the results will be compared with the structural model. The geometrical coverage will be analysed from migrated sections for all shot points by using the modeling results to outline the limits of the spatial coverage and the quality of the data. Connections between reflections shown in several shot point data will be defined using trend analysis. Statistical best fit surfaces (non-planar) for reflector elements will be defined. A concept for the quality assessment (reflectivity and noise criteria etc.) and presentations will be designed.

- The second task consists of a description of the existing seismic sounding data in relation to the investigated volume coverage and spatial data uncertainties of the structures interpreted thus far. The 3-D location of the reflection elements will be defined for each shot point. The validity of the locations will be assessed. The results will be compared with the results of the previous 3-D interpretation. This will be used for the design of new surveys and the assessment of the possibilities to produce supplementary information.

- The third task consists of designing new computer programs for fast and efficient 3-D interpretation, modelling and visualisation. The homogeneous rock matrix will be implemented as an analytic background model where relatively thin zones of heterogeneity will be superimposed. Their influence on the travel times is obviously minor, so the use of the reflections will be emphasised. Model parameters are fixed for the P- and S-wave velocities, model 3-D geometry, and velocity and density contrasts. Seismic ray paths, reflecting element locations, reflectivities, attenuation and polarisation will be defined for the model. Also, wave form conversions will be included. Synthetic seismograms for the models will be produced and presented. The interpretation will be developed to utilise directionality analysis as well as elastic wave 3-component recordings. Fast analytic 3-D modelling, a package has been prepared already thus far and it is ready for modelling work.

- Data analysis and software development parts (steps 1 ... 3) will be ready in 1993. After that a field test with a new combination of instruments will be carried out. The goal is to have new instrumentation and interpretation tools tested and ready for field data acquisition starting from the spring of 1994.

7 CONCLUDING REMARKS

The experiences gained from TVO's site characterisation during 1987–1992 emphasize the importance of the decision and selections made early in the programme. The selection of conceptual assumptions to form the basis for the planning of the programme have to be made at a very early stage. These assumptions give guidance to decision on investigation methods, siting the borehole locations etc. The uncertainties associated with these assumptions give the reason to plan the actual characterisation in a stepwise fashion. This gives an opportunity to study tentatively during the implementation of the programme whether the assumptions hold good or not.

Another decision necessary to make in the early stage is the scope of the characterisation in proportion to performance assessment of the final disposal. The question especially important is: "as one part of the repository system, how geosphere is used in the safety assessment?" In TVO's case the main scope was to assist the safety assessment by providing the basic understanding on the hydrogeochemistry and giving a well based perception on the amount of the groundwater flowing in the bedrock. The aim was not to collect information for so called site specific safety analysis but further selection of sites for more detailed characterisation.

The investigation areas were identified in Finnish bedrock by assuming that bedrock is broken into mosaic structure characterised by crush zones and more intact bedrock in between. This conceptual model was selected originally for this purpose since it can have, better than others, an effect in increasing safety margins providing that crush zones act as "relief valves" regarding bedrock movements. The site characterisation programme was, however, not planned in the first place to confirm this assumption but to characterise and understand the bedrock inside the block boundaries. In planning the fieldwork the approach was more to take a "random sample" of the typical bedrock within the block than concentrate to study fracture zones interpreted in earlier lineament studies.

Several practical reasons confine the investigations. In TVO's case following practical issues have been considered:
- boreholes cannot situate too far from each other, otherwise the extrapolation of results becomes totally impossible
- the number and depth of boreholes is limited due to the time available for characterisation

- use of some methods, like hydraulic testing, is limited to certain test type due to the resources available
- a conflict between groundwater chemistry and other borehole investigations has been solved in favor for other investigations due to the known difficulties of representativeness in sampling the groundwater
- model calculations of flow velocity has been neglected due to the evident uncertainty in results since the collected initial data is not able to satisfy comprehensive analysis

The investigation methods used in the preliminary site characterisation were in accordance with the investigation programmes drawn in advance. A systematic, standard programme has been implemented at each site. The possibility to implement a similar programme at each site was that essential conceptual uncertainties are basically similar, keeping in mind that areas had already undergone one evaluation process during 1983-1985. This fact was also helpful to acknowledge when evaluating the suitability of sites for further characterisation.

The division of the programmes into stages has its benefits, especially by arranging the thought process during the course of the programme. In practice, studying five sites at the same time, it was naturally difficult to keep the stages in their original, ideal scope and time schedule.

