Kari Rasilainen (editor)

Nuclear Waste Management in Finland

Final Report of Public Sector's Research Programme
JYT2001 (1997–2001)

Final Draft

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Abstract

According to Finnish nuclear energy legislation, each producer of nuclear waste is responsible for the safe handling, management, and disposal of its waste, as well as for the costs arising. The Posiva company, owned by the nuclear energy-producing power companies, is in charge of spent nuclear fuel management in Finland. The authorities supervise the management of nuclear waste and issue regulations for this purpose. In these demanding tasks the authorities have been supported by the Public Sector's Research Programme on Nuclear Waste Management (JYT2001).

The objective of JYT2001 was to provide the authorities with independent expertise and research results relevant to the safety of nuclear waste management. Emphasis was placed on the geological disposal of spent nuclear fuel. The research area was divided into (1) technical studies on the safety of spent fuel disposal, and (2) social science studies related to nuclear waste management. The technical studies covered bedrock behaviour, the hydrogeology and geochemistry of the bedrock, the stability of the bentonite buffer, and the migration of radionuclides in the bedrock. In addition, performance assessment methodology was covered, as well as waste management technologies and costs. The social science studies were focussed on observing the Decision in Principle (DiP) process including the Environmental Impact Assessment (EIA), and media issues related to the spent fuel disposal facility.

JYT2001 provided considerable support to the authorities in helping them deal with technical and social science questions. The Government's positive Decision in Principle (DiP) on Posiva's application for a spent fuel disposal facility in Eurajoki was ratified by Parliament in May 2001. The existence of a credible JYT2001 programme, independent of Posiva, obviously contributed to the high level of public confidence in the Finnish nuclear waste management programme.

According to the schedule of the Finnish nuclear waste management programme, the next major milestone is Posiva's spent fuel disposal facility construction licence application, due around 2010. After that the operating licence application will be submitted around 2020. Reaching these milestones will require continued high-quality research on the technical safety of the facility.

Key words

nuclear waste management, spent nuclear fuel, disposal, safety, environmental impact assessment

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Foreword

The Public Sector's Research Programme on Nuclear Waste Management in Finland (JYT2001), covering the years 1997-2001, was planned to support the Finnish authorities in dealing with spent fuel management issues. It is a direct continuation of the previous programme stages JYT (1989-1993) and JYT2 (1994-1996). The programme was mainly funded by the Ministry of Trade and Industry (KTM) and co-ordinated by the Technical Research Centre of Finland (VTT). The leader of the programme was Dr. Seppo Vuori of VTT Energy. The Radiation and Nuclear Safety Authority (STUK) was actively involved in defining the research guidelines for the programme.

The programme consists of several projects that were carried out by various research institutes of VTT, the Geological Survey of Finland, Helsinki University of Technology, and the Universities of Helsinki, Jyväskylä, and Tampere. This report has been edited by Kari Rasilainen on the basis of contributions from the different research projects. The following project managers have co-ordinated the writing of the most multidisciplinary contributions:

P. Vuorela (Chapter 2.1), P. Pitkänen (Chapter 2.2), T. Carlsson (Chapter 2.3), P. Hölttä and T. Carlsson (Chapter 2.4), A. Lempinen (Chapter 2.5), K. Rasilainen (Chapters 2.6 and 2.7), P. Hokkanen and T. Litmanen (Chapter 3.1), P. Hokkanen (Chapter 3.2), and P. Raittila (Chapter 3.3). The writers of individual subsections are indicated in the text; the scientists who contributed to the actual results are mentioned in Annex A for each project. The language of the manuscript was checked by Barole Oy.

Helsinki, May 2002

Ministry of Trade and Industry

Energy Department

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1 Introduction[1]

1.1 Nuclear waste management policy in Finland

The Nuclear Energy Act and Decree provide a clear framework for nuclear waste management in Finland. According to the legislation, the producers of nuclear waste are responsible for all measures needed for the safe management of the waste and for the costs that arise. The authorities supervise the management of nuclear waste and issue regulations for this purpose.

The objectives and timetables for nuclear waste management in Finland, as well as for the related research and planning, are defined in a policy decision issued by the Government in 1983 (see Table 1). Subsequently, the authorities have made decisions on the more detailed principles and requirements that power companies have to comply with. The Nuclear Energy Act was amended at the end of 1994, and it now[2] stipulates that all radioactive waste produced in Finland must be handled and disposed of in Finland.

The Finnish spent fuel management programme has so far kept to its original schedule, at least partly as a result of the clearly-defined division of responsibilities the legislation makes between the nuclear energy-producing industry and the authorities. There has also been genuine commitment among the parties to the schedule. Furthermore, the importance of active dialogue between the implementor and the local public, as well as between the authorities and municipal representatives, was already recognised at the beginning of the site selection process.

There are three main actors in Finnish nuclear waste management, each with different responsibilities. In order to fulfil their responsibility to take care of their spent nuclear fuel in Finland under the amended Nuclear Energy Act, the nuclear power companies[3] Teollisuuden Voima Oy and Fortum Oyj (previously Imatran

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[1] By Rasilainen, K., Vuori, S.

[2] The reactors of the Loviisa nuclear power plant were acquired from the former USSR. The owner of Loviisa NPP, Imatran Voima Oy, made initially contractual arrangements for the whole fuel cycle service from USSR, including the return of spent fuel. Spent fuel shipments to Russia were halted after 1996.

[3] Both companies own two nuclear reactors, Teollisuuden Voima at Eurajoki and Fortum at Loviisa.

Voima) formed a jointly-owned company, Posiva. Posiva started its operation in 1996, and its mission is to plan and implement the disposal of spent nuclear fuel generated in Finland.

Overall leadership and control in nuclear energy matters in Finland is the responsibility of the Ministry of Trade and Industry (KTM). The ministry prepares the relevant national legislation and international agreements, as well as monitoring compliance with them. The Radiation and Nuclear Safety Authority (STUK) is responsible for the supervision of nuclear and radiation safety. The STUK prepared the national general safety requirements for spent fuel disposal issued as a decision of the Government in March 1999 (VnP 478/1999 [STUK 1999]). The requirements cover the operational phase of the encapsulation and disposal facility, as well as the post-closure safety of spent fuel disposal. The preparation of more detailed guidance (YVL 8.4) on the assessment of the long-term safety of the spent fuel repository has been completed at the STUK [STUK 2001]. The preparation of guidance (YVL 8.5) for the operational safety of the disposal facility for spent fuel is under way.

Table 1. The schedule for Finnish spent nuclear fuel disposal. The built-in stepwise approach was exemplified in particular in the site selection process[4].

Time period	Main activity	Comment
1983–1985	Screening research of areas covering the entire country	As planned
1986–1992	Preliminary site investigations	As planned
1993–2000	Detailed site investigations	As planned
2000	Selection of final disposal site in the Decision in Principle process	Eurajoki was selected as the site for the repository in the favourable Decision in Principle in May 2001
2000–2010	Investigation shaft, and complementary investigations	Application for construction licence planned for around 2010
2010–2020	Construction of the encapsulation and final disposal facility	Application for operating licence planned for around 2020
2020	Beginning of final disposal	Planned

To make sure that the remaining activities in the national nuclear waste management programme can be implemented under all conditions, the power companies are obliged to set aside money in the State Nuclear Waste Management Fund. The power companies must present cost estimates for the future management of their nuclear wastes to the KTM annually. The cost estimates are based on the power companies' latest technical plans, and they also include the decommissioning of nuclear power plants. The Fund is administered by the KTM, and, on the basis of the cost estimates and on expert reviews of these, the KTM decides, annually, the contributions to be made to the Fund. For uncovered costs, the power companies must furnish securities. At the end of the year 2000 the money that had been paid in covered some 96 % of the liability.

[4] It may be noted that the Government's policy decision of 1983 does not require the best possible site, but that "one suitable site where the final repository can be constructed, if so desired, has been selected by the year 2000" [OECD/NEA 1984].

Licencing of nuclear installations

The Nuclear Energy Act regulates all nuclear installations in Finland. Installations, for example a disposal facility for spent nuclear fuel, must be licensed through a three-step procedure, the first step of which is the Decision in Principle (DiP) (cf. Table 1). The other two steps are the construction licence and the operating licence. The Act requires that the Environmental Impact Assessment (EIA) report be annexed to the DiP application. According to the Act, the KTM must request the STUK to make a preliminary safety appraisal of the DiP application in order to see whether there are factors that could compromise the safe construction of the proposed installation. The Act gives an absolute right of veto to the proposed host community of the installation. If the general prerequisites are met and if the municipal council of the site in question is in favour of the construction of the installation, the Government may make the DiP. The decision is then submitted for further handling to Parliament, which either ratifies or rejects it.

Posiva's DiP application for a disposal facility for spent fuel

On May 26, 1999 Posiva submitted an application for a Decision in Principle (DiP) to the Government to establish a spent fuel disposal facility in the Olkiluoto area, in the Eurajoki municipality (Fig. 1). The application was backed by, inter alia, a safety analysis and an extensive Environmental Impact Assessment (EIA).

After the submission of the DiP application, the KTM requested an extensive round of statements, in line with the Nuclear Energy Act. The STUK gave its preliminary safety appraisal on January 12, 2000, in which it stated that it did not see any hindrances to the safe construction of the facility and the continuation of the project. The municipality of Eurajoki gave its favourable statement on January 25, 2000. Two complaints concerning the legality of the decision by the municipality of Eurajoki were made, but the complaints were found to be without cause first by the Regional Administrative Court at Turku and later by the Supreme Administrative Court. The Government made its favourable DiP on December 21, 2000. Parliament ratified, by a clear majority, the Government’s favourable DiP on May 18, 2001. Posiva's DiP application, as well as the whole decision-making process, will be discussed in detail later, in Section 3.

Fig. 1. Site candidates (squares) in Posiva's detailed site investigation stage for a spent fuel repository (cf. Table 1). In its DiP application Posiva suggested Eurajoki as the host municipality. Helsinki is marked on the map for general orientation purposes.

The practical implementation of the spent fuel disposal facility further requires that Posiva separately applies for a construction licence and operating licence from the Government (see schedule in Table 1). The applications will have an estimated time difference of around 10 years and, therefore, they must be backed by increasingly detailed safety analyses.

1.2 Context of the JYT2001 Programme

In their supervisory role, the authorities set safety requirements for nuclear waste management. They further assess the power companies' plans against objectives and safety requirements and evaluate the scope of power companies' annual research programmes. Finally, to ensure sufficient financial preparedness, the authorities review the cost estimates drawn up by the power companies (see previous section). In carrying out these quite demanding tasks the authorities

need outside support to complement their own expertise. A public sector's research programme on nuclear waste management, independent of that of Posiva, was set up for this purpose.

The idea of organising a research programme among public research institutes proved to be a sensible solution, as the resources of the Finnish authorities are quite limited, both in terms of manpower and in scientific experience. A research programme is considered to be a practical way to pool the necessary expertise. VTT Energy acted as the co-ordination unit for the research programme. Its background in performance assessments of nuclear waste management helped to focus the programme on safety relevant issues. Besides the Technical Research Centre of Finland (VTT), the other research institutes in the programme were the Geological Survey of Finland, Helsinki University of Technology, and the Universities of Helsinki, Tampere and Jyväskylä.

1.3 Structure of the JYT2001 Programme

The main objective of the Public Sector's Research Programme on Nuclear Waste Management (JYT2001) was to provide the authorities with expertise and research results relevant to the safety of nuclear waste management, which support the activities of the authorities. The main emphasis in this multidisciplinary research was placed on the final disposal of spent fuel. The first phase of the research programme was conducted in 1989–1993 [Vuori 1990, 1991, 1993], the second phase in 1994–1996 [Vuori 1997], and the current third phase, JYT2001, in 1997-2001. A midterm report of JYT2001 has been prepared [Vuori 2000a].

The KTM set up a group of senior experts in 1996 to review the status of nuclear waste management in Finland and the related research needs. On the basis of the group's report [KTM 1996], the emphasis in the technical studies was placed on questions related to the geological disposal of spent nuclear fuel. The need for social science research was based on the new amendments to the Nuclear Energy Act, the new law concerning the Environmental Impact Assessment (EIA), and the controversial views on the siting plans held by the residents of the possible hosting municipalities [KTM 1996]. The social science studies were linked to the decision-making process. The implementation of a technical plan for the handling of spent fuel requires that the plan should also be accepted outside the circle of technical experts on nuclear waste.

On the basis of the request for statements by the KTM in 1996, the STUK expressed its views [STUK 1996] on the research needs. This view was subsequently specified in 1997 [STUK 1997]. The overall plan of the JYT2001 research programme was outlined on the basis of these documents. The current research areas of the research programme are shown schematically in Fig. 2.

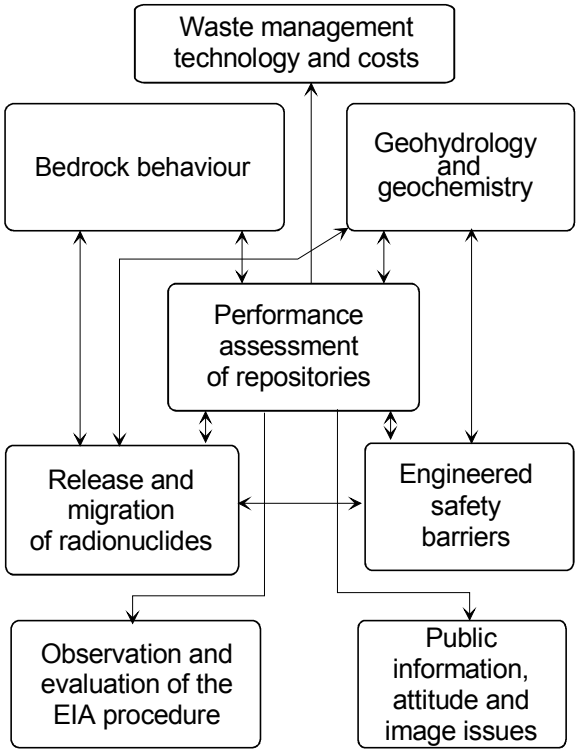

Fig. 2. The research areas of the Public Sector's Research Programme on Nuclear Waste Management (JYT2001).

Posiva's research programme has been essentially based on repeated safety assessments of the proposed disposal concept, supported by site investigations and other safety-related research, in line with its mission. In contrast, because of the limited resources available, JYT2001 never aimed to conduct independent full-scale performance assessments of a spent fuel repository. Rather, emphasis was placed on studies to reduce uncertainties associated with the basic principles and main phenomena related to the geological disposal of spent fuel, and to be able to model these phenomena more accurately and reliably for the purposes of safety assessment. The second primary objective of the public sector's research was to develop and introduce new methods for research and analysis. Thus, Posiva can also benefit from the results obtained by JYT2001.

JYT2001 was organised so as to be of maximal use to the authorities. There was a Steering Group with representatives from independent expert organisations and the authorities (see Annex C). The Steering Group reviewed submitted project proposals on an annual basis and made recommendations concerning the prioritisation of research topics and their respective funding. The funding for the research projects was decided on an annual basis by the KTM. The research projects were associated with two Co-operation Groups: one for technical projects (the topmost 6 blocks in Fig. 2), and the other for social science projects (the lowermost 2 blocks in Fig. 2) (see Annex C).

The STUK named special contact persons from among its staff for each research project in the technical projects' Co-operation Group. It can thus be seen that the authorities in general, and the STUK in particular, have had good control over the substance of the research. In the second Co-operation Group, besides the authorities and other experts, the representatives of the candidate municipalities (four candidates during the detailed site investigation phase during 1993-2000) were able continuously to follow the progress of the research and to express their views on the choice of research topics.

1.4 Structure of the report

In the report, a brief review is provided of the most important results obtained by the JYT2001 programme during 1997-2001. The space available in the report does not allow for going deeply into detail and therefore the interested reader is advised to consult the original publications.

The results are grouped into two main chapters, in line with the overall twofold structure of the research programme (cf. Fig. 2). The technical studies which contribute to the technical safety of geological disposal are described in Chapter 2. The social science results which are linked to the political decision-making process are described in Chapter 3. In Chapter 4 a summary of communication between the research programme and domestic and international interest groups is provided.

Each research project is described formally in Annex A. A list of the most important publications is given in Annex B. The organisation of the research programme is described in Annex C. Finally, the funding of JYT2001 is shown in Annex D.

2 Technical studies on disposal safety

The main results of the technical studies of the research programme related to the safety of the disposal concept are reviewed briefly in this chapter. The studies cover geological, geochemical, hydrological, and engineering aspects of the geological disposal of spent nuclear fuel. The technical studies are based on a variation of the KBS 3 concept for spent fuel disposal, selected as the reference concept in Finland (see Fig. 3).

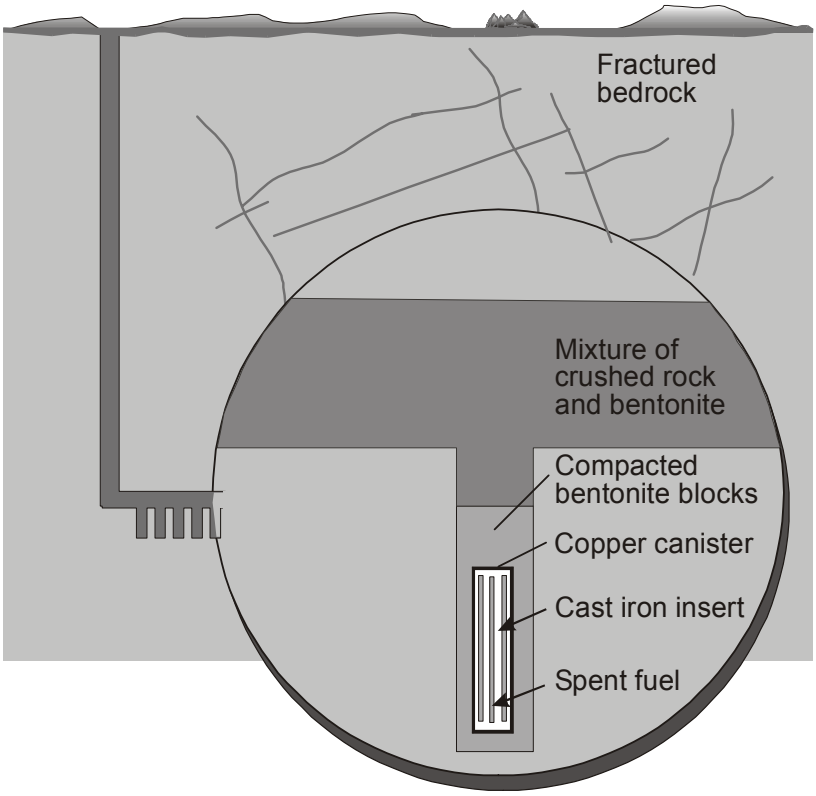

Fig. 3. Reference concept for spent fuel disposal, modified from Posiva [2000a]. The disposal depth is around 500 m.

The technical studies are long-term and international in nature, because, during 20 years of intensive international research in the field, progress has been relatively slow. In addition to the above-mentioned aspects, performance assessment methodology and more general considerations of spent fuel management options are touched upon. On average, around 80 % of the funding of the research programme was allocated to technical studies (cf. Annex D).

2.1 Role of bedrock in disposal safety[5]

The safety of the final disposal of spent nuclear fuel is dependent on a multibarrier system, which is formed of both technical and natural barriers. Technical barriers are expected to guarantee safety for a time period from the present to at least the next ice age. Technical barriers and the whole repository system are, however, situated in a geological environment, which emphasises the role of the bedrock in long-term safety. Large-scale effects are related to the detailed bedrock structures of the disposal sites. Interpretations of structures are based on a variety of drill hole studies of inner and deeper parts of the bedrock formation around a planned repository. In addition to conventional geometric modelling, statistical methods have also been used [Laine 1998].

The most important question is to predict the long-term behaviour of the bedrock. The significant factors of the bedrock, such as its stability and hydrogeology, are related to local and regional fracturing and fracture zones. The Finnish Precambrian basement is composed of a network of homogeneous blocks surrounded by regional fracture zones. This was also a basic idea in the Finnish geological site selection programme [Salmi et al. 1985]. Past and present bedrock movements and faulting are supposed to be related to old fracture zones, especially in the crystalline bedrock of Finland. Earthquakes, which take place annually in Finland, remain on a very low level of magnitude and new breaking of intact bedrock or bedrock blocks is not presently indicated. Stresses caused by land uplift and the spreading of the Mid-Atlantic Ridge can be slowly released as a creep-like slow motion along fracture zones.

A significant question has been how to obtain real measured evidence of the long-term behaviour of fracture zones. Just after an ice age the land uplift rate is very high (dozens of cm/a) and severe earthquakes occur. The conclusion has been drawn that future movements or faulting will occur in already broken zones or zones of weakness and that the bedrock blocks between fracture zones will stay intact. The creep-like motion of the bedrock and small earthquakes indicate the present motion of the bedrock. By mapping the location of the present bedrock movements it is possible to draw conclusions as to future bedrock movements and avoid unstable zones in site selection and repository construction.

The possibility that significant new faults could appear in previously intact bedrock blocks, especially after the next ice age, could form a certain risk. Therefore, in the performance assessments carried out in Finland, such major

[5] By Kuivamäki, A., Vuorela, P.

postglacial failure scenarios have been considered. The only way to experimentally study this kind of fault is to study the spatial distribution and properties of post-glacial faults. Present-day bedrock movements are also significant in this respect [Kuivamäki et al. 1998] because present-day slow motions in the bedrock indicate zones where motions of a higher rate would most probably take place after the next ice age.

2.1.1 Postglacial faults

The block structure of the Finnish Precambrian bedrock was the starting point in the Finnish site selection programme. The bedrock has been deformed several times during its geological history and this has resulted in a mosaic-like block structure, where fracture zones surround more or less intact bedrock blocks of different sizes. On the basis of the age and structural history of fracture zones, the conclusion has been drawn that the old block structure has achieved such a stage of maturity that it will stay in a similar shape during the next million years, the period needed for the safe disposal of the nuclear waste. A logical mechanism for stress release along fracture zones in the already broken bedrock is well-known and has been thoroughly studied.

Large postglacial faults (PG faults) were discovered in the 1960s in northern Finland [Kujansuu 1964] and, later, all over northern Fennoscandia [Lagerbäck 1979; Olesen 1984]. The area is now called the Postglacial Lapland Fault Province [Olesen et al. 2000]. Faults have been classified as postglacial on the basis of the fact that the fault also cuts the younger Quaternary deposits above the fault zone or cuts a bedrock surface polished by glacial ice.

Postglacial faults are, on a geological timescale, clear evidence of young bedrock movements and therefore offer good opportunities for testing the bedrock block model. Large faults and indications of severe earthquakes just after the ice age create the possibility of unexpected events and faulting in the bedrock. That is why postglacial faults have been the objects of keen interest in Finland.

Investigations into postglacial and recent bedrock movements in Finland were carried out over short periods of time during the years 1987–2001 [Kukkonen & Kuivamäki 1985; Paananen 1987, 1989; Vuorela 1990; Veriö et al. 1993; Kuivamäki et al. 1998].

The main purpose was to find answers to questions relevant to nuclear waste disposal:

- Are the PG faults located in old, reactivated fracture zones as predicted by the block model, or have they caused new fracturing in a previously intact bedrock block?
- How and why did PG faults originate? Are there PG faults only in northern Finland (Fennoscandia) or also in other parts of Finland?
- Why do most PG faults strike in the SW–NE direction and dip to the SE?
- What is the structure of PG faults deeper in the bedrock?
- Did the individual PG faultlines originate with one large movement or as a result of several separate, small movements, and how powerful were the earthquakes?
- Are the PG faults still active and what is the mechanism of the movements?
- How and where are the present bedrock movements taking place?
- When and where will the next strong bedrock movements take place in Finland?

The summary report of the investigations conducted in 1987–1997 was published in 1998 [Kuivamäki et al. 1998], and in the present report the results are reviewed on the basis of the investigations conducted in 1998–2001.

Regional distribution of postglacial faults

In Finland large-scale postglacial faults cutting Quaternary deposits have hitherto been recognised only in the northern part of the country (see Fig. 4). Small PG faults located in ice-polished bedrock outcrops and with a scarp height of 0–20 cm have been found in southern Finland [Edelman 1949; Tynni 1966; Nenonen & Huhta 1993], but larger PG faults have not so far been recognised. This fact does not, however, rule out the possibility of large PG faults existing also in southern Finland. The main part of southern Finland belongs to an area which was below the highest shore level of the post-glacial evolutionary stages of the Baltic Sea and the action of waves eroded and redeposited Quaternary material. For this reason it is difficult to recognise postglacial fault scarps and, on the other hand, to make dating of fault scarps if they are postglacial.

Investigations 1987–2001

The Pasmajärvi PG fault in Kolari is the most thoroughly studied PG fault in Finland. Around the fault lineament interpretations and geophysical ground measurements have been carried out and the fault zone has now been penetrated with three drill holes (47, 92, and 250 metres long). Three levelling networks and

one GPS network have been established to indicate the recent movements of the PG fault area [Kiviniemi et al. 1992; Veriö et al. 1993]. Other faults studied in detail are the Ruostejärvi PG fault and the Vaalajärvi fault, which was earlier regarded as a PG fault. Systematic geophysical ground measurements, profile measurements across the fault scarps with ground-penetrating radar, excavation across the fault scarp, and drillings thorough the faults were performed in 1999–2000 [Kuivamäki et al. 2001].

In order to study the strong seismicity connected with the origin of PG faults, lake sediments were drilled around the Pasmajärvi PG fault. In 2001 the acoustic-seismic sounding method was tested for mapping possible seismites/disturbed structures in the lake sediments of Lake Pyhäjärvi in Artjärvi municipality, in SW Finland. Lake Pyhäjärvi is located in an area known to be seismically active even at the present time.

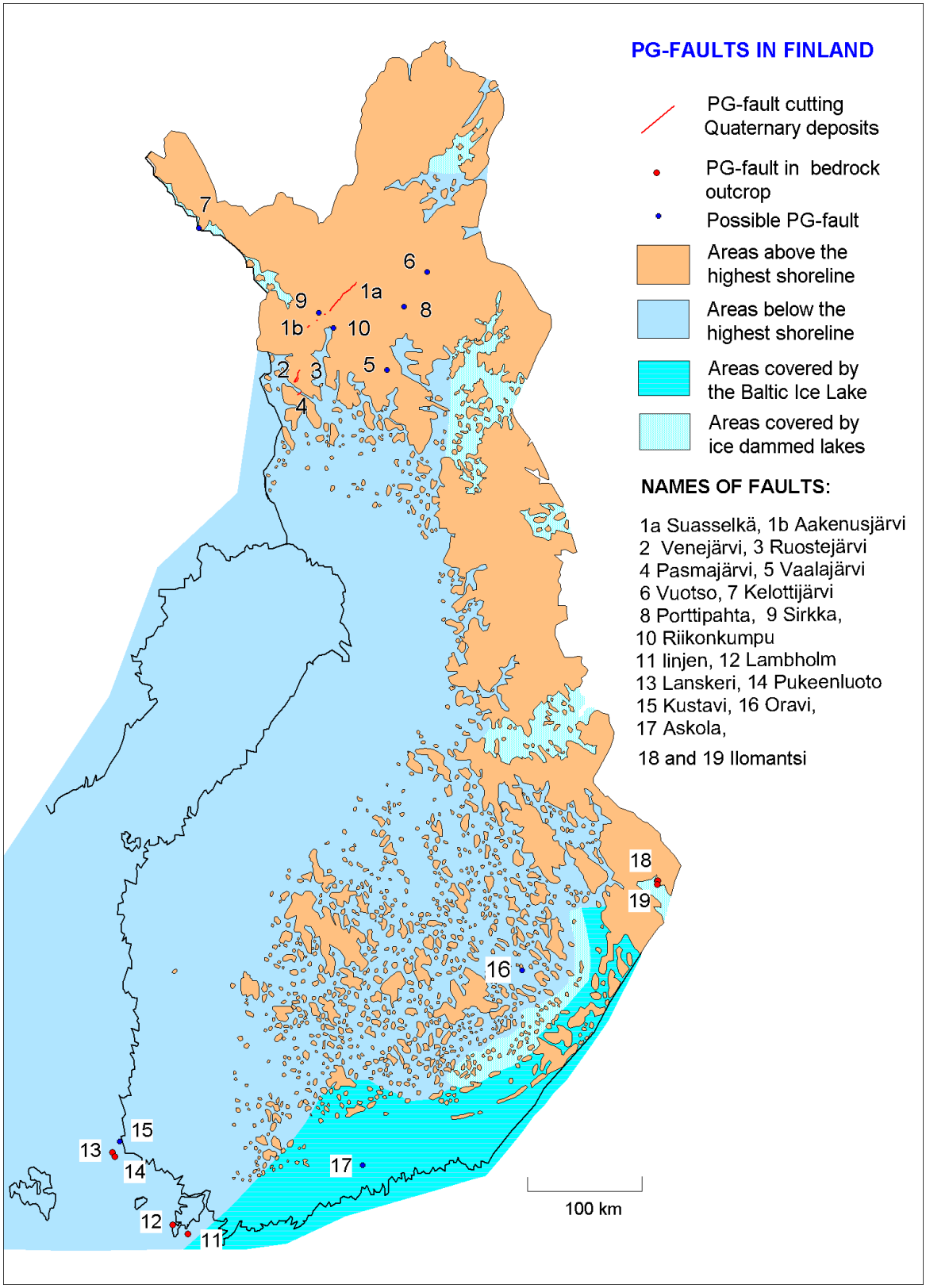

Fig. 4. Postglacial faults (PG faults) of Finland. Modified after Kuivamäki et al. [1998].

Results of postglacial fault studies

The investigations carried out in 1987–1997 and 1998–2001 revealed that:

- The PG faults studied so far are situated in old, reactivated fracture zones. In Pasmajärvi the old fracture zone has been reactivated several times, but in Ruostejärvi the evidence of repeated reactivation is less distinct.
- The Finnish PG faults, with the exception of the Ruostejärvi fault, are reverse faults with a SW-NE strike direction and dipping to the SE. The Ruostejärvi PG fault is a normal fault dipping to the SE, which, together with the Venejärvi PG fault (reverse fault), borders an uplifted bedrock block. The horizontal loop EM survey has revealed several new possible fault scarps parallel to the known Ruostejärvi PG fault. The strike direction of the PG faults in Finland is perpendicular to the direction of the prevailing maximum horizontal stress field (NW–SE) and evidently the same stress field direction has existed for a longer time [Wahlström & Assinovskaya 1998].
- The Vaalajärvi fault was earlier regarded as an exceptional PG fault with a differing strike direction to NW–SE. It was thought to be the result of the regional block structure, which had possibly given rise to a secondary stress perpendicular to the Vaalajärvi fault. A detailed study of the fault (geophysical ground measurements, drilling, and excavation) carried out in 1999–2001, revealed that under the Vaalajärvi 'PG fault scarp' there exists an old fracture zone. The excavation across the scarp shows, however, no clear indications of faulting in the overburden and that is why the Vaalajärvi PG fault is now classified only as a possible postglacial fault (Fig. 5).
- The results of resistivity soundings in 1987–1989 in the Pasmajärvi PG fault zone indicated that the dip angle of 45° in the scarp starts to turn more horizontal in the upper (>150 m) parts of the bedrock. Also, the block structure formed by the Venejärvi and Ruostejärvi PG faults was interpreted with dips becoming gentler with increasing depth [Kuivamäki et al. 1998]. These results were thought to be noteworthy when planning repositories for nuclear waste disposal. That is why the verification of the structure of the Pasmajärvi PG fault at deeper levels was carried out in 2000 and 2001 by drilling new 150 metre- (KR4) and 250 metre-long (KR3) drill holes at distances of 145 and 290 metres from the fault scarp (Fig. 6). In the KR3 drill hole two distinct fracture zones were penetrated, the upper one at a depth of 71–76 m and the lower one at a depth of 175–180 m. In the KR4 drill hole only one fracture zone was penetrated, at a depth of 85–92 metres, and it correlates with the lower fracture zone of the KR3 drill hole. These results did not coincide with the interpretation of results of resistivity soundings, as a

constant steeper dip angle of 47° was indicated for the PG fault, at least in this upper part (0–180 m) of the bedrock. Resistivity results may be related to a general change of fracture density in the surface part of the bedrock.

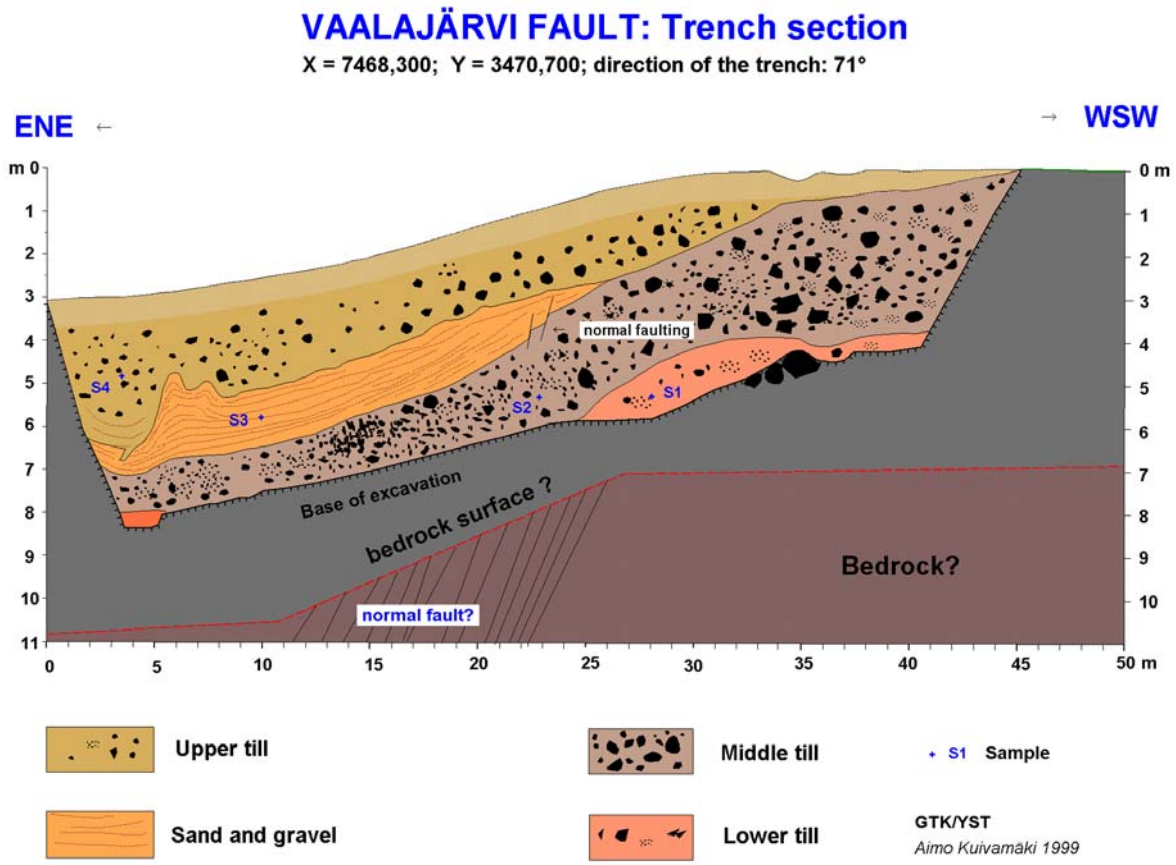

Fig. 5. *Trench section across the Vaalajärvi fault scarp.*

- It is still unclear if an individual PG fault originated in one or several phases. When the seismicity of PG faults has been estimated, every PG fault is, however, thought to have originated in one phase. Different methods were used for estimations of earthquake magnitudes connected with PG faults in Finnish Lapland. The magnitude estimations varied from 5.3 to 7.5 [Kuivamäki et al. 1998]. Those magnitudes are, in any case, much greater than those of recent earthquakes in the same area. The epicentres of the recent earthquakes seem to be located mainly on the SE side of PG fault lines and to form parallel zones with PG fault lines. This possibly indicates that PG fault lines are surface expressions of old, reactivated, and still active regional fracture zones, which are dipping to the SE.

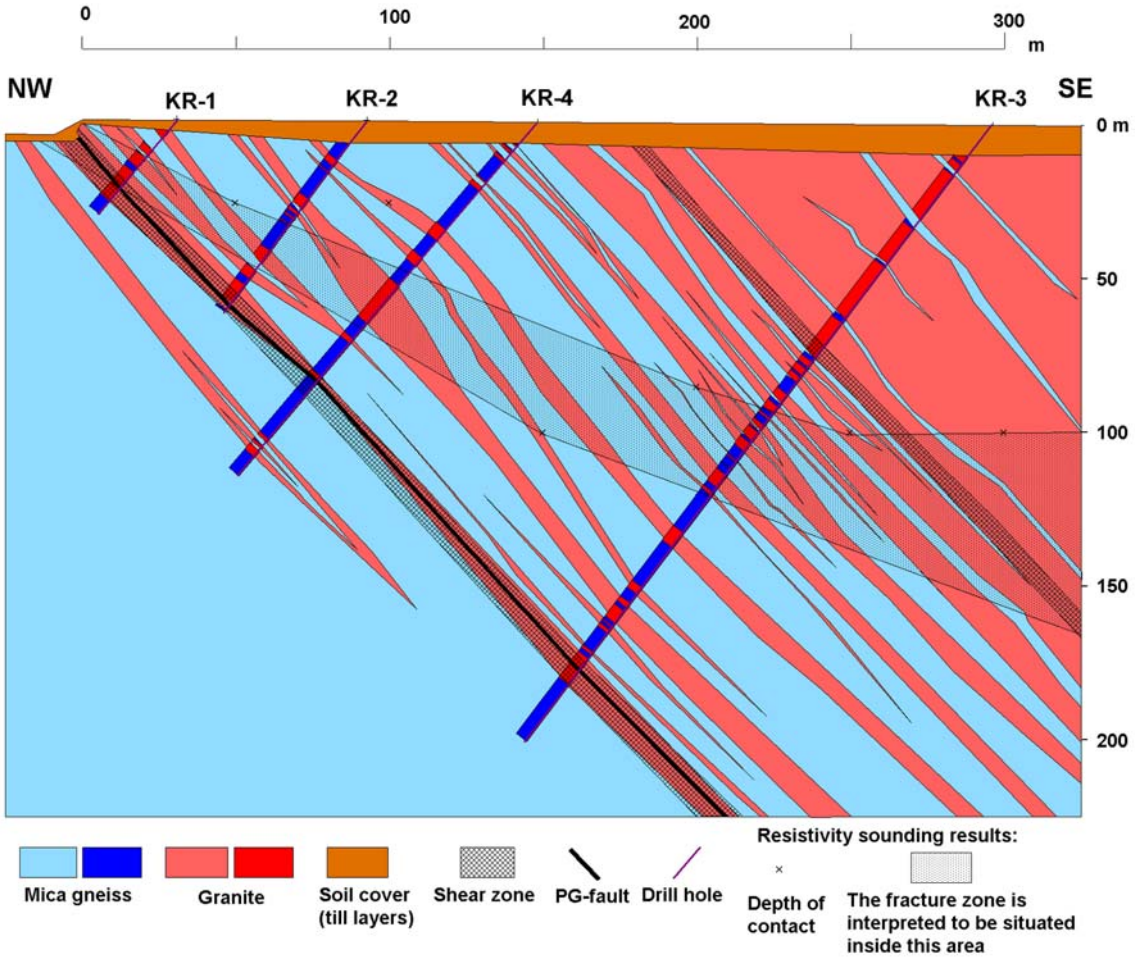

Fig. 6. *Cross-section of the Pasmajärvi PG fault based on the interpretation of drilling data (KR1, KR2, KR3, and KR4) [Kuivamäki et al. 1998, 2001] and resistivity soundings [Paananen 1989].*

- In Russian Karelia there are several seismotectonic domains and Russian scientists have reported results for the repetition of high seismic periods at about 2 300-year intervals after the last deglaciation [Lukashov 1995]. Field trips to the seismotectonic domains of Lake Ladoga and Lake Onega in Russian Karelia in 1995–1997 gave other possible answers for the observations [Kuivamäki et al. 1998]. The boulder fields at the foot of high bedrock scarps seem to be at least partly of seismic origin, but the question of their age is still disputable. During the short field trips it was not possible to verify the arguments presented for the repetition of high seismic activity. On the contrary, preliminary analysis of sediment samples collected from the Onega area indicates only one deformation phase near the deglaciation age of the Onega basin [Saarnisto 1998]. The result would be in accordance with those from northern and southern Sweden, where quite undeformed sedimentary layers are lying over the deformed and disturbed sediments. Contra-

dictory results have, however, been presented from central Sweden [Mörner 2001]. According to Mörner's interpretations a very large earthquake occurred in the varve year 9 663 BP and he also mentions six additional earthquakes in the time range of 9 800–3 200 BP.

- The preliminary results of the acoustic–seismic sounding of Lake Pyhäjärvi in southern Finland indicate that there exist disturbed structures in the bottom part of sediments with an age of 10 700–10 200 BP, but the upper sediments are undisturbed [Kotilainen & Kuivamäki 2001]. The origin of the disturbed structures is still unclear, but in any case these results seem to verify the conclusion that the possible high level of seismic activity is connected just with the beginning of a postglacial period and that there is no later repetition of high seismic activity. For the verification of this conclusion new acoustic-seismic soundings should be made for the bottom sediments of Lake Onega. Those places where repeated high seismic activity has been reported are of especial interest.

On the origin of PG-faults

The location of large PG faults, strike directions, and SE dipping of fault planes are in agreement with the model presented by Muir Wood for the origin of PG faults [Muir Wood 1989]. According to Muir Wood, the origin of PG faults can be explained as a result of horizontal tectonic stress induced by the Mid-Atlantic Ridge and quick isostatic land uplift combined with material flow beneath the crust toward the uplift centre. The friction of material flow caused extra shear stresses in the crust, and the stresses relaxed as reverse faulting dipping to the SE after the loading of the ice sheet disappeared. The ice loading was especially heavy in the area south-west of the Caledonian mountains and for this reason it seems logical that the longest PG faults are located in northern Fennoscandia.

The first results of the BIFROST GPS network have revealed that in postglacial rebounding phenomena, there is, in addition to the vertical component, also a horizontal component [Milne et al. 2001]. As a reason for the origin of PG faults it may be worthwhile to observe that the largest horizontal strain components are situated in the same area as where the known PG faults also occur (Fig. 9). The direction of maximum horizontal movements is also opposite to the direction of the horizontal tectonic stress induced by the Mid-Atlantic Ridge.

2.1.2 Recent crustal movements

A measurement network around the Olkiluoto site was founded by power companies approximately two years ago, and as new bench marks (measurement

points) in the surroundings have still been planned, results will be available after some years of monitoring. A difficulty in these measurements is the shortage of time available for continuing monitoring. Long-term monitoring of bedrock movements has, however, been studied in the JYT2001 programme. Measurement fields were established in Pasmajärvi, Finnish Lapland, several years ago in co-operation between three Finnish research institutes. The precise levelling network in Finland has, in part, an age of one hundred years and it has also offered an opportunity to study vertical bedrock movements over longer time intervals.

At the beginning of the ’90s measurement networks were established in the Pasmajärvi and Nuottavaara areas by the Geodetic Institute of Finland and the National Land Survey of Finland for the monitoring of recent bedrock movements (Fig. 7). This is important because:

- An objective is to understand the regional dynamics of the bedrock by collecting measured data along different fracture zones.
- The Pasmajärvi–Nuottavaara area and the Olkiluoto area have their main fracture zones in a NW–SE direction, which is a common direction of fracture zones in Finland. Postglacial faults have not, however, been found in Olkiluoto, but the bedrock type is almost identical and fracture zones border a bedrock block structure. The results from the Pasmajärvi–Nuottavaara area can be compared with those from the Olkiluoto area.

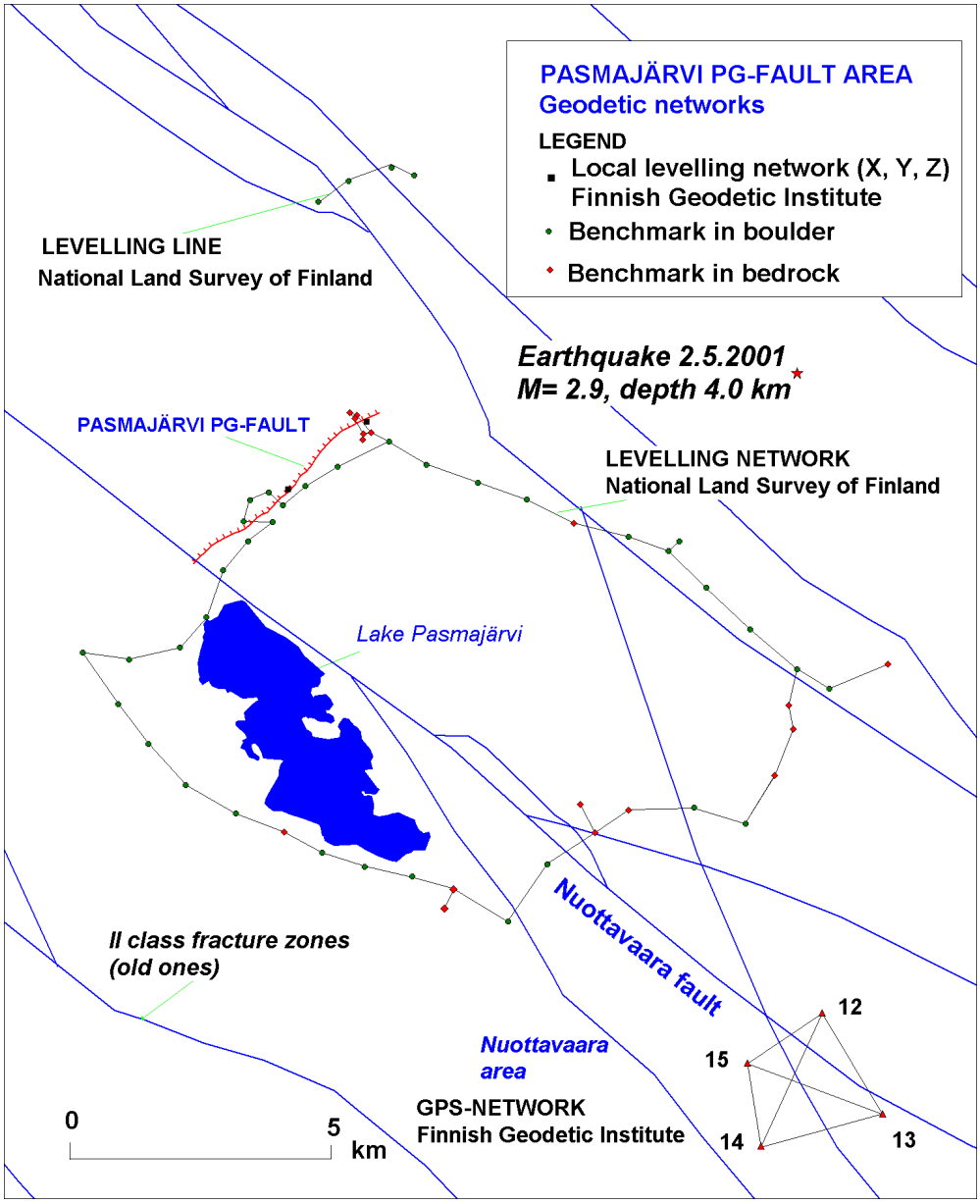

Fig. 7. Geodetic networks of the Pasmajärvi PG fault area and the Nuottavaara fault area. Location of the earthquake of 2.5.2001 added. Modified after Kuivamäki et al. [1998].

Relevellings have not until now indicated any movements along the Pasmajärvi PG fault [Konttinen 1994; Kääriäinen & Takalo 1995].

A four-point network was established in the Nuottavaara area in 1991 to follow movements in an old fault zone (fault in NW–SE direction and tectonically connected with the Pasmajärvi PG fault). The network has been measured three times, in 1991, 1992, and 1995 [Poutanen & Ollikainen 1995]. A fourth observation campaign was mounted in the summer of 2000.

On the basis of the results obtained so far, nothing certain can be said about the current movements of the Nuottavaara faults. The quality of the observations in 1991 and 1992 was poor. The reasons were poor satellite geometry, brief observation times, and squaring receivers in 1991 and 1992. The observations in 1995 and 2000 are of good quality, but no indication of possible bedrock movements just on the basis of these results has yet been found [Ahola 2001].

Near the Pasmajärvi area there occurred on May 2, 2001 an earthquake with a magnitude of 2.9 (Fig. 7). The epicentre of the earthquake was located at a depth of 4 kilometres. The occurrence of the earthquake proves that the Pasmajärvi area is still tectonically active. More long-term monitoring is still needed to determine possible deformations of the Pasmajärvi PG fault and the Nuottavaara faults. Additionally, the levelling network established in the same area by the National Land Survey of Finland should be relevelled.

The present vertical bedrock movements of Finland have been studied in several areas with levelling profiles crossing fault zones of different size categories [Veriö et al. 1993]. Of the 53 profiles levelled by the National Land Survey of Finland, 28 recorded statistically significant local changes in elevation, while 7 showed variations that deviate substantially from predictions based on uniform plastic uplift (Fig. 8). Magnitudes of uplift rate, classified statistically as significant to highly significant, varied from 0.24 mm/year to 1.52 mm/year.

Seven of those 17 lines levelled three or four times indicated that bedrock movement had stopped. The rest (16) of those 53 lines indicated immobility or slow tilting in accordance with the assumed present-day bedrock uplift.

The lineament interpretations revealed that 53 relevelled lines crossed 652 fracture zones. According to calculations, 27.5 % of all the fracture zones studied were situated in places where clear height differences were measured.

These results, together with the results of the third precise levelling of Finland carried out by the Geodetic Institute of Finland [Lehmuskoski 1996], support the notion that the present-day land uplift is taking place on a regional scale plastically, but on a local scale as block movements. These block movements are preferentially concentrated within old fracture zones.

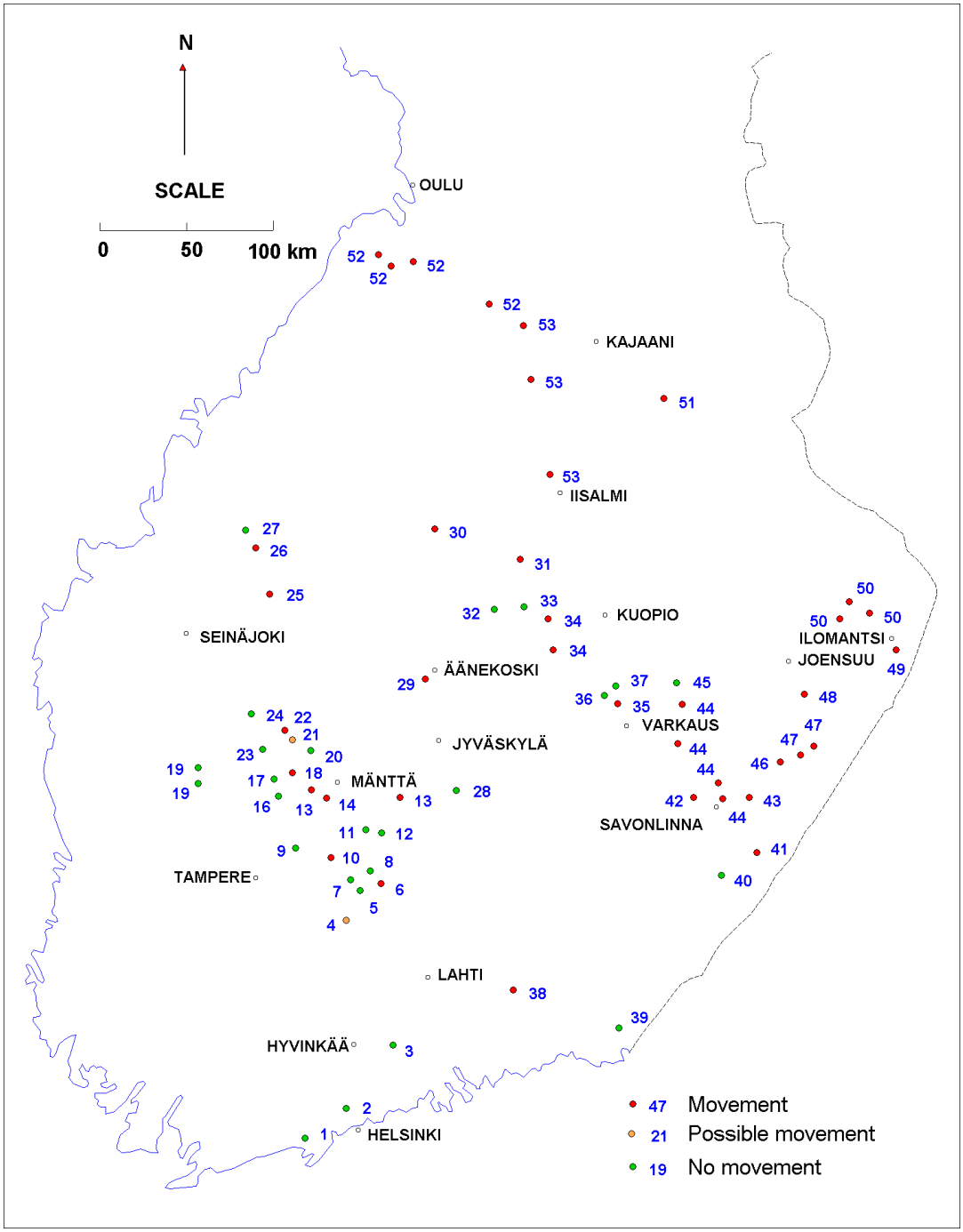

Fig. 8. Results of the relevellings carried out by the National Land Survey in 1974–1992 [Veriö et al. 1993].

Preliminary knowledge of horizontal crustal deformations in Finland has been gained by using measurements of the first order triangulation network. For the country as a whole, a maximum compression in the NW–SE direction is clearly visible [Chen 1991]. The GPS and the Finnish Permanent GPS Network nowadays offer good opportunities for obtaining new data, especially on horizontal

bedrock movements [Chen & Kakkuri 1994, 1998]. The first horizontal movements revealed by GPS were from the Lake Lappajärvi area in 1990, where sinistral horizontal movement (111±30 mm) was detected; the movement had possibly taken place in connection with the Lappajärvi earthquakes in 1976 [Veriö 1992].

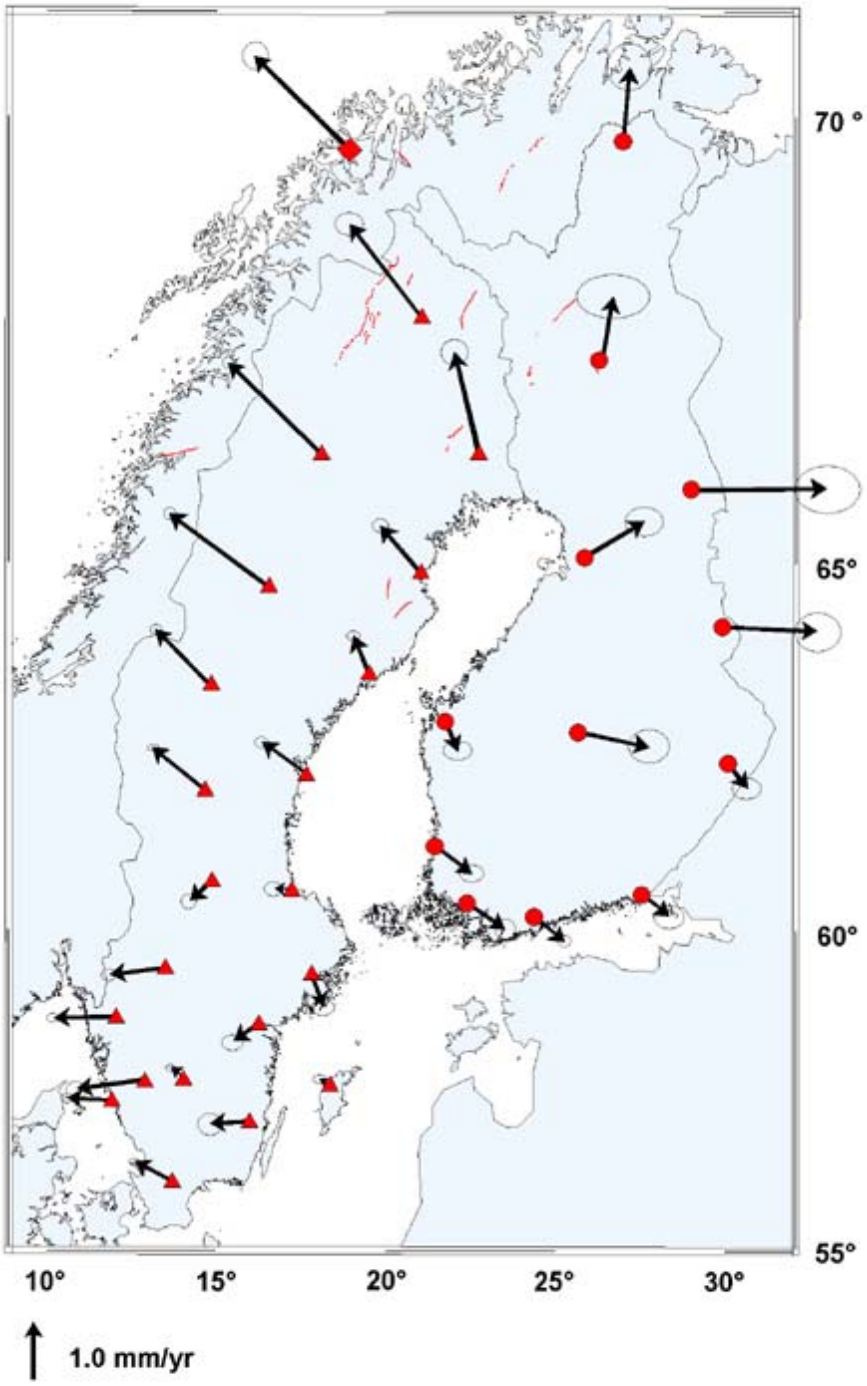

Fig. 9. Horizontal velocity vectors estimated at each of the BIFROST sites. The scale associated with each of these vectors, as well as with the associated 1σ error ellipses, is given at the base of the plot [Milne et al. 2001]. The locations of known PG faults have been added to the map.

The best knowledge of the deformation of the Fennoscandian shield in three dimensions will be achieved in the near future, when more data will be collected by the BIFROST GPS network of Fennoscandia [Milne et al. 2001]. The network consists of two subnetworks: the Swedish SWEPOS network (21 receivers, operating since 1993) and the Finnish FinnRef network (with 12 receivers, operating continuously since 1995). The first analysis of BIFROST data demonstrates that the ongoing three-dimensional crustal deformation in Fennoscandia is dominated by the Glacial Isostatic Adjustment (GIA) [Milne et al. 2001]. The vertical uplift maximum of 11.2 ± 0.2 mm/year is located near the site at Umeå. It is very interesting that for the first time the horizontal component connected with the uplift has also been measured. The horizontal velocities are relatively low in areas where the radial uplift rates are highest (such as the central Baltic Sea), and the horizontal movements are directed outward from this location on all sides (Fig. 9). In further agreement with the numerical predictions, these rates increase according to their distance away from the uplift centre, and they reach about 1 to 2 mm/year at sites marking the perimeter of the BIFROST network. The Fennoscandian region is thus presently subject to widespread extension. Horizontal rates have greater amplitude west of the Gulf of Bothnia than east of this region [Milne et al. 2001]. It is also interesting to find out that horizontal rates are quite different in the Pasmajärvi area, as compared with the ones in the Olkiluoto area. This can be one explanation for the fact that there exists no postglacial faulting in the Olkiluoto area.

2.1.3 Conclusions from bedrock studies

The most significant geological factors in the final disposal of spent nuclear fuel are the location, behaviour, and properties of fracture zones. The primary idea of the block-mosaic bedrock structure and the behaviour of fracture zones is logical and based on a large amount of investigation results. At the present stage, after several years of investigations, many estimations have been fixed and models have become more realistic. This work has concentrated on measuring and analysing the present and long-term effects related to regional and local bedrock structures and promoting possibilities for the forecasting of future events. The following conclusions can be drawn:

- The block model of bedrock is realistic. Even large postglacial movements have been concentrated in the existing old fracture zones, and no new fracturing in old intact bedrock blocks is known to have happened.
- The Pasmajärvi PG fault, drilled through to a depth of 180 metres, shows a constant dip angle of 47° and indicates no turning of the fault plane to a more

horizontal position. The extension and geometry of postglacial faulting deeper (>180 m) in the bedrock is, however, not yet verified.

- The occurrence of high seismic activity seems to be restricted to the final stage of a glacial period or the beginning of a postglacial one. There seems to be no indisputable evidence for the repetition of high seismic activity at a later time. To verify this conclusion, sampling and acoustic-seismic soundings should be carried out in the Lake Onega area, from where Russian scientists have presented some data with a differing conclusion.
- The localisation and origin of PG faults has not been finally clarified. More data with GPS measurements, relevelling results, and microseismic studies is needed. In the near future (5–10 years) new GPS measurements from the BIFROST network, together with better models of the Earth's crust in Fenno-scandia, will give us new data and evidence to understand the dynamics of the block structure model and also the origin of PG faults.

2.2 Hydrogeology and geochemistry[6]

Groundwater and fractures in bedrock, together with technical barriers, form the system in which the possible release of radionuclides from a repository can occur. Therefore, understanding and modelling the interaction between technical barriers, the hydrogeological and mechanical properties of the repository, and its surrounding bedrock are crucial. External impacts resulting from the construction of the repository or climatic change (the palaeohydrogeological aspect) should also be taken into account. The detailed characterisation and prediction of bedrock conditions requires the development of hydrogeological investigation methods (both measurement methods and data processing), which can be divided in the current research programme into methods to study current hydrogeological conditions and to evaluate palaeohydrogeological conditions.

The impacts of the glacial cycle on a hydrogeological system may form potential risks for repository safety. One which has been generally debated is the infiltration of O_2-rich meltwaters deep into the bedrock, developing oxidising conditions at repository depths. Indications of significant recharge in a distinctly colder climate than that presently prevailing have been reported from several sites, for example Hästholmen, Palmottu, and Olkiluoto in Finland [e.g. Kankainen 1986; Blomqvist et al. 1995; Pitkänen et al. 1996].

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[6] By Pitkänen, P., Ahonen, L., Blomqvist, R., Kaija, J., Korkealaakso, J., Luukkonen, A., Okko, O., Poteri, A., Ruskeeniemi, T., Suksi, J.

Groundwater flow models are based on short-term hydraulic tests and hydraulic measurement data are available from time-spans of months to approximately two years. Therefore, long-term (>10^3 years) hydraulic simulations based on data gained from hydrological measurements include possibly significant but practically incalculable uncertainties. Both the primary hydrochemical data and the conceptualisation of the hydrochemical evolution (from past to present) give information about hydrogeological events in the past. The conceptualisation of the past geochemical evolution of groundwater is also a key for predictions of the future geochemical evolution of groundwater. The use of geochemical data in the calibration of hydrological simulations reduces the uncertainties the models display. Furthermore, by utilising hydrogeochemical conceptual future scenarios, long-term hydrodynamic predictions can be produced with more confidence and an integrated hydrodynamic-geochemical view can be developed for a research site [Bath & Lalieux 1999].

Consistency between geoscientific (geology, structure and mechanics, groundwater flow, and hydrogeochemistry) models is considered to be a basic requirement for the reliable safety assessment of a geological repository, and an important aspect of building confidence in data. The discrete character of fractured rock makes the interpretation of groundwater flow, chemical interaction, and transport complex. One important task has been to develop and apply methods for interpreting and modelling interaction between groundwater flow, chemistry, and structural properties of the bedrock. The improvement of hydrodynamic and geochemical approaches and modelling tools is therefore essential in order to simulate current and potential future hydrogeological conditions in bedrock more realistically.

The objectives of hydrogeological and geochemical studies relevant for repository safety can be divided, in the current research programme, into three parts:

- to augment detailed knowledge of potential hydrogeological and geochemical conditions and risks prevailing in bedrock at present and in the future as a result of climatic changes
- to develop methods for improving consistency within hydrogeological data and models
- to improve geochemical and hydrodynamic modelling know-how so as to consider details and changes in the hydrogeological system more realistically.

2.2.1 Palaeohydrogeology and glacial effects

During the last two million years the geologically stable Fennoscandian Shield has been subjected to several glacial cycles. During at least the last half million years glaciated periods and warm interglacial periods have been repeated in cycles of about 110 000 years. Consequently, the effects of major changes in climatic conditions in Fennoscandia have to be accounted for in assessing the long-term stability of a nuclear waste repository. The main climatic changes include the accumulation of a continental ice sheet covering the repository area (as much as several kilometres thick) or the development of cold, periglacial conditions without an ice sheet, allowing the penetration of permafrost down to a depth even more than 500 metres into the bedrock.

Both thick continental glaciations and the advancement of permafrost deep into the bedrock may affect the repository. Possible hydrogeological effects include

- the intrusion of oxygenated meltwater to the repository's depth, with consequent changes in redox conditions and canister corrosion
- the formation and advancement of a saline front below the permafrost, which may affect the properties of the buffer material around the canister
- the channelling of flow to non-frozen parts of otherwise frozen bedrock (formation of 'Taliks').

Understanding the processes and conditions of possible future cold periods can be achieved by studying the conditions and effects of the last glacial cycle, which ended about 10 000 years ago. According to the latest results the view of the last glaciation, the Weichselian Ice Age, has evolved significantly. Ukkonen et al. [1999] suggested that southern Finland had a glacial cover for only 20 000 years, which is much less than previously estimated. This implies that periglacial and possibly also permafrost conditions prevailed for longer during the cold Weichselian period (between 115 000 and 11 500 years ago).

Glacial signatures in deep groundwaters have been observed at many sites in Finland. It is generally concluded that the observed $\delta^{18}O$ values in deep groundwaters, which are lighter compared with current recharge, can be linked to glacial cycles, either to pressurised meltwater intrusions created during deglaciation and/or to permafrost conditions preceding the advance of glacial cover. In the latter case a similar decrease in $\delta^{18}O$ value is achieved by just removing ice with the heavy oxygen isotope from the water (isotopic fractionation) and driving a

concentration front with low $\delta^{18}O$ deeper down [Smellie et al. 2001]. These aspects have been studied in more detail at two field sites, Palmottu in SW Finland and Sukkulansalo in eastern Finland. Both are located in the foreground of the Salpausselkä formations, thus demonstrating the potential for massive meltwater intrusions into the bedrock.

Palmottu

The Palmottu U-Th mineralisation at Nummi-Pusula in south-western Finland has a number of features relevant to issues considered in performance assessment (PA) of spent fuel repositories in fractured crystalline bedrock. Furthermore, it includes some unique characteristics, owing to its glacial and post-glacial history. The Palmottu U-Th mineralisation was the target of intensive uranium exploration from 1979 to 1984. The uranium deposit proved to be too small for mining purposes, but it was considered to provide an excellent opportunity for studying radionuclide transport along well-characterised groundwater pathways. The site itself is a source of radionuclides, comprising a U-Th deposit in mica gneisses and granites typical of the rocks in the Fennoscandian Shield. During the years 1996–1999 the EU-funded Palmottu project studied the migration of uranium in the natural flow system at the site, and produced versatile paleohydrological information (cf. Annex A).

Hydrogeochemistry

The hydrogeochemical model of the Palmottu site is based on the integration of geochemical and hydrological data; carbon isotopic data have also been utilised in testing the model [Blomqvist et al. 1998, 2000; Pitkänen et al. 2001a]. The upper 100 m of the bedrock is characterised by dilute HCO_3 groundwater, where calcium is the dominant cation near the surface, changing to sodium in the lower parts of this zone. This dynamic flow system penetrates to a depth of at least 200 m in the southern part of the site, as is indicated by high tritium contents. Below the HCO_3 type water, the groundwater is brackish, of an Na-SO_4 or Na-Cl type. Both the hydrochemistry and isotopic results indicate long residence times and stagnant flow conditions. The Na-SO_4 water is present only around the central mineralised zone of the site, between the Na-HCO_3 and Na-Cl-type waters. In the area westward from the Western Granite, the Na-Cl water type is observed directly below the Na-HCO_3 water.

The δ^2H and $\delta^{18}O$ isotope signatures of the different groundwater types (Fig. 10) indicate a meteoric origin of the water without palaeoevidence of seawater mixing during post-glacial times. In the Na-SO_4, Na-Cl, and some of the Na-

HCO_3 type groundwaters, there is a significant depletion in the heavier isotopes, which indicates cold conditions. The local, present-day meteoric groundwater signature can be observed in the shallow bicarbonate waters. The depleted values deeper in the bedrock may represent a colder climate recharge, which took place during the retreat of the Weichselian ice sheet, about 10 000 BP. These depleted values should reflect a higher portion of glacial meltwater.

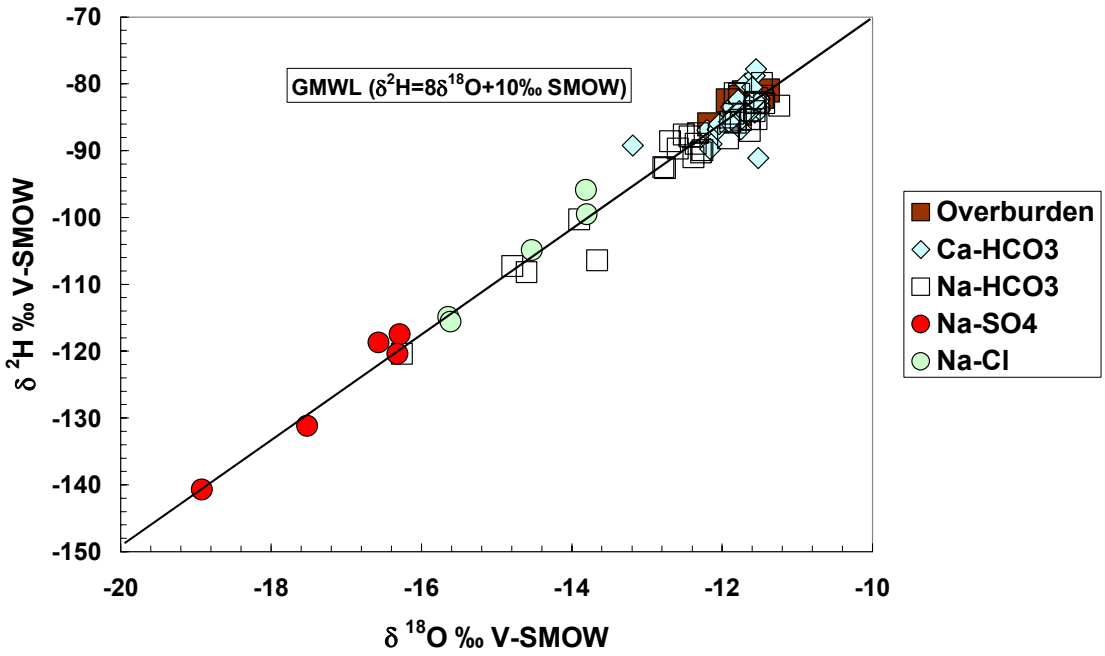


Fig. 10. Stable isotope plot (δ^2H and $\delta^{18}O$) for the Palmottu groundwater samples compared to the Global Meteoric Water Line ($\delta^2H = 8 \cdot \delta^{18}O + 10$; Craig [1961]).

Palaeohydrogeological implications at Palmottu

It is evident from Quaternary evidence that Palmottu experienced a continental ice margin palaeoclimate and was not subsequently submerged beneath sea water [Donner 1995; also Blomqvist et al. 2000, 2001] after Weichselian glaciation. The main glacial processes influencing the evolution at Palmottu, and therefore influencing the hydrochemical stability of the groundwater system, were permafrost and the closeness of the ice margin [Smellie et al. 2001]. The features which seem to be potentially relevant to understanding past perturbation of the hydrochemical system are the significant U-series disequilibria (USD) in fracture coatings and in the rock matrix around fractures [Suksi et al. 2001a, b], the presence of a glacial water component at depth, and the presence of Na-SO_4 type groundwater at depth [Blomqvist et al. 2000].

The USD measurements produced important information concerning groundwater flow. The $^{234}U/^{238}U$ activity ratios in the groundwater indicated the locations where the mixing of groundwaters had taken place. It was possible to use fracture coatings to further characterise groundwater flow. They included uranium, which had recently either been removed or accumulated. The formation ages of the U accumulations showed clustering, suggesting periodicity during the long-term accumulation of uranium. Most ages ranged from 110 000–40 000 years ago (Fig. 11), further implying that glacial events may have contributed to U behaviour. The indication of U accumulation in some fractures and its removal in others demonstrates that certain fractures/fissures were isolated from the main groundwater flow pathway, either because of much lower transmissivity, sealing, or because of distance. The observations support the channelling of groundwater flow.

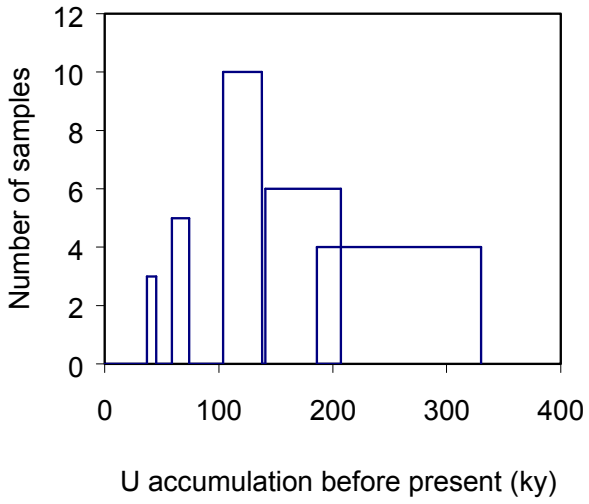


Fig. 11. Distribution of closed system model ages of U accumulations found on fracture surfaces [Suksi et al. 2001b].

The USD data obtained from rock around water-conductive fractures showed massive and recent U out-diffusion from the rock matrix (Fig. 12), indicating that oxic groundwaters may have had an effect in these fractures [Suksi et. al. 2001a, b]. The history of the out-diffusion in sample R384 was studied in more detail, using mass balance calculations and USD modelling. The results showed that out-diffusion cannot be explained by a steady long-term release of U. Neither could the U release during the last post-glacial period explain this, limiting the occurrence of major out-diffusion to between 10 000 and 200 000 years ago, i.e. within the two last glacial cycles. Furthermore, in order for past development to have

accomplished the observed U release, the involvement of an extra process, possibly pressurised oxic meltwater intrusion, is needed [see Rasilainen et al. 2001b].

Na-SO_4 and Na-Cl groundwaters with notable glacial $\delta^{18}O$ signatures have been found at depths from 200 to 350 m at Palmottu [Blomqvist et al. 1998, 2000; Pitkänen et al. 2001a]. The extreme $\delta^{18}O$ value of -19 ‰ obtained at Palmottu is close to the expected isotopic value of glacial meltwater [cf. Ferronsky et al. 1983; Pitkänen et al. 1999b, 2001a], and $\delta^{18}O$ values lighter than -15 ‰ would already have a notable glacial water component. This may suggest that glacial waters were introduced under high hydraulic pressures at the margins of the ice mass during glacial melting and retreat, dispersed into much lower transmissivity fractures and mixed with existing groundwaters (see the USD discussions above). Subsequently (i.e., during the last 10 000 years), the glacial component was flushed out from the upper part of the highly permeable bedrock, but was retained in the low permeable parts of the deep bedrock, mostly below a depth of 200 m. Nevertheless, it is unlikely that the glacial waters would have retained their oxidation capacity to any great depth, because of the significant buffering capacity of first the overburden and then the bedrock itself. However, indications of the possible temporary presence of oxygenated waters have been obtained in U-series disequilibrium profile studies in the rock matrix around water-conducting fractures at shallow depths [Suksi et al. 2001a; Rasilainen et al. 2001b].

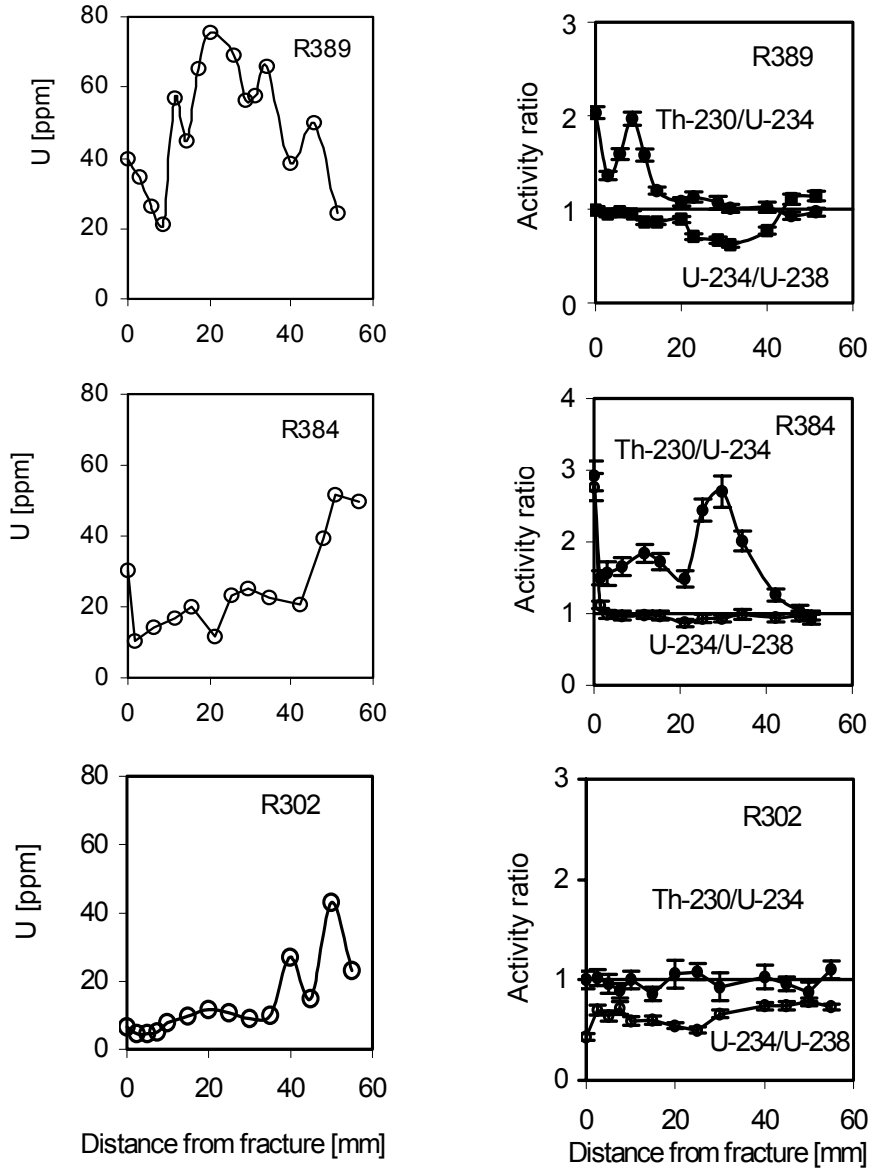


Fig. 12. U-series profiles measured as a function of distance from three water-conductive fractures sampled from the eastern flow system at Palmottu. The effect of fracture on the formation of profiles is seen in all samples. Absolute U concentration profiles show U removal, which can be seen as decreasing gradient towards fracture (in sample R389 from the distance of 20 mm). Furthermore, the $^{230}Th/^{234}U$ activity ratios (>> 1) in samples R384 and R389 from a depth of a few dozen metres imply that U has been recently removed. In sample R302 $^{230}Th/^{234}U$ activity ratios representing depth at about 70 m show radioactive equilibrium (≈1), indicating that in this sample the major U release took place earlier than 300 000 years ago.

The presence of Na-SO_4 type groundwaters makes Palmottu unique, since there is no other recorded occurrence from a crystalline rock environment in the open literature. It appears to be restricted to the area of uranium mineralisation in the central part of the Palmottu site, located between the Na-HCO_3 and Na-Cl type groundwaters [Blomqvist et al. 1998, 2000].

Basically, four hypotheses can be considered to explain the presence of sulphate in these groundwaters: 1) sulphide dissolution and oxidation during hydrothermal events creating an in situ residual sulphate fluid/solid; 2) continuous, long-term oxidation of sulphide minerals during geological times, including the oxidation of sulphide minerals due to the incursion of oxygen-rich meltwaters, 3) significant oxidation of sulphides in uranium deposits may be caused by the radiolysis of water molecules and α-radiation damage to the mineral matrix in the process of the decay of radioactive elements during geological times [Vovk 1987], and 4) the enrichment of sulphate waters by freezing under permafrost conditions. It is possible that a combination of all four mechanisms was involved in creating the observed sulphate concentrations.

There appears to be reasonable evidence to show that the origin of the sulphate is closely related to uranium mineralisation, and that sulphate-forming processes may have been active over geological times. Furthermore, it is considered unlikely that the oxidation of sulphides under present conditions or even in the case of meltwater penetration could produce any significant amounts of sulphates, due to the small amount of dissolved oxygen available [cf. Pitkänen et al. 2001b]. To explain the measured concentrations would require some additional mechanism, and presently the cyclic enrichment of sulphate by freezing under cold climate or permafrost conditions is considered a viable explanation. The basis of this hypothesis is the formation of solid mirabilite ($Na_2SO_4 \cdot 10H_2O$) in fractures (or possibly at the surface), resulting from the freezing of waters initially containing some sulphate. A similar effect is also achieved without the intermediate solid phase by just removing ice from the water and driving a concentration and decreasing $\delta^{18}O$ front deeper down. These freezing mechanisms would conveniently explain the association of Na-SO_4 groundwaters with $\delta^{18}O$-depleted cold climate recharge waters (Fig. 10). Permafrost conditions could have a major influence in producing sulphate waters in surface/near-surface environments, where a cyclic freeze-out process of groundwater in an advancing permafrost front could contribute to the character of these groundwaters [Smellie et al. 2001]. The fact that brackish Na-SO_4 and Na-Cl groundwaters are still present at depths of 300–350 m indicates the stability of the hydrochemical system under low permeable conditions since the last glaciation, close to 10 000 BP.

Sukkulansalo

The Sukkulansalo site is located in the SE part of the Proterozoic ore-potential Outokumpu formation. The characteristic rock types are mica gneisses, quartzites, serpentinites, black shales, and various types of skarn rocks. The formation dips towards the SE at a 45° angle (Fig. 13). A characteristic feature of the formation is the existence of faults parallel to the lithological structure and slides from regional to local scales. Typically they are related to black schists. Interestingly, the conformable faults display a subparallel trend with the nearby Salpausselkä ice-marginal formation, having thus provided a geometry susceptible to the intrusion of meltwaters during deglaciation.

At Sukkulansalo one major fracture zone is intersected with two boreholes. On the basis of the previous groundwater studies it was already known that the old OKU-551 exploration borehole penetrates a hydraulic zone at a depth of 441–447 m (427–433 m vertical depth) and that the brackish water in the zone has a depleted $\delta^{18}O$ signature [e.g. Blomqvist et al. 1987]. The fracture zone was recorded using a down-hole video camera and its orientation was defined. The zone is composed of subparallel discrete fractures (10–15 major ones) with apertures from 2 to 20 mm. A new borehole was drilled in the summer of 2000 and the zone was intersected at 423 m, as predicted by the structural modelling. Essentially similar fracturing was observed, although the apertures were somewhat smaller. The distance between the intersections is about 70 m. The aim was to verify the lateral extensions of the $\delta^{18}O$ depleted water body, to facilitate the hydraulic testing of the fracture zone, and to obtain solid samples for detailed mineralogical research.

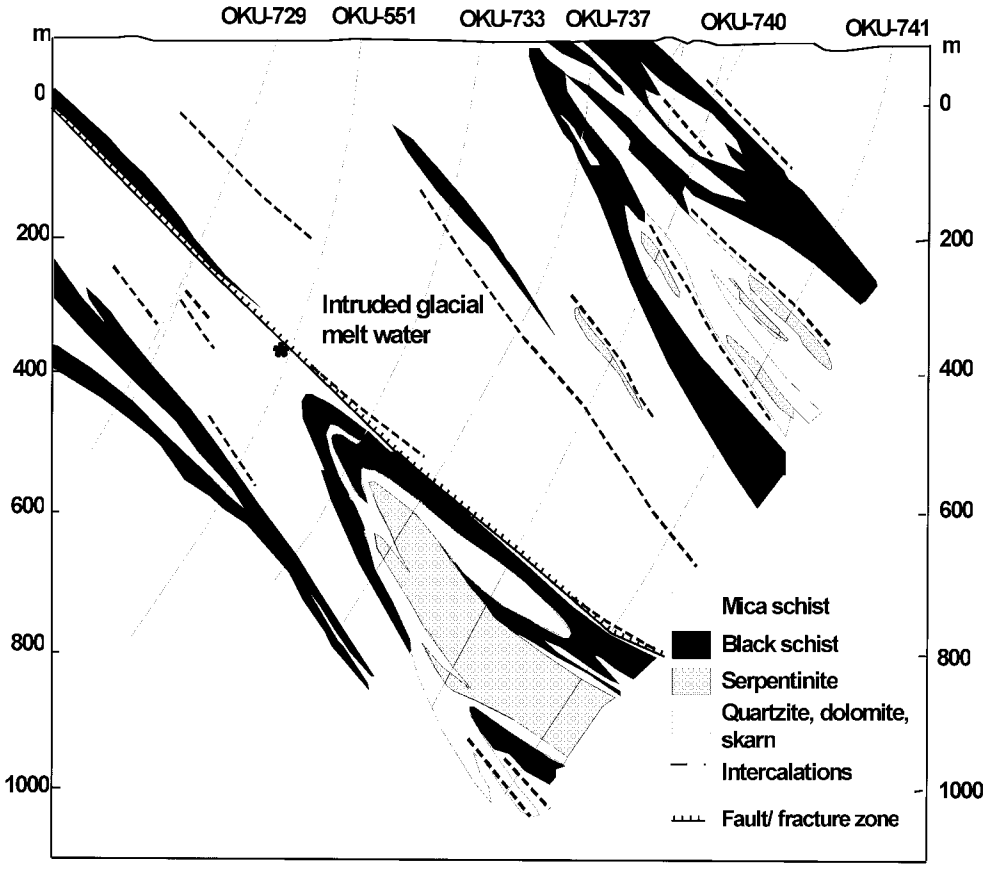


Fig. 13. Geological cross-section of the Sukkulansalo area showing the major geological features, research boreholes, and the fracture zone hosting the glacial water. In this projection the new borehole, 301, is located close to the OKU-551.

Hydraulic response monitored in the nearby drillhole confirmed the presence of a continuous planar fracture zone connecting the drillholes. The mineralogical loggings show that thin calcite and zeolite fracture infillings are characteristic of the local bedrock. Hydrothermal, crosscutting veining (zeolites + sulphides) is typical for certain sections. However, secondary mineral coatings in the open fractures within the water-conducting zone turned out to be rare. Most fractures have polished chlorite and/or graphite-bearing surfaces, indicating that they were originally formed during ancient bedrock movements. The scarcity of hydrothermal coatings tends to imply that the sliding surfaces remained rather tight during the process, and the presently observed opening came into being at a much later stage. Detailed mineralogical studies are still going on, but there are some indications of the oxidation of sulphides (Fig. 14). However, it is not currently possible to say whether the oxidation can be connected to the intrusion of oxidising meltwaters or is related to some older events.

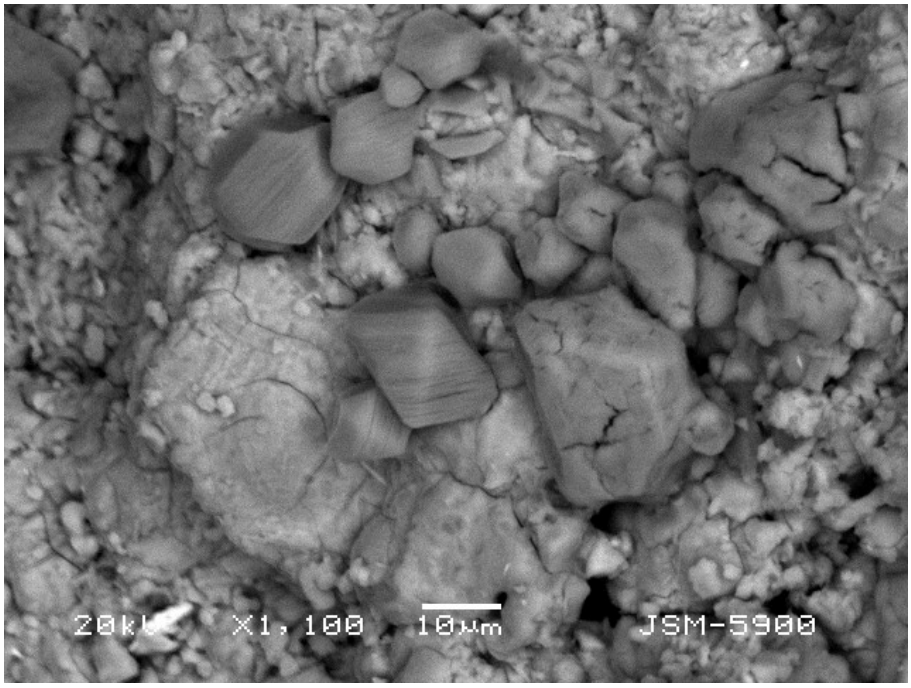


Fig. 14. Secondary iron compounds on strongly oxidised pyrrhotite veinlet exposed to a fracture surface at a depth of 440 m in OKU-551.

Hydrogeochemistry and palaeohydrogeological implications at Sukkulansalo

Five different groundwater types with various salinities characterise the Sukkulansalo site: (1) and (2) fresh Na-Ca-HCO_3 or fresh Ca-Na-HCO_3-SO_4 (TDS 0.1–0.2 g/l); (3) brackish Na-Ca-Cl (TDS 1–2 g/l); (4) saline Ca-Na-Cl (TDS 5–15 g/l), and (5) a deep saline Ca-Na-Mg-Cl type (TDS 25–30 g/l). Generally, the less saline water types are underlain by more saline ones, but occasionally, saline waters have also been recorded close to the surface [Blomqvist et al. 1987]. Mixed groundwater types of the various end members have also been recorded.

The distribution of different water types based on isotope signatures is consistent with the hydrochemical characterisation of water types. However, δ^2H and $\delta^{18}O$ signatures indicate that saline Cl-rich water is divided into two different layers, the heavier layer being present deeper in the bedrock ($\delta^{18}O$ values range from -12.9 to -14.9 ‰). The Mg-rich waters, in connection with the serpentinite, plot above the Global Meteoric Water Line (GMWL) and also show heavier $\delta^{18}O$ signatures. It is suggested that this is due to extensive water-rock interaction. The heavier water is meteoric in origin and has obviously recharged during climatic conditions similar to those at the present day.

The brackish Na-Ca-Cl water sampled from the fracture zone shows clearly depleted $\delta^{18}O$ values from -16.2 to -16.6 ‰ [Blomqvist et al. 1989; Blomqvist 1999]. Similar results were obtained from resampling between packers in 2000, demonstrating that the water body is stable and has not been changed, for example, as a result of mixing along the borehole. As expected, a chemically and isotopically identical water type was also found from the new borehole, 301. The good hydraulic connection of the two boreholes had already been established during drilling. Consequently, it was confirmed that the structural control is essential for the occurrence of the unique water type.

The opening of the ancient fracture zone during deglaciation and the mixing of glacial meltwater with the local saline groundwater are likely mechanisms for the infiltration of isotopically depleted water [Blomqvist 1999]. The ^{14}C and uranium series studies from OKU-551 also support a post-Weichselian residence time for this depleted water [Ivanovich et al. 1992]. Optionally, the cyclic freezing of water and the generation of a descending waterfront might also explain the observed isotopically light waters.

The slight hydraulic overpressure in the zone and the temporal stability and spatial distribution of the isotopically light water all seem to indicate that the fracture zone may host an extensive water body generated under cold climatic conditions. Unfortunately, all the other numerous boreholes drilled during ore exploration have been destroyed and it is not possible to follow the gently dipping structure towards the up-stream, presumably more oxidising, direction. New drillings are needed to obtain additional information.