New methods like borehole radar and offset VSP made possible to develop more detailed structural models of sites than was anticipated. This again helped in evaluation of the feasibility for locating and construction of the repository. Also the rather detailed models gave the justification to use the ease for continued characterisation as a selection factor.

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8 REFERENCES

Anttila P (Ed.), Paulamäki S, Lindberg A, Paananen M, Koistinen T, Front K and Pitkänen P, 1992. The geology of the Olkiluoto area, summary report. Nuclear Waste Commission of Finnish Power Companies. Report YJT-92-28.

Autio H and Hakanen P, 1991. Digital terrain model and interpretation using image processing from Olkiluoto (in Finnish). TVO / Work Report 91-58.

Autio H and Hakanen P, 1992. Digital terrain model and interpretation using image processing from Hyrynsalmi, Veitsivaara (in Finnish). TVO / Work Report 92-11.

Council of State (Valtioneuvosto), 1983. The decision in principle, 10.11.1983 of the Council of State on the research and development targets of nuclear waste management. (in Finnish)

Davis S N and De Wiest R J M, 1967. Hydrology, 2nd edition. Wiley, New York.

Dimmock N A, Settle C and Webber H M, 1979. The use of Ferrozine for the absorptiometric determination of iron in boiled-feed water. Central Electricity Research Laboratories. Laboratory Note no RD/L/N 41/79.

Hakkarainen, V, 1985. The geological conditions at Olkiluoto island and its surrounding regarding site identification survey. Geological Survey of Finland, Nuclear Waste Disposal Research. TVO/Final Disposal of Spent Fuel, Work report 85-09. (in Finnish)

Heikkinen E (ed.), Saksa P (ed.), Hinkkanen H (ed.), Kurimo M, Ahokas H, Öhberg A, Front K, Pitkänen P, Vaittinen T, Cosma C, Heikkinen P, Keskinen J and Korhonen R, 1991. Geophysical investigations in the Veitsivaara area, Finland, summary report. Nuclear Waste Commission of Finnish Power Companies. Report YJT-91-20.

KBS-3, 1983. Kärnbränslecykelns slutsteg - Använt kärnbränsle - KBS-3. Stockholm, Svensk Kärnbränsleförsörjning AB (SKBF).

Kuivamäki A and Vuorela P, 1985. Importance of geological processes in final disposal of spent fuel, Olkiluoto as a reference area.

Geological Survey of Finland, Nuclear Waste Disposal Research. TVO/Final Disposal of Spent Fuel, Work report 85-12. (in Finnish)

Kuusela-Lahtinen A. 1992. Interpretation of flow dimension using constant pressure well test data. Teollisuuden Voima Oy, Site Investigations, Work Report 92-50.

Laaksoharju M, Smellie J A T, Lampén P and Snellman M, 1993. SKB/TVO joint project for groundwater chemistry; Phase II - An approach to quality classification of deep groundwaters in Sweden and Finland, GeoPoint Ab, Conterra Ab, Fintact Ky, Imatran Voima Oy.

Lahermo P W, Ilmasti M, Juntunen R and Taka M, 1990. Geochemical Atlas of Finland, Part 1. Geological Survey of Finland.

Lampén P and Snellman M, 1993. Summary report on groundwater chemistry. Nuclear Waste Commission of Finnish Power Companies, Report YJT-93-14.

Lampén P, Laaksoharju M and Smellie J A T, 1992. A compilation of existing Finnish and Swedish groundwater data; SKB/TVO joint project for groundwater chemistry- Phase I. Ekono-Energy Ltd, GeoPoint Ab, Conterra Ab, TVO/Work Report 92-51.

Löfman J and Taivassalo V, 1993. Solving of Coupled Equation for Flow, Heat Transfer and Solute Transport. Technical Research Centre of Finland, Nuclear Engineering Laboratory. Nuclear Waste Commission of Finnish Power Companies, Report YJT-93-30.

Moye D G, 1967. Diamond drilling for foundation exploration, Civ. Eng. Trans. 7th Insst. Eng. Australia, 95-100

Niemi A and Kontio K, 1991. Composition and variability conductivity data: Romuvaara and Veitsivaara. Technical Research Centre of Finland, Road and Traffic and Geotechnical Laboratory. TVO/Site Investigations, Work Report 91-12. (in Finnish)

Niemi A and Kontio K, 1993. Geostatistical analysis of hydrological data in five crystalline rock sites in Finland. Technical Research Centre of Finland, Road and Traffic and Geotechnical Laboratory. Nuclear Waste Commission of Finnish Power Companies. Report YJT-93-11.