General palaeohydrogeological implications

The results from the above two study sites, together with the experience from other research sites, show that the effects of glacial or periglacial conditions can reach down to several hundred metres in crystalline bedrock [Ahonen et al. 2001]. At some sites meltwater has been shown to make a significant contribution to the upper groundwater (e.g. Olkiluoto), while in some others discrete, structurally controlled water bodies are observed (Palmottu, Sukkulansalo). Considering the potentially high gradients experienced under a warm-based glacier or at the edge of a melting ice sheet, this is more or less what could be expected.

It is much more difficult to establish the level of disturbance caused to the geochemical conditions at these depths. A key question is whether, and to what extent, dissolved oxygen is introduced to the system. There is evidence from Palmottu that the remobilisation of labile uranium has taken place both in the

fracture network and related rock matrix within the timescales which can be correlated with the events of the last glacial cycles and which may be limited to a few dozen metres in depth. Currently, the supporting data covers only the upper 30 m of the system, but efforts are being made to gain credible data from greater depths. At many other sites the lack of a suitable geochemical tracer (uranium), which simultaneously provides a tool for dating, makes it difficult to demonstrate the possible disturbance. For example, at Sukkulansalo the oxidation of primary sulphides (rust) is observed at depth in relation to the anticipated meltwater intrusion, but essentially similar oxidation products may have formed under ancient, high-temperature conditions.

The role of permafrost in the generation of isotopically and/or chemically anomalous groundwater bodies needs further consideration. Especially on those occasions where an obvious structural control (recharge route) is lacking, freeze-out processes may provide an adequate evolutionary explanation for the observations. However, even in this case a network of water-carrying fractures is needed to provide an escape route for the residual fluids. The major difference between the two mechanisms (meltwater intrusion/permafrost) is that no oxygenated front is expected to be related to the latter.

2.2.2 Integration of hydrogeological and geochemical data

Geophysical measurements and data interpretation

Field measurement methods and techniques to map bedrock structures are continuously being improved. The shallow seismic reflection technique was applied at the Loviisa Hästholmen site to map sub-horizontal fractured sections in the bedrock in a similar manner as in the late 1980s [Okko 1991]. The use of updated equipment and processing techniques revealed the shallow fractured structures at a depth of 80–200 m more precisely than earlier [Okko 1998; Okko & Front 1999, 2001].

Moreover, the analysis of full wave sonic logging was integrated with the quantitative interpretation of geophysical borehole logging results. The combined log of acoustic and density measurements that presents Young's modulus was used as the quantitative estimate of mechanical weakness in fractured sections. This log also presents the numeric estimate of rock in the densely fractured and, therefore, poorly cored sections of rock. The hydraulic properties of the fractures were estimated from the tube wave logs in accordance with hydraulic tests.

The recent development of digital borehole and tunnel scanners will allow, in the near future, more quantitative integration and interpretation of hydrogeological information. These new scanners provide a digital, continuous, high-resolution, 360-degree unfolded image of the interior surfaces of the pipeline, borehole, and tunnel. This information has enabled the investigation of the feasibility of applying pattern recognition techniques to these digital images [Pantsar 2000; Pantsar & Korkealaakso 2000].

The crack-joint detection algorithm was developed as an example to test the automatic recognition technique. It is based on a custom crack filter embedded in a multiscale platform, which provides accurate and crisp results even with varying crack size, curvature, or depth. The algorithm has reasonable computational requirements and is thus suitable for almost real-time or interactive analysis. Key detection parameters are estimated statistically from actual data, which leads to an adaptive algorithm that is (almost) independent of surface material properties and illumination parameters. Variations in the detected cracks are presented as area or length distributions. Joints are detected accurately, even with missing data, using the Hough–transform with heuristic rules to reduce the amount of calculation required in the otherwise rather computation-intensive operation. The crack-joint detection algorithm can also be applied to map automatically the changes (in class membership space) between the repeated, time-lapse measurements. This time-lapse possibility allows for the direct analysis of the progress of growing features, e.g. dynamic changes in fractures during excavation.

In view of the large sets of data that will be collected during the excavation of the shafts, access tunnels, and galleries of a repository, new data interpretation methods have been under examination. As a case study, the practically continuous geophysical borehole measurement data were correlated to measured bedrock hydraulic conductivity data with neural network systems [Kulikoff 2001]. The studies aimed to produce a generalised predictive neural network tool that will predict hydraulic conductivities for given geophysical inputs.

Five types of networks were designed. The two MLP (Multi-Layer Perception) and the three ANFIS (Adaptive Neuro-Fuzzy Inference System) networks differed from each other in their architecture and number of input parameters. The sets of input parameters for the networks were chosen from P-wave and S-wave velocities, P-, S-, and tube-wave attenuation, Poisson value, Young's modulus, and groundwater temperature. The responses of the optimised neural networks were compared to actual measured hydraulic conductivities, and the conclusion was that the MLP network with all eight inputs gives the best

responses. However, all optimised ANFIS networks with fewer input variables give good responses as well.

In summary, it was found that the chosen geophysical variables identify fractured bedrock well, and because the bedrock in Finland is normally saturated with groundwater, fracture-sensitive geophysical variables are suitable for hydraulic conductivity predictions. In general, it was found that the neural networks are suitable for regression analyses of non-linear, variously heterogeneous, and large numerical data sets. However, calculation procedures with a diverse set of input variables or multiple regressions between inputs and outputs may take extensive amounts of time. Therefore, the choice of the network architecture and the optimal choice of the number of input and output parameters are the starting points for optimisation.

Geochemical interpretation and modelling

The country-wide survey of the geochemistry of deep groundwaters provides a clear insight into the occurrence of saline groundwaters in Finnish bedrock. Almost without exception a layered hydrochemical structure is observed. Fresh waters in the upper part of the bedrock become saline with increasing depth after a rather narrow transition zone. The location of this transition zone varies, but in inland areas it is frequently observed at a depth of 300–600 m, while in coastal areas it is located somewhat higher [Blomqvist 1999]. On the basis of the extensive geochemical database the average Cl concentration of deep groundwaters is around 5 g/l (Fig. 15). This value exceeds the present Cl concentration in the Baltic but is close to the salinity proposed for the Litorina stage. Another, less pronounced maximum (30 g/l) corresponds to the salinity of the ocean. Research results from the Olkiluoto site are in agreement with the above observations [Pitkänen et al. 1999b].

The bedrock has a distinct impact on saline groundwaters. For example, groundwaters from serpentinite areas have distinct Br/Cl ratios as compared to groundwaters from mafic-ultramafic layered intrusions. In both these areas the Ca/Na ratios are considerably lower than those recorded from schist belts and gabro intrusions. The classification is effective, despite the large variation in elemental concentrations and total salinity. It is suggested that the major controlling factor is related to the mineralogy of the rocks [Blomqvist 1999].

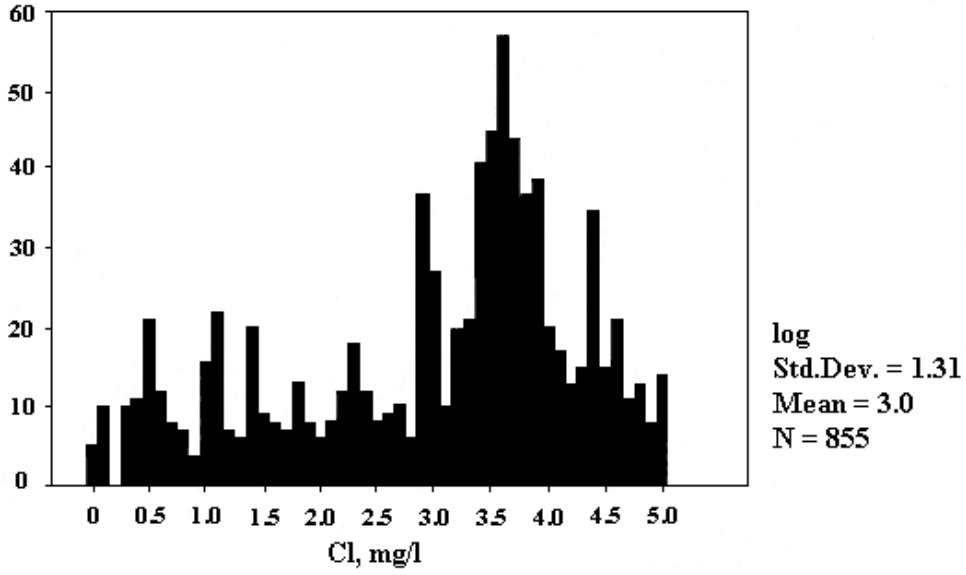


Fig. 15. Distribution of chloride concentrations of deep groundwaters in Finland based on the Deep Groundwater Project (855 samples, logarithmic presentation, Blomqvist [1999]).

The transition from fresh to saline waters frequently takes place at the depth where the future repository for spent nuclear fuel is planned to be constructed, e.g. at Olkiluoto this boundary is at 500 m [Pitkänen et al. 1999b]. Additional research is needed to evaluate what kinds of impacts the possibly moving boundary could have on the backfill materials and on the corrosion behaviour of the engineered barriers.

Detailed interpretation and numerical testing of hydrogeochemistry provide the basis on which adequate information about evolutionary processes in geochemical predictions and flow simulations can be obtained. Geochemical modelling is essential for the understanding of the chemical processes controlling pH and redox conditions in groundwater and the assessment of the buffering capacity of these processes. Geochemical modelling has been divided [Plummer et al. 1983] into inverse and forward methods, i.e. mass-balance reaction and thermodynamic reaction path calculations, respectively.

The NETPATH [Plummer et al. 1994] and PHREEQC codes [Parkhurst & Appelo 1999] are used to create net geochemical mass-balance reactions along flowpaths, and to test an interpreted chemical evolution hypothesis. The mixing of end-member waters from different climatic states can be studied by mass-balance geochemical calculations and corresponding geochemical impacts in the past. Mixing time-dependent end-member waters (e.g. glacial melt, Litorina sea, and current meteoric recharge) has also been discovered to be a useful tool to

calibrate hydrodynamic calculations and examine mass transfer during a certain time period [e.g. Pitkänen et al. 1999c; Blomqvist et al. 2000].

Isotope applications are particularly important in the interpretation of the evolution history of groundwater and palaehydrogeological events, as shown, for example in the cases of Palmottu and Sukkulasalo [Pitkänen et al. 2001a; Smellie et al. 2001]. Rayleigh distillation calculations are applied to isotopic fractionation by NETPATH in mass-balance models to adjust carbon and sulphur isotopic compositions in final waters at Palmottu [Blomqvist et al. 2000, see also next paragraph]. This makes a comparison between calculated and measured isotopic values possible and provides one extra tool to assess the reliability of the hydrogeochemical interpretation. Inverse reaction models are also used to adjust radiocarbon data, permitting hydrochemical estimation of flowpath age and the mean residence times of water samples.

Hydrogeochemical testing using thermodynamic forward calculations is very important, because it is the method by which it is possible to examine the potential extent of interpreted processes caused by future climatic changes and to predict chemical conditions and the solubility of elements in the repository system [Luukkonen & Pitkänen 2001]. Comparison between calculated results and data from field studies (e.g natural analogues) increases confidence in forward modelling and future predictions.

Several teams from Finland and Spain participated in the geochemical blind predicting modelling (BPM) exercise of the Palmottu natural analogue site [Bruno et al. 1999, 2001; Blomqvist et al. 2000]. The aim of the calculations was to arrive at predictions of heavy metal concentrations (e.g. strontium, uranium) in the bedrock groundwater on the basis of the major chemical components and fracture mineralogical data of samples, and to compare the various calculation methods and geochemical databases of the modelling teams. The results of the exercise show that the concentrations of several weakly soluble heavy metals can be predicted accurately by means of geochemical modelling. However, there were several differences in predictions among the teams, which can be attributed to differences in the calculation methods and databases used.

Groundwater geochemical studies were extended to the development of geochemical modelling methods and research on geochemical modelling possibilities [Luukkonen & Pitkänen 2001]. These studies aimed at developing qualitative and semiquantitative geochemical modelling tools for studies in the canister near-field, repository tunnel backfill, and the repository's surroundings. Specific problems borne in mind during developments were, for example, concrete–bentonite interactions beside the canisters, chemical changes in the crushed rock–

bentonite mixture of the backfill, and natural mass and radionuclide fluxes from the repository to the biosphere. Studies concentrated on modelling possibilities with the PHREEQC code, which handles a diverse set of geochemical modelling methods, and is capable of simulating batch-reaction and one-dimensional hydrological advection-dispersion problems.

Batch-reaction calculations[7] are useful in simulating hydrogeochemical evolution after the closure of a repository system. For example, Fig. 16 shows predicted pH, some dissolved species, and redox levels as a function of possible organic carbon input, assuming anaerobic redox reactions similar to those interpreted [e.g. Pitkänen et al. 1999b] in the current Olkiluoto groundwater conditions. The results show that pH hardly decreases below 7 in the assumed groundwater conditions (SO_4-rich or HCO_3-rich brackish water), because even 0.002 mol/kg organic carbon represents a concentration one order of magnitude higher than in natural deep groundwaters. Methane formation requires complete reduction of SO_4 from groundwater and still higher organic carbon concentrations. Performing a series simulation of batch-reactions by forward geochemical codes makes it possible to examine hypothetical chemical conditions derived from artificial or climatic changes, e.g. the effect of an increasing amount of infiltrating water types, and to assess reliable ranges for hydrogeochemical conditions in a repository system.

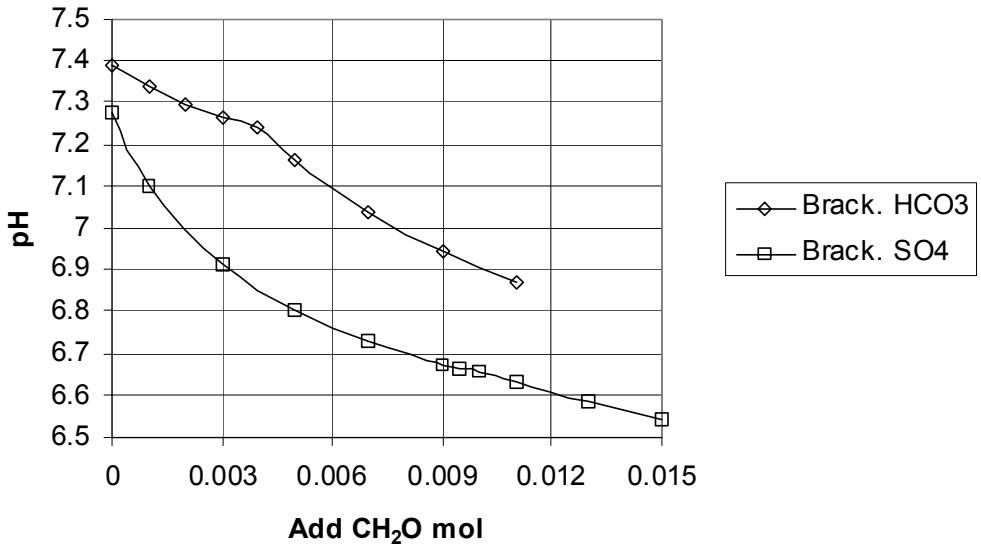


Fig. 16. Calculated pH conditions in Olkiluoto SO_4 and HCO_3 groundwater types as a function of organic carbon input [Luukkonen & Pitkänen 2001].

[7] A closed system that is allowed to equilibrate chemically.

Integration of geochemical and hydrogeological models

The integration of interdisciplinary data in a combined model is a complicated task. A fully-coupled numerical model on a site scale may actually increase uncertainties and may, therefore, decrease confidence in the model [Bath & Lalieux 1999; Pitkänen et al. 1999a; Vomvoris et al. 1999]. There are many practical considerations which impede such models, for example, numerical complexity resulting from the variety of geochemical processes, the lack of knowledge of the parameters in such complex models, and the basic inconsistency of time scales represented by hydrogeochemical information and groundwater flow models based on present testing. Accordingly, coupled or closely integrated models are more suitable for problems consisting of 'fast pathways' and/or a restricted, well-known hydrogeological system. Examples of such modelling exercises and applications have been performed in the Palmottu project (migration modelling exercise [Blomqvist et al. 2000]) and in the Äspö Hard Rock Laboratory (groundwater movement due to excavations [Pitkänen et al. 1999b; Luukkonen & Kattilakoski 2001]). The potential of coupled thermohydrochemical and mechanical modelling in nuclear waste disposal has also been evaluated by an expert group [Rasilainen et al. 1999, see Section 2.4].

It has been considered appropriate for work on a site scale to develop methods that improve the potential for comparing hydrogeochemical and hydrogeological parameters in a standard manner. The modelling process is part of a developed iterative methodology for flow analysis (Fig. 17). Hydogeochemical data and interpreted evolutionary information are used to test flow models and to assess the viability of alternative conceptual models. This method systematically integrates site-specific individually interpreted hydrological and hydrogeochemical information with regard to indications of possible unobserved physical boundaries inside the fracture zone model [Blomqvist et al. 1998, 1999; Pitkänen et al. 1999a]. The integration of parameters (hydraulic head and concentrations of conservative chemical tracers) is carried out with the help of the TRINET code [Karasaki 1987; Korkealaakso & Kontio 1996], which provides a quantitative approach to the tracing of groundwater flow along conducting fracture zones.

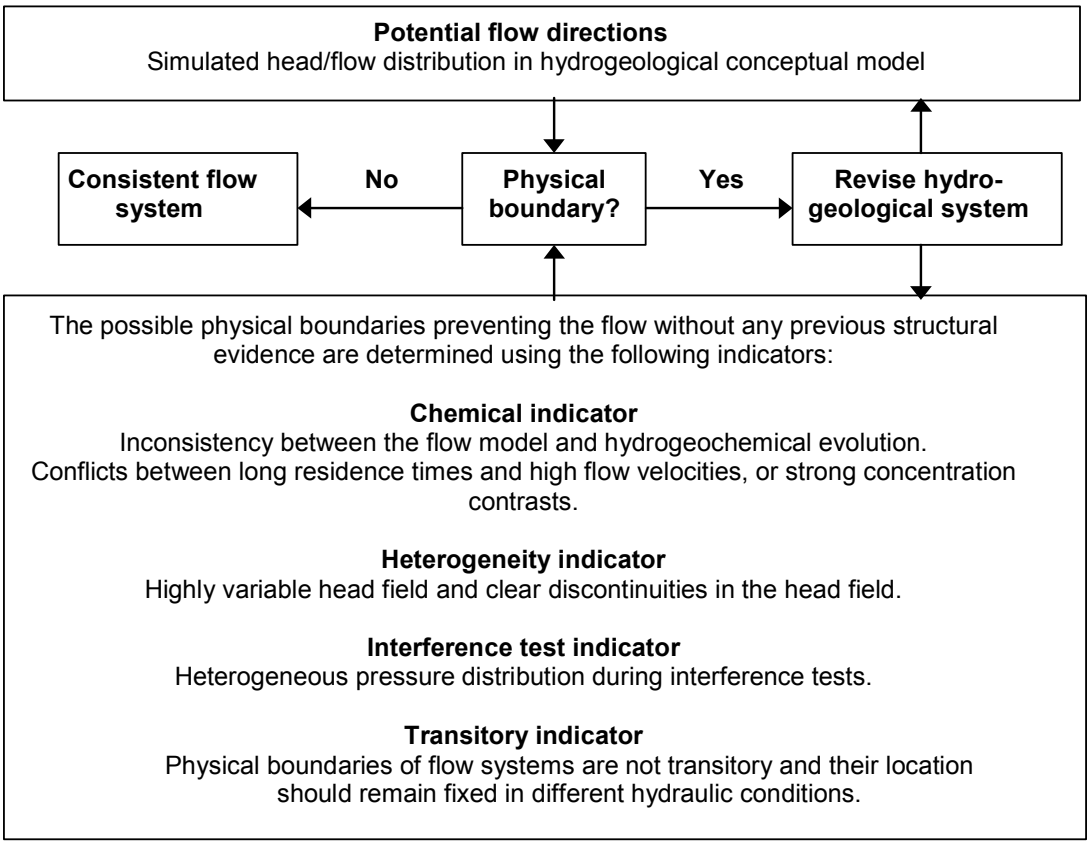
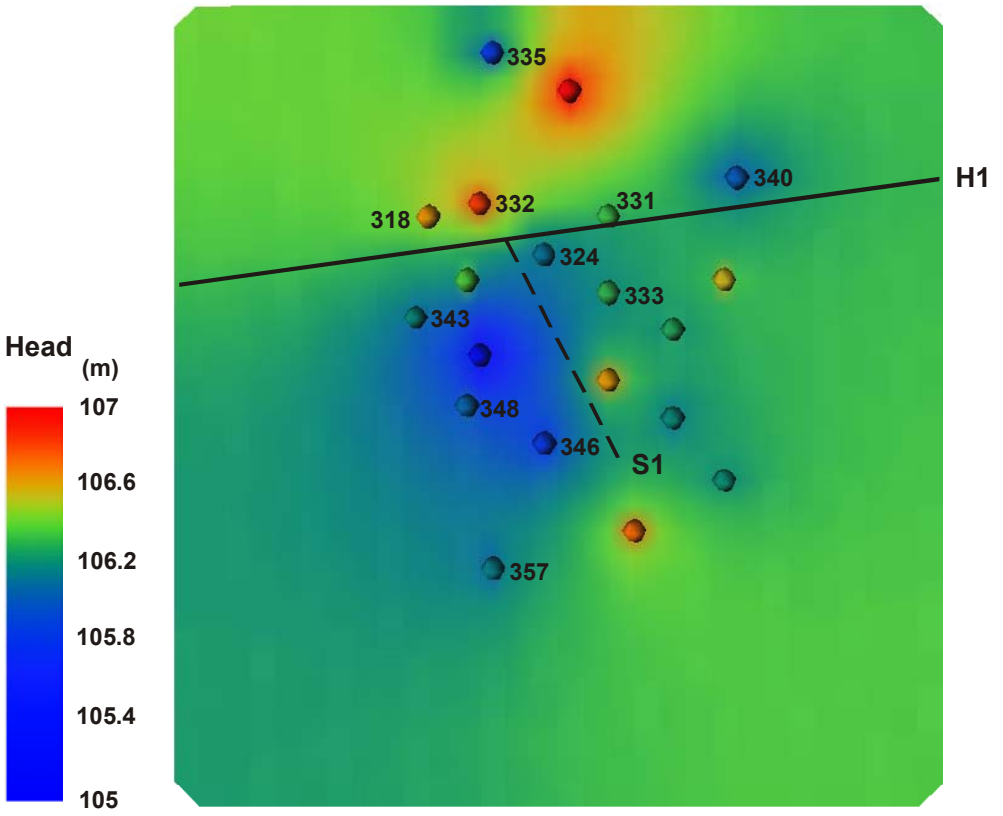


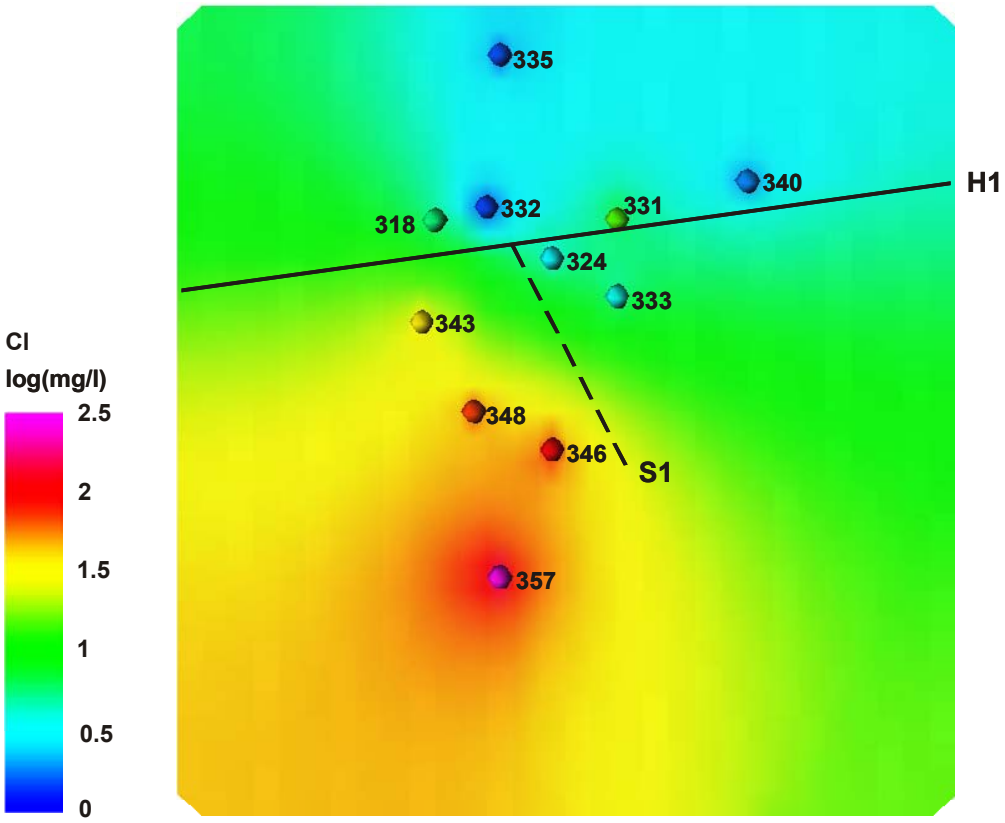
Fig. 17. A schematic flow chart showing a stepwise integrated process for conceptualising the movement of groundwater through a hydrogeological (fracture zone model) system.

The methodology of flow analysis was utilised in the hydrogeological evaluation of the Palmottu site [Blomqvist et al. 1998, 1999, 2000]. The integration process was fixed on a hydrogeological fracture zone model, because conducting fracture zones control most of the groundwater movement within crystalline bedrock. In order to interpret groundwater flow directions, the presence of physical boundaries within the study site was identified, i.e. whether there are barriers to flow continuity (e.g. structural or lithological) maintaining high head difference and preventing flow between areas of high and low head values.

The determination of flow directions was further constrained by chemical parameters. The long-term consistency of flow and geochemistry assumes an inverse dependence on head and concentration values of conservative tracers (Cl and SO_4), and any deviation from this inverse dependence or strong concentration contrasts will indicate the presence of flow barriers in the hydrogeological system (Fig. 18, Fig. 20). The boundary (S1) presented in Fig. 18, delineating the deep low-pressure area from the deep high-pressure area, and the stagnant sulphate-

and chloride–rich groundwater body from deep low concentration groundwater (de facto young HCO_3-rich water type), respectively, indicates an important impermeability between the areas. On the basis of later drilling and drill-core observations this hydraulic barrier was confirmed as a previously unknown, cross-cutting fracture zone which discharges groundwater flowing from right to left. The fracture zone acts as the major flow route from the western area to the Palmottu brook structural unit and as a hydraulic divide preventing flow from south to north in this area (Fig. 20).


Head
(m)
107
106.6
106.2
105.8
105.4
105
335
340
H1
318
332
331
324
333
343
348
346
S1
357


Cl
log(mg/l)
2.5
2
1.5
1
0.5
0
335
340
H1
318
332
331
324
333
343
348
346
S1
357

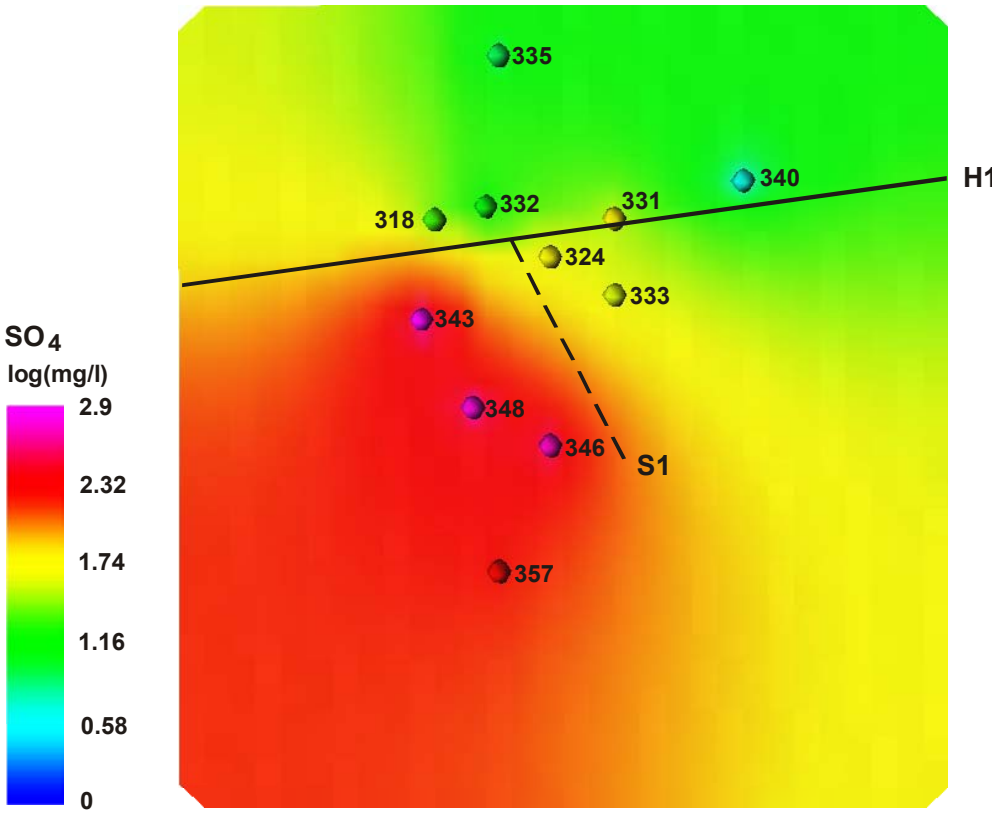


Fig. 18. TRINET-calculated distributions of hydraulic head (uppermost), Cl (middle), and SO_4 (lowermost) concentrations along a vertical structure, V2, at Palmottu. Numbers and codes refer to intersecting boreholes (e.g. 346) and interpreted structures (e.g. S1).

Flow analyses, unfortunately, require a consistent and relatively large and dense observation network for chemical samples and hydraulic information, and are applicable only to concentrations of conservative chemical tracers such as Cl, $\delta^{18}O$, or a mixing portion of end-member water type. Therefore, another approach with two different numerical models was used, one to interpret hydrogeochemical evolution and the other to determine hydrodynamics (Fig. 19). Although the integration level is comparative, the approach enables more detailed geochemical evolutionary paths comprising both space and time elements in consistency checks. The schematic flow chart shown below (Fig. 19) describes the strategy for testing a hydrodynamic model against site-scale hydrogeochemical information [e.g. Blomqvist et al. 1998, 2000; Pitkänen et al. 1999a, c].

The goal in hydrogeochemical modelling (the lowest box in Fig. 19) is to identify the processes probably responsible for the evolution of groundwater and which

control the basic hydrochemistry, and to predict the quantity of material transferred as a result of these processes. Sampling points along a flowpath in a groundwater system will show progressive changes in chemical and isotopic properties. These changes reflect the mixing of groundwater types as well as geochemical processes, such as mineral dissolution and precipitation, ion exchange, gas exchange, and redox reactions. Understanding the hydrogeochemical progress is, therefore, also the basis for using geochemical data to infer long-term flow at a site.

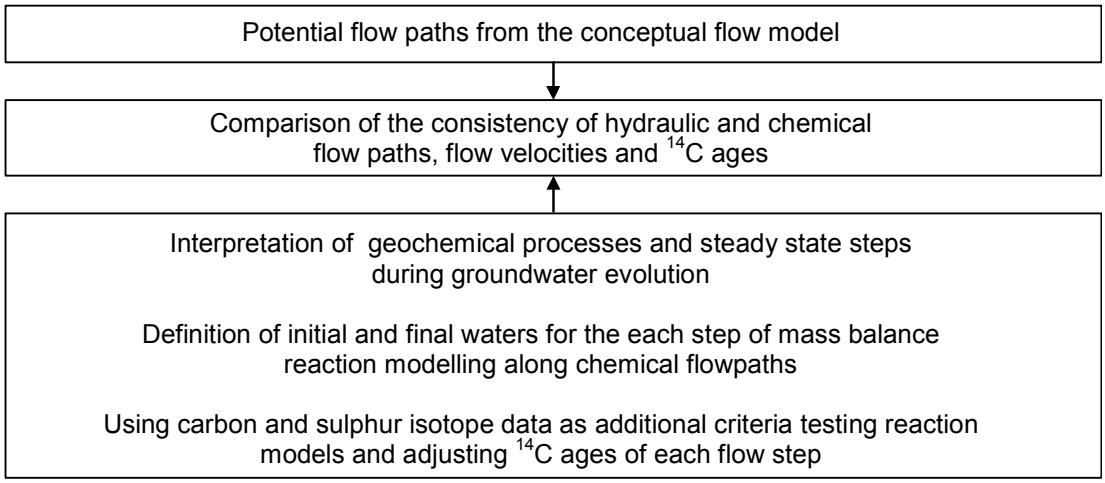


Fig. 19. Schematic flow chart showing the process used to infer flow information from geochemical data and the consistency between hydrogeochemistry and the hydrogeological model.

The interpretation of groundwater evolution is based on analysing trends in hydrochemical and isotopic data, and the tendency of the groundwater to dissolve or precipitate minerals (as reflected by the fracture mineral observations and solubility calculations of the water samples). In addition, it is important to distinguish the steps of chemical steady states in order not to depart from the principle of mass balance modelling [see Plummer et al. 1994]. The next step is to derive reaction models that can be plausibly used to explain the changes in water chemistry between chosen points along chemical flowpaths (cf. the geochemical modelling paragraph). Finally, potential flowpaths derived from groundwater flow simulations are checked against favourable chemical flowpaths (Fig. 19); simulated flow velocities are checked against adjusted radiocarbon ages.

A detailed interpretation of hydrogeochemical evolution was performed during Phase II of the Palmottu project [Blomqvist et al. 2000]. Hence, it was possible to

compare the consistency between hydrogeochemical evolutionary paths and conceptual groundwater flow model with the help of the approach presented in Fig. 19. The conceptual hydrogeological model of Palmottu (Fig. 20) summarises the dominant hydrogeochemical processes of the site. The processes occurring in the overburden during infiltration into bedrock start with biogenic CO_2 input, followed by the weathering of silicates and sulphide minerals according to isotopic signatures. Carbon isotopic calculations and tritium data indicate that rapid dissolution of fracture calcites is the dominant process in the upper part of the bedrock [Pitkänen et al. 2001a]. This increases pH and alkalinity, thus modifying the recharge to a Ca-HCO_3 type groundwater. The groundwater subsequently evolves to a deeper Na-HCO_3 type along the flow within a few decades as a result of a Ca-to-Na ion-exchange process, which further maintains calcite dissolution. Thermodynamic reaction path simulations [Gimeno & Peña 1999] were also used to augment these hydrogeochemical evolutionary hypotheses.

Mass-balance calculations with carbon isotopic data were utilised to test the groundwater flow model, particularly to specify the recharge area of each groundwater sample. The results calculated indicate a different $\delta^{13}C$ level in dissolving calcites in different source areas for groundwater samples, as shown in Fig. 20. Corresponding variability was also observed in fracture calcites between hydrogeological units; the highest $\delta^{13}C$-values (up to +6 ‰) in the Western granite, the lowest (-7 to -4 ‰) in the Eastern granite, with intermediate values dominant westwards from the Western granite [Ruskeeniemi 1998]. Geochemical source areas correspond well with hydrogeological units, thus supporting the division of an HCO_3-type groundwater system into different flow systems reported by Blomqvist et al. [1998] and demonstrating the consistency of the hydrogeological model of Palmottu.

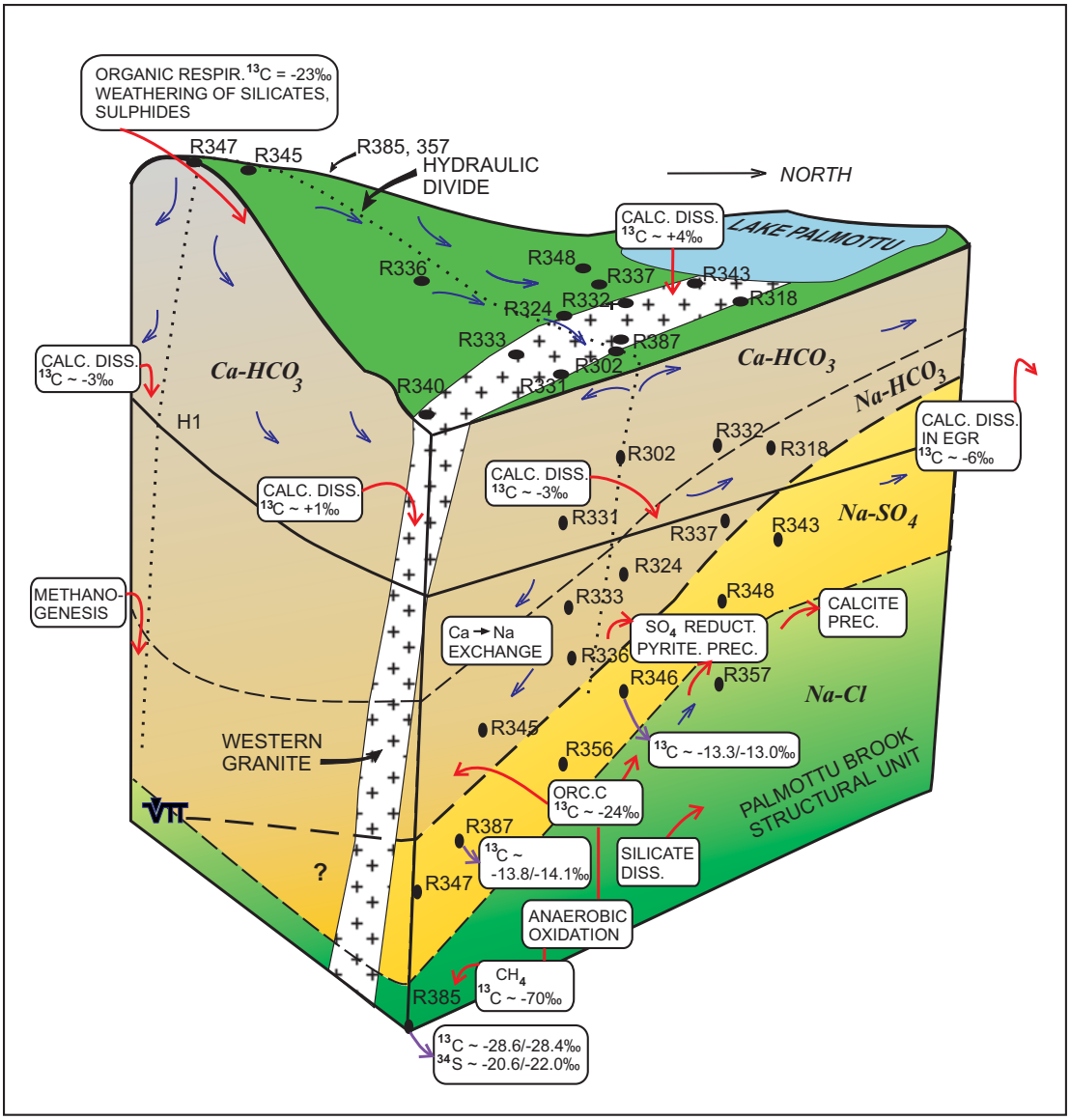


Fig. 20. Illustrated block diagram of current hydrogeochemical and hydrogeological conditions in the bedrock of the Palmottu site. Changes in colour depict alteration in water type. Blue arrows represent flow directions [Blomqvist et al. 1998]. Text boxes show main source and sink reactions controlling pH and redox conditions. Calculated $\delta^{13}C$ values are presented for dissolving calcite in the recharge zone. Deeper in anaerobic conditions measured/calculated $\delta^{13}C$ and $\delta^{34}S$ values of selected samples are shown, expressing the plausibility of the modelling results [details in Blomqvist et al. 2000].

2.2.3 Groundwater flow modelling

Groundwater flow is the principal transport route for dissolved material in the bedrock. The non-dissolved material deep in the bedrock can be exposed only by

erosion or during major deformations of the rock mass itself. Both of these mechanisms are expected to be much slower in Finland than migration via groundwater flow. In the disposal of spent nuclear fuel this means that the groundwater flow system has an important role in the performance assessment.

The bedrock in Finland is fractured crystalline rock. This gives a special character to the groundwater flow system. The rock matrix between the fractures is, in practice, impermeable and the groundwater flow takes place through fractures. The fracture apertures govern the groundwater flux through the flow paths. This leads to very heterogeneous spatial distribution of the total groundwater flux. This also serves to emphasise the importance of the structural model of the bedrock and the positions of the fracture zones and large fractures.

Modelling of the groundwater flow is based on the hydraulic characterisation of the fractures and fracture zones. Different aspects of the characterisation, modelling, and calibration of the groundwater flow in the fractured rock are discussed below. Interpretation of the structural model in the numerical model is not a straightforward task. Fracture zones and fractures are two-dimensional discontinuities inside the three-dimensional model. The large number of fracture zones of different orientation usually causes the geometry of the model to be very complicated. Sufficient resolution is required in specified regions, but at the same time the extent of the model is determined by boundary conditions. Problems concerning mesh generation and subsequent model calibration are discussed separately.

Model calibration and mesh generation

Automatic model calibration

It is usually necessary to calibrate the groundwater flow model against the measured hydrological information. Building the groundwater flow model involves incorporating the structural model and hydraulic conductivity measurements, together with the determined boundary conditions. However, it is not usually possible to reproduce the hydrological monitoring data, such as hydraulic head measurements, using a structural-hydraulic model as such. Simulation of the present groundwater flow situation requires the fine-tuning of hydraulic properties, and in some cases the structural model or boundary conditions are also adjusted.

The calibration of the hydraulic model is an example of inverse modelling. The properties of the model should be estimated, starting from the solution of the flow equations. According to Mészáros [1997a], this type of inverse modelling is often

referred to as quantification. Mészáros [1997a] also notes that the true values of the system's hydraulic response (z) are never known, but only seen as observations (z*) and computed model predictions (z'). Because the true values are not known the measurement error (z*-z) or computation error (z'-z) cannot be known. The difference z*-z' = (z*-z)+(z-z') for the same location is called 'residual' and the examination of the differences between the measured and computed data, residual analysis, is a crucial element of the model calibration.

Calibration is usually built upon the following steps:

- select initial set of model parameters, p
- determine the model response, h
- calculate residuals, r
- assess the model response in the light of the residuals
- stop if residuals are below a threshold
- otherwise, at the locations of the largest discrepancies, change model parameters by Δp and continue iteration from the beginning with new $p + \Delta p$ parameters.

In automatic calibration the agreement between observed and computed data can be defined by a more general distance function than the arithmetical difference that defines the residual. The cost functions of the calibration can be based on, for example, least squares, generalised least squares, the maximum likelihood method, the method of moments, etc. [Carrera 1984]. The parameter estimation is transformed into a problem of minimisation of the selected objective function. In principle, the minimisation of the objective function is a straightforward numerical task. The emphasis of automatic calibration is on the definition of the objective function. However, Mészáros [1997a] concludes that in order to develop an automatic calibration procedure, the concept of manual trial-and-error calibration can be used.

In practical applications the observed data applied in the calibration usually results from different pumping experiments. Modelling pumping experiments requires a high quality mesh, which is generated separately for each pumping configuration. This broadens the requirements of up-to-date numerical groundwater flow modelling to the mesh generation routines.

Mesh generation techniques

The hydraulic properties of the crystalline rock may vary abruptly and by orders of magnitude. This sets demanding requirements for the numerical model. One of the key factors in successful numerical modelling is the meshing of the modelling domain. The computer resources that are available bound the number of elements, and require that the discretisation should be correctly focussed.

Mészáros [1997b, 1999] has reviewed different automatic mesh generation techniques. Mesh generation is a sub-area of computational geometry. There exists a vast amount of information about computational geometry. For closer examination Mészáros [1997b] selected the quadtree (and octree) technique, adaptive mesh refinement, and Delaunay triangulation.

- Quadtree (octree) is a classical technique to hierarchically break down space into smaller and smaller quadrats (hexahedra). This approach easily lends itself to incorporate adaptivity with properly selected solvers.
- In adaptive mesh refinement the mesh and the solution develop side by side. According to a predefined policy, the results are monitored over the actual resolution, and according to some error measures the mesh is refined in areas of inadequacy.
- Delaunay triangulation is a way to systematically connect a set of points so that they form a triangular mesh. It can be defined using Dirichlet tessellation, which is a subdivision of the space, guided by a set of distinct points, so that each point has a region of the space nearer to it than to any other point. In a closed domain this process generates a set of convex and distinct polygons called Voronoi regions, which cover the entire domain. If we connect all the pairs of points sharing a border of a Voronoi region, we obtain a triangulation of the convex space that is known as Delaunay triangulation.

Mészáros [1999] has further developed a mesh generation technique that is based on the quadtree technique. The user can define the boundaries of the Well-Characterised Area within the model which is generated using smaller elements. The model can also include internal boundaries (fracture zones) and the locations of points that can possibly be used as internal boundary conditions. These entities can also be thought of as 0D, 1D, and 2D seeds or sources for mesh refinement. An example of the quadtree mesh is presented in Fig. 21. The quadtree program generates only 2D element meshes. A three-dimensional version, octree, is currently under development.

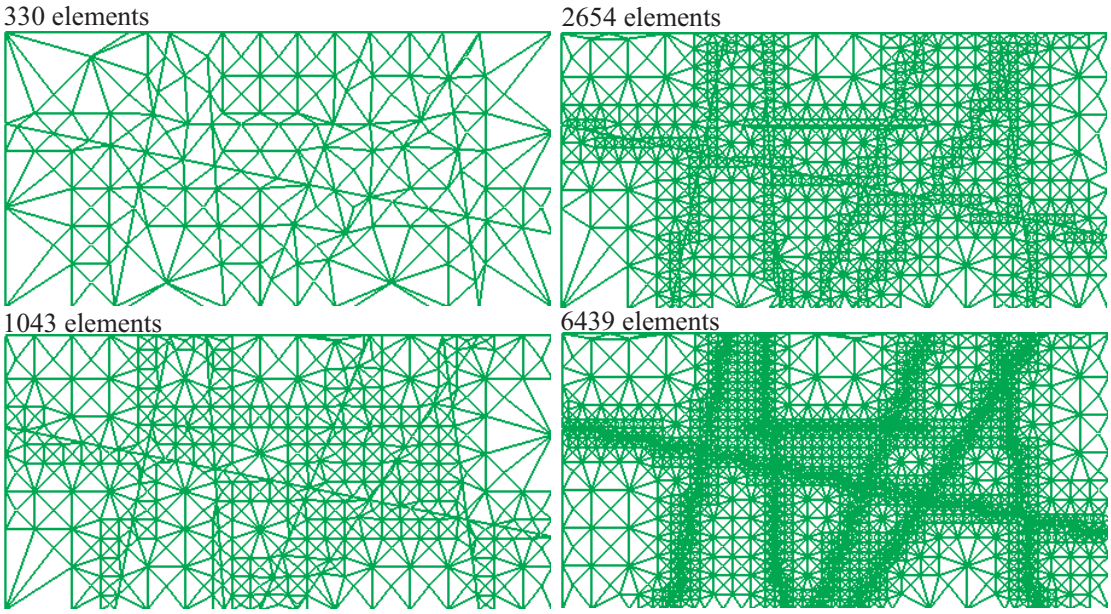


Fig. 21. Example of the element mesh generated using a quadtree program. The mesh is refined in four different stages to take into account the geometry of the fracture zones.

Groundwater flow in fractured rock

Fracture transmissivity measurements

The hydraulic conductivity of the rock is estimated using pumping tests in boreholes. These tests are often interpreted to give the average permeability of the measured interval. In reality, the water flows through a network of connected fractures that are intersected by the pumped borehole section. Tukiainen [2000b] has examined the interpretation of the pumping experiment if the nature of the fracture flow is taken into account. He concentrated especially on the influence of the boundary conditions applied in the interpretation of the experiment.

Tukiainen [2000b] examined the boundary effects in the three-dimensional fracture network model and the one-dimensional resistor network of the pumping of the packed borehole section. The boundary effects were studied in order to evaluate the influence of the model's size on the results of the simulation. Simulations were carried out by applying lognormal transmissivity distribution for the fracture's transmissivity. Three-dimensional simulations using the fracture network model indicated clearly that the mean flux in the borehole section depends on the model's size, i.e. on the distance between the model's boundary and the pumped borehole section. However, the variance in flux distribution is not sensitive to the model's size. Visual inspection of the flow field shows that

the flow is concentrated in a part of the modelling domain. At low fracture intensity the flow behaviour is close to one-dimensional. If the fracture intensity increases, the flow field's behaviour becomes closer to that of a radial flow field. On the other hand, increasing the variance of fracture transmissivity distribution changes the flow field towards one-dimensional behaviour.

Simulations with a one-dimensional resistor network support the above conclusions. One-dimensional networks were also used for the sensitivity analysis of the determined fracture transmissivity distribution. If the branching of the network has only a small number of intersections (i.e. low fracture intensity) then the mean flux decreases as the distance between the model's boundary and the borehole section increases. The rate of decrease depends on the degree of branching in the network.

Flow paths through fracture network

Laitinen [1998] has studied the calculation of the flow paths through a fracture network. Streamline data is very valuable, e.g. in the estimation of transport properties through a fracture network. However, earlier simulation cases have shown that traditional particle tracking methods face problems in fracture networks. In particular, if the velocity field is discontinuous problems can already be found with quite simple cases. The main problems are connected to passing from one fracture plane to another or the fact that the flow may be directed outwards from the fracture. Basically, all these problems are connected to the complex nature of the outer boundary of the modelling domain.

Application of the continuous flow velocity field that conserves the mass is an essential part of particle tracking. However, it cannot solve the problems usually encountered at fracture intersection lines. In a two-dimensional flow domain the streamlines can be solved as equipotential curves of the stream function. In three-dimensional flow conditions this approach can be applied only in very special cases. According to Laitinen [1998], the most promising approach is based on the method developed by Cordes & Kinzelbach [1992]. This method can be applied in numerical models that are based on the finite element method. It is assumed that the hydraulic head is solved for the nodes. The flow velocity is calculated from the computed head values in such a way that the velocity field is continuous at the element boundaries and in the nodes. In this approach the elements are divided into patches of triangular subelements, which are used to calculate the velocity field. This method can also be easily adapted to different modelling systems, because the calculation of the velocity field does not rely on the solution method used for the head field.

Spatial distributions of the fractures

Tukiainen [2000c] has studied the spatial structure of the fracture in deep crystalline rock. Fracture network models commonly assume that the fractures are uniformly distributed in space. Besides the uniform fracture location model (Poisson process) there exist a large number of different spatial models for the simulation of fracture locations. Tukiainen [2000c] examined actual borehole data from the fracture locations against the simulation results of the Poisson process, nearest neighbour, and geostatistical and fractal models of the fracture locations.

The Poisson process is the simplest one. It assumes that the position of each fracture is determined randomly and independently of the other fractures. This spatial model is very popular, because it does not require exhaustive fracture mapping. It is enough to know the intensity (or number) of the fracturing.

In the nearest neighbour model it is assumed that fracture intensity decreases exponentially as a function of distance from the predetermined structures. The predetermined structures are usually the large fracture zones.

In the geostatistical model the fractures are in clusters. The occurrence of one fracture indicates a high probability of other fractures in the vicinity. The strength of the clusters depends on the correlation in fracture intensity. This is commonly given as a semivariogram of the fracture locations.

Fractal models of the spatial distribution of fracture locations usually measure how uniformly the fractures are distributed in space. It is assumed that the fracture locations are the result of a stochastic process. Mandelbrot [1983] calls these fractals random fractals, and Sahimi [1995] statistical fractals. The fractal dimension of the fracture locations can be determined from fracture location data, but it is not possible to evaluate the stochastic process that has produced the observed spatial structure. The fractal model is characterised by the fractal dimension, which can be calculated from the outcrop or borehole data.

Tukiainen [2000c] tested the four spatial models above using borehole data from the Olkiluoto site. The result of the comparison was that only the geostatistical model is able to explain the measured distribution of the fracture locations in the boreholes.

Hydraulic characterisation of fractures

Different conceptual and mathematical models to describe the hydraulic properties of a single fracture have been examined by Tukiainen [2001]. The modelling can be divided into two parts: the geometric modelling of the fracture and the modelling of the flow in the geometric model. All the geometric models found in the literature are stochastic, which means that the geometry is generated by probabilistic methods. These methods were divided into two main classes: the geostatistical approach and fractal geometry.

The flow in the variable two-dimensional aperture field is usually modelled using the assumption of the cubic dependence of the local transmissivity on the local aperture. This means that in the fracture the groundwater flow can be described using a two-dimensional equation (Reynolds equation). However, various authors have investigated the accuracy of this approximation as compared to the full three-dimensional Navier-Stokes equation. The input data uncertainty is probably more significant than the difference between the solutions of the 2D flow equation and the full Navier-Stokes equation. Furthermore, the Navier-Stokes equation is considerably more difficult to solve numerically than the traditional cubic law approach. In this light, the use of the cubic law is justified.

The survey of Tukiainen [2001] showed that there exists a solid theory and numerous different models to describe the spatial structures of the fracture aperture. It is also justified to model the flow in fractures using two-dimensional models. The main problem with detailed fracture characterisation is connected to the fracture parameters. The parameters of the models must be in accordance with the properties of the real fractures. It is a difficult task to determine the detailed geometry of fractures, especially for fractures deep in the rock. Thus, efforts should be addressed to the development of detailed fracture characterisation techniques.

2.2.4 Conclusions from hydrogeological and geochemical studies

Significant progress has been made in the JYT2001 programme concerning new hydrogeological information and methods to conceptualise site hydrogeology and hydrogeochemistry and to integrate geoscientific data. The methodological development was performed, in particular, in connection with the Palmottu project, but data from the Finnish nuclear waste repository candidate sites, the Äspö Hard Rock Laboratory, and various ore prospecting sites in Finland was also utilised in the studies. Therefore the results have a wider perspective on potential hydrogeological bedrock conditions in Finland.

Glacial impacts must be taken into account in assessments of the hydrogeological performance of a nuclear waste repository. It is generally known that glacially-derived water is mixed into contemporary groundwater. Recent results indicate that a significant portion of glacial water may generally occur between a depth of 100-300 m in the bedrock. The estimates were based mainly on the depleted stable isotope composition of groundwater, particularly on low $\delta^{18}O$ values. However, it is unclear to what extent this decrease is caused by the mixing of glacial meltwater, or isotopic fractionation derived by the freezing of groundwater during the permafrost stage. Uranium disequilibrium studies from the Palmottu fracture surfaces show that glacial meltwater intrusion is evident at least at shallow depths (to a depth of a few dozen metres) and that dissolved oxygen has intruded as well. The studies also indicate that the oxygenation caused by meltwater intrusion predominates over the oxygenation occurring in current groundwater conditions. Deeper in the bedrock, such oxygenation has not been observed, but the data is incomplete and slightly uncertain.

The complexity of fractured bedrock may cause uncertainties in the hydrogeological conceptual model of a site, which are necessarily reflected in flow models and performance assessment. The complex nature of lithology, structure, geochemistry, and palaeohydrogeology creates exceptionally high demands for interpretation and modelling in order to reach a consistent view of hydrogeological conditions. Obtaining more detailed data, the integration of different types of data, and interpretation are considered the primary tools in solving these problems. Measurement and numerical methods and data processing and modelling tools form an important field of development. The research concerns particularly methods to increase confidence in the structural model in combination with flow models.

Methodological development is concentrated mainly on the integration of hydrogeological and geochemical interpretations (Fig. 19, Fig. 20) in which significant progress has been achieved as the results of the Palmottu project. It was possible to achieve improved consistency using hydrological and geochemical information in an iterative modelling process, which revealed inconsistencies in the structural model and led to a new examination of geological and geophysical data and finally to revision of the hydrogeological model. Geochemical modelling with isotopic applications was also able to confirm flow paths between recharge and discharge areas. In addition, geochemical modelling capabilities have been extended to areas important for performance assessment. Predictive modelling approaches are important in evaluating chemical conditions and the solubility of

trace metals occurring either in current groundwater conditions (e.g. blind predicting modelling) or after the closing of a repository, or climatic changes.

The development of data-processing routines of digital scanner, seismic measurements and geophysical borehole data have succeeded which enabled more detailed and versatile interpretation of the hydrogeological properties of bedrock. Groundwater flow modelling has developed to respond better to the nature of fractured bedrock. This concerns both model calibration and mesh generation, as well as the fracture properties used in models.

Regardless of progress in the integration of different hydrogeological and geochemical data or models, the process still needs qualitative evaluation. The reliability of results is partly subjectively judged and therefore, any confidence limit estimates are, actually, impossible. Hence, in the future the emphasis must be on integration methods, which produce more reproducible results. The development should be concentrated on computational methods using different types of measured data as extensively as possible. This evaluation process can show alternative conceptualisations confirming the data, makes it possible to calculate uncertainty limits, and perform sensitivity analyses for the interpretations.

2.3 Near-field chemistry[8]

The near-field of the planned Finnish repository for spent nuclear fuel represents a complex chemical system, the main components of which are the spent fuel, the iron/copper canisters, the bentonite buffer, and the groundwater. The repository is a dynamic system, which is initially in a non-equilibrium state with regard to, among other things, temperature, redox conditions, and hydrological conditions. However, the evolution of the repository may be governed not only by the initial conditions; future environmental changes, such as shoreline displacement or glaciation, may also have an influence.

State-of-the-art knowledge concerning such interactions in the repository was determined from literature studies focussing on redox reactions and their role in the repository [Kumpulainen 1997] and the interactions between the fuel, canister, and bentonite [Kumpulainen et al. 1998]. The latter reference also discusses suitable computer codes for calculating the effects of such interactions.

[8] By Carlsson, T., Kumpulainen, H, Ollila, K.

Later work describes modelling of the chemical evolution of the near-field [Kumpulainen et al. 1999, 2000].

2.3.1 Interactions in the near-field

Importance of redox reactions

Quantitative redox measurements are mostly carried out by measuring the electrode potential Eh related to the standard hydrogen electrode. Kumpulainen [1997] lists and discusses some of the technical difficulties associated with Eh measurements. Lindberg & Runnels [1984] also stress that natural waters are often in a state of non-equilibrium, and that natural waters in situ may be in equilibrium with minerals or gases that are not present during Eh measurements in the laboratory. Such difficulties have to be carefully considered when, for example, using published Eh data in groundwater modelling. However, in the case of deep groundwaters in granitic bedrock, it has been possible to measure stable and reproducible redox potentials both in the laboratory and in the boreholes. The Eh values (accuracy: ± 25 mV) corresponded to the reaction [Grenthe et al. 1992]

$$\text{"Fe(OH)}_{3(s)}\text{"} + 3H^+ + e^- \Leftrightarrow Fe^{2+} + 3H_2O \qquad (1)$$

Redox reactions are often governed by reaction kinetics and this makes it difficult to explain measured Eh values in terms of solution chemistry by, for example, modelling the water in question by means of geochemical equilibrium computer codes. The chemistry of the natural waters is further complicated by the fact that 1) reactions are often catalysed by microbes, and 2) some redox pairs may be in thermodynamic equilibrium while others are not.

Spent fuel

More than 90 % of the radionuclides in spent fuel are inside the UO_2 grains. The slow dissolution of the fuel matrix (UO_2) in reducing, deep groundwater is considered to be the most effective barrier to radionuclides entering the groundwater [Grambow 1989; Ollila 1993]. The release of actinides to groundwater presupposes the dissolution of the UO_2 matrix. Some radionuclides, such as Cs and I, may be released via, for instance, the spacing between the cladding and the spent fuel pellets, or between the grain boundaries. The dissolution of the spent fuel is complicated, owing to various solid reaction products on its surface, some of which are in contact with water while others are not [Grambow 1989]. The release of the sparingly soluble radionuclides (Pu, Np, Am, Th, Ra, and Pa) depends on the solubilities of these reaction products.

The UO_2 matrix is sparingly soluble under reducing conditions and therefore keeps the radionuclides trapped inside its boundaries. The solubility of UO_2 depends on the redox conditions at its surface. Under reducing conditions the dissolution can be described as

$$UO_2 + 4H^+ \Leftrightarrow U^{4+} + 2H_2O \quad (2)$$

while the dissolution under oxidising conditions can be written

$$UO_2 \Leftrightarrow UO_2^{2+} + 2e^- \quad (3)$$

The reaction products (U^{4+} or UO_2^{2+}) hydrolyse or form complexes in the water.

The literature survey by Kumpulainen [1997] discusses in detail various surface reactions associated with the dissolution of UO_2, for example, oxidative dissolution, in which the dissolved uranium takes the form UO_2^{2+}, chemically controlled oxidative dissolution, leading to the formation of dissolved species such as $U(OH)_n^{(4-n)+}$ and UO_2^{2+}, and non-oxidative chemical dissolution, where UO_2^{2+} is formed. In the latter case, secondary solid phases, such as $UO_3 \cdot xH_2O$, form during the dissolution.

According to the literature, the radiolysis of water (mainly α- and β-radiolysis) has been investigated extensively both theoretically and experimentally. The main products from the radiolysis of water are the radicals e_{aq}^-, H·, ·OH and HO_2·, the ions H^+, OH^-, and O_2^-, and the molecules H_2, O_2, and H_2O_2. These products play an active role in UO_2 dissolution. For example, the radicals O_2^- and OH are more important to the oxidation of UO_2 than H_2O_2, since they oxidise UO_2 much faster than H_2O_2 [Sunder et al. 1989].

Copper corrosion

Copper is an element with the same type of filled d orbital (electronic configuration: $[Ar]3d^{10}4s^1$) as the noble metals gold and silver and, therefore, it is extremely stable from the chemical point of view. Kumpulainen [1997] discusses a number of elements: chloride; sulphide; iron, and oxygen, that may a priori lead to the corrosion of the copper canister under varying conditions. Under reducing conditions, sulphide, originating from the groundwater and/or the bentonite, is the most important corrosion risk. However, the slow diffusion of sulphide in the bentonite makes the impact of sulphide corrosion negligible. Based on recent corrosion studies, the lifetime of a copper canister in a repository has been estimated to be several million years [Werme & Salo 1991; Werme et al. 1992].

The physico-chemical conditions in the near-field of the repository change with time. For example, the temperature is initially relatively high (around 80–90 °C) but later drops to the same level as is found in the surrounding bedrock. A simultaneous change occurs for the redox conditions, which are initially oxidising, but gradually change towards being reducing. The potential for copper corrosion in the near-field environment has been subjected to a considerable number of studies. Provided that no oxidising substances or complexing agents are present in the water, there seems to be little risk of copper corrosion [Grenthe 1987].

In the Finnish repository concept, the only significant corrosion risk is sulphide [Ahonen 1995]. A discussion of copper corrosion is found in Kumpulainen et al. [1998]. Some of the topics discussed are oxygen remaining in the repository after the construction period, chloride complexation, and glacial meltwater penetrating the repository.

Spent fuel dissolution

Uranium oxide, UO_2 or U_4O_9, is stable under reducing conditions. The reaction $UO_2(fuel) \rightarrow U(IV)_{aq}$ is very slow. For example, Bruno et al. [1988] measured dissolution rates of ~ $4 \cdot 10^{-5}$ g m^{-2} d^{-1}, a value that was constant in the pH range 7–11. The solubility of UO_2 depends on its crystal form. The following oxides are listed according to their increasing solubility: crystalline $UO_2(c)$ (uranite); $UO_2(fuel)$, and amorphous UO_2. Under reducing conditions uranium solubility is governed by the solubility of the mixed U(IV)(VI) phase U_4O_9 (or $UO_{2.25}$), provided that the UO_2 matrix is thermodynamically stable. This condition is fulfilled if there is no uranium phase with a solubility lower than that for the UO_2 matrix.

UO_2 is not thermodynamically stable under oxidising conditions. It may therefore oxidise into higher compounds such as U_4O_9, U_3O_7, U_3O_8, and $UO_3 \cdot H_2O$, or to other uranium phases, such as uranophane, $Ca(UO_2)_2(SiO_3)_2(OH)_2$. The formation of the latter solid is favoured in, for example, a bentonite-groundwater environment. Factors that may potentially contribute to the dissolution of the UO_2 matrix are [Grambow et al. 1990]

- UO_2 surface reactions
- the growth of alteration products
- transport of oxygen to the dissolving surface
- solubility limited dissolution rate

- the rate of formation of oxidants by radiolysis.

It is not presently known to what extent these mechanisms influence the UO_2 dissolution rate. For a thorough discussion concerning the UO_2 dissolution/solubility mechanisms, see Kumpulainen et al. [1998] and references therein.

Bentonite

The term "bentonite" refers to a natural rock, which has the smectite mineral montmorillonite as its dominant component. In the Finnish repository concept, commercially available MX-80 bentonite, consisting mainly of Na-montmorillonite, is planned to be used as a filling material around the canisters in the deposition holes, while mixtures of bentonite and crushed rock are used in the tunnels (cf. Fig. 3). The approximate percentages of bentonite and crushed rock are 80 % and 20 %, respectively. The advantages of using bentonite as a repository filling material are well known: compacted bentonite has a high ion-exchange capacity, a high swelling capacity, good mechanical properties, and a long performance time, i.e. these properties are expected to be maintained for hundreds of thousands of years. These properties make bentonite a suitable repository barrier material.

Most conditions in the repository (physical, chemical, hydrological, geological, and climatic conditions) will slowly change with time. These changes will also, more or less, influence the properties and behaviour of the bentonite. The extent to which this happens is, in many cases, qualitatively or quantitatively foreseeable with present knowledge. However, the consideration of all relevant reactions and processes occurring simultaneously and/or consecutively is difficult and requires special tools such as Process Influence Diagrams (PIDs) and Rock Engineering Systems (RES). Kumpulainen et al. [1998] use a PID in order to show the major interactions in the repository.

The chemical evolution of the repository can either be modelled directly, by using coupled models, or by using equilibrium models in a step-wise manner. The near-field chemical interactions have usually been modelled with coupled models by taking into account co-existing migration and chemistry. These models often calculate the transport of solutes in porous media relatively accurately, but frequently oversimplify the chemical interactions of the aqueous species and their heterogeneous reactions with solid phases. The coupled models have been used to compute, among other things, the evolution of pH, Eh, aqueous speciation, and solid phases in porous materials. In addition, attempts to model the migration of the redox front have been made. The diffusion in bentonite and the bentonite/water chemistry have typically been of major concern, but often at least one

of the following aspects has also been present: the redox front; precipitation/dissolution, and the alteration of the bentonite.

The method of using equilibrium modelling of chemical interactions in the near-field has been realised by a sequential closed-systems approach [Arthur & Apted 1996]. The modelling was based on computations performed using the geochemical computer code EQ3/6 [Wolery 1992]. The groundwater and the three barriers of the near-field (spent fuel, canister, and bentonite) were accounted for by this modelling approach, with particular emphasis being given to the evolution of pH, Eh, and actinide solubilities. The water was first allowed to equilibrate with the bentonite. The resulting bentonite water was subsequently permitted to react with the canister. Finally, the reaction of the canister-equilibrated water with the spent nuclear fuel was considered. The modelling results of Arthur & Apted [1996] indicate that different site-specific groundwaters may lead to similar near-field chemistries and, consequently, to similar actinide solubilities as a result of the chemical buffering effects of the near-field materials. Kumpulainen et al. [1999] applied Arthur & Apted's [1996] approach to the Finnish disposal concept. The modelling of Kumpulainen et al. [1999] involved the three successive closed systems and the choice of fresh groundwater, bentonite, and a canister that is planned to be used in the Finnish repository for spent fuel. The following assumptions were used:

- In the model, a single spent fuel canister was considered.
- After the closure of the repository, oxygen and other oxidants accumulated during the operating phase of the open repository are reduced due to reducing agents in the bentonite, surrounding rock, and groundwater.
- The breakdown of the canister was assumed to occur ~ 1 000 years after the closing of the repository. At this time, the initially oxidising conditions have become the reducing ones which normally prevail in deep groundwaters.

With these assumptions, a case with fresh reducing groundwater and MX-80 bentonite was calculated. A temperature of 25 °C and a pressure of 1 bar were used in the modelling.

The composition of the synthetic fresh groundwater used in the EQ3/6 calculations is shown in Table 2. For the model calculations, a pH of 9.1 (measured) and an Eh of - 0.25 V (assumed) for the water were applied.

The groundwater in the repository equilibrates with the bentonite and eventually penetrates the bentonite bed before coming into contact with the canister. The modelling of the interaction of bentonite-equilibrated water with the canister was

based on a number of assumptions. Due to the stability of copper in the anoxic repository conditions [Ahonen 1995], it was supposed that only iron would react with the bentonite-equilibrated water. In addition, it was presumed that the iron inside the canister had already been altered to magnetite (Fe_3O_4) according to the reaction

$$3\ Fe + 4H_2O \Leftrightarrow Fe_3O_4 + 4H_2(aq) \qquad (4)$$

Table 2. Composition of the synthetic anaerobic groundwater used in the bentonite equilibrium calculations [Muurinen & Lehikoinen 1999].

Element	Concentration (mol/l)
Na	$2.3 \cdot 10^{-3}$
Ca	$4.6 \cdot 10^{-4}$
Mg	$1.9 \cdot 10^{-4}$
K	$1.0 \cdot 10^{-4}$
C_{tot}	$1.8 \cdot 10^{-3}$
SiO_2	$1.3 \cdot 10^{-4}$
SO_4^{2-}	$1.0 \cdot 10^{-4}$
Cl	$1.5 \cdot 10^{-3}$
Ionic strength (mol/l)	$4.4 \cdot 10^{-3}$
pH (-)	9.1

Two alternative paths for the reactions with the canister were followed. In the first one, the precipitation of hematite was considered to be kinetically hindered, while in the second one, hematite precipitation was allowed.

The modelling results for the bentonite-equilibrated water/magnetite equilibration showed roughly the same results, although the case in which hematite was allowed to form exhibited a slightly higher pH (12.8) and a slightly lower Eh (-0.60 V) than the case in which hematite was suppressed (pH 11.0, Eh -0.46 V).

Finally, the canister-equilibrated water was allowed to react with the spent nuclear fuel. The water reacting with the spent fuel was that which was canister-equilibrated, in which the precipitation of hematite was not allowed. The elements that were considered in the spent fuel were for a PWR fuel with a burn-up of 33 MWd/kg initial heavy metal and contributing >0.1 % of the radionuclide inventory between 1 000 and 100 000 years. For further details concerning the assumptions underlying the calculations, see Kumpulainen et al. [1999].

Table 3. Calculated (EQ3/6) solution chemistry for the magnetite water/spent fuel equilibration.

Element	Concentration (mol/kg solution)	Element	Concentration (mol/kg solution)
Na	0.11	I	$1.5 \cdot 10^{-4}$
Ca	$4.4 \cdot 10^{-5}$	Se	$2.4 \cdot 10^{-5}$
Mg	$9.3 \cdot 10^{-8}$	Tc	$7.8 \cdot 10^{-4}$
K	$3.7 \cdot 10^{-5}$	U	$3.9 \cdot 10^{-4}$
C	$2.7 \cdot 10^{-3}$	Am	$3.1 \cdot 10^{-7}$
Si	$2.5 \cdot 10^{-11}$	Np	$1.1 \cdot 10^{-7}$
Cl	$1.5 \cdot 10^{-2}$	Pu	$1.7 \cdot 10^{-9}$
S	$5.3 \cdot 10^{-2}$	Ionic strength (mol/l)	0.16
Fe	$9.9 \cdot 10^{-14}$	pH (-)	7.6
Ra	$1.4 \cdot 10^{-9}$	Eh (V)	0.17

The modelling results for the canister water/spent fuel equilibration are shown in Table 3. The uranium concentration in the solution is high as a result of U(IV) carbonate complexation under oxidising conditions. It was not supposed that the highly crystalline NpO_2 and PuO_2 would precipitate. Furthermore, the formation of the aqueous species $Np(OH)_5^-$ and $Pu(OH)_5^-$ was not considered in the modelling, since their occurrence at pH above 7 was not regarded as probable. According to the computed results, the solubility-limiting solid phases for the actinides turned out to be $AmOHCO_3$ for Am, $Np(OH)_4$ for Np, and $Pu(OH)_4$ for Pu.

The effect of groundwater type (fresh or saline, see Table 4) on the near-field chemistry and actinide solubilities was investigated in another modelling study by Kumpulainen et al. [2000]. The equilibrium modelling of chemical reactions in the near-field was realised by means of the sequential-closed-systems approach and the underlying assumptions were similar to those used in the previous work [Kumpulainen et al. 1999]. The calculations were performed using the computer codes EQ3/6 and HYDRAQL/CE, a descendant of HYDRAQL [Papelis et al. 1988]. HYDRAQL/CE was used in the equilibration of water with bentonite, since it included the effects of cation exchange, the major reaction of bentonite with water.

Table 4. Compositions of the synthetic groundwaters (in mol/L) [Kumpulainen et al. 2000].

Component	Fresh	Saline
Na^+	$2.26 \cdot 10^{-3}$	$2.09 \cdot 10^{-1}$
K^+	$1.00 \cdot 10^{-4}$	$5.40 \cdot 10^{-4}$
Ca^{2+}	$4.64 \cdot 10^{-4}$	$9.98 \cdot 10^{-2}$
Mg^{2+}	$1.90 \cdot 10^{-4}$	$2.30 \cdot 10^{-3}$
HCO_3^{2-}	$1.80 \cdot 10^{-3}$	$3.50 \cdot 10^{-5}$
Cl^-	$1.48 \cdot 10^{-3}$	$4.17 \cdot 10^{-1}$
SO_4^{2-}	$1.00 \cdot 10^{-4}$	$4.40 \cdot 10^{-5}$
pH (-)	9.1	8.2

Near-neutral and slightly oxidising chemistries in the fuel-contacted water were found for both fresh and saline groundwater. Changing from fresh to saline groundwater

- had only a minor effect on the pH and Eh of the water in contact with spent fuel
- increased Am solubility three-fold
- increased Np solubility two-fold
- decreased U solubility.

Changes in actinide solubility occurred concurrently with changes in speciation, whereas no changes in Pu speciation were seen. The decrease in uranium solubility in the saline groundwater was probably due to lower carbonate formation when compared to the case of fresh water.

2.3.2 Uranium solubility[9]

The solubility of uranium(IV) was studied in dilute 0.01 M NaCl solution under anoxic conditions. The solubility data for U(IV) is one of the key pieces of data for the prediction of UO_2 fuel behaviour under the disposal conditions of spent fuel. The solubility of U(IV) has been studied by several authors. The solubility

[9] By Ollila, K.

of amorphous uranium dioxide [Bruno et al. 1987; Rai et al. 1990, 1995], crystalline UO_2(s) [Yajima et al. 1995] and unirradiated UO_2(fresh fuel) [Torrero et al. 1991; Ollila 1995; Ollila et al. 1996; Quiñones et al. 1998; Ollila & Ahonen 1998] has been determined. The extent of the dissolution is known to be dependent on the morphology of the solid phase. However, the reported solubility data varies over orders of magnitude for similar morphology. The solubility determinations in literature give varying values for the U(IV) hydrolysis constant:

$$U^{4+} + 4\ H_2O \Leftrightarrow U(OH)_4\ (aq) + 4\ H^+ \qquad (5)$$

The values vary from -4.5 ... -9. The hydrolysis constant value of log β_{14} = -4.5 was chosen for the NEA database for U [Grenthe et al. 1992a].

In an experimental study, the solubility of U in 0.01 M NaCl was measured from oversaturation under N_2 atmosphere in the glove-box. The method in the precipitation experiments was as follows. The U(IV) stock solution was prepared by dissolving U(IV)Cl_4 in 1 M HCl. Just before the initiation of the experiments, the U(IV) stock solution was diluted with de-aerated deionised water. An aliquot of this solution, U(IV) in 0.1 M HCl, was added to 0.01 M NaCl. The pH was immediately readjusted with NaOH to values varying from 2 to 12. Upon pH adjustment dark green precipitates were immediately formed in all solutions. After this, the precipitates in the solutions were allowed to equilibrate. The aqueous concentration of U was measured during the ageing of the precipitates with ICP-MS. The crystallisation of the precipitations is known to progress gradually [Yajima et al. 1995]. The total experimental time in this study was 14 months.

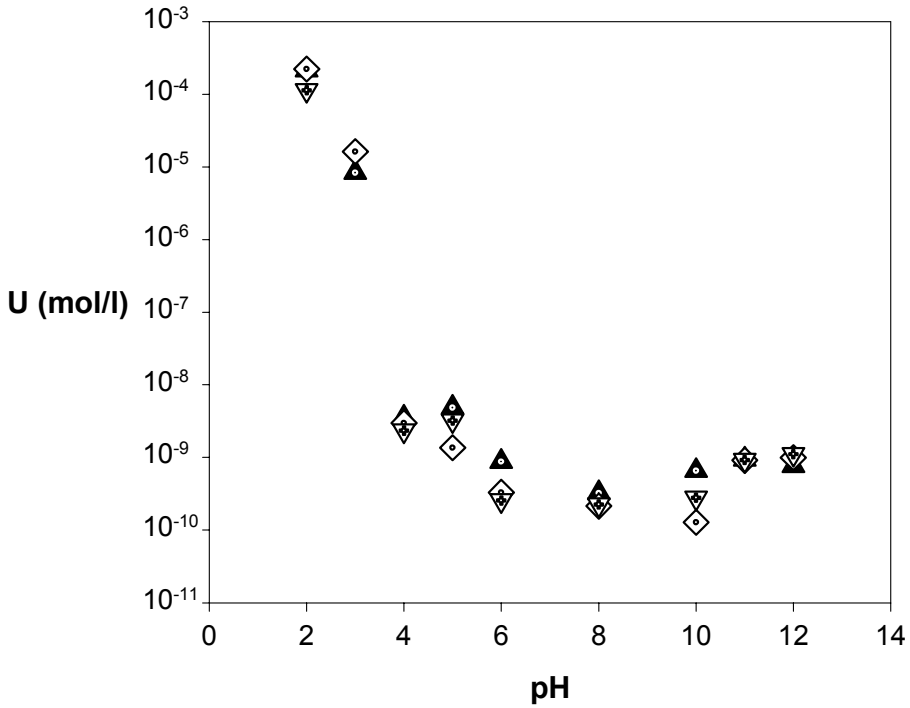


Fig. 22. Solubility of U in 0.01 M NaCl under anoxic conditions (N_2). The results are for three parallel experiments.

The measured aqueous concentrations for U are shown in Fig. 22 as a function of pH. The experiments were made in triplicate. The concentrations represent the average U in soluble form. The ultrafiltration was performed for the samples using filters with a 30 000 molecular weight cut-off (~ 3.2 nm pore size). The solubility is at its lowest at neutral pH 6-8, showing a slight increase at high pH values. The measured solubilities suggest lower stability in the neutral or slightly alkaline pH range for $U(OH)_4$ (aq) than the NEA database for U. The measured solubilities are in good agreement with the solubilities measured in the dissolution experiments with unirradiated UO_2 pellets in synthetic groundwaters under anoxic conditions [Ollila 1999; Ollila & Vuorinen 2001].

2.3.3 Conclusions from near-field chemistry studies

Understanding redox processes is crucial for the safety assessment of the nuclear waste repository. The reactions between water and spent fuel presuppose the breakage of a canister. Once this has occurred, spent fuel and radionuclides inside the fuel matrix will dissolve. The solubility is strongly dependent on the redox conditions. For example, the solubility of UO_2 under reducing conditions is fairly low, but may increase by several orders of magnitude if the conditions become

oxidising. However, the high amount of metallic iron in the canister is expected to keep the uranium and radionuclides in their reduced, poorly soluble states.

The copper in the canister is thermodynamically stable under repository conditions. In principle, sulphide from bentonite or groundwater is the only factor that might induce copper corrosion. However, the high density of the bentonite prevents sulphide-induced corrosion from being an important corrosion risk factor.

The near-field chemical interactions are usually modelled by taking into account co-existing transport phenomena and chemistry. These coupled models often calculate the transport of solutes in porous media relatively accurately, but frequently oversimplify the chemical interactions of the aqueous species and their heterogeneous reactions with the solid phases. The models have been used, in, for example, describing the movement of redox fronts, the speciation of radionuclides in the groundwater, and the corrosion of the copper canister. An alternative to using coupled models is to use an equilibrium model combined with a sequential closed systems approach. This method was used in order to investigate the effects of ionic strength in the groundwater. The modelling results indicate that changing from fresh to saline groundwater

- had only a minor effect on the pH and Eh of the water in contact with spent fuel
- increased Am solubility three-fold
- increased Np solubility two-fold
- decreased U solubility.

It should be stressed that the results from the modelling reflect reality only in a rough way. The database used was extensive, but has low internal consistency and contains data of varying dependability from different sources. The quality of data is of crucial importance in modelling but the checking of data quality is far from trivial [Carlsson & Vuorinen 1998]. However, the modelling can help in finding the important near-field parameters from the point of view of radionuclide release affecting the evolution of Eh and pH, as well as element solubilities. It is also valuable in being able to cover a larger range of parameters than is possible in experimental studies.

The solubility of UO_2 matrix under reducing conditions is a critical parameter for predicting the stability of spent nuclear fuel under disposal conditions. The data in the literature varies over orders of magnitude. In practice, there are difficulties

in maintaining reducing conditions in experiments. The purpose of the study described above was to measure the solubility of U(IV) in dilute solution (0.01 M NaCl) under anoxic conditions. The idea was also to compare the results of this study with the results of the UO_2 solubility studies, which were performed under more complicated water chemical conditions in solutions simulating the groundwaters at great depths. Thus it was also possible to evaluate the reliability of the experimental methods applied.

The solubility was measured from oversaturation as a function of pH. The measured solubilities at the neutral or slightly alkaline pH range, 10^{-10}–10^{-9} M, are in agreement with the lowest reported values under similar conditions in the literature. They are at the same level as the solubilities measured from under-saturation in the dissolution experiments with unirradiated UO_2 pellets in synthetic groundwater in the absence of carbonate. The measured data predicts lower stability for $U(OH)_4(aq)$ than the NEA database for U.

MX-80 bentonite is a natural product, which is available world-wide in large quantities. The properties of MX-80 make it suitable as a buffer and backfill material for several reasons. Some of the most important features of MX-80, with regard to long-term safety, are listed below (without any ranking).

- Its high swelling capacity causes MX-80 to swell during water uptake. This swelling tendency results in low hydraulic conductivity in the bentonite and also in an effective tightening of both the nearby rock fissures and the inter-spacings between the canister/bentonite and bentonite/rock. The upper limit of the swelling pressure is at the same time sufficiently low (< 50 MPa) to ensure that the swelling processes do not cause any damage to the canister or bedrock.
- Its rheological properties lead to thixotropic behaviour on the part of MX-80, which protects the canister from mechanical damage in the event of rock movements that might occur along possible faults passing through the deposition hole.
- The cation exchange capacity delays the transport of radionuclides that might be released from a damaged canister.

MX-80 bentonite has been subject to intensive research throughout the years, both in Finland and abroad. The factors affecting the relevant features of MX-80 seem to be well-known, and the same holds true for the conditions that may lead to a reduction of, for example, its swelling capacity. Based on present knowledge, it seems that the relevant properties of MX-80 bentonite will also largely be maintained in the long-term perspective, within the expected or pessimistically

estimated variations of future repository conditions. However, more research on MX-80 bentonite seems to be needed, and it is also planned, on two special topics - swelling mechanisms and coupled THMC processes.

2.4 Migration of radionuclides in bedrock[10]

Finnish nuclear waste disposal facilities are planned to be excavated in saturated bedrock under ground water level. The migration of radionuclides potentially escaping from the repository will thus take place along water-carrying fractures, with groundwater acting as the carrier. While migrating away from the repository along the flow of groundwater, the radionuclides are retarded by geochemical and physical reactions within the bedrock-groundwater system. Part of the radionuclides are attached to the mineral surfaces along the water-carrying fracture by sorption, and thus removed from the mobile inventory. In addition, part of the radionuclides will slowly diffuse from the flowing water into the stagnant pore water of the rock matrix surrounding the fracture.

In order to be able to model the migration of radionuclides, retardation mechanism studies are essential. As a prerequisite, experimental studies on the small-scale structure of the rock matrix are required, as well as determination of the speciation of the migrating radionuclides. In the following, a brief review will be given of the prospects of coupled migration modelling. It is well-known that the standard models used in performance assessments are simplified. But the question is: is there anything better available?

2.4.1 Retardation mechanism studies[11]

A well-founded migration modelling in a performance assessment requires that the modelling concepts applied have a link to the ones used in interpreting migration experiments. The experimental retardation mechanism studies described here were performed either in the laboratory or as part of natural analogue research. These experiment types differ in many ways from each other.

Obviously, laboratory experiments are short-term, while natural analogues have evolved over geological periods of time. A laboratory experiment is relatively well-controlled, while natural analogues have evolved under uncontrolled and possibly even unknown conditions. Laboratory experiments inevitably face the

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[10] By Hölttä, P., Carlsson, T., Suksi, J., Marcos, N., Rasilainen, K., Siitari-Kauppi, M., Ervanne, H.
[11] By Hölttä, P., Carlsson, T., Suksi, J., Marcos, N., Rasilainen, K.

question of realistic experimental conditions and representativity, while natural analogues have undoubtedly evolved under in situ conditions.

Laboratory studies

The underlying assumptions in the migration models used in performance assessments were tested in dynamic column experiments. The main processes tested were sorption, hydrodynamic dispersion, and matrix diffusion using non-sorbing (HTO, ^{36}Cl) and sorbing tracers (^{22}Na, ^{45}Ca, ^{85}Sr, ^{134}Cs). Static batch and thin section sorption experiments and standard diffusion tests were performed to support the column experiments, and also to provide independently-obtained input data. The rock samples studied were obtained from the hole SY-KR7 drilled in the Syyry area in Sievi in western Finland. Mica gneiss, unaltered, moderately altered, and strongly altered tonalite represented different rock features and porosities, offering an opportunity to determine experimental boundary values for parameters describing radionuclide transport and retardation and rock matrix properties.

Batch experiments

A new model was developed for a more detailed interpretation of batch experiments. In the model, crushed rock grains are tentatively assumed to be spheres of equal radius. The idea is to take into account matrix diffusion from water into the rock grains [Tukiainen 2000a]. The model can explain the recurrent observation in batch experiments that, after an initial rapid decrease of tracer concentration in the solution, there usually follows a slower trend of decrease. An example of a model fit is shown in Fig. 23:

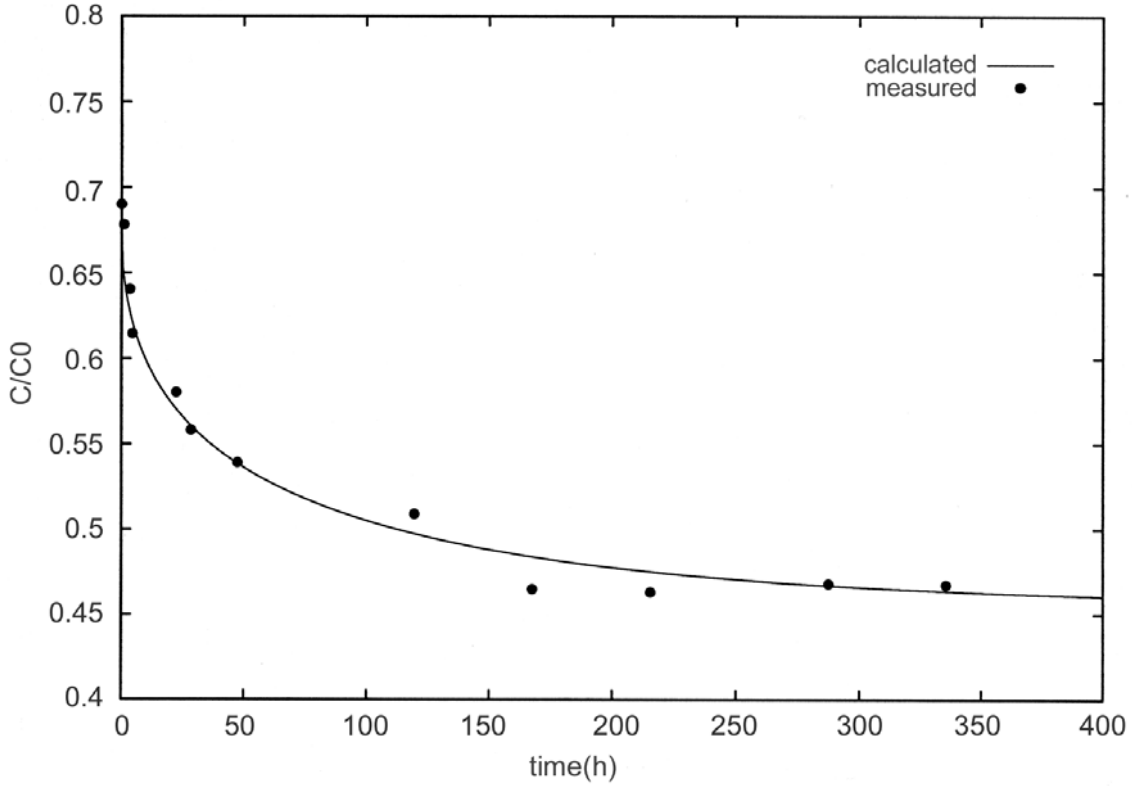


Fig. 23. Matrix diffusion - sorption model fit to an experiment for crushed rock, grain size 300–500 µm [modified from Tukiainen 2000a].

Column experiments

Column experiments have been performed on fractured and crushed rock columns. The preparation of columns and the apparatus used in the column experiments have been described in more detail by Hölttä et al. [1992, 1996, 1997, 1998]. The transport of non-sorbing radionuclides was studied using different volumetric groundwater flow rates, in order to distinguish matrix diffusion from hydrodynamic dispersion. Relatively long and narrow rock columns were introduced for the purpose, together with an experimental set-up enabling very low water flow [Hölttä et al. 1996].

In-diffusion of calcium into rock cubes was introduced in order to determine diffusion parameters and to predict retardation in fracture columns. Radionuclide retardation in column experiments was estimated by using a retardation factor, which was determined as the ratio of tracer velocity to groundwater velocity. Elution curves from fracture column experiments were interpreted using a numerical code FTRANS and parameters obtained from in-diffusion calculations (Fig. 24).