Paulamäki S and Paananen M, 1991. Characterisation of bedrock structures at the Olkiluoto study site, Eurajoki, Western Finland. TVO/Work Report 91-33. (in Finnish)

Peltoniemi M, Bärs R and Väisänen M, 1993. Modeling of airborne electromagnetic anomalies related to fractured bedrock and overburden. Nuclear Waste Commission of Finnish Power Companies. Report YJT-93-18.

Pitkänen P, Front K and Hassinen P, 1991. Characterisation of bedrock structures at the Olkiluoto test site, Eurajoki, SW Finland. TVO/Work Report 91-31. (in Finnish)

Pitkänen P, Snellman M and Leino-Forsman H, 1992. Modelling of water-rock interaction at the TVO investigation sites - Summary report. Nuclear Waste Commission of Finnish Power Companies. Report YJT-92-30.

Rouhiainen P, Lampén P, Snellman M and Helenius J, 1992. Water sampling equipment, technical description and operating instructions. Revision III (in Finnish). TVO / Work Report 92-71.

Rouhiainen P, 1993a. The use of the TVO-flowmeter in groundwater sampling and in hydraulic conductivity tests, preliminary study. TVO/Work Report PATU-93-02. (in Finnish)

Rouhiainen P, 1993b. TVO-Flowmeter. Nuclear Waste Commission of Finnish Power Companies. Report YJT-93-01.

Ryhänen V and Palmu J, 1993. Spent fuel management of the Finnish nuclear power plants. Paper presented at the International Conference on Nuclear Waste Management and Environmental Remediation, September 5-11, 1993. Palác Kultury, Prague, Czech Republic.

Rönkä E, 1983. Drilled wells and groundwater in the Precambrian crystalline bedrock of Finland. Publications of the Water Research Institute, 38.

Saksa P (ed.), Paananen M, Paulamäki S, Anttila P, Ahokas H, Pitkänen P, Front K and Vaittinen T, 1991. Bedrock model for Romuvaara, Kuhmo, summary report. Nuclear Waste Commission of Finnish Power Companies. Report YJT-92-06.

Saksa P (ed.), Kuivamäki A, Kurimo M, Anttila P, Ahokas H, Front K, Pitkänen P, Korkealaakso J and Vaittinen T, 1992a. Bedrock model of the Veitsivaara area, summary report. Nuclear Waste Commission of Finnish Power Companies. Report YJT-93-17.

Saksa P (ed.), Paulamäki S, Paananen M, Anttila P, Ahokas H, Front K, Pitkänen P, Korkealaakso J and Okko O, 1992b. Bedrock model of the Kivetty area, summary report. Nuclear Waste Commission of Finnish Power Companies. Report YJT-93-16.

Saksa, P. (ed.), Paulamäki S, Paananen M, Anttila P, Ahokas H, Front K, Pitkänen P, Korkealaakso J and Okko O, 1992c. Bedrock model of the Olkiluoto area, summary report. Nuclear Waste Commission of Finnish Power Companies, Report YJT-93-15.

Saksa P (ed.), Kuivamäki A, Kurimo M, Paananen M, Anttila P, Ahokas H, Front K, Pitkänen P and Okko O, 1992d. Bedrock model of the Syyry area, summary report. Nuclear Waste Commission of Finnish Power Companies. Report YJT-93-20.

Saksa P, Ahokas H, Oksanen J and Anttila P, 1991a. Geometrical model of the fracture zone structures of the Olkiluoto site, Eurajoki. TVO/Work Report 91-52. (in Finnish)

Saksa P (ed.), Paananen M, Ahokas H, Öhberg A, Pitkänen P, Front K, Okko O, Vaittinen T, Cosma C, Heikkinen P, Keskinen J and Korhonen R, 1991b. Geophysical investigations of the Romuvaara area, Finland, summary report. Nuclear Waste Commission of Finnish Power Companies. Report YJT-91-15.

Saksa P and Silvennoinen H, 1989. Site investigations for spent nuclear fuel in Finland: Theoretical aspects of high resolution airborne survey. Paper presented at 51st E.A.E.G. meeting and technical exhibition, Berlin 29.5 - 2.6.1989. Abstract D-9, p. 143 - 144.