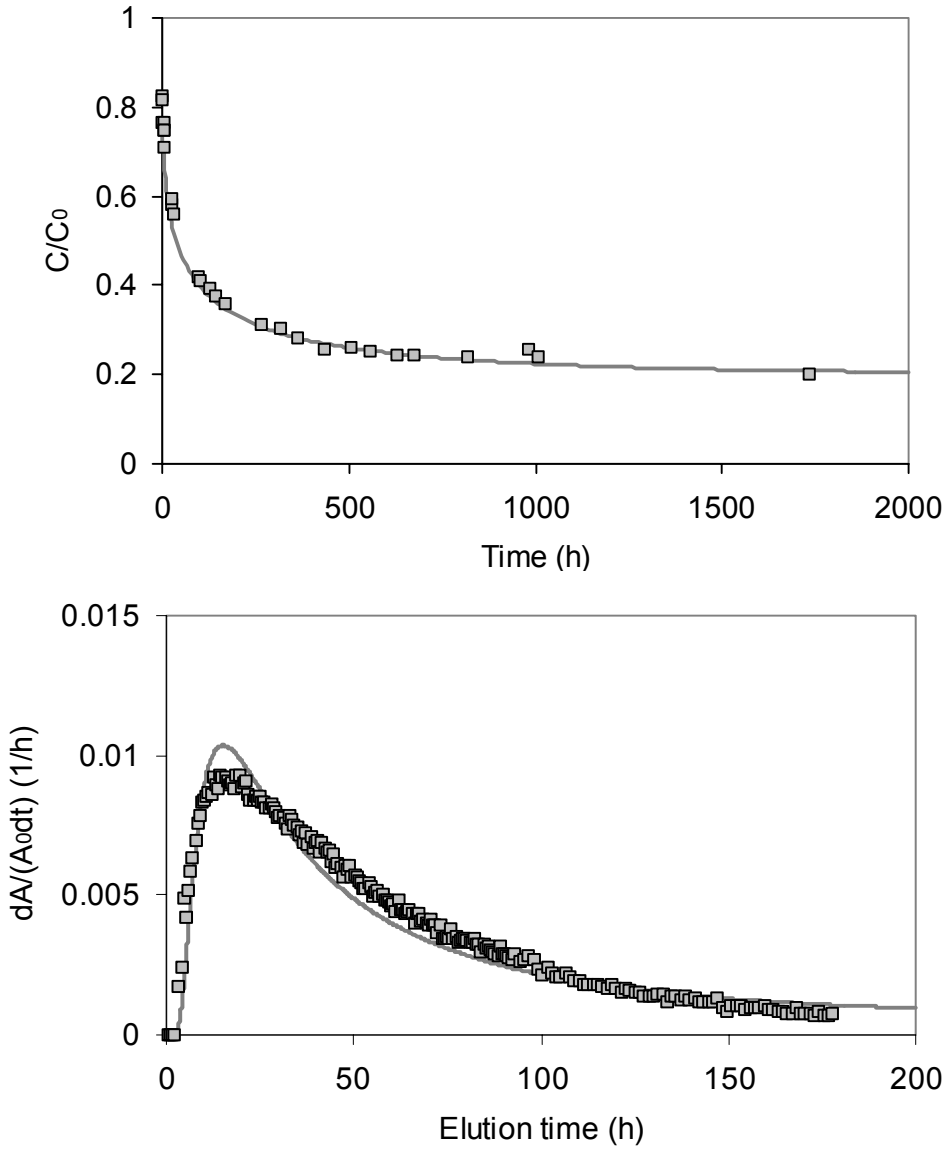


Fig. 24. Upper picture: experimental and calculated in-diffusion of calcium into a strongly altered tonalite cube. Lower picture: experimental and calculated elution curve of calcium for a strongly altered tonalite fracture column.

The possibility of directly observing the effect of matrix diffusion on the breakthrough curve under well-controlled flow conditions is a valuable test of the classical advection-dispersion-matrix diffusion model used in performance assessments. It is well-known in literature that the response of matrix diffusion may be very difficult to distinguish in practice from that of dispersion, or from diffusion into stagnant pools in a channelled flow system. Experience suggests that the response of matrix diffusion can be distinguished when water flow is slow enough that dispersion can be controlled technically.

It is quite a common observation that no single conceptual model can be calibrated to fit the measured breakthrough curve perfectly. Although 'blind' model calibration as such does not guarantee that the modelling concept is correct, the impossibility of calibrating the model probably means that the concept needs improving.

A common technique to improve model fit is to postulate more than one flow channel in the system, because the channelling of groundwater flow has been observed on all scales of observation. The different flow channels may have different properties and the final breakthrough curve is obtained by superposing the individual channel-specific breakthroughs. There is, however, a problem, because one can obtain model fits that are seemingly equally good with different sets of channels, Fig. 25.

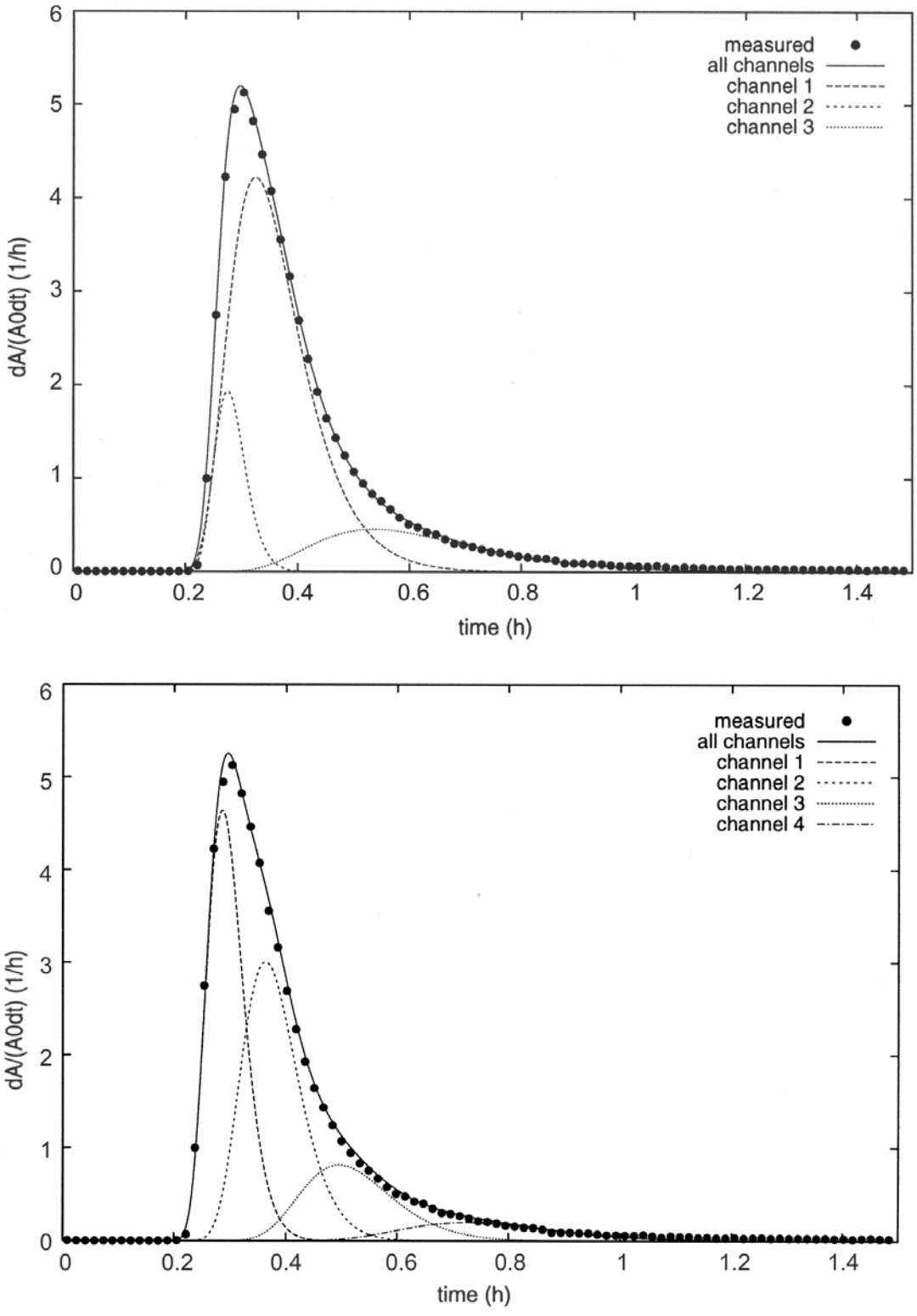


Fig. 25. Measured and calculated breakthrough curves. Calculated curves have been obtained using three (upper picture) or four (lower picture) independent flow channels [modified from Tukiainen 2000a].

Anion exclusion studies

Diffusion in porous media is affected by the structure of the pore network in such a way that electrically neutral solutes may experience the pore structure as a tortuous geometric hindrance only, whereas ionic solutes interact with charged pore walls through different mechanisms. Attractive interaction leads to an increase in concentration in close proximity to the pore wall, which may result in an increased mass transfer along the diffusion path in the direction of the macroscopic concentration gradient. Repulsion, in turn, gives rise to a local deficit of co-ions in the vicinity of the charged pore wall in comparison with the equilibrium solution. This deficit has also been termed negative adsorption (or co-ion exclusion), which can occur only for species distributed in the diffuse part of the electric double layer. In practice, this is reflected as an apparent reduction of the pore space accessible to a solute.

The diffusion and adsorption results presented by Valkiainen et al. [1995] for six rock types from the Olkiluoto investigation site showed a general tendency towards chloride ion exclusion with decreasing equilibrating solution ionic strength (behaviour typical of (hydr)oxides and layer silicates). The porosity accessible for Cl^- (Cl-36) was found to be an order of magnitude less than that for non-sorbing tracer (H-3). However, the exact phenomenological explanation for this observation suffered from a lack of pore-specific data, including the surface chemical properties of the rock pores.

Because of the inherent uncertainties in the surface properties of the pore walls in natural rocks, it was decided to test whether the surface chemistry of certain (hydr)oxides could qualitatively reproduce the observed exclusion behaviour and, it was hoped, provide a deeper insight into the mechanisms leading to this behaviour. By doing this, the parameters required to quantify the experimental observations would then be known more precisely. An additional benefit of using reference materials is that the porosity and the diffusion coefficient are larger than in rocks, thus shortening the experimental time needed.

Among the reference materials considered, vitreous mesoporous silica was found to be the most suitable, because of its variety of pore sizes within the nanometre range (2.5, 5, 7.5, and 20 nm), where the surface-induced effects are most clearly visible. The samples were equilibrated in NaCl solutions of 0.00255, 0.01, and 0.1 mol/l containing H-3 and Cl-36 as tracers. The pH of these solutions ranged from 4.6 to 8.6. The exclusion of Cl-36 was studied in relation to H-3, which was taken as a non-interacting solute (see Valkiainen et al. [2001] for the substantiation).

A surface complexation model, based on the application of the electric double layer theory, was developed to quantify the surface charging of silica surfaces and, consequently, to explain anion exclusion. According to this model, silica acquires its negative surface charge in an aqueous electrolyte by releasing a proton, $SiOH \Leftrightarrow SiO^{-} + H^{+}$. A pair of tortuous parallel planar surfaces with a uniform charge density and a fixed separation distance was taken as the model geometry for a silica pore. This way, the calculations were greatly simplified.

The mathematical solution to the problem of an aqueous electrolyte confined between two bounding charged walls was based on a number of assumptions: i) use of the Poisson-Boltzmann equation; ii) the charge-regulation boundary condition at the pore wall, and iii) the symmetry boundary condition at the mid-plane of two overlapping double layers.

The distribution coefficient, K_d, was defined in terms of the double layer surface excess in a way that is both self-consistent and fully compliant with the most general definition of adsorption. This definition states that adsorption merely implies a change in concentration relative to some suitably chosen reference concentration.

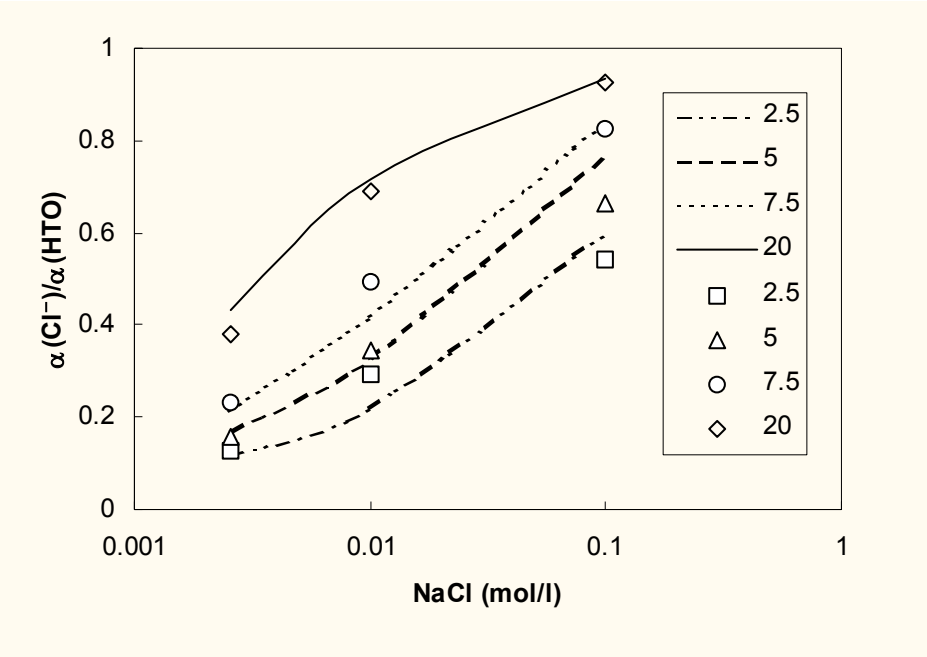


Fig. 26. The extent of anion exclusion in mesoporous silica expressed as the ratio of the capacity factor[12] for Cl^- (Cl-36) to that for H-3 as a function of solution molarity. A value close to unity or zero indicates no or substantial exclusion, respectively. Pore size is taken as a parameter.

The electric double layer theory lends itself well to justifying the existence of surface diffusion, which is to be looked upon as the transport of counter-ionic surface excess along an equipotential surface parallel to the pore wall, encountering no electrical energy barriers. The theory may also supply a quantifiable basis for obtaining an order of magnitude estimate for the surface diffusion term in the macroscopic definition of the diffusion coefficient.

The potential of a surface complexation approach in quantifying adsorption and co-ion exclusion was unambiguously demonstrated. An example of this, for chloride ion exclusion in porous silica, is shown in Fig. 26. It must be emphasised, however, that the good quantitative results above were obtained for simple reference materials. Natural rocks are usually much more heterogeneous and therefore, testing the same type of model with natural rocks is more demanding. Although it is the natural bedrock that must be studied for performance assessment purposes, investigations with well-defined reference materials are invaluable in that they serve to pinpoint the relevance of various

[12] The capacity factor, α, measures the total rate of change of the number of molecules residing in the bulk solution and adsorbed phase in a given element of the porous solid relative to the rate of change of the number of molecules in the bulk phase in that element.

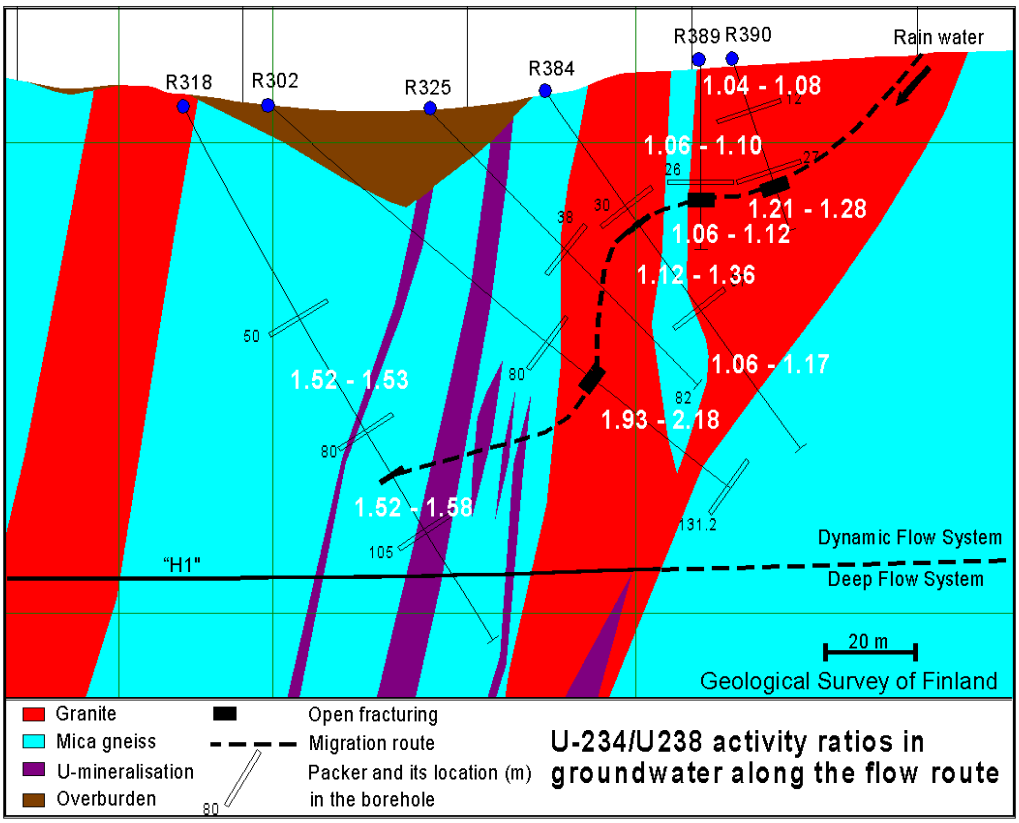
mechanisms. For further details on this matter, see Rasilainen et al. [2001a] and references therein.

Natural analogue studies

Palmottu uranium deposit

The natural analogue site at Palmottu in SW Finland comprises a U-Th ore deposit located in the granitic bedrock, see Fig. 27. Natural analogue studies have been pursued at Palmottu since 1988, and between 1996 and 1999 the site was studied as an international EU project [Blomqvist et al. 1998, 2000]. The studies within the EU project provide the results discussed here.

Being located at various depths and geochemical conditions within the fractured bedrock, the deposit covers structurally, mineralogically, and geochemically the same spectrum of physicochemical conditions as expected at disposal depth, and above, for a spent nuclear fuel repository in crystalline bedrock [Blomqvist et al. 1998, 2000].



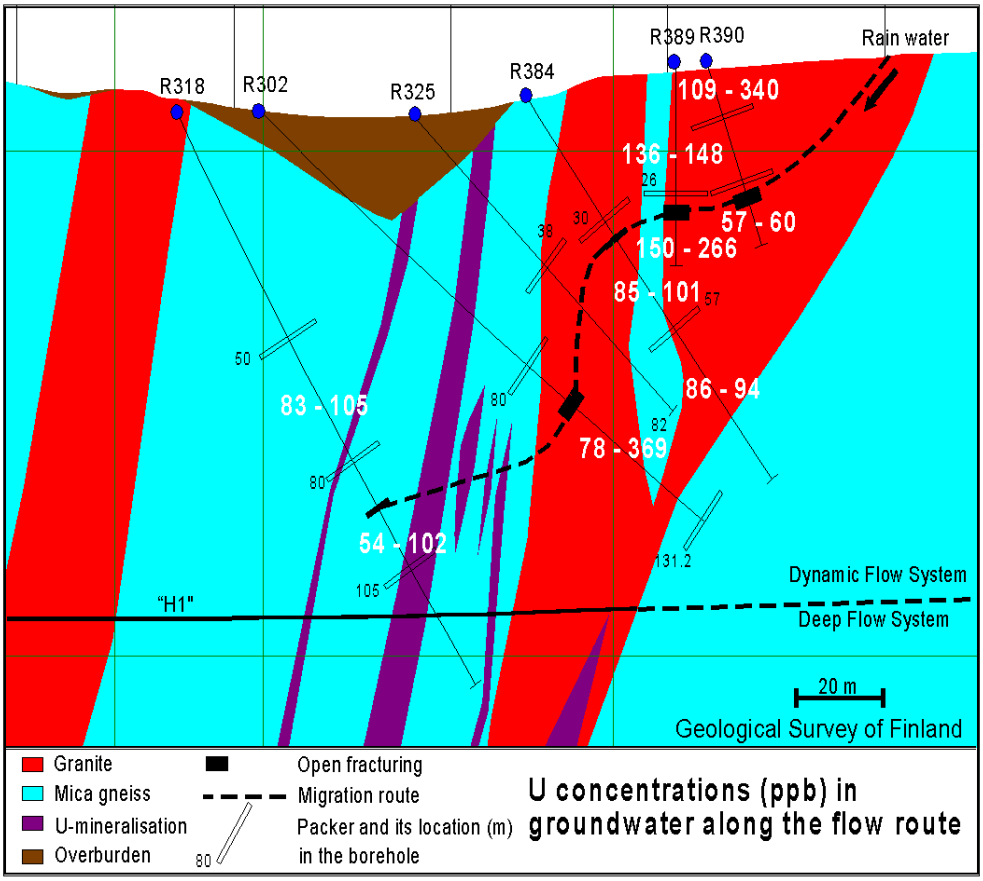


Fig. 27. The extensively studied Eastern Flow System at Palmottu. The drill holes were sampling holes for groundwater and rock material. Activity ratios ($^{234}U/^{238}U$) and uranium concentrations along the flow route are shown. The packer intervals applied in groundwater sampling are shown as distance (m) from the top of the respective borehole [Blomqvist et al. 2000].

The most important feature about the ore deposit at Palmottu is that it has survived all the glaciations that have occurred at Finnish latitudes. Thus, in principle, the effect of repeated cycles of permafrost - glaciation - deglaciation - interglacial period can be studied. This fact makes the site particularly relevant for performance assessments that have to cover glacial scenarios in countries like Finland, Sweden, and Canada.

The retardation mechanism studies at Palmottu were focussed on the sorption and matrix diffusion of uranium. In this context the term 'sorption' refers to fast reversible adsorption, in line with the K_d concept used in performance assessment modelling. Chemical extractions were used as the technical method to obtain information about uranium fixed to mineral surfaces. Because the extracted inventories thus obtained do not automatically represent any single fixation

mechanism, great care had to be taken to extract only the adsorbed inventories. In other words, it was necessary to ensure that it was possible technically to separate the adsorbed inventory from a whole spectrum of other inventories also fixed in situ. Both fracture surfaces and rock matrix were studied in the sorption investigations [Suksi 2001].

The results obtained for uranium indicate that fixation on mineral surfaces in situ is to a large extent irreversible. In this sense, the assumption of fast reversible adsorption used in performance assessments over-estimates the mobility of radionuclides. Sorption has been observed to be only one interaction mechanism between dissolved radionuclide and water-rock system among a set of others, many of which (e.g. precipitation) are actually more important. This is demonstrated by the fact that on average K_d-based sorption covers about 1 % of the attached radionuclide inventory on fracture surfaces.

An effort was made to study the relationship between laboratory-derived 'standard' K_d value and in situ K_d value obtained by careful extractions. The results are within a factor of three, which can be regarded as a good agreement [Blomqvist et al. 2000]. The two lines of reasoning behind a standard K_d concept and an in situ K_d concept are illustrated in Fig. 28.

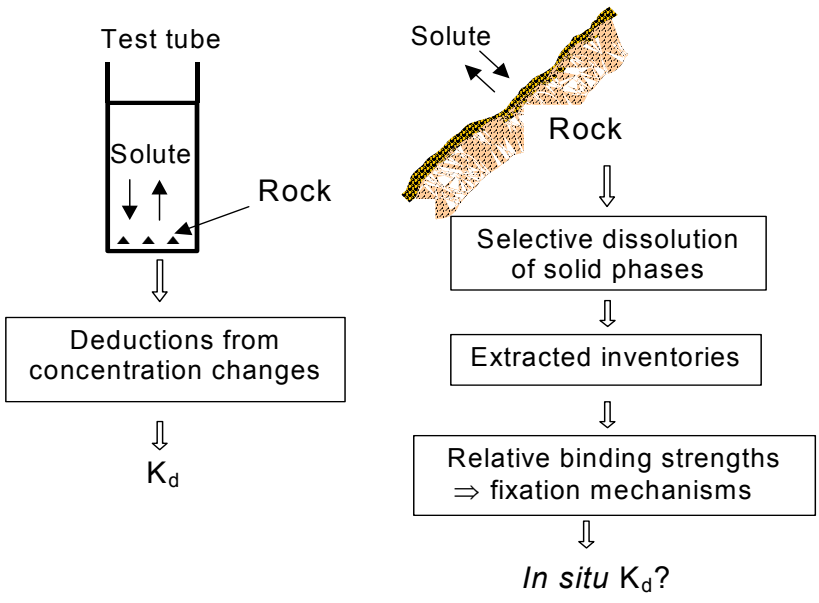


Fig. 28. Solute distribution between solid and liquid phases in the laboratory (K_d) and in the natural environment (in situ K_d) [Suksi et al. 2001c].

An extraction with $CaCl_2$ solution was used in an attempt to desorb in situ adsorbed uranium from fracture surfaces [Blomqvist et al. 2000]. The idea was that if the extracted uranium represents the adsorbed component then its $^{234}U/^{238}U$ activity ratio should match that of the corresponding groundwater. The extraction results were variable; identical activity ratios were obtained[13] only in one case.

Matrix diffusion studies used measured uranium concentration and activity ratio distributions as experimental references against which modelled results were compared [e.g. Rasilainen 1997; Blomqvist et al. 2000]. The standard matrix diffusion model could not reproduce the measured concentrations well enough, which led the researchers to suggest a slow-moving redox front within the rock matrix. The postulated movement of the redox front is controlled by diffusive oxygen flow from the fracture and by the oxygen-consuming redox reactions within the rock matrix. U release was postulated to follow rapidly after the oxidation of a previously anoxic part of the rock matrix. This idea is discussed in more detail by Rasilainen et al. [2001b].

In general, matrix diffusion on the scale of centimetres was indicated both by the measured reference and model simulations. Rock matrix appears anoxic inside, although the groundwater flowing along fractures that bound the matrix block would be strongly oxidising. This indicates a strong redox buffering capacity on the part of the rock matrix. All the samples studied indicated a continuous open pore network in the rock matrix with, however, natural heterogeneity in the distribution of the quantified porosity. This is in line with the basic assumptions applied in Finnish performance assessments.

Boulder studies

A boulder containing a considerable uranium accumulation was found on top of a morainic hill in the Kolkanmäki area, close to the town of Hämeenlinna in southern Finland. The study area is covered with glacial till and more sorted sediments (see Fig. 29). In contrast to the multi-targeted natural analogue studies at Palmottu, where retardation mechanisms were only one research area among others, the granitic boulder sample is studied specifically as a matrix diffusion (and sorption)

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[13] Here one must keep in mind that the $^{234}U/^{238}U$ activity ratio in a groundwater sample represents a weighted average over the whole packed-off section of the drill hole, which "dilutes" individual signals from fractures with less groundwater flow. In addition, the dominating flow channels that discharge into the packed-off section may derive their composition from a further location. In contrast, the $^{234}U/^{238}U$ activity ratio of the fracture coating sample is always strictly site-specific. In addition, many uranium-rich fracture coating samples have been found only in closed fractures off the main flow channels.

analogue. Another difference is that uranium accumulation within the boulder is apparently recent (postglacial), as compared to the very old ore deposit at Palmottu.

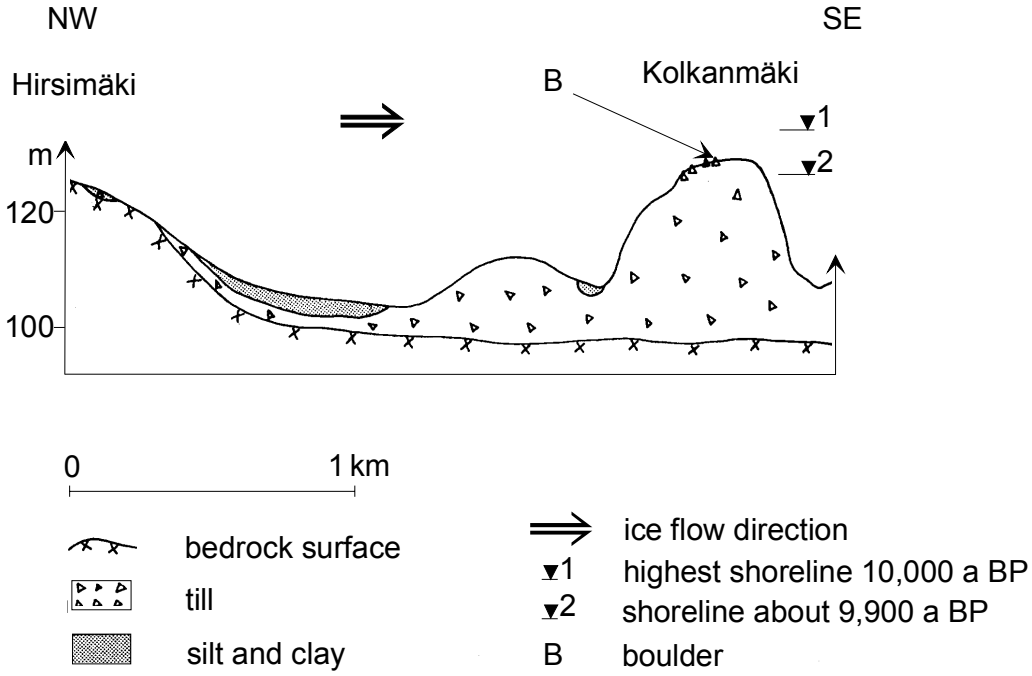


Fig. 29. Cross-section of the geological surroundings of the boulder sample. The boulder (B) is assumed to have been transported to its current location by ice [Rasilainen 1997].

Deglaciation took place in the Hämeenlinna region about 10 000 years ago. The highest shoreline of the subsequent Yoldia sea stage was 133 m above the current sea level. As the location of the boulder is only 2–3 m lower, it can be approximated that the boulder was below the Yoldia sea level for 50–100 years. Estimates of ice velocities towards the margin vary from a few to dozens of metres per year. This rate means a travel time of 50–500 years for the boulder over the estimated distance of 1–2 km. For at least part of this time the boulder was in wet conditions near the basal layers of the ice.

Up till now three boulders from the area have been studied and several drill core samples have been analysed across the boulders. U-series disequilibrium studies indicated unambiguously that most of the U has been accumulated recently, about 10 000 years ago [Rasilainen et. al. 1996; Rasilainen & Suksi 1997].

The measured uranium concentration profile through the most intensively studied boulder is clearly asymmetrical, which indicates a partly different history for the

two sides of the boulder. Its currently-postulated accumulation history includes a rapid in-diffusion period (100 years) from uranium-rich waters that discharged onto the boulder, or into which it was submerged at the end stage of glaciation. The in-diffusion process included nearly simultaneous precipitation of uranophane [Marcos et. al. 2001]. This was followed by a rapid out-diffusion period (50 years) due to the Yoldia Sea stage, during which the boulder was submerged in the sea. After out-diffusion the histories of the two sides of the boulder differed.

The upper part of the boulder was on dry land and there was no diffusion, only radioactive chain decay for the post-glacial period of 10 000 years. In contrast, the lower side, lying against the moist ground, experienced out-leaching due to the fact that capillary forces 'soaked' the lower part at a depth of 2 to 4 cm.

Mathematical simulations applying the classical matrix diffusion model have roughly reconstructed the observation that U levels are clearly higher in the upper part of the boulder than in the lower part. However, they also indicate that matrix diffusion combined with adsorption is not enough to reconstruct the past U accumulation alone. This is in line with the overall conceptual model that includes the precipitation of uranophane, a phenomenon not included in the classical matrix diffusion model applied so far. The next step in modelling is to combine the matrix diffusion model with a geochemically sound interaction model including adsorption and precipitation.

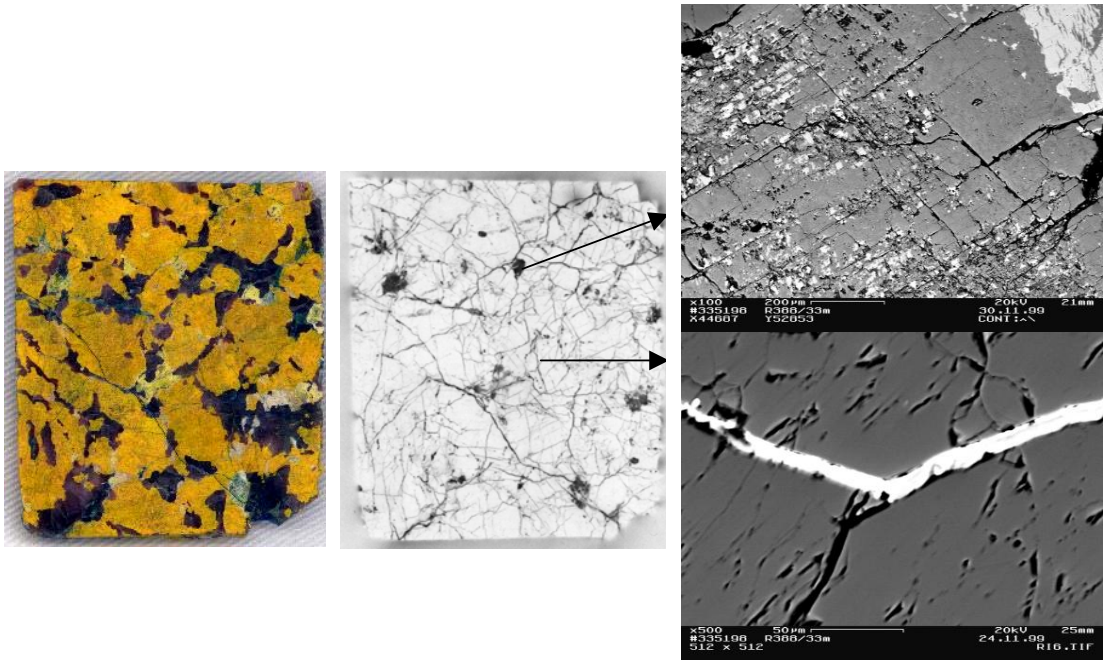
2.4.2 Structural studies of rock matrix[14]

Modelling radionuclide migration in bedrock requires reliable experimental data about the inner structure of the rock matrix. Most often this data is obtained by laboratory measurements of drill core samples taken from the site under investigation. Below, a brief description is given of the PMMA method; there is a more detailed discussion in Rasilainen et al. [2001a] and the references therein.

The PMMA technique measures directly the connective porosity of rock matrix, but it also gives the spatial porosity distribution, i.e. 2D and 3D information about different porous minerals inside the centimetric scale rock sample. Combined with mineralogical and petrographical characterisation of the water-filled pore space, it provides the mineral-specific porosity, as well as the porosity distribution in the pore space. An example of C-14-PMMA impregnated rock sample (R388, 33 m) from the Palmottu natural analogue site (cf. Fig. 27) and the corresponding autoradiograph are presented in Fig. 30. The PMMA-filled rock

[14] By Siitari-Kauppi, M.

matrices were studied by means of scanning electron microscopy and energy-dispersive X-ray analysis (SEM/EDS). The aim in the experiment shown in Fig. 30 was to study the pore apertures of grain boundaries and fissures in greater detail and to detect the uranium phases (see Fig. 30c).



a b c

Fig. 30. Photograph (a), corresponding autoradiograph (b) and backscatted electron images of PMMA-filled porous phases (c) showing structures of connective pore network of granite sample from Palmottu [Siitari-Kauppi et al. 1999; Kemppainen et al. 2001].

C-14-PMMA and H-3-PMMA methods involve the impregnation of centimetric scale rock samples with, respectively, C-14- or H-3-labelled methylmethacrylate in a vacuum, polymerisation by irradiation, autoradiography, and optical densitometry with digital image processing techniques. The low molecular weight and low-viscosity carrier monomer MMA, which can be fixed after impregnation by polymerisation, provides direct information about the accessible pore space in crystalline rock. The method gives the spatial porosity distributions, which information cannot be obtained by water or gas phase methods.

A practical drawback of the C-14-PMMA method is that after measurements the rock samples are impregnated with PMMA and, therefore, no longer available for other physical studies, but these studies can be performed in advance. Chemical analyses, however, for instance USD studies, are possible, because after sub-sampling the impregnated rock sample, the rock sub-samples can be technically

analysed so that the small PMMA amount involved (of an order of at most few per cents) does not disturb the results. Another practical drawback is that the amount of sample material required for the C-14-PMMA technique is not negligible.

Methylmethacrylate has been observed to penetrate into pores down to 2.5 nm in diameter, on the basis of tests with a purpose-constructed standard material. The size of a water molecule is 0.193 nm [Relyea 1980]. Electrical charges on mineral surfaces make the minimum size of pores that can be detected by water or MMA molecules somewhat complicated. Mineral surfaces are most often negatively charged. Water, being a natural substance found in rock matrices, penetrates smaller pores than methylmethacrylate. However, the pore size is of the same order of magnitude.

The porosity data obtained by the C-14-PMMA method is very detailed, and a new approach based on the random walk method is being developed for this detailed diffusion modelling. The new approach is to utilise the information about heterogeneous structures provided by the PMMA method. For the time being, it cannot be used to its full potential in current matrix diffusion modelling. The reason is that diffusivity data must be measured independently. With current techniques the measurements of samples with a thickness of less than one cm have been observed to be disturbed by artificial connections created by the sawing of the sample. For the time being there is no defensible method for providing the diffusivity data other than direct measuring.

2.4.3 Oxidation state of uranium[15]

Redox processes are key phenomena controlling the behaviour of uranium under groundwater conditions. The knowledge of its speciation in both liquid and solid phases helps to model the behaviour of uranium in the performance assessment of a nuclear waste repository. Thus the development of methods to determine the oxidation states of uranium is essential. In previous studies experimental methods have been developed to analyse uranium oxidation states in both groundwater and solid phases.

The aim of this study was to further develop the method for the determination of uranium oxidation states. Geochemically complex samples, especially secondary fracture coatings and whole rock samples, can contain high amounts of iron. Both valence states of iron can mitigate the original uranium oxidation state data

[15] By Ervanne, H.

during the analysis. The effect of different iron minerals such as pyrite, goethite, and biotite were studied in different concentrations. As expected, pyrite reduced uranium easily, whereas goethite was able to oxidise uranium. The disturbances of the other minerals studied lay between these two. To minimise the mitigating effect of iron compounds, several organic complexing agents were screened. The most promising was PAA (polyacrylic acid), which was further tested. A suitable concentration of this acid was discovered to be 2.5 %. Some natural samples were analysed with this acid.

In previous studies it was observed that not all the uranium from a smectite matrix was dissolved. To broaden the application area of the method to cover bentonite, it was necessary to study this problem. Various pretreatment approaches to the issue of how to obtain all the uranium from the sample to the solution were studied. Different reagents, such as HF, KCl, and H_3BO_3 were studied in various concentrations. All higher concentrations of the studied reagents changed the uranium oxidation state distribution in the reference material. Dilute HF and KCl can be used in pre-treatment procedures. In addition, higher dissolution temperatures were tested. The temperature during the analysis should not exceed 55 ºC because of uranium oxidation at higher temperatures. The determination of uranium oxidation states from bentonite containing freshly sorbed uranium was successful. The mitigating effects of possible iron compounds in bentonite are still under study.

2.4.4 Prospects of coupled migration modelling[16]

The potential of coupled modelling was reviewed with a view to its possible use in performance assessments [Rasilainen et al. 1999]. The study was focussed specifically on the migration of radionuclides.

The practical focus was on approaches that have been sufficiently developed that a significant improvement in performance assessments can be expected from applying them. Thus, the practical issues of defining boundary conditions in model validation and the availability of reliable input data were emphasised. The specific objectives were

- to describe relevant couplings in a systematic way

[16] By Rasilainen K.

- to address the question of where the simplified direct couplings currently used in performance assessments are defensible and where a more detailed analysis is required
- to address the question whether there are prerequisites for these more detailed analyses, e.g. the feasibility of obtaining sufficient data.

Even though a large number of sophisticated and powerful coupled models have been developed during recent decades, their current applicability to field scale radionuclide transport modelling depends on how well the issues of model validation and provision of sufficient data can be addressed. Transport modelling in particular depends on the many preceding analyses which provide the necessary understanding and input data, and, therefore, these should be considered first. The most important ones are the modelling of groundwater flow and radionuclide solubility in groundwater. These factors, in turn, depend on hydrological, chemical, and mechanical processes that can be affected by the elevated temperature of the repository.

A schematic representation of the various physico-chemical interactions present in the repository-bedrock system is given in Fig. 31.

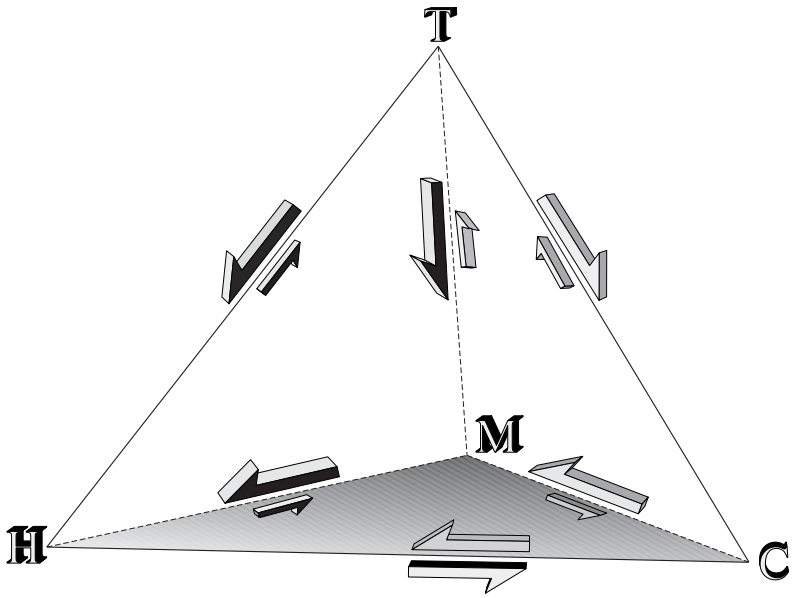


Fig. 31. Potential coupled interactions affecting the transport of radionuclides from a leaking repository [Rasilainen et al. 1999]. H is the hydrological, C the chemical, T the thermal, and M the mechanical system. The couplings usually considered most significant are shown by large arrows, and those considered insignificant by small arrows. Note that a coupling is not necessarily equally strong in both directions, e.g. the effect of temperature on chemistry (T->C coupling) is strong, whereas chemistry is not expected to affect the temperature distribution much (C->T coupling is weak).

Two basic effects that can trigger various couplings in and around a spent fuel repository in Finland were studied in more detail. Heat generation is considerable during the first thousand years after disposal. Considering the assumedly corrosion-resistant copper-steel canister, it can be concluded that heat generation-triggered couplings are most effective for cases with initially defective canisters, as these can release radionuclides during the high heat generation period. For longer-lasting canisters heat generation is a lesser problem.

Deep, saline groundwaters have been observed at Olkiluoto, located on the Gulf of Bothnia, which was selected as the site candidate for the Finnish spent fuel repository. Saline groundwaters are usually considerably less mobile than fresh waters and increasing salinity may decrease the retention of radionuclides by the rock mass.

A systematic survey of the possibilities for, and requirements of, coupled modelling, in particular those related to heat generation or groundwater salinity, has identified some features that make coupled migration modelling a challenging task. In groundwater flow modelling there appears to be wide background uncertainty related to the conceptualisation of complex flow systems. Correspondingly, input data requirements are not always apparent. In the case of migration-related chemistry there seem to be areas with large gaps in the basic database for geochemical modelling. Rock mechanical predictions are heavily dependent on knowing the location, structure, and properties of the dominant fractures, information which is extremely difficult to obtain. The transfer of heat is well understood in principle.

Coupled migration modelling did not appear to be yet at the stage of development that would allow its use as a standard modelling tool in performance assessments. In other words, the potential of coupled modelling to improve precision in the consequence analysis of performance assessment remains open. To a considerable extent this is due to the large natural variability in the background data, for instance in the groundwater flow and in the distribution of reactive species in the rock-groundwater system.

The above conclusion must, however, be regarded as interim, because the survey was mainly based on other surveys or studies not specifically aimed at migration modelling. In this sense, a more reliable basis for conclusions can only be formed by a systematic modelling exercise considering a realistic site-scale migration problem. The need for a practicable methodology to incorporate coupled modelling in the performance assessment approach became apparent.

Although the present applicability of coupled modelling in Finnish performance assessment appeared limited, coupled approaches could, nevertheless, prove useful. For example, systematic sensitivity studies using coupled models could be used in scenario definition. The reason is that in performance assessment the objective is to bracket the possible futures of the repository system using different scenarios, rather than to aim at the ‘right’ scenario of maximum probability. The ultimate aim of a performance assessment is to study whether the proposed disposal concept is likely to be safe; predicting exactly what will happen in the future is, of course, impossible.

2.4.5 Conclusions from migration studies

Migration studies are needed to estimate the release barrier function of bedrock for a geological nuclear waste repository. So far, migration modelling in Finnish

performance assessments has been based on the advection-dispersion-matrix diffusion model, in which sorption is taken into account by using the K_d concept. Anion exclusion has been taken into account by using smaller values for porosity and diffusivity. In order to be conservative, no other retardation mechanisms have been applied. The studies discussed above have aimed at contributing to a more realistic migration modelling.

Different modelling approaches were taken for a more integrated interpretation of batch and column experiments. K_d values obtained from the model fits of column experiments were lower than those of the batch experiments. K_d values for intact rock obtained from fracture column experiments were lower than those for the same rock when crushed, indicating that batch experiments tend to overestimate the retardation of weakly sorbing radionuclides onto the rock matrices.

Column experiments were useful in providing well-controlled tests for the classical advection-dispersion-matrix diffusion model. True matrix diffusion was observed when using extremely small water flows through the column. In some cases it appears, however, difficult to match a modelled breakthrough curve with a measured one equally well for all parts of the curve. The reason appears to be channelled water flow through the column. For the current experimental set-up there is, unfortunately, no direct technical method to obtain independent data for channelled water flow.

The surface complexation model has appeared feasible in explaining anion exclusion observations in natural rocks and structurally simpler artificial reference rocks. The heterogeneity of the samples, in particular natural rock samples, has been observed to be a major hindrance for detailed model testing.

Natural analogue studies have shown that sorption and matrix diffusion take place in situ. The results obtained for uranium at Palmottu indicate that fixation on mineral surfaces in situ is, to a large extent, irreversible. Sorption was observed to be only one interaction mechanism between dissolved radionuclides and the water-rock system among a set of others. Thus, in this sense, the assumption of fast reversible adsorption (K_d) used in performance assessments over-estimates the mobility of radionuclides. Good agreement was obtained between ‘standard’ K_d and in situ K_d values.

It has been observed at Palmottu that the rock matrix appears anoxic inside, although the groundwater flowing along the fractures that bound the matrix block would be strongly oxidising. This indicates a strong redox buffering capacity in the rock matrix. All Finnish natural analogue studies have indicated a continuous open pore network in the rock matrix with, however, natural heterogeneity.

Laboratory-scale structural studies of rock matrix fulfil the current need for porosity and diffusivity data in performance assessments. The porosity data obtained by the C-14-PMMA method is so detailed that it cannot be used to its full potential in current matrix diffusion modelling. The reason is that diffusivity data must be measured independently. New experimental and modelling approaches are needed.

A method for the determination of uranium oxidation states in solid phases was developed and validated. Homogeneity of the sample and the identification of possible disturbing redox elements are essential in order to apply a suitable dissolution method for the analysis of complex geological samples.

A systematic survey of requirements of coupled modelling identified features that render fully coupled migration calculations a challenging task. In groundwater flow modelling there appears to be wide-ranging uncertainty related to the conceptualisation of flow systems and to the corresponding input data. In terms of migration-related chemistry, there appear to be large gaps in the underlying thermodynamic database for geochemical systems. Rock mechanical predictions are heavily dependent on knowing the location, structure, and properties of dominant fractures; information which is extremely difficult to obtain. The conduction and convection of heat is well understood in principle.

It appears, therefore, that coupled migration modelling may not yet be at the stage of development that would allow its use as a standard modelling tool in performance assessments. Nevertheless, application of, for instance, mechanistic sorption modelling, rather than K_d's, would better utilise the current state of the art in understanding. Thus, the strategic question remains: what is the practical value of extremely detailed modelling of some specific mechanism when some other parts of the performance assessment will always contain considerable uncertainties?

2.5 Stability of bentonite barrier[17]

Bentonite is a material with a clay content varying between 52 % and 95 %. The main clay component is smectite, which swells considerably when it is in contact with water. Bentonite occurs in very old geological formations dating from the Ordovician (about 500 million years ago) to the Quaternary (about 1 million years ago). It is considered chemically stable and suitable for use as a barrier material

[17] By Lempinen, A., Marcos, N.

between the bedrock and the waste canisters. The bentonite that is used in nuclear waste disposal is, however, not purely natural, since it has been physically processed (excavated, air-dried, and ground into powders and granulates) and is compacted under a pressure of 1 000 bar. Therefore, research on the hydro-thermo-mechanical behaviour of the bentonite barrier is needed. The main goal is to ensure the stability of the barrier in a mechanical sense; that is, the waste canister should not move significantly within the bentonite. Also, the effect of the waste canister as a heat source has to be taken into account.

Predicting the behaviour of this kind of material requires mathematical models for material behaviour, which cannot be developed and justified without sufficient measurement data and knowledge about the microstructure of the material.

2.5.1 Bentonite studies

Material properties of bentonite

In order to perform the hydro-thermo-mechanical simulations, the material parameters in the mathematical model of bentonite behaviour have to be determined. Most of these parameters can be calculated from measurements described in the literature, but because some of these measurements are based on defective material models, and because the values of material parameters vary from one kind of bentonite to another, a series of swelling pressure measurements was conducted [Lempinen 2002].

The determination of mechanical parameters relies on a modified Bishop effective stress theory. The modification is needed to introduce the swelling phenomenon. This simplification of the Biot model for porous material reduces greatly the number of measurements required. Although its validity cannot be established theoretically, the likely deviation of the actual behaviour of bentonite in the confined space and moist conditions of the disposal tunnel from that predicted by the effective stress theory is considered to be small.

The viscosity parameters cannot be determined by laboratory tests, because they would require unrealistically long periods of time. Furthermore, the extrapolation of results from short experiments is not justified, since the long-term behaviour probably does not originate from the same physical phenomena. Therefore, such parameters were chosen that the viscous flow in the short-term experiments would remain at the threshold of observability. In other words, a worst case scenario is simulated.

Natural analogue studies

The bentonite occurrences in Almeria (Spain) and Wyoming (USA) were studied (in the field and in the literature) as a natural analogue to the long-term mechanical behaviour of the bentonite barrier in the final nuclear waste repository [Keto 1999]. The study was focussed on the geology and the deformational features of these two deposits. Both of them are commercially exploited. The products ('FEBEX' and 'MX-80' respectively) from these deposits are under consideration for use as the buffer material around the waste-bearing metallic canisters in the final repository for spent nuclear fuel (cf. Fig. 3). The materials have been relatively well studied under laboratory conditions, but the short-term tests are inadequate to predict their behaviour under repository conditions in the long-term.

The bentonite deposits in Almería and Wyoming differ quite significantly from each other. The Wyoming bentonites are Cretaceous (66.4–144 million years) and the Almería bentonites are Tertiary (24 million years) in age. Both bentonites are the result of the hydro-thermal alteration of rhyolitic volcanic ash. The mineralogies of the bentonite deposits of these two areas are fairly similar. The most significant difference between these two bentonites is in the exchangeable cation. Wyoming bentonite consists of Na-smectites and Almerian bentonite of Ca-smectites (Na-smectites are more expandable than Ca-smectites).

The bentonite deposits in Wyoming occur as 1–2 metre-thick horizontal seams within other marine Cretaceous sediments, mainly shale. There are no significant deformational features in these deposits. The bentonite deposits in Almería occur in fractures. The width of the deposit varies from a few metres to dozens. One of the most important deformational features in the Almería bentonites is the intrusion and overlapping of Tertiary bentonite within and over a 2–10 metre-thick layer of Quaternary sediments in the Cortijo de Archidona quarry. The non-commercially exploited bentonite quarry of Pozo Usero (Fig. 32), below a much denser carbonate layer, offers an interesting opportunity for further studies on the deformational features of bentonite on meso- and micro-scales.

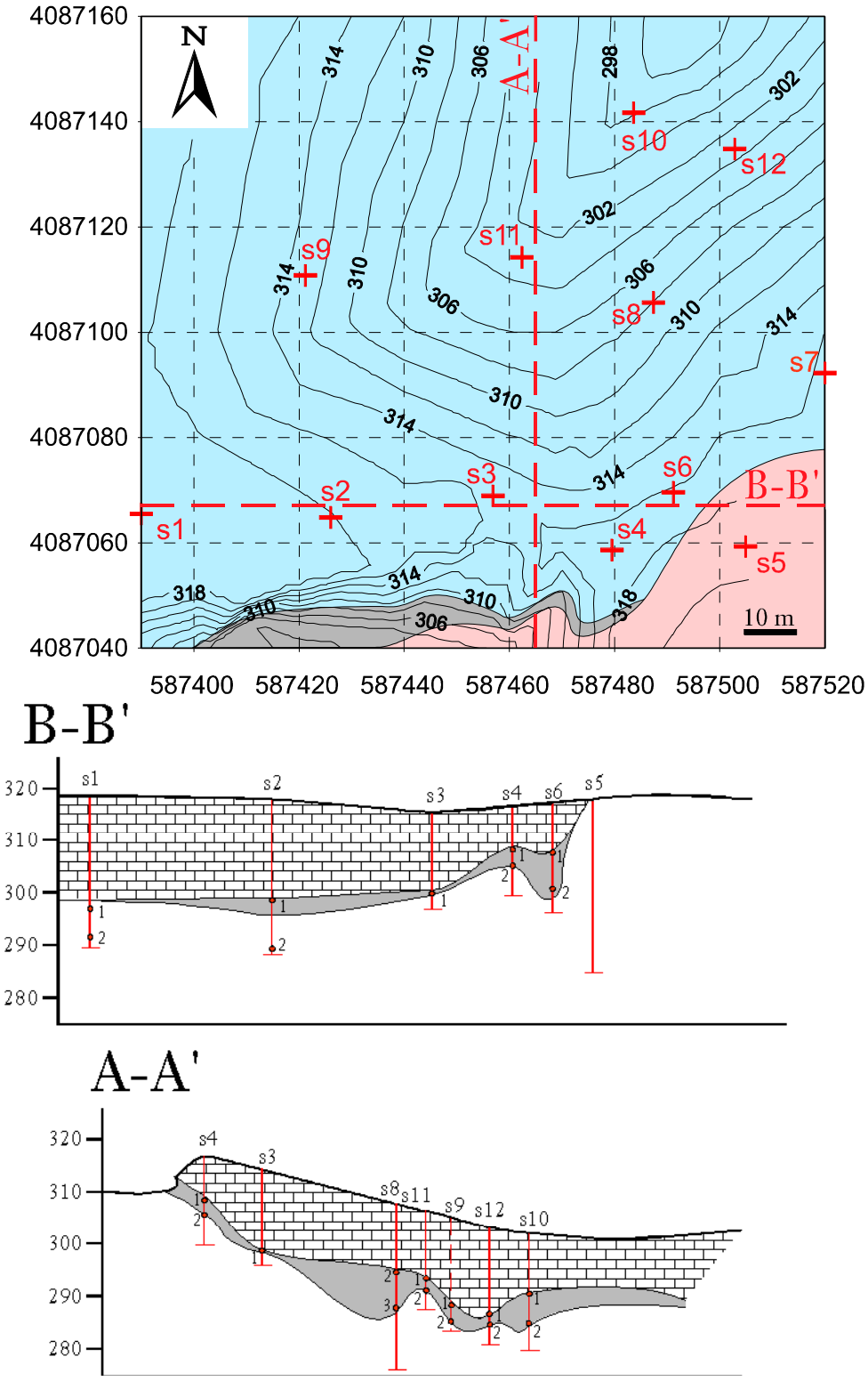


Fig. 32. A map and cross-sections of the Pozo Usero outcrop. Reefal limestones cover the volcanic unit, the uppermost part of which is locally altered to bentonite [after Arcos et al. 1999].

Petrophysical studies

Many studies have been performed on the chemical and geotechnical properties of bentonite [Marcos 1997], but data on its petrophysical (electrical) characteristics is scanty. The aim in studying the electrical behaviour of bentonite is not only to cover this gap, but also to apply petrophysics in order to measure eventual changes in the porosity of bentonite in situ. Marcos et al. [1998] measured the electrical resistivity of cylindrically-shaped compacted samples (length 6 cm and basal area 20 cm^2) of the commercial bentonite MX-80. Fig. 33 shows the resistivity (in ohm) versus saturation time of two samples of different density. As expected, the resistivity decreases with increasing water content. At the time of the experiments absolute porosity values could not be obtained, but it was observed that more loosely packed bentonite (dry density 1.64 g/cm^3) has much greater porosity than the tightly packed bentonite (dry density 1.73 g/cm^3). This has also been observed in geotechnical measurements of bentonite [e.g. Johannesson et al. 1995]. Further studies on the electrical properties of bentonite would give information on its pore-space texture.

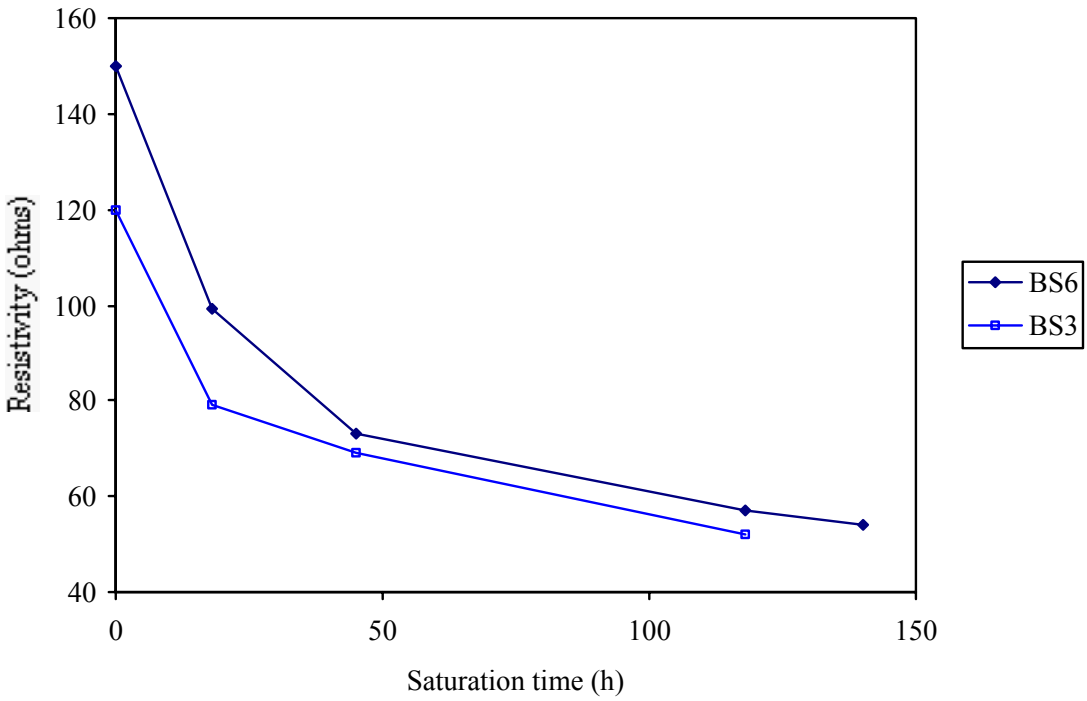


Fig. 33. The changing resistivity (ohms) as a function of the saturation time for two bentonite samples (densities: BS6 = 1.64 g/cm^3 and BS3 = 1.73 g/cm^3).

Microstructural studies

Most of the physical properties of smectites, such as swelling, adsorption, plasticity, permeability, and shear strength, are related to the interactions between electrically charged interlamellar surfaces and water molecules. Thus, the macroscopic properties of bentonite can be reduced by using the so-called upscaling techniques. In the case of bentonite in the repository, the physico-chemical conditions on the microscopic level can be used to model the macroscopic behaviour of bentonite in space and time, for example by simulating the distribution of clay platelets in bentonite (Fig. 34). Stepkowska [1990] has presented the delamination process when the water content of bentonite increases. Using stochastic imaging, the effect of wetting could be predicted. In addition, the possible anisotropy caused by loading in the repository could be taken into account.

In practical applications of groundwater modelling, we are interested in describing solute transport phenomena on a scale much larger than the scale at which the underlying processes take place. Typically, the underlying physico-chemical processes are best understood and quantified on a small scale. The approach could be applied in the case of bentonite by predicting the aggregation process at the microscopic level. The porosity forms with aggregation; its anisotropy and value determine the possible paths for water flow in bentonite.

Hydro-thermo-mechanical simulations

The examination of the stability of bentonite in a mechanical sense can be divided into three phases: 1) saturation with water, which takes 10–100 years; 2) bentonite flows around the canister in consequence of pressure caused by its swelling, and 3) the possible sinking of the canister as a result of gravitation.

A B

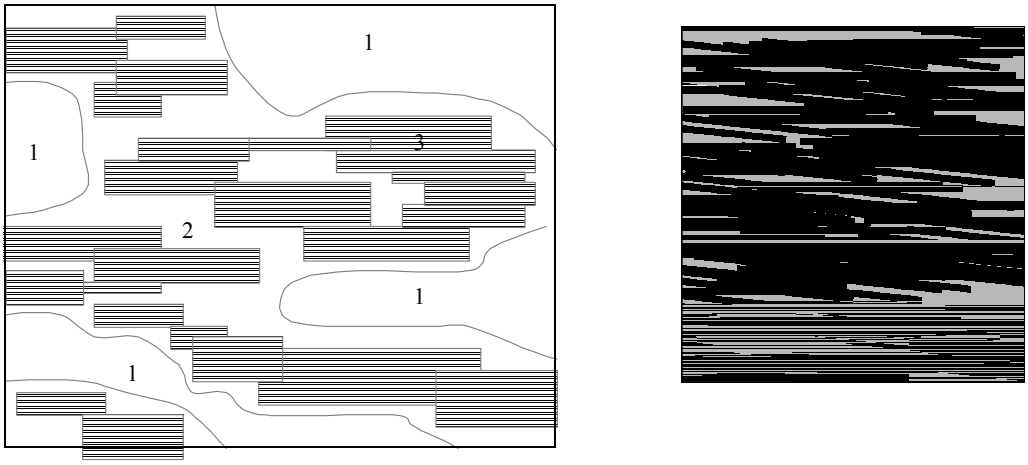


Fig. 34. (A) Schematic drawing of clay platelets forming aggregates; 1 refers to macropore water, 2 to diffuse layer water and 3 to crystal phase water. (B) Stochastic imaging of the distribution of clay platelets in bentonite.

When the saturation phase is simulated, a mathematical model that couples thermal, hydrological, and mechanical phenomena is needed. A great deal of effort was put into finding out how the swelling can be modelled and coupled with thermo-mechanical behaviour, since the conventional models for porous media cannot describe it correctly [Lempinen 1999, 2000, 2002]. The computational model of the saturation phase also needs special consideration, and there exists no commercial application with the required models. Therefore, a general purpose finite element code [Freund & Lempinen 1994] was used. The calculations were kept as simple as possible in order to retain numerical reliability [Lempinen 2002]. The validity of these models is being tested in the international DECOVALEX III project, the results of which will be published in the year 2002 (see http://www.decovalex.com).

The movements of the canister in the saturation phase are not significant, but the deformation of the bentonite is assumed to be in equilibrium with the forces in the system. These forces consist of the gravitation acting on the great mass of the canister and swelling pressure, which is modified by the non-linear material behaviour and the hydro-thermal coupling. The resulting force field depends greatly on the initial conditions, and can vary in direction and magnitude [Lempinen 2001]. In the study of bentonite buffer behaviour after its resaturation, the assumption of equilibrium between deformation and forces in the bentonite was rejected. Instead, very slow viscous motion was taken into consideration. It is assumed that this motion is too slow to be detected in short-term laboratory

measurements, and the worst-case scenario is that there is viscous behaviour just below the observation limit. In this case, calculations with simple models suggest that it is possible that the waste canister will penetrate the bentonite barrier in a few thousand years [Lempinen 2000].

Mechanical instability phenomena, such as sensitivity to small variations of geometry, do not seem to exist under imaginable conditions. However, variation in material properties can result in modifications to the force field and, thus, the long-term motion of the canister [Lempinen 2002].

2.5.2 Conclusions from bentonite studies

In order to describe the mechanical stability of the bentonite barrier, a mathematical model of the bentonite's behaviour has to be formulated. Most of the parameters required can be obtained or calculated from measurements described in the literature, but, unfortunately, some of these measurements are based on defective material models. Furthermore, the viscous parameters, for example, cannot be determined by laboratory tests at all, because they would require unrealistically long periods of time.

The stability of bentonite in a spent fuel repository can be divided into three conceptual steps: 1) saturation with water, which takes 10–100 years; 2) bentonite flows around the canister in consequence of pressure caused by its swelling, and 3) the possible sinking of the canister as a result of gravitation.

Much effort was put into finding out how the swelling can be modelled in saturation and coupled with thermo-mechanical behaviour, since the conventional models used for porous media cannot describe it correctly. The validity of the sub-models developed is being tested in the international DECOVALEX III project.

Concerning the second and the third conceptual steps of stability, very slow viscous motion was taken into consideration, instead of the assumption of equilibrium between deformation and forces. It was assumed that this motion is too slow to be detected by short-term laboratory measurements, and the worst-case scenario is that the viscous behaviour is just below the observation limit. In this case, calculations with simple models suggest that it is possible that the waste canister will penetrate the bentonite barrier in a few thousand years.

The bentonite occurrences in Almeria (Spain) and Wyoming (USA) were studied as a natural analogue to the long-term mechanical behaviour of the bentonite

barrier. Wyoming bentonite consists of Na-smectites and Almerian bentonite of Ca-smectites (Na-smectites are more expandable than Ca-smectites). Both deposits are commercially exploited ('FEBEX' and 'MX-80' respectively). The results supported the long-term mechanical stability of the bentonite.

2.6 Performance assessment methodology[18]

The JYT2001 research programme has paid much attention to the performance assessment methodology. The reason is that the transparency and clarity of the methodology are essential factors for decision-making, and for communicating the results of performance assessments to non-technical audiences. The aim in the research programme has, however, never been to conduct full-scale performance assessments for a spent fuel repository; rather, the aim has been to develop the Finnish performance assessment methodology, and to communicate Finnish experiences.

Collaboration in international working groups dedicated to full-scale performance assessments, or some limited sub-systems, has been the general approach to further Finnish performance assessment methodology. In the following, brief reviews are given of the results obtained within the Nuclear Energy Agency of the OECD (OECD/NEA), and work done with reference biospheres, most notably within the BIOMASS Project under the auspices of the International Atomic Energy Agency (IAEA).

2.6.1 OECD/NEA collaboration

The research programme included the active involvement in the work of the 'Performance Assessment Advisory Group' (PAAG) of the OECD/NEA and the joint 'Core Group' of the PAAG and the 'Co-ordination Group on Site Evaluation and Design of Experiments' (SEDE). The two working groups were merged into the 'Integration Group for the Safety Case' (IGSC) in 2000. There was fruitful communication between the PAAG and the BIOMOVS2 and BIOMASS Projects of the IAEA in that these adopted the PAAG's idea of starting the development of stylised biosphere scenarios. The idea was suggested to the PAAG by the Finnish representative, and it was originally based on the WELL-94 drinking water scenario applied in Finnish performance assessments.

[18] By Rasilainen, K., Vuori, S.

The PAAG set up an ad hoc working group on 'Integrated Performance Assessment of Deep Repositories' (IPAG), chaired by the representative of VTT Energy, in 1994, to discuss, compile, and systematically compare documented performance assessments from among its member countries. The Finnish performance assessment TILA-96 [Vieno & Nordman 1996] was included in the comparison. The working group reported a comparison of 10 published performance assessments in 1997 [IPAG 1997]. The second stage of the working group (IPAG-2) expanded the area of research to regulatory reviews of performance assessments [IPAG 1999]. The Finnish performance assessment TILA-99 [Vieno & Nordman 1999] was included in this comparison. In addition to VTT Energy, the Radiation and Nuclear Safety Authority (STUK) participated in IPAG-2. Currently, the third stage of the working group (IPAG-3) has further expanded the scope of work towards communication of nuclear waste management questions.

VTT Energy has joined the 'Active user' group of the FEP database of the OECD/NEA. The group is also financially committed to the maintenance and development of the database. Features, events, and processes (FEPs) are the conceptual building blocks from which the scenarios and calculation cases in performance assessments are derived.

The research programme has participated actively in the work of the 'Radioactive Waste Management Committee' (RWMC) of the OECD/NEA with annual reporting of the progress of the Finnish nuclear waste management programme, including spent fuel management. The RWMC is a forum for senior experts and it co-ordinates the work of the OECD/NEA's technical subcommittees, such as the IGSC and the 'Forum on Stakeholder Confidence' (FSC).

The OECD/NEA set up an Ad Hoc Expert Group of Spent Fuel Management Options in 1997 to compare the basic strategies of spent nuclear fuel management, i.e. with or without reprocessing. The technical objectives of the study were to compile the most recent data and information on radioactive release from the two options, and to analyse the radiological impacts in a systematic manner. Furthermore, the group was to interpret the results from the scientific and technical viewpoints and to contribute to informed discussion in the NEA member countries. The group was chaired by the representative of VTT Energy.

The reference fuel cycles were selected so as to be as comparable as possible. For the reprocessing option it consists of the reprocessing of spent fuel and one-time recycling of separated plutonium as mixed oxide (MOX) fuel. For the once-through (i.e. direct disposal) option the spent fuel is not reprocessed, but is considered as waste. The overall conclusion of the working group [OECD/NEA

2000] was that from the radiological point of view there is no reason to prefer one option to the other. Estimated collective doses from the major fuel cycle stages of the two options are shown in Table 5.

Table 5. Collective dose estimation for the general public from major fuel cycle stages of the two waste management options [OECD/NEA 2000].

Fuel cycle stage	Collective dose to public truncated at 500 years (manSV/GWa)	
	Once-through	Reprocessing
Mining and milling	1.0 (other studies: 1–1000)	0.8
Conversion, enrichment, fuel fabrication	0.0009	
Power generation	0.6	0.6
Reprocessing, vitrification	-	1.2 (site specific 0.6)
Transportation	trivial	trivial
Disposal	no release during first 500 years deferred releases similar for both options and concentration & doses smaller than for other stages	
Total	1.6	2.6

2.6.2 Reference biospheres

The safety criteria applied in all countries are today based on dose limits, derived most often from the recommendations of the International Commission on Radiological Protection (ICRP). This means that in order to compare the radiological impact of a planned nuclear waste repository with safety criteria, performance assessors must have a methodology at their disposal to convert the calculated release rates (Bq/a) to dose rates (Sv/a). Biosphere modelling is required for this purpose.

Biosphere modelling is, of course, part of the performance assessment and, therefore, its level of ambition and detail must be in balance with those of the rest of the performance assessment. The overall level of detail, in turn, depends on the

purpose of the performance assessment. For instance, the biosphere modelling of the TILA-99 performance assessment was criticised as being too simplified and inadequate [Ruokola 2000], which is undoubtedly true. But one must keep in mind the fact that the raison d'etre of TILA-99 was to study the technical feasibility of the repository system, and to assist in selecting a site for the repository, in line with the Decision in Principle (DiP) process [Rasilainen et al. 2001c].

With the favourable DiP, Posiva will focus its studies on Olkiluoto, on the coast of the Gulf of Bothnia. In this environment, possible recipients under today's biosphere conditions are drinking water wells and the local coast area. As post-glacial land uplift continues, there is an element of evolution in the biosphere, and shallow sea areas will slowly be isolated to form inland lakes. In the Finnish climate a lake may gradually become swampy and later turn into a peat bog. Both lake sediment and peat bogs have a well-documented tendency to concentrate radionuclides from the surrounding water.

The geosphere-biosphere interface requires special consideration in biosphere modelling. One aspect is that the effective dilution volumes are particularly important parameters, because dose rates are usually directly derived from radionuclide concentrations in the biosphere. For the drinking water well scenario this parameter has recently been estimated by numerical 3D groundwater flow modelling based on detailed site-specific data for Olkiluoto [Kattilakoski & Suolanen 2000]. The researchers adopted different approaches in calculating the effective dilution volumes. In the approach considered the most realistic, the effective dilution volume was defined as:

$$\frac{\text{well capacity } (\text{m}^3/\text{a})}{\left(\frac{\sum_i Q_{\text{well route i}}}{Q_{\text{repository}}}\right)} \qquad (6)$$

where $Q_{\text{well route } i}$ is the flow rate (m^3/a) associated with the flow route i entering the well and $Q_{\text{repository}}$ is the total flow rate from the repository (m^3/a). The denominator thus represents the portion of water flowing through the repository to the well. The results obtained indicate large overall variation (30 000–460 000 m^3/a), depending on the location of the well. This, in turn, indicates considerable channelling of groundwater flow, and a relatively complicated groundwater flow field in the area under observation. The channelling of groundwater flow was clearly seen in the simulations, in which flow lines starting from different parts of the repository discharged in different areas of the island.

The Finnish safety criteria [STUK 2001] include a dose limit of 0.1 mSv/a for a period of a few thousand years after the closing of the repository for the critical group. After that, nuclide-specific release rate limits (Bq/a) are applied.

In this context, the possibility of applying internationally recommended reference biospheres would be of great practical value. The reason is that the user would not have to 'prove' that the biosphere would be something deterministic in the future. Rather, a comprehensive set of alternative reference scenarios would allow more easily defensible variation in the analysis. For the time being, however, there are no internationally accepted reference scenarios, even for the simplest drinking water well case.

BIOMOVS2 and BIOMASS

The IAEA has traditionally launched efforts to develop international reference biospheres within its research programmes. The objective of the BIOMOVS2 research programme [BIOMOVS II 1996] was to develop the required methodology and to provide a sufficiently comprehensive set of reference biospheres. The general requirement for the methodology was to provide a reliable lead track by detailed reasoning for the assumptions, and for the choice of numerical data. These objectives turned out to be too ambitious, however, and the main achievements of BIOMOVS2 were restricted to the establishment of the basic methodology, including a database (FEP, i.e., features, events, and processes) for the biosphere and dose exposure analyses.

In the follow-up programme, BIOMASS Theme 1, the aim was to derive practical examples, in addition to the further development of the reference biosphere methodology. A set of increasingly complex reference biospheres was defined, starting from very simple drinking water scenarios. The aim of the other scenarios was to put the well scenarios into perspective with a more comprehensive set of exposure pathways. The possibility of having a set of internationally agreed reference biospheres to provide support for simplified stylistic approaches was the main incentive for Finnish participation in the BIOMASS project. For the time being the final reporting of BIOMASS is in progress. There is a review under way at the JYT2001 research programme to identify and analyse the practical outcomes of the BIOMASS project for future Finnish performance assessments.

2.6.3 Conclusions from performance assessment methodology studies

Performance assessment methodology has mainly been studied in the form of international collaboration. The development of overall methodology has taken place within the PAAG group of the OECD/NEA, nowadays called the IGSC. From the Finnish point of view, the work done in the first two phases of the IPAG group has been most useful in that it has provided systematic comparisons of published performance assessments. These comparisons have considerably improved the prerequisites for understanding the real differences between performance assessments in different countries. The clarity, transparency, traceability, and repeatability of a performance assessment report obviously help in communicating the results to non-expert audiences as well.

Biosphere studies are required to convert the calculated release rates (Bq/a) from the geosphere to dose rates (Sv/a) in the biosphere. This in turn is required because all safety criteria applied today include dose rate limits, in Finland 0.1 mSv/a for the most exposed group. With the positive DiP the biosphere studies in Finland will be focussed on the Olkiluoto site, selected as the reference site for the spent fuel repository.

There are acknowledged needs to develop an internationally accepted set of stylised reference biospheres. From the performance assessor's point of view, it would enable more easily defensible variability in biosphere modelling. The development of reference biospheres has so far taken place within the IAEA's BIOMOVS2 and BIOMASS research programmes. Unfortunately, for the time being there are no accepted reference biospheres, even for the simplest drinking water well scenarios.

2.7 Waste management technology and costs[19]

2.7.1 Alternative spent fuel management options

According to current plans the spent nuclear fuel from the Finnish nuclear power plants will, after intermediate storage, be disposed of in a deep repository in the bedrock at Olkiluoto employing the direct disposal method, in which the spent

[19] By Rasilainen, K., Vuori, S.

fuel elements are encapsulated in double-layered copper-iron canisters (cf. Fig. 3).

As backup material for the DiP process, a survey was carried out on alternative spent fuel management options. The two most oft-mentioned alternatives were reviewed, namely continued long-term interim storage and nuclide partitioning and transmutation [Anttila et al. 1999]. The objectives of the review were to analyse the short- and long-term radiological safety of the alternative options, as well as to examine the technical and economical feasibility of these options in comparison to the direct disposal option.

As concerns interim storage, the current management policy already includes a long storage period that can be extended, in the event that it is required. During that time the choice between the different main options can still be contemplated. Even if one wishes to emphasise the retrievability of spent fuel, it is still not considered rational to construct a new type of monitored storage facility located close to the surface of the bedrock. That type of concept would still be an interim solution and would thus not fulfil the requirements of the Nuclear Energy Act, which prescribes the management of spent fuel in Finland in a manner that 'can be considered permanent'.

Concerning nuclide transmutation, during the last decade major research programmes in several countries have been reinitiated in order to study the possibilities of improving the efficiency of reprocessing. These programmes are investigating the possibility of separating minor actinides and some long-lived fission products from spent fuel. These separated products would be transmuted to other radionuclides either in ordinary reactors or in special transmutation facilities.

The intended benefit to be achieved by transmutation would be a substantial reduction in the time period during which the radionuclides contained in the waste could potentially bring about radiological impacts to the population in the vicinity of the repository. Some kind of final disposal is required for the wastes remaining, however.

The reactor-based or accelerator-driven transmutation concepts for the treatment of spent nuclear fuel are still at an early phase of development. It is uncertain whether the required technology can be developed within the coming decades to a level that could be applied in large-scale facilities. One important precondition for the development of this new technology is that nuclear power remains an important, or rather, growing, energy source worldwide. Only in that case can the

nuclear industry be expected to make heavy investments in such a technically demanding area.

Anttila et al. [1999] concluded that as a result of the complexity of the required new technology and the small size of the Finnish nuclear power programme, it is, at the present time, neither reasonable nor economically feasible to base the management of spent fuel in Finland on the transmutation option. Notwithstanding this, it appears reasonable to at least follow international developments in this research field.

2.7.2 Costs of nuclear waste management

The management of all nuclear waste arising in Finland, including operative reactor waste, the decommissioning waste of nuclear power plants (NPPs), and spent nuclear fuel, is estimated to cost around 1 700 million euro (i.e. 10 000 million FIM). Spent fuel management covers more than half of the costs.

Nuclear waste management is a particularly long-term project extending over dozens of years, which means that technical and economic preparations must be made in advance for operations that will be realised in the far future. For instance, the decommissioning of NPPs and the closing of disposal tunnels in a spent nuclear fuel repository are activities which are already in sight, but will not take place for the next few years (cf. Table 1). In order to make sure that the required funding is available when needed, the State Nuclear Waste Management Fund has been established. On the basis of the Nuclear Energy Act, the fund is administered by the KTM.

The basic principle in the fund is that at all times it can cover the liability, i.e. all future management costs of currently existing nuclear waste. At the end of 2000 the money in the fund covered around 96 % of the liability. For the liability not yet covered by the contributions paid into the fund, the power companies must furnish securities as a precaution against insolvency. The power companies are entitled to borrow back 75 % of their contributions against securities.

To make sure that the remaining liabilities are covered, the power companies, i.e. Fortum Heat and Power Oy, and Teollisuuden Voima Oy, are obliged to set aside money into the State Nuclear Waste Management Fund. The power companies must annually present cost estimates for the future management of their nuclear wastes to the KTM. The cost estimates are based on the power companies' latest technical plans, and they also include the decommissioning of NPPs. The authorities review the cost estimates and, on the basis of the review, the KTM

stipulates the power companies' contributions, as well as when the contributions are required. The need for contributions depends, for instance, on the accumulation rate of nuclear waste and on the nuclear waste management activities carried out so far.

In order to support the KTM in its work, the JYT2001 research programme systematically compiles data on cost estimates from domestic and international sources, and analyses the data thus obtained. Nuclear waste management provision needs are reviewed annually in statements prepared to meet the needs of the KTM. The statements on the plans of the power companies are based on a critical review of the cost estimates submitted to the KTM.

3 Social science studies on decision-making

The main results of the social science studies of the research programme are reviewed briefly in this chapter. The studies covered decision-making on both a national and local level related to spent fuel disposal, Environmental Impact Assessment (EIA), and media issues related to spent fuel disposal. The social science studies were mostly based on national features of the legislation. There are two reasons for this: (1) every country has its own 'tailor-made' way of making difficult decisions, and (2) the studies were originally started specifically to support the Finnish authorities in the EIA process. The EIA was the first-ever programme for spent fuel disposal in Finland and, therefore, neither Posiva nor the authorities had any experience of it. In the previous stage of the research programme (1994–1996) an extensive literature survey was carried out on EIA practices and experiences in other countries [Harmaajärvi et al. 1997].

The proposed municipality for the nuclear waste repository has an absolute right of veto in the DiP process. This, together with the local nature of the EIA process, has emphasised the role of the candidate municipalities. This emphasis was also reflected in the social science studies of the research programme. Altogether, around 20 % of the funding of the research programme was allocated to social science studies.

3.1 Decision-making for the spent fuel repository [20]

In Finland, decision-making for the spent fuel repository is carried out in successive steps that consist of the DiP, the construction licence, and the operating licence. As the host municipality of the repository has an absolute right of veto in the DiP process, the first step in the decision-making is strictly local in nature, although it is linked to the overall national policy.

[20] By Hokkanen, P., Ponnikas, J., Kojo, M., Suominen, P., Litmanen, T.

3.1.1 Description of the decision-making process [21]

The basic idea in the Finnish model for spent nuclear fuel management (cf. Fig. 3) is derived from the legislation:

"Nuclear waste generated in Finland in connection with or as a result of the use of nuclear energy shall be processed, stored, and disposed of in Finland in a permanent manner." (Amendment to the Nuclear Energy Act 1420/1994, § 6a).

The Nuclear Energy Act and Decree provide a clear framework for the implementation of nuclear waste management, as well as a clear division of responsibilities (see Fig. 35). On the basis of the Nuclear Energy Act, the Government regulates the use of nuclear energy in Finland, the KTM grants the required licences, and the Radiation and Nuclear Safety Authority (STUK) supervises the safety of the use of nuclear energy [KTM 1998, 5; Rasilainen & Vuori 1999, 16-18].

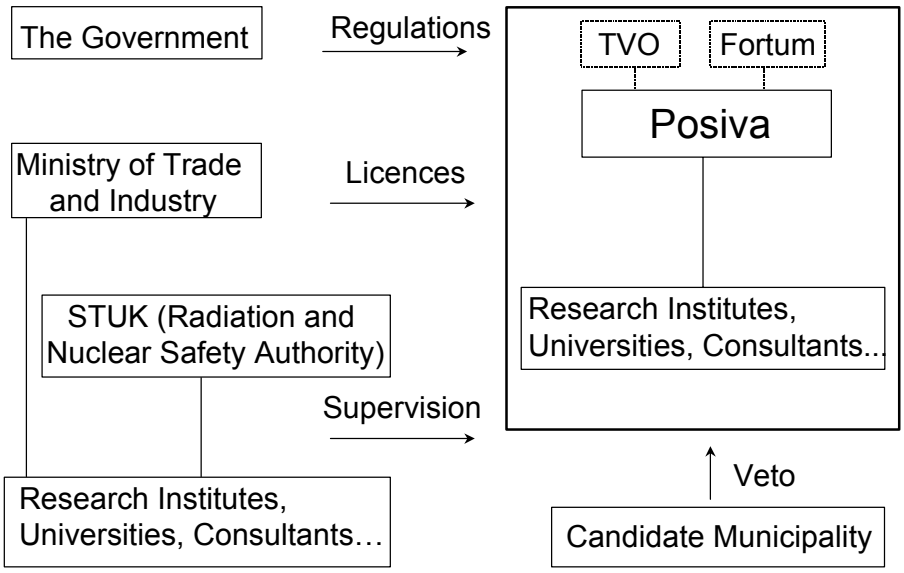


Fig. 35. Main actors in Finnish nuclear waste management.

The decision-making process for the final disposal of nuclear waste involves many stages (Fig. 36). A Decision in Principle (DiP) by the Government is required for the final disposal facility. Furthermore, a preliminary safety appraisal by the STUK is required by the law for the consideration of the DiP by the Government. The municipality in which the facility is to be constructed must give

[21] By Hokkanen, P.

their approval. The DiP needs to be ratified by Parliament before it is enforced. Apart from the DiP, separate construction and operating licences need to be applied for for the encapsulation plant and, at a later stage, the final disposal repository (cf. Table 1).

At the time of the Government's policy decision of 1983, the aim was to "dispose of the spent fuel abroad in an irrevocable manner" by contractual arrangements. Despite this, it was specified that the objective of research activities, investigations, and planning work related to nuclear waste management was that Finland should prepare for the final disposal of spent nuclear fuel after about the year 2020. According to the Government's policy decision, the selection and characterisation process of the site for a final disposal facility was to have been completed by the end of the year 2000 (see Fig. 36).

At the beginning of the 1980s, site screening was carried out in different parts of the country to find areas suited for final disposal, and, in 1987, field research was started at five sites. Detailed further research was carried out later in four areas: Romuvaara in Kuhmo, Kivetty in Äänekoski, Olkiluoto in Eurajoki, and Hästholmen in Loviisa. The EIA process was also carried out in these four candidate municipalities. The EIA programme was completed at the beginning of 1998 and the EIA report in May 1999. At the same time Posiva submitted its application for the DiP, including only one candidate municipality, Eurajoki. According to the Nuclear Energy Act, the progress of the DiP application requires both approval by the host municipality and a preliminary safety appraisal by the STUK.

The so-called 'Vuojoki agreement' was concluded between the municipality of Eurajoki and Posiva in May 1999[22]. This agreement was the most important activity outside the EIA process. The Eurajoki municipality set an additional precondition for its preliminary approval of the plan, viz. that the application for the DiP could only include one alternative site (Olkiluoto). The agreement guaranteed financial compensation to Eurajoki if the attitude of Eurajoki were positive. The agreement is seen as a final factor in the site selection process. It dropped the other three candidates from the 'competition for the final disposal' as early as 1.5 months before the public hearing of the EIA report and the application for the DiP. Even if the agreement between the company and the municipality was lawful and according to custom, it caused bitterness in the other munici-

[22] According to Vuojoki-agreement Posiva gives a loan about 7 million Euro at a low interest rate to the municipality for building a municipal old people's home. The municipality pays back the loan from incomes from renting the Vuojoki manor to Posiva.

palities, particularly in Loviisa, which had plans for the same kinds of compensation and co-operation [Kojo 2000; Rosenberg 1999, 278; Silvàn 2000, 4–8].

1983-1999 Countrywide site screening, preliminary site investigations and detailed site characterisation in several candidate locations

Environmental Impact Assessment Procedure (EIA) according to EIA Act

1998 Preparation of Programme for EIA
* Programme submitted to the Ministry of Trade and Industry (KTM) in February 1998
* Public hearings in 4 municipalities
* Statements and written opinions to the KTM
* Statement by the KTM in June 1998

1999 EIA report
* Report covering 4 sites completed in May 1999
* Public hearings in the municipalities
* Statements and written opinions to the KTM
* Statement by the KTM in November 1999

Decision in Principle Process (DiP) according to Nuclear Energy Act

1999 Application for DiP
* Application submitted to the Government in May 1999
* EIA Report required to be annexed to the application

Handling of the Application
* Public hearing in the Eurajoki municipality
* Statements and written opinions to the KTM

2000
* Preliminary Safety Appraisal by the Radiation and Nuclear Safety Authority (STUK) in January 2000
* Statement by the Eurajoki municipality in January 2000
* Decision in Principle made by the Government in December 2000

2001 * Ratification of DiP by the Parliament in May 2001

Pre-construction and Licensing Phases according to Nuclear Energy Act

~2010 * Application and granting of construction license by Government
~2020 * Application and granting of operation license by Government
~2020→ * Operation of the encapsulation and disposal gacility

Fig. 36. Decision-making process concerning the final disposal of spent nuclear fuel in Finland.

The STUK issued a favourable statement on the safety of the final disposal system in January 2000. According to the STUK, the DiP can be taken on the basis of safety criteria, and Olkiluoto is suitable for the safe disposal of spent nuclear fuel. Subsequently, the municipality of Eurajoki took a decision

supporting the selection of Olkiluoto as a repository site on January 24, 2000. The votes in the municipal council were 20 in favour of a supporting statement and 7 against. In February 2000 two appeals were made to the Regional Administrative Court against the decision of the Eurajoki municipality. The court dismissed the appeals in May, not finding any errors in the decision-making process of the Eurajoki municipality. A new appeal against the decision of the municipality was made to the Supreme Administrative Court in June. After the Supreme Administrative Court dismissed the appeal as well, the governmental decision-making process proceeded.

In December 2000 the Government made the DiP concerning the final disposal. According to the DiP, the disposal plan is in accordance with the overall interest of Finnish society. Taken as a whole, the DiP was very similar, with regard to its contents, to Posiva's application. Later, in May 2001, Parliament ratified the DiP after two plenary sessions (see also Section 3.1.4).

3.1.2 The role of local inhabitants in decision-making [23]

The attitudes of the policymakers in Eurajoki, Kuhmo, Loviisa, and Äänekoski concerning the making of decisions about the disposal of nuclear waste are explored in this section. The research question is how the policymakers behaved with regard to the empowerment of the citizens in the making of decisions about the disposal of nuclear waste.

The empowerment of citizens requires an open and democratic political and administrative system. This kind of administrative system gives people equal opportunities and access to expertise and knowledge and the capacity to influence the decisions which affect them [see, for example, Barber 1984, XVii; 226–227 or Rogers & Ryan 2001, 282–285]. The empirical research material used in this study consists of the responses to a survey which was carried out in the above-mentioned four municipalities as a part of the JYT2001 project. More detailed discussion on the attitudes of the policymakers is given by Ponnikas [1998, 2000].

According to the findings an average of 66 % of the policymakers in the four municipalities thought that nuclear waste could not be placed in their municipality if most of the inhabitants were against it. However, 27 % of the policymakers were ready to act against the will of the majority. The policymakers of Eurajoki and Loviisa in particular were ready to make a positive decision,

[23] By Ponnikas, J.

regardless of public opinion if necessary. In these two municipalities the majority of the citizens were, however, ready to accept the siting of the facility, according to opinion polls. The policymakers of Kuhmo and Äänekoski were inclined to respect the will of the majority. More than half of all the policymakers and most of the local councillors supported the local veto defined in the Nuclear Energy Act. The local veto means power especially for the municipal council, because the municipal council will make the final decision related to the disposal of nuclear waste at the local level.

Most of the policymakers were not satisfied with the empowerment of citizens in Finnish democracy, but were satisfied with the power of the citizens in decision-making related to the disposal of nuclear waste. 44 % of the policymakers reasoned that Finnish democracy works defectively. At the same time, however, almost 50 % of them thought that citizens already had enough opportunities to express their opinions on decision-making related to the disposal of nuclear waste. More than 10 % of the policymakers actually thought that citizens had even had too many opportunities to influence decision-making related to the disposal of nuclear waste. The policymakers of Eurajoki were the most satisfied and the policymakers of Äänekoski were the least satisfied with the power of the citizens in decision-making related to the disposal of nuclear waste. The policymakers of Kuhmo and Loviisa were more satisfied than the policymakers of Äänekoski, but not as satisfied as the policymakers of Eurajoki. It is possible that the policymakers thought that national interests concerning the disposal of nuclear waste are more important than the interests of the local inhabitants and that when set against national interests, local ones had to be put aside.

Referendum or not?

The government makes a policy decision on the disposal of nuclear waste, but before that the municipal council makes a final policy decision at the local level. It would have been possible to organise a consultative municipal referendum supporting the making of decisions on the issue of the final disposal of nuclear waste. Almost half of all the policymakers wanted to organise a consultative municipal referendum. This was the case especially in Kuhmo and Äänekoski.

Only 28 % of the policymakers who accepted the disposal of nuclear waste in their municipality wanted to organise a referendum. In comparison, as many as 86 % of those who did not accept the disposal of nuclear waste in their municipality wanted to organise a consultative municipal referendum. It appears from this that they wanted to follow the approach of local decision-making, so that the result would not be against their will. Although the referendum would only have been consultative, it would have been difficult for the councillors to make a

decision that went against its results. This is one of the reasons why some policymakers were against a referendum. The EIA was not seen as a sufficiently strong measure. Many saw it only as an empty gesture, because by using only the EIA people did not gain any real power either to change the decision concerning the final disposal or to stop it. For example, Thomas Rosenberg [1999], a civic activist and the leader of the Loviisa Movement, saw it only as a frustrating charade.

Sutela [1999, 38–43] has analysed municipal referenda organised in Sweden, because no referendum concerning the disposal of nuclear waste has been carried out in Finland and because Sweden's provisions on municipal referenda are almost the same as in Finland. Consultative referenda on the local level have been arranged in Finland since 1990. Most referenda have dealt with municipal mergers. Plans for road construction and concerning provincial issues have also been voted on a few times. The nuclear waste referendum would have been very different from previous ones in its contents.