Salmi M, Vuorela P and Kuivamäki A, 1985. Site identification survey for final disposal of spent nuclear fuel. Geological Survey of Finland, Nuclear Waste Disposal Research. Nuclear Waste Commission of Finnish Power Companies. Report YJT-85-27. (in Finnish)

Smellie J A T, Laaksoharju M, Snellman M and Lampén P, 1993. SKB/TVO joint project for groundwater chemistry; Phase III - Groundwater quality and sampling recommendations based on experience of existing Finnish and Swedish hydrogeochemical data. Conterra Ab, GeoPoint Ab, Imatran Voima Oy, Fintact Ky.

Suomen Malmi Oy Finnexploration, 1988. Airborne geophysical survey at Kuhmo, Hyrynsalmi, Sievi, Konginkangas and Eurajoki. TVO / Work Report 88-22.

Taivassalo V, Koskinen L and Meling K, 1994. Groundwater flow modelling in the preliminary site investigations - Modelling strategy and computer codes. Nuclear Waste Commission of Finnish Power Companies. Report YJT-94-04 (to be published).

TVO, 1992. Final disposal of spent nuclear fuel in the Finnish bedrock, preliminary site investigations. Nuclear Waste Commission of Finnish Power Companies. Report YJT-92-32.

TVO, 1993. Programme for site characterisation in 1993-1996, TVO/Work Report PATU-93-01.

Ylinen A and Väätäinen A, 1993. Interpretation of the 1989-1992 hydraulic interference tests at the five TVO sites in Finland. Technical Research Centre of Finland, Road and Traffic and Geotechnical Laboratory. Nuclear Waste Commission of Finnish Power Companies. Report YJT-93-10.

Äikäs K, 1991. Interpretation of fracture zones using site investigations of TVO I and TVO II and VLJ-site investigations. TVO/Work Report 91-42. (in Finnish)

Äikäs T, 1985. Site investigation for the disposal of spent fuel - investigation programme. Nuclear Waste Commission of Finnish Power Companies. Report YJT-85-29.

Äikäs T, 1987a. Investigation programme for the Veitsivaara area in Hyrynsalmi. TVO/Site investigations, Work Report 87-04. (in Finnish)

Äikäs T, 1987b. Investigation programme for the Romuvaara area in Kuhmo. TVO/Site investigations, work report 87-05. (in Finnish)

Äikäs T, 1988a. Investigation programme for the Kivetty area in Konginkangas. TVO/Site investigations, Work Report 88-33. (in Finnish)

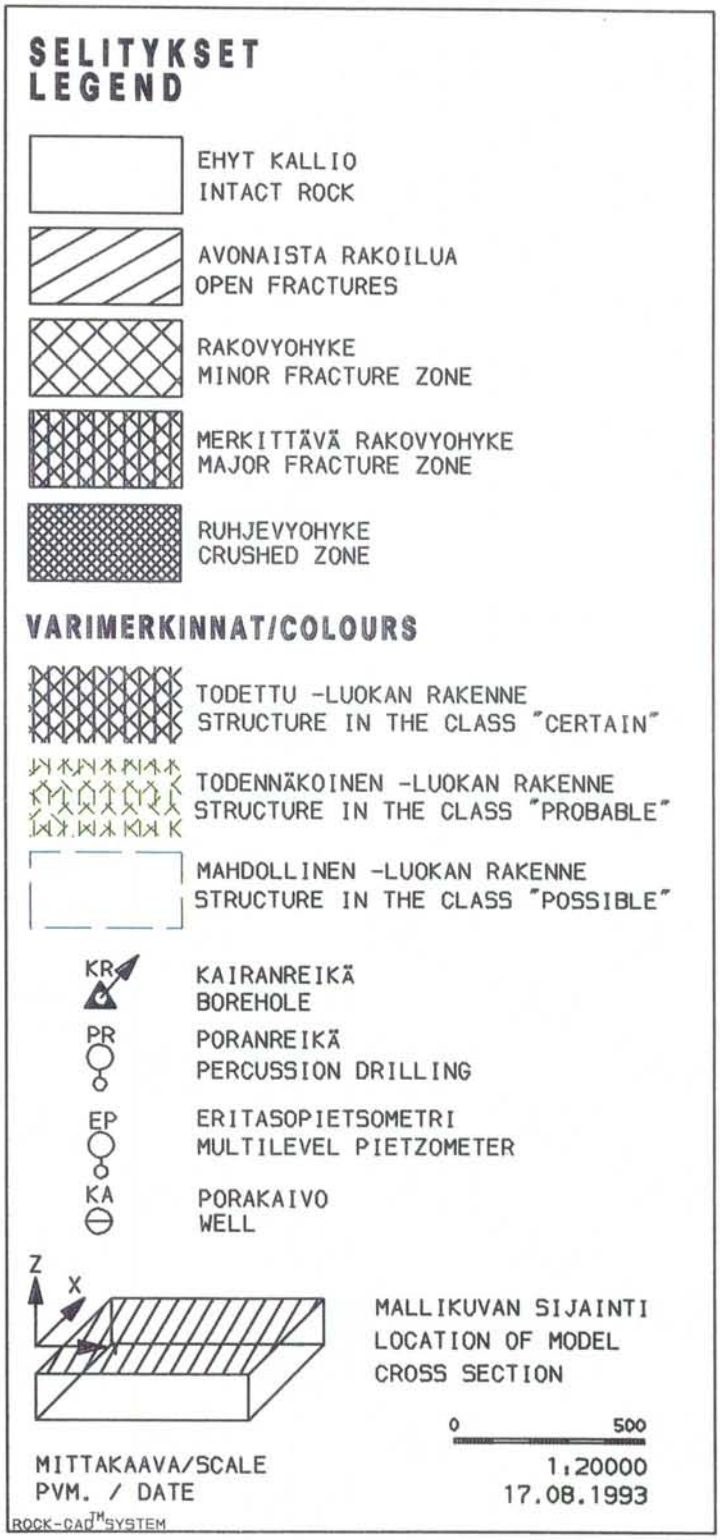
Äikäs T, 1988b. Investigation programme for the Syyry area in Sievi. TVO/Site investigations, Work Report 88-34. (in Finnish)