In Sweden there was a referendum on nuclear power in March 1980. As a result it was decided that nuclear power in Sweden should be decommissioned by the year 2010. The referendum created a strong civic movement [Lidskog 1994, 68–69]. The Finnish civic movements against nuclear waste disposal wanted to organise a local consultative referendum on the disposal of nuclear waste as part of an open decision-making process. In Äänekoski and Kuhmo the citizens’ movements succeeded in demanding a referendum. In Loviisa and Eurajoki there would not have been any referendum. In Eurajoki in particular, where there is no movement against the disposal of nuclear waste, the decision-makers were against the referendum. Movements shifted citizens’ attitudes towards the disposal of nuclear waste in a more negative direction. That was particularly the situation in Äänekoski and Kuhmo.

Radwaste disposal is a very complex issue. High-level nuclear waste needs to be disposed of in a very safe way for a time-span far beyond human understanding. Nuclear waste is one of the risks produced by modern societies [see Beck 1999, 62–63]. The concept of 'risk' is at the core of nuclear power issues [see Litmanen 2001]. That is why the decision-making process concerning nuclear waste disposal should be very open to public participation. The EIA process and a consultative municipal referendum are useful means for widening civic participation in the process of nuclear waste disposal. They also represent a means how citizens' empowerment could be realised more fully than by using only representative procedures.

3.1.3 The opposing local movements[24]

The main focus in the study of local movements is on the tension between the Environmental Impact Assessment process (EIA) and the activity of local opposing groups during the years 1997–1999. The analysis includes local movements in the municipalities of Eurajoki, Kuhmo, Loviisa, and Äänekoski. Although the tactics used by the movements were peaceful and non-violent and so in line with Finnish traditions, the conflicts were deeply characterised by the local culture [Litmanen 1994, 2001; Suominen 1998; Kojo 2001].

Nuclear waste disposal became an actively-debated local question in the late 1980s, when the power company Teollisuuden Voima Oy (TVO) started its preliminary site investigations in different places (cf. Table 1). The company needed only the permission of the landowner (the state) for the studies. TVO entered into discussions only with the local authorities, and these did not ask for the opinions of the local people. Some local citizens started to struggle against the disposal of nuclear waste and for more open decision-making.

The main differences between the local movements

The Romuvaara Movement (Kuhmo)

The Romuvaara Movement (founded in 1989) had strong ties with the local council and political parties. By recruiting local party politicians from every party into the movement the activists wanted to remove party political obstacles to a nuclear waste-free Kuhmo. As a result of the activity of the movement, the city council made, as early as 1990, a decision not to allow the disposal of nuclear waste in the bedrock of Kuhmo. Fear of radiation, the image of Kuhmo as an area of unspoiled wilderness, and colonialism were the main arguments in the struggle.

In the early 1990s demonstrations against TVO's local PR work were an intensive way of showing the 'enemy' to the local public. The activists learned how to deal with the media and how to gain publicity. After TVO chose Kuhmo as one of the places for further bedrock studies in 1993, the movement improved its own action culture; for example, new communication channels and a public discussion forum for local people were created and the movement's internal planning was reorganised [see Kojo & Suominen 1999].

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[24] By Kojo, M.

Attitudes concerning the EIA process were, at first, careful and reserved, but then the activists decided it would be best to take part in the meetings etc. arranged by the developer, Posiva. The local citizens and the supporters of the movement were also encouraged by the activists to take part in all the EIA arrangements. For instance, during the public hearing of the EIA programme the citizens were asked by the movement to criticise the programme to the KTM. This can be categorised as an exploiting tactic. Besides participating in the EIA process, the movement carried on arranging its own 'happenings', for instance a campaign against radwaste transportation [see Kojo 1999a]. Its own activity was partly related to the EIA process, but also to local circumstances, such as the formation of the pro-siting group called the Possibilities of Kuhmo and discussion about a local referendum, which created the need to gain publicity for critical views.

The Kivetty Movement (Äänekoski)

The most characteristic feature of the Kivetty Movement (founded in 1988) was its close co-operation with the Finnish Association for Nature Conservation and its local associations, and later with the Greens. Co-operation meant more resources and a wider base for support, but as a result the movement itself remained internally less organised. The major threats seen in the future, if Kivetty were to be the site of disposal, were the fear of importing nuclear waste from Europe, a negative image that would damage tourism, and the danger of the effects of radiation on health. The movement argued about transportation and the temporary nature of the economic benefits of the disposal project, too.

Before 1996 the activity of the movement was mainly based on two petitions and letters to the editor of the local newspaper [Litmanen 1994]. Because these did not have the desired effect on the local council, the activists decided to put up their own candidates in local elections in 1996. The idea was to offer the voters an absolutely sure chance to vote for a party in which all the candidates were against the disposal of nuclear waste. As part of their campaign the movement launched an initiative for a local referendum and arranged an inquiry for all local candidates. They succeeded in getting four seats out of 35 on the local council. In Äänekoski the public attitude against the siting was so strong, approximately 60 % of the population being against it [Kiljunen 1998], that there was no need for large-scale participation in the EIA process.

The Loviisa Movement (Loviisa)

The Loviisa Movement was organised in February 1997, only one month after Posiva had announced that Loviisa had been selected as one of the candidates for the site. The tactics of the movement were to activate and represent critical voices in neighbouring municipalities, too. The movement, for example, demanded a referendum in the whole Loviisa region. The Loviisa Movement needed to reform the political style of the local citizens' activism in order to gain support from the public. Approximately 60 % of the population favoured the plan [Kiljunen 1998]. There was also a pro-siting group in Loviisa.

One of the strongest features of the movement was its ability to gain local media publicity. This was partly due to the active role of the newspapers in Loviisa, but the movement also had expertise in the realm of journalism. Despite its lean organisation the movement had a lively presence on the pages of the local newspapers. The movement argued by proposing alternative solutions, and it placed a very strong emphasis on criticising the whole idea of final disposal in the bedrock.

Inside the Loviisa Movement, attitudes towards the EIA process were very critical. The movement arranged its first public meeting, "There are alternatives!", in April 1997, and started collecting names for a petition at the same time. The movement emphasised that the final decision depended on citizens themselves, not on the results of assessments for those who could not say whether citizens wanted the nuclear waste or not. Later in the hearing period in 1998, the Loviisa Movement declared that a simple "No" would be enough, in the form of a written opinion sent to the Ministry. Activists recommended the signing of the citizens' petition, because it would guarantee the power of the masses. This way citizens' participation was channelled through the movement's action, and an attempt was made to displace the EIA process. The petition was finally signed by almost 3 900 people, whereas only 20 written opinions were given during the EIA process by the lay people of the Loviisa region.

Friends of the Earth in the Pori Region (Eurajoki)

In Eurajoki there is no organised local opposing citizens' movement at the moment, although about 30 % of the population are against the plan [Kiljunen 1998]. In the early '90s there were some efforts to organise citizens' activism against the nuclear industry, but they failed after pro-nuclear citizens took control of the association [Litmanen 1994]. One obvious reason for the situation is the strong economic influence of the nuclear industry on Eurajoki.

During the last few years the Friends of the Earth (FoE) have been active in Eurajoki with regard to nuclear power. The Friends of the Earth in the Pori region were founded in 1996 as a part of the national organisation. FoE is classified as a part of the fourth wave of the Finnish environmental protest movement, which means that it has an orientation of a counter-culture character and better international connections [Konttinen 1999]. In Pori the FoE united many themes, such as animal rights and solidarity, under the umbrella of a single association.

The main difference, in comparison with the other movements, is that the FoE are not solely focussed on the nuclear waste issue, but deal with nuclear power, nuclear weapons, and the mining of uranium, too. The problem was therefore not defined so narrowly as it was by other local groups. Unlike the other movements, the FoE had no connections to the municipal councillors and to traditional party politics in Eurajoki. The Friends of the Earth took part in some EIA arrangements. Besides the EIA process, the FoE organised, together with other citizens' groups, a Uranium Evening (mining), a Sun Bus tour (alternative energy resources), and an Action Weekend (anti-nuclear camp).

3.1.4 Discussion of the DiP in Parliament [25]

According to Finnish law, the governmental Decision in Principle (DiP) concerning nuclear waste disposal needs to be finally ratified by Parliament. In this procedural model Parliament has two alternatives. It can either approve the DiP or reject it, but Parliament can in no way modify the DiP or set any conditions. The parliamentary procedure includes two plenary sessions, Committee treatment, and the final decision. The Committees have a very powerful role in the work of the Finnish Parliament. Parliament approved as such the motion of the Finance Committee. Only three Members of Parliament voted against the motion and 159 MPs voted in its favour. Two out of these three MPs represented the Left Alliance and one represented the Finnish Christian Union (currently the Christian Democratic Party of Finland). There was one important reason why Parliament was so unanimous. Nobody could introduce an actual alternative to the disposal model, so Posiva could introduce its disposal model as the only rational way to manage nuclear waste.

Most of the MPs of the Left Alliance expressed critical opinions about the plans to build the disposal facility for spent fuel in Finland. There were, however, three

[25] By Suominen, P.

MPs who were in favour both of nuclear waste disposal and nuclear power in general. The Left Alliance was the only party which was divided by this issue. Although the Green Alliance was also very critical, the MPs of the party voted positively on this issue. The other five parties represented in the Finnish Parliament were more or less unified.

In this research, the argumentation and the rhetorical means used by the MPs in the parliamentary discussions were analysed, too. The safety issues of nuclear waste disposal were in the forefront in these discussions. Most of the MPs considered that the plans to build the disposal facility were excellent and very thorough. The MPs who expressed critical views thought that there were some weaknesses regarding safety issues. They also considered that the decision-making procedure model was not democratic enough.

International affairs seem to have played an absolutely essential role in the parliamentary discussion of the procedure. There are two explanations for this. Firstly, for many reasons, nuclear energy is a very sensitive topic. This is because of the potential risks of using nuclear power, and the potential military use of spent fuel. Secondly, international affairs present a good rhetorical opportunity. Many MPs used international affairs as an argument in order to convince the public of the validity of the argument.

3.1.5 On the role of social science studies in decision-making[26]

The Environmental Impact Assessment (EIA) of the disposal facility for spent fuel was an instrument to evaluate the possible impact the facility might have on the host community, but also a way to increase its social acceptance. Thus Posiva invested much time and efforts in their EIA [see Posiva 1999; Hokkanen & Kojo 1998a]. For the authorities this meant that they also had to start social science studies in order to be able to review Posiva's results.

Overall support for decision-making

At the beginning the necessity to develop a basis for the evaluation of Posiva's EIA for the needs of the authorities was evident. The study by Harmaajärvi et al. [1997] described international EIA experiences, made a scoping analysis of the types of impacts to be considered in a nuclear waste EIA, and analysed local nuclear waste conflicts. This study was continued by another project, which concentrated on residents' views towards the EIA [Harmaajärvi et al. 1998].

[26] By Litmanen, T.

Through a large survey, people in Eurajoki, Äänekoski, and Kuhmo were able to express their views about the most important environmental impacts to be studied.

All the municipalities studied felt that one important issue for their decision-making was the possible effect of a nuclear waste facility on the municipality's public image. As Posiva produced a research report on the possible impacts of a nuclear waste facility on the public image of the municipalities in question, a parallel piece of research [Kankaanpää et al. 1999; Harmaajärvi et al. 1998] was carried out in JYT2001.

The studies produced detailed information about the municipalities. Although the technical plans could, according to Posiva, be implemented in all of the municipalities in question, social factors, such as social acceptance or disputes over the issue, made it more difficult for Posiva to proceed in some municipalities. Thus great efforts were made to identify the local cultural [e.g. Litmanen 1997; Kojo 1999a; Suominen 1998], political [e.g. Hokkanen & Kojo 1998b] and social [e.g. Harmaajärvi et al. 1997, 1998] features in order to understand the cultural, political and social rationales of local inhabitants.

At a very late stage of the research programme, experiences were collected from the decision makers of Eurajoki [Heikka 2000]. The study indicated that the local decision makers knew of only some of the social science studies (some attitude surveys and studies of the images of different municipalities), that they had hardly familiarised themselves with the reports in greater detail at all, and that they got information about research results mainly in face-to-face interaction situations. They used research results to strengthen their decision-making and improve the preparation of different issues in the decision-making process.

In another study, national nuclear waste experts and authorities were invited to give their views about the aims, significance, and effectiveness of social science research in the nuclear waste management system [Heikka et al. 2001]. The study pointed out that the use of and need for social science research could be divided into four categories: (1) the practical advancing of general objectives (e.g. public sector research, such as surveys, and its effect on Posiva's research); (2) the evaluation of operational models and solutions (e.g. follow-up to and evaluation of Posiva's EIA procedure); (3) the theoretical evaluation of general objectives and views (e.g. to affect the actors' 'everyday theory' or provide theoretical background for the EIA), and (4) developing fundamental theories and models (e.g. about the EIA). The interviewees' responses reflected how the research results affected their own conceptions of different issues about nuclear waste

management. With the help of social science research they were able to revise their opinions or become even more convinced about them.

The JYT2001 research programme participated in the national discussion about spent fuel management issues, but, however, to a limited extent (cf. Section 4 below). Popular writings and books [e.g. Litmanen et al. 1999] based on research findings were the main contributions of scholars to the public debate. Thorough studies also made it possible to take part in international research projects. For instance, at the end of the research programme Hokkanen [2001] produced a comprehensive evaluation of the EIA from the point of view of decision-making and made his contribution to the comparison of large-scale EIA cases within Nordic countries.

Developing an evaluation basis for Posiva's EIA

A large survey (1839 interviewees) was carried out concerning the expectations of residents in three possible host communities towards the nuclear waste EIA [Harmaajärvi et al. 1998]. The results of this survey provided information which enabled the authorities to examine the coverage of Posiva's nuclear waste EIA from the point of view of local people. Residents of Eurajoki, Äänekoski, and Kuhmo were able to present their views through the survey and the results were compared to the average views of Finnish people. The idea was to find the factors the residents considered the most important in evaluating the environmental impacts. According to the survey, the most important issues for inhabitants were safety, health, and nature issues (Fig. 37).

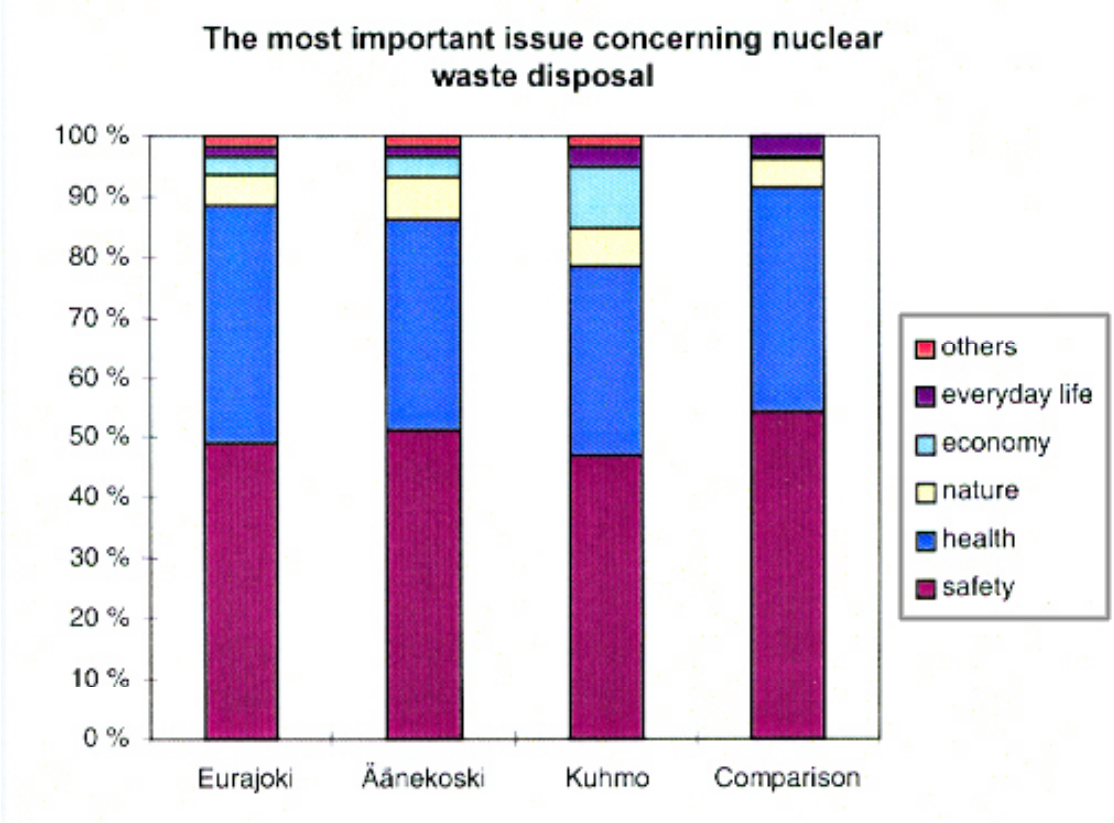

Fig. 37. The factors local inhabitants considered most important in the EIA process [Harmaajärvi et al. 1998].

As the survey indicated that economic impacts and the public image of the municipalities were rated highly, the KTM set up two research projects concentrating on these issues in all candidate municipalities [Karhu et al. 2001; Kankaanpää et al. 1999, respectively]. First, a general assessment framework was developed to obtain commensurable results [Harmaajärvi & Koski 2000].

The study of Karhu et al. [2001] concentrated on the long-term economic effects the disposal facility might have on the hosting municipality. The data was gathered through a survey administered to persons elected to a position of trust (local council and local government), leading municipal officials, chairpersons of local voluntary associations, and a discretionary sample of local entrepreneurs. The results varied. Both in Eurajoki and in Loviisa the disposal facility could have furthered the one-sidedness of the economic life of the municipality. In Kuhmo the impacts were perceived as being deleterious to the prospects of industries based on an image of 'clean nature'. In Äänekoski the perceived impacts were of two kinds: first, as sharpening the technological image of the town, and second, as exploiting more effectively the local natural environment in order to develop the tourism industry and related economic activities.

The main task of the study carried out by Kankaanpää et al. [1999] was to find out what kind of an impact a final disposal facility would have on the host municipality's image. The study comprised both a nationwide telephone interview (800 interviews) and some group interviews of people in another municipality. The conclusion was that the current attitude towards a final disposal facility is calm and collected, and that the matter is often considered from the standpoint of an outsider, provided that the facility will not be placed too near one's own home. The study also emphasised that behind this 'calmness' there are deeply-rooted beliefs concerning the facility, and strong negative or positive attitudes. Regarding the municipalities' current images, the results showed that Eurajoki does not have any distinct profile at all. Kuhmo's profile was characterised by culture and music, nature, and a customer-friendly atmosphere. Äänekoski's image is that of an industrial centre, e.g. the paper and pulp industry.

3.1.6 Conclusions of studies on decision-making

According to the idea of citizens' empowerment, local inhabitants should have the right to decide about land use in their municipality and to make the essential decisions concerning its territory. The final disposal of nuclear waste should not be seen only as a matter of strictly rational and scientific planning, where national interests take precedence over local ones. By means of a consultative municipal referendum and the EIA process it would have been possible to get local interests truly noticed in the making of decisions regarding the disposal of nuclear waste.

Local movements had a strong political role, especially in Kuhmo, Loviisa, and Äänekoski, where they managed to generate critical attitudes against the plan. Their influence on local decision-making can also be seen very clearly in decision-making concerning local referenda. In Äänekoski and Kuhmo the movements succeeded in demanding a local referendum, which meant uncertainty for Posiva's plan. Another good example was the local elections. The movements campaigned against siting before elections and put up their own candidates. In Loviisa the connection to party politics was not so strong as in Kuhmo and Äänekoski, but still the movement managed to influence the local discussion about nuclear waste disposal. In this sense the Friends of the Earth were an exception because the FoE's 'general' style was so different in comparison to the power-orientated groups. The FoE were not attached to local decision makers.

Local groups were sceptical towards the EIA process, mainly because of Posiva's central role in its implementation. In Kuhmo and Loviisa especially, the EIA Act was criticised. They adopted different tactics concerning the EIA, such as exploiting and displacing. The movements demanded a more active controlling

role for the authorities. According to the movements, Posiva's attempts to utilise the EIA for building local acceptance were all too obvious, e.g. EIA bulletins were considered as advertisements. The lack of alternatives was also criticised. In spite of the criticism, all the opposing local groups – the Romuvaara, Kivetty, and Loviisa Movements and the Friends of the Earth in the Pori region – took part in the EIA dialogue arranged by Posiva. However, the EIA did not remove the movements' need to arrange their own activities. They had already found better ways than the EIA to influence local decision-making. The dominant local decision-making system was challenged by demands for a local referendum, local election campaigns, press releases etc. The EIA did not disturb the 'juristic-bureacratic' style in local decision-making, which was one of the main reasons why local groups were born.

After the eventful phase of the decision-making process on a local level, the Government made the DiP regarding the final disposal. Parliament ratified it, with wide unanimity through almost all parties. In Parliament no one was able to introduce an actual alternative to the disposal model, so Posiva could introduce its disposal model as the only rational way to manage nuclear waste. The only existing alternative, that the spent nuclear fuel would remain stored in the water pools in Eurajoki and Loviisa, was noted in Parliament as an inadequate solution.

3.2 The Environmental Impact Assessment procedure (EIA)[27]

Posiva's EIA for the final disposal of nuclear waste covered four candidate municipalities, Eurajoki, Kuhmo, Loviisa, and Äänekoski, where the possibilities for the final disposal of spent fuel were being investigated. The implementation of the EIA was a comprehensive process in many ways, when considering the history of the EIA in Finland. There was an 'EIA era' for almost three years in all candidate municipalities. The EIA process was seen in the everyday life of the municipalities. The EIA process has been dubbed "the EIA of the century" in Finland. The central political aim of the EIA – to increase participation – brings the question of nuclear waste into a new arena.

[27] By Hokkanen, P.

3.2.1 Description of the EIA process

According to the Nuclear Energy Act (990/1987), the final disposal of nuclear waste is a matter of such clear general importance that the realisation of the plan needs a Decision in Principle (DiP) by the Government regarding the overall interests of Finnish society. According to the nuclear energy legislation, the EIA report should be included in the application for the DiP. The EIA process, in accordance with the EIA Act, is one part of the assessment of the safety and environmental impacts of the plan. The EIA process regarding the final disposal includes all phases of the plan, i.e. the research, construction, operation, and decommissioning of the disposal facility.

Main actors

The implementor of the EIA process of the final disposal of spent nuclear fuel is Posiva Oy. Posiva is responsible for the EIA programme and the EIA report on the final disposal of spent fuel. The role of the implementor is quite large and visible, since it has free hands to conduct the process, as well as to carry out the information distribution and to organise participatory action. Posiva has operated in many ways and fields. The head office of Posiva is located in Helsinki, but Posiva also had local offices in all four candidate municipalities, founded before the EIA process started. The operation of Posiva was very prominent throughout the process, which was marked by its status as the implementor. Posiva aspired to interaction with as many actors as possible in the sphere of influence of the plan. It utilised many means to participate in councils, local authorities, and local civil movements and groups, as well as interacting with municipal inhabitants. The aim of the EIA process, with its strong emphasis on participation, information, and interaction, was to increase the acceptability of the plan and to bind the important actors to the EIA process and to the plan. Posiva arranged public meetings, small group encounters, information sessions and discussion meetings for the councils, collaborative or follow-up groups for the public and association officials in the municipalities, exhibitions, municipal inquiries and thematic interviews, regional administration-based discussion meetings, central administration-based seminars, and discussions in newspapers.

As distinct from the ‘normal’ practices of an EIA in Finland, the contact authority of the EIA process for the final disposal of nuclear waste is the Ministry of Trade and Industry (KTM) (EIA Decree 268/1999, § 2). Usually, the contact authority is the regional environmental centre (EIA Decree 268/1999, § 4), but for facilities in which the Nuclear Energy Act is invoked, the contact authority is the KTM. This special role of the KTM could be considered somewhat uncommon from an international perspective. However, this nature of the legislation clarifies the

whole process and avoids possibly conflicting parallel decision-making processes by environmental authorities and the main process conducted according to the Nuclear Energy Act.

Even though the Radiation and Nuclear Safety Authority (STUK) has a very important status in nuclear waste management in general, its role in the EIA process was quite limited. It was one of those authorities from whom the KTM asked for statements regarding the EIA programme and report. After the EIA process, at the DiP stage, the role of the STUK became much more prominent and important, because the safety issue is attached to the DiP. The preliminary safety appraisal by the STUK was important for the decision by the municipal council in Eurajoki.

In the case of the final disposal of nuclear waste the role of the candidate municipalities is emphasised. After Posiva concentrated their site investigations on four candidate municipalities, Eurajoki, Kuhmo, Loviisa, and Äänekoksi, the main focus of the discussion on nuclear waste also turned to these municipalities. In the candidate municipalities the final disposal became a remarkably controversial question in local politics. Because of the unconditional right of veto of the candidate municipality, defined in the Nuclear Energy Act, it was very important for Posiva to use the EIA as an instrument to gain acceptability. In the EIA the local decision-making bodies and processes are in a key position. In practice, the municipalities participated in the EIA process in many ways. They gave statements regarding the EIA programme and report, they had collaborative or follow-up groups with Posiva, they took part in formulating social science research topics for the Public Sector's Research Programme on Nuclear Waste Management (JYT2001), they had their own EIA contact persons etc. In fact, the EIA was the instrument for municipalities to commit themselves to the disposal plan.

Finally, the citizens and inhabitants of candidate municipalities had a very important role in the EIA process. According to the EIA Act, the main aim of the EIA process is to draw inhabitants and other participants into participation and encourage them to voice queries. The role of citizens and civic movements and ways of public participation is analysed in more detail in Section 3.2.2.

Procedural steps

In the preparatory phase of the EIA process in the autumn of 1997, Posiva arranged four public meetings in each candidate municipality. The aim of these meetings was to collect local opinions and views regarding the impacts of the plan. Posiva especially needed information about the impacts that local

inhabitants appraised as being most important to include in the EIA process. Thus, Posiva started the EIA process in a fairly massive and visible way.

Formally speaking, the EIA procedure began when Posiva, in February 1998, submitted its Environmental Impact Assessment programme to the contact authority, i.e. the KTM, which had the EIA programme on public display in each candidate municipality and in the adjacent municipalities. The existence of a public hearing was announced in 16 newspapers. The contact authority asked for statements regarding the EIA programme from 54 actors. In the summer of 1998, the KTM issued its own statement on Posiva's programme, based on statements the Ministry had requested from various authorities and other parties and on citizens' opinions. In its statement the contact authority considered the EIA programme extensive enough and a good basis for the assessment of environmental impacts. However, the contact authority presupposed that the final disposal alternatives should be more widely investigated in the EIA process than had been suggested in the EIA programme. Furthermore, there should be sufficiently extensive investigations regarding radiation impacts in all phases of the plan. Image issues of the candidate municipalities, the economy of the community, and the convenience of inhabitants should be evaluated especially carefully when the social impacts of the plan were considered [Posiva 1998, 2000b; KTM 1998].

Posiva investigated the environmental impact in compliance with the programme and the comments of the KTM. The EIA procedure continued with the production of the EIA report, which is the other main EIA document. The EIA report was completed in the spring of 1999. The EIA report assessed the feasibility of the various alternatives. It suggested action that would prevent or restrict harmful impacts resulting from final disposal. The report also contained a proposed follow-up programme for the project.

The EIA report was placed on public display from 21 June to 20 August 1999, to give the citizens an opportunity to express their opinions on the project again. KTM asked statements from the same authorities and other parties as for the EIA programme and announced a public hearing in the newspapers. The EIA report was attached to the application for a Decision in Principle, which was submitted to the Government in May 1999 [KTM 1999].

The EIA report was reviewed according to the national EIA law. The EIA procedure was completed when the contact authority issued its statement on the EIA report in November 1999. In its statement the Ministry considered the EIA report sufficiently comprehensive and detailed. In the view of the Ministry, the report fulfilled the requirements laid down by the law as well as the goals of the

EIA programme published by Posiva in 1998 and complied with the authorities' comments on the programme.

Contents of the environmental assessment: why Eurajoki?

According to Posiva, there were no remarkable differences between the candidate municipalities. The analysis showed that the most important environmental impacts of the plan were quite equal at all sites. According to the EIA report, all the candidates were, in principle, suitable for the final disposal. Posiva, however, chose Eurajoki. Why? Perhaps the most important reason was the Vuojoki agreement, but the acceptability and social convenience of the plan were important factors, too.

In fact, there are no reasons of either a technical or natural science nature that make Eurajoki any better as an alternative for disposal than the other candidates. However, as concerns the question of transport, it does make technical sense to dispose of the waste where it is mainly produced. It is an undisputed fact that in Eurajoki the attitude of the inhabitants, as well as of politicians, is most favourable. Eurajoki is a nuclear power plant locality already. Perhaps for that reason, the social atmosphere is ready for such plans as the final disposal of nuclear waste.

According to Posiva, the environmental impact remains, in respect to all siting alternatives, minimal. The differences in regard to bedrock conditions are merely limited to siting either along the coast or inland. Each has its own advantageous features, so that solely on the basis of safety analysis it is not possible to resolve which site is the most favourable. Final disposal can be implemented within the bedrock of each and every one of the investigation sites. Spent fuel is stored at the power plants. In the event that the final disposal facility is built in Äänekoski or Kuhmo, the amount of fuel transport required will be roughly double when compared with the power plant localities [Posiva 2000b].

The appearance of anxieties and fears is less apparent in the nuclear power plant localities than in Kuhmo or Äänekoski. Questionnaires and interview-based research, indeed, indicate that the residents of the nuclear power plant localities – Eurajoki and Loviisa – voice fewer worries and fears than the people of Kuhmo and Äänekoski. A representative opinion survey of the views of the inhabitants in each of the nominee municipalities was conducted. The majority in Eurajoki and Loviisa would approve of final disposal in their municipalities, in contrast to Äänekoski and Kuhmo. Furthermore, the municipality of Eurajoki made a decision supporting the plan [Posiva 2000b].

3.2.2 Evaluation of public participation

The Environmental Impact Assessment Act (267/1999, § 1) underlines public participation. This echoes a similar requirement included in the Nuclear Energy Act. There are many forms of public participation available at the local level. Some are 'direct' and some 'representative' in nature. For example, in the case of the final disposal of nuclear waste, local inhabitants had a number of opportunities to take part in and to influence the ongoing process (see also Section 3.1.1). In the EIA process of the final disposal there were three 'official' ways to participate: 1) public hearings (and other meetings) before and after the EIA programme and report; 2) written opinions to the contact authority (the KTM) after the EIA programme and report, and 3) direct contacts with the EIA contact persons of the candidate municipalities.

Written opinions

At the same time as the requested statements, individual citizens and associations had a chance to submit written opinions concerning the EIA programme and EIA report. At the public hearing stage of the EIA programme the KTM received 21 written opinions from associations or companies. In addition, individual citizens submitted 104 written opinions. Public participation was most active in Kuhmo and the surrounding areas (61), whereas only 8 written opinions were received from Eurajoki. It can be clearly seen that the candidate municipalities without a nuclear power plant, namely Kuhmo and Äänekoski, were the most active. Almost all the opinions included criticism of the disposal plan in particular and the EIA process in general. The issues arising out of the consultation process concerned: 1) a lack of alternatives to the plan; 2) social impact assessment and the methods used in assessment; 3) the impact of the final disposal on local image issues; 4) safety issues (especially the safety of nuclear waste transportation); 5) methods of defining the expected impacts; 6) the technical details of final disposal; 7) questions relating to the bedrock; 8) general safety issues concerning radiation, and 9) the credibility of the EIA process [KTM 1998, 7–9, 36–58; Kojo 2000].

Posiva submitted the EIA report and the application for the DiP at the very same time, in May 1999. The application included only one candidate site (Eurajoki) for final disposal. During this stage of the EIA public activity in general, and the amount of written opinions in particular declined substantially. Only 15 opinions were received regarding the EIA report, whilst the EIA programme itself generated 125 responses. Contrary to the opinions relating to the EIA programme, at this stage of the process, the highest levels of participation were to be found in Eurajoki. The reason is that Eurajoki was the only site included in the DiP

application, whereas the EIA report included all four site candidates. Another reason was the so-called Vuojoki Agreement (see Section 3.1.1), which was viewed as symbolising the selection of Eurajoki even before the EIA process was closed. The issues covered in the written opinions were similar to those found in the previous stage of the EIA programme. The most critical views came from individual citizens and from civic associations. It is obvious that they were displeased with the credibility, reliability, and implementation of the EIA process [KTM 1999, 12–36; Kojo 2000].

EIA contact persons

There were designated EIA contact persons in all candidate municipalities. Their task was to act as a link between the municipality, the inhabitants, and Posiva. EIA contact persons were local officials and they were selected at the beginning of 1997, i.e., before the EIA process was officially in motion. The initiative came from Posiva, though all the municipalities selected their own contact persons [Hokkanen & Kojo 2000, 6].

The basic idea was to create a permanent institutional actor in each of the candidate municipalities who would serve the information needs of the inhabitants and interaction needs between the municipality and Posiva. As 'impartial' actors, the contact persons were useful, given their ability to chart the progress of the disposal plan and its current level of acceptability [Hokkanen & Kojo 2000, 38].

The contact persons appeared to suffer from: 1) an undefined job description; 2) low visibility, and 3) a lack of public accessibility. They failed to raise the level of public participation in any candidate municipality. As can be seen in Table 6, few contacts took place during the public hearing of the EIA programme. The total number of contacts in all four candidate municipalities was 12. During the public hearing stage of the EIA report no contacts at all took place in any municipality. Thus, regarding the issue of public participation, the EIA contact persons were insignificant actors. For Posiva the contact persons were key actors, guiding the organisations of candidate municipalities through the process as a whole [Hokkanen & Kojo 2000, 28–32, 38].

Table 6. Contacts with the EIA contact persons during the public hearing of the EIA programme [Hokkanen & Kojo 2000, 28].

	Eurajoki	Kuhmo	Loviisa	Äänekoski
Private persons	2	-	1	1
Associations	-	-	1	1
Politicians	-	-	-	1
Officials	-	-	3	-
Media	-	1	-	-
Companies	-	-	-	1

Public activity was directed towards participation in public meetings and to the submission of written opinions to the contact authority rather than to the EIA contact persons. Public activity also focussed on issues and actors that strictly lay outside the 'official' EIA process. Individual inhabitants and civic associations contacted local politicians, local and national authorities, and Posiva directly [Kojo 1999a; 1999b; Kojo & Suominen 1999]. The most visible way of participating in the process was through writing letters to local newspapers (see also Section 3.3).

Public meetings

When examining participation in public meetings of the EIA quantitatively, it can be seen that activity was low. Absolute levels of participation in public meetings at the stage of the preparation and the public hearing of the EIA programme are shown in Table 7. Meetings 1, 4, and 5 were open and meetings 2 and 3 were designed for representatives of local associations. The participation was singularly weak in Äänekoski, even if the participation trend was decreasing in all the municipalities during the EIA process. On the other hand, the participants represented local associations and, therefore, participation was also representative [Hokkanen 1998, 12–14; Hokkanen & Kojo 1998a, 25–32].

Table 7. Participation in public hearings [Hokkanen & Kojo 1998a, 26–30; Hokkanen 1998, 12].

	The preparation stage of the EIA programme				The public hearing stage of the EIA programme
	Meeting 1	Meeting 2	Meeting 3	Meeting 4	Meeting 5
Eurajoki	46	17	10	41	32
Kuhmo	70	24	20	25	14
Loviisa	58	22	7	27	44
Äänekoski	18	20	5	25	11

From the viewpoint of representativeness, the number of participants was very small. Even at its maximum (in Eurajoki), the number of participants was less than one per cent of the population of inhabitants over 15 years of age. The ratio was particularly small in Äänekoski. When considering the effectiveness of the public participation in the EIA, such a low level of activity is rather alarming. Interactive participation takes place in public meetings, which cannot be compensated for by any other mode of participation or procuring information. After the EIA programme was completed, participation decreased further. The ratio was, at its maximum, under one per cent. This reflects a certain lack of representativeness, thus bringing into question the credibility of the public participation process as a whole. It is also important to take into consideration the quality and versatility of such activities.

An interesting dimension of public participation is illustrated by the notion of accumulation. Because of the unequal division of resources for participation, the participants are very often the same ones. As the number of participants is small, and general resource levels dedicated to facilitating the participation of the general public are limited, the consequence, as might be expected is the emergence of a selected group of participants. That is to say, a kind of participating oligarchy emerges. It is usually the political stratum which takes part in such processes as the EIA. People in the political stratum are active in general, they operate in many arenas, and they have many ways to participate and to exert influence. It is obvious, therefore, that this political stratum has a disproportionate ability to influence policy-making at the planning stage. The essential point is that the group of participants in the EIA process is composed in such a manner that the extreme groups do not meet each other. At its best the EIA was able to act as a direct forum between public opinion and decision-makers.

Studies of the public hearings of the EIA have shown that participation levels were high among the local activists. Moreover, in the public meetings, the same individuals tended to debate the same issues repeatedly. A survey of the identities of participants in the meetings revealed that such people were generally active members or executives of local associations [Hokkanen 1998, 30–32].

Why was participation in the EIA so low in general and why did it revolve around a small group of individuals? Good conditions surely existed for wide participation; it was an exceptionally interesting project of great importance to local inhabitants, and Posiva offered many different ways for interested parties to participate and advertised these opportunities. Indeed, in every respect the EIA process was carried out to a higher standard than the minimum standards required by the EIA Act.

The reasons for the low levels of participation can be condensed into six factors.

(1) In Finland, the tradition of institutional public participation has historically been based on representative democracy. There is no great tradition of direct participation in Finland, especially in planning processes.

(2) As an instrument of participation, the EIA is thus a novel form of political engagement. As such, the intricacies of the process are not well-known to the general public.

(3) In general, the EIA process is felt to be ineffective. The effectiveness of EIA-based 'policy-making' is indirect, and the relationship between the EIA and the decision-making process is usually unclear, at least for the general public. Some people may feel that it is useless to take part in the EIA, believing that there are other ways of participation outside it, such as direct contacts with decision-makers, use of the media, demonstrations etc.

(4) The final disposal of nuclear waste is an exceptionally long process. For example, in Kuhmo the planning and studying process has lasted over ten years. Tiredness and exhaustion clearly represent one reason for the weakness of public activity. On the other hand, it is reasonable to remember that the continuous visibility of the project and the repeated opportunities for participation may activate some citizens.

(5) The long duration of the process itself, several public meetings, and massive information activities, increased the knowledge of local inhabitants about nuclear waste management and the final disposal of nuclear waste. Some citizens may feel their knowledge is sufficient to approach the project and to form their own opinions. In such a situation it is not necessary to take part in the EIA process, at least not many times.

(6) The amount of participation is also explained by the resources available for participation and their uneven accumulation. The typical participant in the EIA is selected from a large mass of citizens, with the result that the basis of participation narrows and groups comprising a small number of activists result.

3.2.3 Conclusions of the studies on EIA procedure

The planning and decision-making process concerning the final disposal of spent fuel, with its multiple licensing stages, is quite complex. There were difficulties in connecting the EIA to policy-making. The distance between, for instance, public participation in the EIA process and the making of the Government's final decision is so great that the meaning of the EIA becomes confused. The contribution of the EIA to decision-making seems to be quite ambiguous in the case of final disposal. However, in nationally important issues the extension of decision-making to the highest political level seems appropriate in order to get political commitment for the issue in question.

Members of the municipal council and leading officials in Eurajoki see economic reasons as being most important when making decisions at local level regarding final disposal. For them the EIA was somehow an undetermined entity of studies. In the final phase of the decision-making process the EIA was not in the leading role. Instead, the decision-makers emphasised economic factors and, for instance, the Vuojoki agreement earlier made between the Eurajoki municipality and Posiva. They saw the EIA as an open and democratic arena for public participation, but there was no mention of the opinions and attitudes of citizens when estimating the contribution of the EIA to decision-making.

Even if the EIA for the final disposal was a success as a planning tool for identifying, predicting, and evaluating the environmental impacts, and even if the quality of the EIA report was good, there were obvious problems with the role of the EIA as a procedure in policy-making. First of all, the disposal plan itself seemed to be 'too big' for the EIA. Its national importance and economic and political interests, as well as the base alternative and the fact that its timetable had been decided in advance, made the context so difficult that the issues included in the EIA were finally unessential. In short, the EIA was not 'strong' enough to operate in this highly controversial project. Furthermore, the timetable for planning and decision-making was not favourable for the EIA. There was a lack of alternatives and the temporal connection between the EIA process and the DiP created confusion. The complex process of the DiP and forthcoming construction and operating licences caused an inflation of the EIA. In other words, many

people believed that the studies included in the EIA were somehow symbolic, since some of the most important basic decisions had already been made in the Government's policy decision of 1983.

From the viewpoint of participation there were several problems with the EIA process. Public participation was, in general, slight when evaluated in a quantitative way. The level of participation decreased throughout the process. The EIA contact persons, especially, were not utilised at all by the citizens. Furthermore, public participation was clearly accumulative. There is a chance that some kind of direct participation élite arises in such processes. It was also regrettable that the inhabitants and policymakers of candidate municipalities did not meet during the EIA process. There were so many arenas of participation that the EIA was not the most effective one in many cases. Therefore, the activities outside the EIA were important for all parties. The meaning of the EIA was especially complicated for the opponents. In one way it was important to use such an instrument, but in another there was a lack of confidence.

3.3 Nuclear waste management issues in the media [28]

This section examines how nuclear waste in general and preparations for the disposal of spent nuclear fuel in particular were discussed in the Finnish media during 1999–2001. The aim is to find out how the mass media presented the opinions and actions of the organisations and citizens that participated in the discussion on nuclear waste. The focus of the study is to analyse the participants' access to publicity and what kind of statements concerning nuclear waste issues were presented by different parties in the discussion in the media. The focus is on the journalistic contents, i.e. the actual and factual material in the media: news, background information, and opinion journalism. Advertisements are not covered in this study.

Public debate on the management of spent nuclear fuel is connected to the discussion about nuclear power, where public opinion has had a crucial influence on the decision-making process in Parliament. It is typical of the risks involved that ordinary Finns have no personal experience of them, and that the possible dangers are not discernible by the senses. Attitudes towards the disposal of spent nuclear fuel are influenced – indirectly or directly – by the information and emotions contained in the media.

[28] By Raittila, P.

Decisions on the disposal of nuclear waste are made on different political levels, but the political actors are crucially dependent on the media. The mass media are often a more important channel of influence for political actors than are party organisations. Therefore, media research is an essential part of the study of the social decision-making process.

3.3.1 Approach and methodology of the study

In this study, the viewpoint from which the content of the media is analysed is the access to publicity of different social interest groups, and the mutual interaction of those groups in the media. This kind of study is connected to the concept of public journalism, in which the idea is to increase citizens' opportunities to influence society, for example by raising new voices as sources in the mass media. Secondly, attempts are made to bring citizens' voices into discussion with each other and with the people in power. Thirdly, discussion requires serious deliberation and the focus should be on constructive solutions [Heikkilä & Kunelius 1998].

In public journalism, the task of journalism is seen more widely than as merely communication and entertainment. Good journalism is not content with the role of a bystander but acts as an active opener of different angles and offers a place for public discussion; in some cases it even mobilises it [Kunelius 2000].

The role of the mass media is examined here from the viewpoint of stimulating public discussion. Special emphasis is placed on how different social interest groups receive publicity in the media and what kinds of arguments these actors use.

The research method used was systematic monitoring of the media and analysis of the relevant newspaper articles, in which the material was classified for statistical analysis according to the contents of the articles [Nordenstreng & Griffin 2000; Berelson 1952].

The collection of the research material was started in February 1999. The central part of the conclusions is based on the analysis of nuclear waste articles in seven newspapers[29] at the time when the DiP was being discussed in the decision-making organs of the Eurajoki municipality and the Finnish state (1.6.1999–

[29] Systematically followed sources were nation-wide newspapers Helsingin Sanomat and Hufvudstadsbladet; Länsi-Suomi, Satakunnan Kansa and Uusi Rauma were local newspapers around Eurajoki; and Loviisan Sanomat and Östra Nyland were local newspapers in Loviisa.

31.5.2001). The material consists of 748 newspaper articles, of which the 629 articles dealing with the situation in Finland form the basic material of this study. In the area of television all the news stories from all national channels were followed.[30]

There was quite a steady flow of articles dealing with the siting of the spent fuel repository during the follow-up period. There was an increase in the number of news stories in connection to three different events: in May 1999, when Posiva published its EIA report and DiP application; in January-February 2000, when the DiP was discussed and approved in the municipality of Eurajoki, and in the spring of 2001, when the DiP was discussed and approved in Parliament. Of those articles, two-thirds were news stories or reports and some 30 % opinion articles. In the articles dealing with foreign countries, reports on nuclear waste transportation in Germany and France had an important role, as well as the new law in Russia that enables the importing of nuclear waste into Russia.

3.3.2 Roles of different interest groups in the media

Table 8 shows how often the representatives of different actor groups either spoke in or were the objects of newspaper articles during the two-year surveillance period. The central themes during the period 1.6.1999–31.7.2000 were statements about the DiP, the positive decision of the municipality of Eurajoki, and the following complaints and discussion. In the next period (15.11.2000–31.5.2001), the articles dealt with the DiP process in the Government and in Parliament, and, as a side theme, with the discussion on the construction of additional nuclear reactors.

[30] In addition to this, 8 other newspapers were followed in spring 2001 when the DiP of the disposal of nuclear waste was discussed in the parliament. These newspapers were Aamulehti, Turun Sanomat, Uutispäivä Demari, Suomenmaa, Nykypäivä, Kansan Uutiset, Kristityn Vastuu ja Vihreä Lanka. All in all, the material on which the conclusions are based consists of 1 310 newspaper articles and 105 television news stories.

Table 8. The roles of different interest groups in news stories and opinion articles [31].