Äikäs T, 1989. Investigation programme for the Olkiluoto area in Eurajoki. TVO/Site investigations, Work Report 89-32. (in Finnish)

Äikäs T, 1993. Programme and results of preliminary site characterisation for final disposal of spent nuclear fuel in Finland. Paper presented at the International Conference on Nuclear Waste Management and Environmental Remediation, September 5-11, 1993. Palác Kultury, Prague, Czech Republic.

Öhberg A, 1991. Site investigation equipment developed by Teollisuuden Voima Oy. Nuclear Waste Commission of Finnish Power Companies. Report YJT-91-06.

LEGEND RELATED TO THE FIG. 4-8.



List of SKB reports

Annual Reports

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The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
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KBS Technical Reports 80-01 – 80-25
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KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
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The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
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Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
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Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

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SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

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Stockholm, May 1990

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SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, April 1992

1992
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SKB Annual Report 1992
Including Summaries of Technical Reports Issued during 1992
Stockholm, May 1993

Technical Reports
List of SKB Technical Reports 1994

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[1] Vibrometric Oy, Helsinki, Finland
[2] Section for Solid Earth Physics, Department of Geophysics, Uppsala University, Sweden
[3] Conterra AB, Uppsala, Sweden
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[1] AECL, Canada
[2] Conterra AB, Uppsala, Sweden
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[1] Department of Geology, Chalmers University of Technology/Göteborg University
[2] Terralogica AB
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[1] GEOSIGMA, Uppsala, Sweden
[2] Conterra, Göteborg, Sweden
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Gunnar Gustafson[3], Ingvar Rhén[4],
Roy Stanfors[5], Peter Wikberg[2]
1 Conterra AB
2 SKB
3 CTH
4 VBB/VIAK
5 RS Consulting
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Institutionen för geologi och geokemi,
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Hans Wanner[1], Yngve Albinsson[2], Erich Wieland[1]
[1] MBT Umwelttechnik AG, Zürich, Switzerland
[2] Chalmers University of Technology, Gothenburg, Sweden
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A R Hoch, S M Sharland
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Hans Widén[1], Patrik Sellin[2]
[1] Kemakta Konsult AB, Stockholm, Sweden
[2] Svensk Kärnbränslehantering AB, Stockholm, Sweden
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J Henshaw
AEA Technology, Decommissioning & Waste Management/Reactor Services, Harwell, UK
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Ignasi Casas[1], Jordi Bruno[1], Esther Cera[1],
Robert J Finch[2], Rodney C Ewing[2]
[1] MBT Tecnología Ambiental, Cerdanyola, Spain
[2] Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM, USA
October 1994