	As a speaker in the news		As a writer in opinion articles		Only as an object (in some other role than that of a speaker or writer)	
	1.6.99-31.7.00	15.11.00-31.5.01	1.6.99-31.7.00	15.11.00-31.5.01	1.6.99-31.7.00	15.11.00-31.5.01
State leadership (Parliament, Government etc.)	6	56	0	1	146	120
Political parties, politicians	12	36	2	8	38	52
Ministry of Trade and Industry	16	6	0	0	80	14
Posiva	29	13	5	2	201	75
Radiation and Nuclear Safety Authority	21	11	0	0	54	20
Eurajoki municipality	24	20	0	1	139	38
The neighbouring municipalities of Eurajoki	22	4	0	0	30	11
Environmental organisations	11	16	4	6	16	32
Citizens	43	18	61	42	**	**
Private industry and trade	25	15	-	1	**	**
Universities, public research institutes	31	4	2	2	**	**
The newspaper itself (editorials, columns etc.)	7	0	18	22	**	**
Other national authorities	13	9	-	-	**	**

** These actors were coded only as speakers and as writers, not in other roles.

[31] All tables in this section are based on the nuclear waste articles in seven Finnish newspapers in 1.6.1999–31.5.2001 (N=629 articles).

The objects of journalists or other speakers were usually Posiva, the state leadership (the President, the Government, Parliament, and individual ministers), or the Eurajoki municipality. These were rarely in the role of a speaker, even though they were often present. There were very few comments from the leaders of political parties or the state before the parliamentary proceedings in the spring of 2001. Politicians on the national level were almost totally absent from the nuclear waste discussion in the newspapers before that.

The environmental organisations and other non-governmental organisations that criticised the final disposal plans were clearly less frequently found as speakers or the objects of other speakers than the 'official' parties. More often speakers were ordinary citizens, but their status was weak in relation to the 'official actors'; the citizens' speeches were often short replies, whereas the representatives of Posiva and the state were more imposing as speakers.

In the opinion articles the occurrence of different interest groups was emphasised differently in news stories than in the other articles produced by the newspaper. Posiva was also the actor most often present in the opinion articles, but now almost totally as an object for other speakers. Opinion articles were dominated by 'citizens', either in their own name or under a pseudonym in the letters section.

3.3.3 Statements and speaker profiles

In addition to the actors' access to publicity, the focus of the study was on what kind of statements concerning the disposal of spent nuclear fuel were presented by different actors in the nuclear waste discussion. 'Statements' mean here the summary of arguments concerning the disposal of nuclear waste, where the same idea may have been expressed in various ways. Statements are formed in pairs so that the justifications for and against are shown clearly. Not all the themes of the discussion – such as the facts and descriptions dealing with the timetable of the process or with its technical implementation – are coded as statements. A summary of statements is shown in Table 9.

Table 9. The occurrence of statements in newspaper articles.

Statement	Agree	Disagree
Posiva's model of nuclear waste disposal is safe	57	72
The site selection process has been morally tenable and/or legal and/or democratic on a municipal and state level	34	81
The DiP on spent nuclear fuel can be made now (Denial: cannot be decided yet, decision must not be hastened)	42	40
The disposal of nuclear waste will/can lead to nuclear waste imports	41	18
The Eurajoki municipality will benefit financially from the disposal of nuclear waste	30	3
The site selection decision requires a municipal referendum	23	8
The disposal facility must be reopenable and/or nuclear waste must be retrievable	26	4
The transportation of nuclear waste is a safety risk	17	5
Those studying the final disposal of nuclear waste are competent and/or independent	9	15
Disposing of the nuclear waste in the bedrock is ethically questionable	15	5
The repository must be able to be monitored	14	4

In the spring of 1999, the most frequently repeated arguments were connected to the safety of the repository and the transportation of high-level nuclear waste, the impacts on local image resulting from the siting, and to the municipal economy [Raittila 2000, 53–57]. At the end of 1999, the statements dealing with the municipal economy and image impacts were fewer. There was a new theme: how legal and democratic the decision-making process was.

Argumentation on safety. Safety and statements connected to it were strongly present during the DiP discussion. Reassurance on the safety of the repository was in the papers most frequently in January 2000, when the decision was made in the municipality of Eurajoki, and also in December of the same year, when the Government made the DiP. Statements questioning the safety of the repository

were most frequent in the early phase of the parliamentary proceedings concerning the matter, in 2001.

The safety of Posiva's model for final disposal was criticised mostly by citizens (in 32 articles), environmental organisations (in 15 articles), and political actors (in 12 articles). The contents of citizens' comments varied, because they were also a group that often spoke positively on the subject of safety (in 13 articles). The safety appraisal by the Radiation and Nuclear Safety Authority (STUK), supporting the final disposal, was cited in 15 articles. Posiva, which had applied for the Decision in Principle (DiP), participated, however, very little in the discussion on safety.

Argumentation on the democracy of the procedure. Together with safety, the other central theme in the discussion was the democracy and legality of the process of making the DiP. It was questioned both in the statements on the EIA and on the DiP, and also in the complaints made on account of the decision by the municipality of Eurajoki. At this stage, it was especially the citizens and representatives of Eurajoki's neighbouring municipalities who questioned the legality of the decision-making procedure.

In the parliamentary discussion in the spring of 2001, criticism was directed particularly to the fact that according to the Nuclear Energy Act, once Parliament has approved the DiP of a spent fuel repository, it does not have a say in the subsequent construction licence and operating licence processes.

The discussion on whether the DiP can be made now was balanced; the supporters of the timetable and its critics were almost the same in numbers. Almost everyone who criticised the proposed timetable was a representative of an environmental organisation or a political party. The Radiation and Nuclear Safety Authority, the representatives of the state leadership, and some of the politicians supported the DiP in the media discussions.

Speaker profiles of the actors

The roles of different actors in the newspaper articles were presented in Table 8, and the whole picture is more complete when the most frequently presented statements by these actors are shown in Table 10 – Table 14.

Table 10. The statements most often presented by Posiva.

Statement	1.6.1999–31.7.2000	15.11.2000–31.5.2001
Denied/doubted: the disposal of nuclear waste will/can lead to nuclear waste imports	6	-
Posiva's model of disposing of nuclear waste is safe	4	-
Other statements in total	6	4

Posiva featured in almost 50 % of the newspaper articles that dealt with nuclear waste in Finland. An interesting point is that the presence of Posiva decreases as the DiP process goes forward. Even more obvious is the diminishing role of Posiva as a speaker in the articles; during the last six months of the surveillance period, the representative of Posiva is cited or referred to in only 13 articles. Posiva was not active in participating in the debate in opinion articles; the few articles in this category were mostly responses to the questions presented by citizens in letters sections.

Another significant feature concerns the contents of Posiva's comments; Posiva did not participate much in the argumentative discussion on the safety of the disposal of nuclear waste and the DiP process. In this connection, it must be kept in mind that Posiva's full-page advertisements in the newspapers in the spring of 2000 were not included in the research material. Posiva could argue in its own terms in those advertisements.

When citizens and the representatives of environmental organisations wanted to challenge the safety of the spent fuel repository, the representatives of Posiva rarely responded, and when they did it was by emphasising the safety of their disposal concept. The Finnish Association for Nature Conservation (Suomen luonnonsuojeluliitto) brought into the discussion in the winter of 1999 a demand that the repository should be able to be monitored and reopened, if necessary, but the representatives of Posiva did not participate in the ensuing discussion in the newspapers. However, they did contradict the opinion, which appeared in a few articles written by citizens, that the construction of the repository in Eurajoki would lead to imports of nuclear waste from other countries.

The newspapers built their stories so that Posiva appeared either alone or together with 'like-minded' actors. Posiva and those that criticised it did not appear in the same story in dialogue with each other. For example, the representatives of

environmental groups and Posiva appeared only once as speakers in the same newspaper article.

Posiva appeared in public as a concerned party but also as an 'official' party that was frequently referred to. The newspapers presented Posiva as the implementor of the final disposal facility and thus the representatives of the company talked mainly about technical issues, the timetable, and choosing the municipality for the site. In these connections, Posiva's disposal plan was seen in newspapers as a self-evident choice. Making Posiva's plan seem natural was actually a strong method of argumentation, and it is not captured in the previous count of the statements.

The role of the Radiation and Nuclear Safety Authority (STUK) in newspaper texts developed in the same manner as Posiva's role. The number of articles in which the STUK or its representative were objects, speakers, or debaters decreased continuously as the DiP process progressed. The STUK had its most visible role at the end of 1999 and the beginning of 2000, when its appearances as a speaker were mostly based on the safety appraisal on the DiP. The STUK did not participate at all in the opinion articles, and the newspapers seldom interviewed its representatives as experts.

Table 11. The statements most often presented by the representatives of the state leadership.

Statement	1.6.1999–31.7.2000	15.11.2000–31.5.2001
The DiP on spent nuclear fuel can be made now	-	8
Denied/doubted: The disposal of nuclear waste will/can lead to nuclear waste imports	1	3
The disposal facility must be reopenable and/or nuclear waste must be retrievable	-	4
Other statements in total	-	6

The representatives of the state leadership (the President, the Government, Parliament, and individual ministers) were, until November 2000, solely seen as objects in nuclear waste articles; after that they were also quite often to be found as speakers. These representatives were mainly two ministers (the Minister of Trade and Industry, Ms Sinikka Mönkäre, and the Minister of the Environment, Ms Satu Hassi). Quotes on the DiP, approved by the Government on 21

December, 2000, and the resolutions by Parliament concerning the disposal were also counted as speaker acts of the state leadership.[32]

The argumentation expressed in the statements of the representatives of the state leadership was quite scanty. In accordance with the formulation in the Nuclear Energy Act, the Government's DiP was crystallised in the wording *"the disposal plan suggested by Posiva is in the general interests of society"*. In the reports of the parliamentary proceedings, ministers Mönkäre and Hassi defended the Government's DiP and responded partly to criticism, but they hardly presented any strongly argumentative statements. The low media profile of the state in the DiP process is illustrated by the fact that from the newspaper material there were no statements in which a representative of the state explicitly said that the disposal concept is safe.

[32] In addition to Minister Mönkäre, the Ministry of Trade and Industry (KTM) was as a speaker in some twenty occasions and present in nearly hundred articles. The speaker acts of the ministry consisted of giving a summary of its documents or of statements by ministry officials, and argumentative statements were almost non-existent in them.

Table 12. The statements most often presented by the representatives of political parties.

Statement	1.6.1999–31.7.2000	15.11.00–31.5.2001
The DiP on spent nuclear fuel cannot be decided yet; the decision must not be hastened	4	16
Denied/doubted: the site selection process has been morally tenable and/or legal and/or democratic on a municipal and state level	3	14
Denied/doubted: Posiva's model of disposing of nuclear waste is safe	2	10
The DiP on spent nuclear fuel can be made now	2	9
The disposal facility must be reopenable and/or nuclear waste must be retrievable	4	4
The disposal of nuclear waste will/can lead to nuclear waste imports	5	3
The repository must be able to be monitored	2	3
The final disposal decision requires a municipal referendum	3	1
Other statements in total	7	11

Political parties and their representatives participated quite infrequently in the discussions on spent fuel disposal in the newspapers. This holds true even if we take into account the fact that a proportion of the municipal level politicians are counted as municipal representatives and ministers as representatives of the state leadership.

Politicians on the national level are almost totally absent from the nuclear waste discussion in the newspapers before November 2000. Moreover, the nuclear waste issue was not an important theme in the newspapers in the Eurajoki district in the municipal elections in the autumn of 2000.

There were a number of statements in the comments by politicians. The majority of them were sceptical towards the democracy of the DiP process and the safety of the repository. Critical arguments or critical comments on the DiP did not, however, prevent these 'dissidents' from voting for the DiP on May 18, 2001.

It is interesting for democracy and for the publicity principle that the representatives of the state or political parties practically participated hardly at all in the dialogue on nuclear waste in the media before the Government had made the DiP. Citizens and their organisations discussed among themselves and with the media, the municipalities, and Posiva, whereas the ultimate decision makers, i.e. the leadership of the state and politicians, came into the discussion just before the decision was made or right after it.

The municipality of Eurajoki and its representatives were central objects of newspaper articles, especially in the early stages of the DiP process, when the statements concerning Posiva's application and the positive resolution of the Eurajoki municipality were discussed. After November 2000, Eurajoki was left in the background in the debate, when national actors became central speakers. Representatives of Eurajoki defended the DiP procedure and the financial benefits for the municipality. The municipality and its representatives did not participate much in the discussion on safety issues.

The representatives of universities and state-funded research institutes were not strongly represented in the nuclear waste discussion in the newspapers. There were so few statements by researchers that they effectively remained non-commenting neutral bystanders in the debate between the defenders and the critics of the disposal plan.

Table 13. The statements most often presented by environmental organisations.

Statement	1.6.1999–31.7.2000	15.11.2000–31.5.2001
Denied/doubted: Posiva's model of disposing of nuclear waste is safe	8	7
The DiP on spent nuclear fuel cannot be decided yet; the decision must not be hastened	5	9
Other statements in total	9	9

The environmental organisations [33] appeared in the newspapers as speakers or in writing opinion articles, but they were hardly ever to be found as an object of other speakers. The environmental organisations appeared most frequently in the

[33] Those coded as environmental organizations are the Finnish Association for Nature Conservation, local environmental organizations and Greenpeace.

spring of 1999 and then again during the final stage of the DiP process after November 2000. Until the summer of 2000, the Finnish Association for Nature Conservation was the one most frequently represented, whilst in the last six months of the surveillance period Greenpeace took its place as the loudest critic. The environmental organisations appeared almost every time as critics of Posiva's disposal plan, as can be seen from the coded statements taken from their comments.

The popular movements opposing the disposal plan were, in the first months of 1999, a more significant group of actors than environmental organisations, but after the EIA report in May 1999 and Posiva's application for the DiP they appeared quite rarely in the press. The main reason is that the debate on the DiP was concentrated on Olkiluoto, and there was not any organised popular opposition movement in Eurajoki (cf. Section 3.1.3). Between 1.6.1999 and 31.5.2001 the opposing movements were represented only in some twenty articles, and in almost every one of them (in 17 articles) they questioned the safety of the repository.

Table 14. The statements most often presented by citizens.

Statement	1.6.1999–31.7.2000	15.11.2000–31.5.2001
Denied/doubted: Posiva's model of disposing of nuclear waste is safe	22	10
Denied/doubted: The site selection process has been morally tenable and/or legal and/or democratic on a municipal and state level	27	1
The disposal of nuclear waste will/can lead to nuclear waste imports	17	5
The final siting decision requires a municipal referendum	17	0
Posiva's model of disposing of nuclear waste is safe	6	7
Disposing of nuclear waste in the bedrock is ethically questionable	7	4
The Eurajoki municipality will benefit financially from the final disposal	6	1
The transportation of nuclear waste is a safety risk	4	1
Denied/doubted: those studying nuclear waste issues are competent and/or independent	6	-
The DiP on spent nuclear fuel can be made now	4	1
Other statements in total	25	10

The 'citizens' were people that appeared in articles either under their own name or a pseudonym (in the letters section) without any title that would refer to any other actors. Therefore, the representatives of different organisations, researchers, politicians etc. are not included in the group of 'citizens'.

The role of 'citizens' in discussion was concentrated on letters to the editor. These were especially abundant during the parliamentary elections in 1999 (mainly in newspapers outside Satakunta, the province where Eurajoki is located) and just before and after the decision of the municipality of Eurajoki in the spring of 2000 (in the newspapers in Satakunta). The 'citizens' who appeared in the news articles were mainly ordinary people from Eurajoki whose role was to give life to the nuclear waste articles by bringing in local colour and the opinions of 'ordinary people'.

There were plenty of statements in the writings and comments of the citizens, both in absolute numbers and in relation to the number of speakers. There is a whole spectrum of opinions from both defenders and critics of the disposal plan. The clear majority of them, however, criticised the DiP procedure and questioned the safety of the repository, which illustrates the greater activity of those who were critical towards Posiva and the municipality of Eurajoki.

The newspaper itself as a speaker group refers to editorials (32 cases) and the columns and comments made by editorial staff (8 cases), and also some occasional attitudes taken in the news stories. The papers themselves rarely issued strong statements, which indicates their reluctance to take a strong attitude for or against the disposal plan. There was a generally positive attitude towards Posiva's plan, but they did not argue strongly in favour of it. Obviously, the newspapers wanted to show themselves as neutral on a question that sharply divided their readers.

3.3.4 Nuclear waste issues on television in 1999–2001

The treatment of the nuclear waste issue on television has been analysed in a more limited way than that in the newspapers. The material consisted of the news stories of all the national channels from the beginning of February 1999 to the end of May 2001. The news stories that dealt with the nuclear waste question in Finland were concentrated on the decision-making stages of the DiP process, i.e. May 1999, January 2000, December 2000, and February and May 2001. A little over half of the nuclear waste stories on television dealt with foreign issues, and the majority of those had to do with nuclear waste transportation or waste disposal problems in Germany (22 cases) or with nuclear waste management problems in Russia and that country's efforts to import nuclear waste.[34]

In the analysis of television news the focus was on how different actors got to be interviewed in the stories. The most frequent speakers were the representatives of Posiva (in 13 news stories), followed by the representatives of political parties (in 9 news stories) and the municipality of Eurajoki (8 news stories). The representatives of the state and environmental organisations were both interviewed only in four news stories, whereas ordinary citizens got their voices heard in five cases. As in the newspapers, independent researchers and the representatives of the Radiation and Nuclear Safety Authority (STUK) were seldom to be found as

[34] In 1.2.1999–31.5.2001 there were altogether 105 news flashes or reports on nuclear waste, of which 45 dealt with the nuclear waste questions in Finland (in the same day one report per channel was included).

speakers: both were interviewed only in a couple of news stories in a period of over two years.

As compared with the newspaper articles, the dialogue between different interest groups succeeded slightly better on television. When there were interviewees in a news report, they usually represented different viewpoints and commented on the arguments of the other party. But there were, all in all, relatively few news stories and when the dialogue was limited to comments of a few lines, the television news did not compensate for the lack of interaction and direct discussion between different actors that was seen in the newspaper articles.

3.3.5 The DiP argumentation in the media

The DiP discussion in Parliament in the spring was analysed more thoroughly than the media follow-up shown earlier in Sections 3.3.1.–3.3.3. The basic material consisted of the aforementioned seven newspapers and the main newspapers of the parliamentary parties, two big regional newspapers, and the national television channels.

In connection with the preliminary debate in Parliament in February 2001, the media emphasised especially the critical and doubtful comments. In addition to the arguments that questioned the safety of the repository, the news stories concentrated on the parliamentarians' criticism of the fact that, according to the Nuclear Energy Act, Parliament cannot in the future influence decisions on the construction and operating licences of the spent fuel repository. Furthermore, in almost every story the discussion of the spent fuel repository was connected in some way to the plans to build more nuclear reactors in Finland; they usually emphasised the point that the disposal of nuclear waste and the decision to build more nuclear power were separate issues.

When the DiP came to the plenary session of Parliament and to the final plenary session in May 2001, the picture given by the media had changed; there was an overwhelming majority that supported the DiP and only a couple of parliamentarians resisted it. The opposition position was emphasised in the news, in which the opponents were presented as dissident troublemakers. The opponents got their voices heard anyway, because for the media they provided some elements of conflict that the news criterion requires. Approving the DiP was presented as a matter of course, but at the same time its meaning was narrowed down in some papers to 'a permit to continue research'.

From the viewpoint of organising the dialogue between different views, the media treatment of the parliamentary procedure worked better than in the previously discussed two years' material. The problem remains, nevertheless, that the media did not build a dialogue between other interest groups than those of opposing politicians. For example, Greenpeace was presented as a group that demonstrated outside Parliament, but their arguments were not organised into a dialogue with the arguments that favoured the DiP. The representatives of Posiva were absent from the newspaper articles during the parliamentary proceedings, but on television they were interviewed.

3.3.6 Journalists' views on nuclear waste issues

In a separate interview survey the experiences of the journalists writing about the nuclear waste issue were examined [Tommola 2001]. The journalists were asked, for instance, their attitude towards the actors in the debate on the disposal of nuclear waste as a possible source of information.

Clearly the most important source of information for journalists was Posiva, which they described in a positive tone; Posiva was dynamic, competent, reliable, and its attitude towards publicity was positive. Journalists stated that the active PR work of Posiva facilitated their day-to-day work. In addition to giving statements, Posiva organised introductory trips and supplied 'good background material', which facilitated the making of a story and decreased the need for journalists' own background work. In their graphic illustrations, the newspapers used material provided by Posiva, and Posiva's own film material was used in television reports.

Therefore, Posiva was not at all, in fact, as passive as the previous analysis of the quantitative speaker structure indicated. Journalists' comments confirm that Posiva practised active and professional news management. The aim in news management is not to be seen in the media but to ensure that one's own viewpoint is presented in public. The relatively minor role of Posiva as a speaker in the reports might have stemmed from the journalists' desire to present themselves as independent actors; even when a report was based on background material provided by Posiva, the name of the company was not seen in any way as a source for that report.

Official authorities and politicians were less important than Posiva as sources for journalists. The journalists interviewed also complained that it was difficult to find a researcher for an interview who was not connected to Posiva. It seems that,

for instance, the JYT2001 programme was not sufficiently known to journalists, or they were not active enough to look for alternative sources of information.

Journalists saw it as a problem that it was difficult to find any balancing material for stories about nuclear waste. They thought that resistance to the disposal of spent fuel, especially in the Eurajoki region, was insignificant and dispersed, 'childish stuff'. The journalists regretted that they could not find, in their opinion, sufficiently competent and reliable citizen activists to challenge the views of Posiva. The opponents were of the wrong kind; instead of 'emotional' laymen they wanted critics with a technical education or with a degree in natural science.

3.3.7 Conclusions of media studies

During the period of a little over two years covered in this study, the disposal of nuclear waste was relatively thoroughly treated, in quantitative terms, in the Finnish mass media. The great majority of the news was, however, routine reports on the ongoing process. One cannot talk about active media discussion.

From local to national media discussion. Media discussion went on for years on a local level, and the most vivid local debate took place before the surveillance period of this study. When the study started in the spring of 1999, the main question in the newspapers was not the actual implementation of the disposal, but whether the siting of a nuclear waste repository 'in our municipality' was accepted at all.

Posiva's DiP application in 1999 meant that the issue became national; it was a question of a 'final solution' for all the spent nuclear fuel that has been, and will be, produced in Finland. The emphasis of the media discussion remained, however, on the local level until, and even after, the municipal council of Eurajoki made a positive decision in January 2000. State level politicians, researchers, and other experts were almost totally excluded from the media discussion.

The decision of the Supreme Administrative Court on the complaints of the decision of the municipal council of Eurajoki, the application of Teollisuuden Voima Oy for a DiP to build an additional nuclear reactor in Finland, and the Government's handling of the application for the DiP for spent fuel, changed the issue of spent nuclear fuel to a nationwide theme of discussion. Only at this stage did national political actors become visibly – but still not actively – involved in the nuclear waste discussion.

The DiP on spent nuclear fuel disposal is in many ways a large and difficult issue. It is large, especially because it is a question on which a decision unique in the whole world has to be reached, one whose risks may extend beyond thousands of years. It is difficult, because the plans for the disposal are based on complex technical and scientific knowledge that is hard for a layman to grasp. When experts from different countries argue about the safety of disposing of nuclear waste in bedrock, ordinary citizens and political decision-makers will have to decide whose expert opinion is to be trusted.

The media discussion on the disposal of spent nuclear fuel seems somewhat odd against this background; the most persistent and visible participants in the discussion were laymen (citizens and representatives of municipalities) and the company, Posiva, that applied for the DiP. The popular movements and environmental organisations that opposed the disposal plan did participate in the discussion all the time, but their role was less significant, because others largely ignored their arguments. The university scholars and politicians who were responsible for the DiP were almost totally outside the debate.

Dialogue of the deaf. In the media discussion under review, which lasted for a little over two years, critical views and arguments regarding the disposal plan were, quantitatively, the most publicly visible ones. Different views were publicised, but the dialogue between them did not succeed. The ideas of public journalism were not realised, even though citizens did get their voices heard in a quantitative sense. But there was no equal encounter, or even any genuine interaction, between citizens, experts and decision-makers. Everyone had a chance to speak, but they rarely listened to each other. The people who followed this 'dialogue of the deaf' could, according to their views, put each speaker in their own category.

Even though doubtful and critical arguments were quantitatively more numerous than positive ones, the process went inexorably forward according to the legal procedure, and according to the plans of the authorities and Posiva. What does this paradox reveal to us? Perhaps the fact that in Finnish society the plans of the power élite will go ahead even if critics try to fight back.

Another explanation could be the limits of our quantitative analysis; the greater number of critical arguments do not compensate for the fact that the less numerous favourable arguments received much more space in the newspapers. Through headlines, pictures, and the positioning of their arguments, the supporters of Posiva's disposal plans displayed a hegemonic approach. It appears obvious that other PR work and news management had a more significant role than media publicity in pushing forward the DiP.

The third possible explanation is a continuation of the previous one. What was essential for the progress of the process was not an argumentative discussion and interaction with critical views, but a neutral-looking type of news reporting in which the plans, timetables, and technical details were discussed. This kind of 'naturalising' of the planning process and the related factualisation of the arguments creates a picture of an inexorable and self-evident advancement of the process.

The fourth explanation for the limited discussion is the temporal distance from the disposal itself. It is perhaps difficult to inspire people and experts to discuss a theme in which the 'actual event', i.e. the disposal of spent nuclear fuel, does not start until after twenty years' time. The time for real media discussion may, therefore, be in the future.

4 Communication[35]

The Public Sector's Research Programme on Nuclear Waste Management in Finland (JYT2001) was designed to support the Finnish authorities in their work. Being for the most part a technical and natural science research programme, its established main forum for communication is the international scientific community. However, with an eye on the EIA and DiP processes, focussed efforts were made to increase communication on technical issues to non-technical audiences in Finland, for instance decision-makers. Focussing was required because of the limited resources available.

Social science projects, in contrast, co-operated actively with the four candidate municipalities (Eurajoki, Kuhmo, Loviisa, and Äänekoski) right from the beginning of this research programme period (1997–2001). At a later stage, the projects observed and analysed the on-going EIA and DiP processes. Media publicity was not a primary aim, because researchers are not stakeholders in the same sense as the main actors in Finnish nuclear waste management. As mentioned in the previous chapter, the media visibility of JYT2001 was low, but that does not mean that the research programme was idle and without significance as a source of objective information; rather, it reflects a different approach.

4.1 Domestic contributions

Domestic communication can be divided into two parts, the first of which is normal communication inside the research programme and between the research programme and the outer world. The other part has to do with the specific stage of the national nuclear waste management programme, and the role of JYT2001 in it. In the following section the main emphasis is placed on the latter mode of communication. A summary of the most important contributions to the domestic discussion of nuclear waste management is shown in Table 15.

The mid-term report of JYT2001 was its first major effort to participate in the national discussion about spent nuclear fuel management [Vuori 2000a]. In contrast to the earlier summary reports of the public sector's research programme, it was intentionally written in Finnish and meant to be easily digestible, but success in this respect was not complete. The second effort was to appear in

[35] By Rasilainen, K., Vuori, S.

seminars and committee hearings organised by Parliament during the EIA and DiP processes. Representatives of the research programme appeared as independent experts.

The most important contributions to the domestic discussion were three objective and digestible reports on the Finnish spent nuclear fuel disposal plan. The series covered the basic features of the Finnish disposal plan [Rasilainen & Vuori 1999], the main principles of safety analysis [Rasilainen et al. 2000], and illustration of the radiation dose impacts assessed in Finnish safety analyses [Rasilainen et al. 2001d]. All the reports were comprehensive in the sense that the whole technical back-end chain of waste management was covered, starting from the NPPs, via transportation, to the encapsulation plant and to final disposal in deep bedrock.

To ensure simultaneous technical correctness and digestibility, wide and repeated commenting cycles were utilised. Representatives of the KTM and STUK and of the social science research projects were of great help in achieving the aforementioned aims.

The size of the edition carrying the report series was unusually large for a VTT report, and, for instance, all candidate sites and their neighbouring municipalities received numerous copies of the first report [Rasilainen & Vuori 1999]. Parliamentary factions received all reports and they were utilised in the DiP discussion within Parliament as an independent source of information. Furthermore, the reports could be downloaded from the research programme's website.

Table 15. Summary of contributions by JYT2001 to the domestic discussion of nuclear waste management issues.

Contribution	Comment
Co-operation Group and Steering Group meetings	Research programme's internal communication
Seminars within JYT2001	Research programme's internal communication
Lecture on nuclear waste management on national television	Education of non-technical audience
Appearance at a national environmental exhibition, OtaEco 1998	Communication with outside environmental experts
Website for JYT2001 with access to latest publications	Communication with outside audience
'Nuclear waste in our hands' book edited by social science project managers of JYT2001 [Litmanen et al. 1999]	A collection of historical, social science, and technical articles about Finnish nuclear waste management
Mid-term report of JYT2001 [Vuori 2000a]	Communication with an outside, also non-technical audience, during the EIA and DiP periods
Appearances in seminars organised by Parliament	Communication with MPs and other experts
Digestible objective reports on spent fuel management [Rasilainen & Vuori 1999; Rasilainen et al. 2000, 2001d]	Focussed communication with non-technical audience during the EIA and DiP processes

4.2 International contributions

International communication is, for the most part, established communication among researchers from different countries that plan or prepare for nuclear waste disposal. For instance, numerous conference series have been going on for years as regular meetings of specialists, and the role of these is to act as nodes in a network of information and experience exchange. Many annual and final reports of the previous stages of the research programmes were written in English so as to reach an international audience [Vuori 1990, 1991, 1993, 1997].

The EU's Palmottu Project (1996–1999) was important, because the study site was in Finland and, therefore, the results were more easily transferable to other

Finnish sites, e.g. to Olkiluoto. Of special importance about Palmottu is the fact that the relatively shallow uranium-thorium deposit has survived all the repeated glacial cycles (i.e. permafrost, ice sheet, and deglaciation with huge amounts of oxic meltwater) that have occurred at Finnish latitudes. The project was the biggest single project within JYT2001 and many research teams participated in it (cf. Annex A).

The most important international forums of communication have been the regular working groups within the OECD Nuclear Energy Agency (OECD/NEA). Annual country reports have been produced both by the 'Radioactive Waste Management Committee' (RWMC) and the 'Integration Group for the Safety Case' (IGSC), as well as its predecessors, the 'Performance Assessment Advisory Group' (PAAG) and the 'Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal' (SEDE), see for instance Väätäinen et al. [2001]. The ad hoc working group on 'Integrated Performance Assessment of Deep Repositories' (IPAG) set up by the PAAG proved to be particularly useful in exchanging information and experiences concerning performance assessments and of the reviews of these (cf. Section 2.6.1).

One international workshop was organised in Finland, thanks to the good communication within the OECD/NEA working groups. The NEA 'Forum on Stakeholder Confidence' (FSC) had its second workshop in Turku, Finland, from November 14–16, 2001, on Stakeholder Involvement and Confidence in the Process of Decision-Making for the Disposal of Spent Nuclear Fuel in Finland. The successful Finnish EIA and DiP experiences were the direct reason for the workshop's being organised in Finland, and the Finnish experiences were used for a case study. A summary of the most important forums of international communication is shown in Table 16.

Table 16. The most important international forums for communication between JYT2001 and outside experts.

Contribution	Comment
'Chemistry and Migration Behaviour of Actinides and Fission Products in the Geosphere' conferences	Scientific communication about migration-related issues, cf. Annex B
'Scientific Basis for Nuclear Waste Management' conferences	Scientific communication about natural scientific and nuclear waste management-related issues, cf. Annex B
EU Palmottu Project	Scientific communication about natural analogue-related issues, cf. Annex A, B
Final reports of previous stages of the research programme on nuclear waste management	Communication with international audience
OECD/NEA Ad Hoc Expert Group of Spent Fuel Management Options [OECD/NEA 2000]	Comparison of direct disposal and reprocessing strategies; the group was chaired by the leader of the JYT2001 programme
OECD Nuclear Energy Agency working groups, e.g. RWMC, IGSC, and its predecessors, PAAG and SEDE	Communication with senior international experts, e.g. via annual country reports on nuclear waste management
IAEA Conferences and Meetings, [e.g. Vuori & Rasilainen 2000; Rasilainen et al. 2001c]	Communication with senior international experts on selected topics concerning nuclear waste management
Invited lecture at Spent Fuel Management Seminar XVI, Washington [Vuori 1999] and presentation in Finnish-French nuclear colloquium [Vuori 2000b].	Communication with foreign experts about the status and plans of the Finnish spent fuel management programme and the ongoing Environmental Impact Assessment for repository siting in Finland.
NEA Forum on Stakeholder Confidence (FSC), 2nd FSC Workshop, Stakeholder Involvement and Confidence in the Process of Decision-Making for the Disposal of Spent Nuclear Fuel in Finland, in Turku, Finland, November 14-16, 2001	International case study of EIA and DiP processes in Finland, just concluded successfully. The experts of JYT2001 made a comprehensive contribution in presenting the views and experiences of Finnish stakeholders

With hindsight, it is difficult to quantify the success (or lack of it) of the communication of JYT2001, or to disconnect it from all other communication. At the FSC Workshop in Turku one conclusion was that the existence of credible information from authorities and experts, independent of that provided by Posiva,

had significantly contributed to the building of public confidence in the Finnish nuclear waste management programme in general, and especially in the spent fuel management plan. This, in turn, has undoubtedly contributed to the positive outcome of the DiP process. With reference to Chapter 3, it may be noted that this communication neither sought nor received media publicity. It was further observed at the FSC Workshop that the Finnish EIA and DiP processes were characterised by a somewhat paradoxical combination of low public involvement and high public confidence.

5 Conclusions

Background

The Finnish nuclear waste management programme has so far kept to its schedule, set as early as 1983, partly thanks to the clear statement of responsibilities in the Nuclear Energy Act, which controls all nuclear installations in the country. In May 2001 Parliament ratified the Decision in Principle (DiP) made by the Government concerning a spent nuclear fuel disposal facility in the Eurajoki municipality.

There are three main actors in Finnish nuclear waste management, consisting of two authorities and the producers of nuclear waste. The overall leadership belongs to the Ministry of Trade and Industry (KTM). The Radiation and Nuclear Safety Authority (STUK) is responsible for nuclear and radiation safety issues. Nuclear energy-producing power companies are responsible for the safe management of their nuclear wastes and for the costs arising. In the case of spent nuclear fuel, the Posiva company, owned jointly by the utilities, is in charge of the planning and implementation of spent fuel management.

The Public Sector's Research Programme on Nuclear Waste Management in Finland (JYT2001) was set up to support the authorities in their work. For this purpose, the research was divided into two main areas: technical studies on the safety of waste management, mainly supporting the activities of the STUK, and social science studies on decision-making, mainly supporting the activities of the KTM. The emphasis in the technical studies was on the final disposal of spent nuclear fuel. Technical studies were allocated around 80 % of the funding and social science studies the remaining 20 %.

Technical studies

The most significant geological factors in the final disposal of the spent nuclear fuel are the location, behaviour, and properties of fracture zones. The idea of a block-mosaic bedrock structure, in which possible movements occur via existing fracture zones while the central block bounded by these remains intact, is logical and based on a large number of investigations. Even the large postglacial movements have been concentrated on the existing old fracture zones, and no new fracturing has been observed in intact bedrock blocks. This further confirms that the block movement scenarios used in performance assessments, in which considerable damage is assumed to the repository inside a rock block, appear

extremely pessimistic. The occurrence of high seismic activity seems to be restricted to the final stage of a glacial period, or the beginning of postglacial one. There seems to be no indisputable evidence for the repetition of high seismic activity at a later time.

Significant methodological progress has been made in the JYT2001 programme concerning new hydrogeological information and methods to conceptualise site hydrogeology and hydrogeochemistry and to integrate geoscientific data. Nevertheless, the integration process still needs qualitative evaluation, because the reliability of the results is, to a large extent, subjective. Glacial impacts must be taken into account in assessments of the hydrogeological performance of a nuclear waste repository. There are geochemical indications that a significant portion of glacial water in the bedrock may occur between a depth of 100 and 300 m. However, it is unclear to what extent these are caused by the mixing of glacial meltwater, or isotopic fractionation due to the freezing of groundwater during the permafrost stage. Uranium series disequilibrium studies from fracture surfaces and the rock matrix at Palmottu show that glacial meltwater intrusion is evident, at least at shallow depths.

Understanding redox processes is crucial for the performance assessment of a nuclear waste repository. Near-field chemical interactions are usually modelled by taking into account the transport phenomena and chemistry. These coupled models often calculate the transport of solutes in porous media relatively accurately, but oversimplify the chemical interactions. Modelling depends strongly on the quality of data, and checking data quality is demanding and laborious. Nevertheless, modelling can help in finding important near-field parameters. The solubility of UO_2 matrix under reducing conditions is a critical parameter for predicting the stability of spent nuclear fuel under disposal conditions. The data reported in the literature varies over orders of magnitude. The data measured in JYT2001 predicts lower solubility for $U(OH)_4(aq)$ than the NEA database for uranium. MX-80 bentonite has been studied intensively, but more research still seems to be needed on its swelling mechanisms and their associated processes, including thermal, flow-related, mechanical, and chemical phenomena.

The migration of radionuclides in bedrock has been studied by means of laboratory experiments and natural analogue studies. Different modelling approaches were taken for a more integrated interpretation of batch and column experiments. In some column experiments it appears, however, that the technical limits are reached. For instance, improving model fitting often requires channelled water flow through the column to be taken into account, but for the current experi-

mental set-up there is no direct technical method for obtaining the information on channelling independently. Natural analogue studies have shown that sorption and matrix diffusion take place in situ. Good agreement was obtained between 'standard' K_d and in situ K_d values. It has been observed at Palmottu that the rock matrix appears anoxic inside, even if the groundwater flowing around the matrix block is strongly oxidising. A systematic survey of the requirements and prospects of coupled modelling indicated that fully coupled migration calculations present a challenging task. Therefore, the practical value of such detailed modelling in performance assessment must be weighed against the fact that some other parts of the performance assessment will always contain considerable uncertainties.

In order to describe the mechanical stability of the bentonite barrier, a mathematical model is needed. Most of the parameters required can be obtained or calculated from measurements described in the literature, but, unfortunately, some of the measurements are based on defective material models. Furthermore, the viscous parameters, for instance, cannot be determined by laboratory tests at all, because they would require unrealistically long periods of time. The validity of the sub-models developed in JYT2001 is being tested in the international DECOVALEX III project.

Performance assessment methodology has been studied through international collaboration. The development of the overall methodology has taken place within the PAAG group of the OECD/NEA, nowadays called the IGSC. From the Finnish point of view the work done in the IPAG group has been most useful, with systematic comparisons of published performance assessments, and reviews of these.

Biosphere modelling is required, because safety criteria are based on dose limits and, therefore, radionuclide release rates into the biosphere must be converted into radiation dose rates. There are acknowledged needs to develop an internationally-accepted set of stylised reference biospheres, but for the time being there are none, even for the simplest drinking water well scenarios. The development of reference biospheres has so far taken place within the IAEA's BIOMOVS2 and BIOMASS research programmes. The geosphere-biosphere interface has remained a fringe area of research, but a recent study for Olkiluoto quantified the variability in the water flow into which radionuclide releases from a repository will be diluted when entering the biosphere.

As backup material for the DiP process, a review was conducted of the two most oft-mentioned alternative options for spent fuel management, namely long-term interim storage and nuclide partitioning and transmutation. Interim storage was

not seen as a permanent solution, which is required by the Nuclear Energy Act. It was concluded that nuclide partitioning and transmutation is still in such an early stage of development that no final conclusion could be drawn as to its technical or economic feasibility. Therefore, it appears reasonable to follow progress in this increasingly popular research area.

Social science studies

The Nuclear Energy Act gives an absolute right of veto to the suggested host municipality of a nuclear waste repository, which emphasises the local element at the beginning of the decision-making process. After an eventful local decision-making process phase, the Government made the DiP regarding the final disposal of spent fuel in Eurajoki in December 2000. Posiva's DiP application was backed up with, among other things, an extensive Environmental Impact Assessment (EIA) report. Parliament ratified the Government's DiP, with wide unanimity among almost all parties, in May 2001. Local groups had been sceptical towards the EIA process throughout its duration, mainly because of Posiva's central role in implementation. The opposing groups at Eurajoki, Loviisa, Kuhmo, and Äänekoski had adopted different strategies in their work.

The planning and decision-making process concerning the final disposal of spent fuel, with its multiple stages of licensing, is quite complex. Therefore, many people found it difficult to connect the EIA to policymaking. Members of the municipal council and leading officials in Eurajoki saw economic reasons as most important when making their decisions regarding final disposal. The national importance of the issue and economic and political interests, as well as the policy decision already made in 1983, made the context so difficult that the issues included in the EIA were perceived as unessential. Public participation in the EIA was low, and, in addition, it was generally limited to the same individuals. For opponents especially, the meaning of the EIA was confusing. On the one hand, it was important to use it, but on the other there was a serious lack of confidence.

With hindsight, it appears that the above-mentioned problems in the EIA process stem from inadequate, or ambiguous, communication on the part of the main actors. First, it was not clarified that the EIA was about this particular disposal facility, not about the general nuclear waste management policy in Finland. Second, it was not clarified that the active role of Posiva in the EIA process is actually stipulated in the Nuclear Energy Act. Third, it was not clarified that decisions are made in the DiP process, not in the EIA process. Nevertheless, the main actors fully realised the importance of gaining local acceptance for the facility.

During the period of a little over two years covered by the media follow-up study of JYT2001, the disposal of nuclear waste was frequently covered in the Finnish mass media. The majority of the news items were, however, routine reports. Posiva's DiP application in 1999 made the issue national. Media discussion remained, however, mostly local until, and even after, the municipal council of Eurajoki made a positive decision in January 2000. State level politicians, researchers, and other experts were almost totally absent from the media discussion. The most persistent and visible participants in the discussion were laymen (citizens and representatives of municipalities) and Posiva, which had applied for the DiP. With the positive DiP in mind, it appears obvious that other PR work and news management had a more significant role in the DiP process than media publicity.

The Finnish authorities have had every opportunity to influence the contents of the research in the JYT2001 programme. Therefore, it appears that the research programme has succeeded in its task of supporting the authorities in the way they wanted. As the nuclear waste management programme will continue for decades, but in a more focussed form, it is important to realise the continuous need for scientific expertise. The various stakeholders naturally have partly different needs, and they may have their own research programmes. It appears clear, however, that the existence of a credible research programme, JYT2001, independent of that of Posiva, has greatly contributed to the high level of public confidence in the Finnish nuclear waste management programme.

Yhteenveto

Suomen ydinjätehuollon ohjelma on vuonna 2001 ottanut merkittävän askeleen kohti suunnitelmien toteutumista. Posiva jätti toukokuussa 1999 periaatepäätöshakemuksen valtioneuvostolle käytetyn ydinpolttoaineen loppusijoituslaitoksen rakentamisesta Eurajoen Olkiluotoon. Hakemuksen tukena oli ydinenergialain mukaisesti loppusijoituslaitoksen ympäristövaikutusten arviointiraportti. Tämä ympäristövaikutusten arviointi (YVA) oli Suomen oloissa ennen näkemättömän kattava ja koko YVA-prosessi oli kestänyt Posivan viime vaiheen sijoituspaikkaehdokkailla Eurajoella, Loviisassa, Kuhmossa ja Äänekoskella useita vuosia. STUK ja Eurajoen kunta antoivat hakemuksesta myönteiset lausuntonsa tammikuussa 2000. Valtioneuvosto teki myönteisen periaatepäätöksen joulukuussa 2000, jonka eduskunta hyväksyi toukokuussa 2001 äänin 159 - 3. Päätöksenteon ripeälle etenemiselle on luonut vankan pohjan Suomessa jo yli 20 vuotta tehty järjestelmällinen tutkimustyö.

Taustaa

Suomalainen ydinjätehuollon ohjelma on pysynyt aikataulussa ja tavoitteissa, jotka määriteltiin valtioneuvoston päätöksellä jo vuonna 1983. Yksi merkittävä syy tähän on, että kaikkea ydinenergiaan liittyvää toimintaa Suomessa säätelevä ydinenergialaki sisältää selkeän työnjaon viranomaisten ja ydinenergiateollisuuden kesken. Toinen syy on eri osapuolien aito sitoutuminen asetettuihin tavoitteisiin.

Suomen ydinjätehuollossa on kolme päätoimijaa, jotka koostuvat viranomaisista ja ydinjätteitä tuottavasta ydinenergiateollisuudesta. Ylin ydinenergia-alan johto Suomessa on kauppa- ja teollisuusministeriön (KTM) vastuulla. Säteilyturvallisuuskysymykset kuuluvat Säteilyturvakeskuksen (STUK) vastuualueeseen. Ydinjätteiden tuottajat ovat ydinenergialain mukaan yksikäsitteisesti vastuussa tuottamiensa jätteiden turvallisesta huollosta ja siitä aiheutuvista kustannuksista. Ydinvoimayhtiöiden (Teollisuuden Voima Oy ja Fortum Oyj) yhdessä omistama Posiva Oy vastaa suomalaisen käytetyn ydinpolttoaineen loppusijoituksesta.

Ydinjätteiden tuottajien vastuulla on tutkia, suunnitella ja toteuttaa ydinjätteiden turvallinen huolto. Viranomaisten vastuulla on valvoa toimintaa ja huolehtia siitä, että asetetut turvallisuuskriteerit toteutuvat. Viranomaiset myös valmistelevat suomalaisen ydinjätehuoltoon liittyvän lainsäädännön teknistä sisältöä ja huolehtivat siitä, että Suomen kansainväliset sitoumukset täytetään.

Julkisen tahon ydinjätetutkimusohjelma käynnistettiin tukemaan viranomaisia näiden vaativassa työssä, sillä viranomaisten omat resurssit ovat varsin rajalliset. Valtion tutkimuskeskusten ja yliopistojen asiantuntemukseen tukeutunut tutkimusohjelma osoittautui järkeväksi tavaksi täydentää viranomaisten omaa asiantuntemusta. JYT2001 toteutettiin vuosina 1997–2001; julkishallinnon ydinjätetutkimusohjelman aiemmat vaiheet toteutettiin vuosina 1989–1993 (JYT) ja 1994–1996 (JYT2).

JYT2001-tutkimusohjelma jaettiin kahteen pääosaan: turvallisuutta selvittäviin teknis-luonnontieteellisiin tutkimuksiin ja poliittiseen päätöksentekoon liittyviin yhteiskuntatieteellisiin tutkimuksiin. Tekniset tutkimukset tukivat pääosin STUKin toimintaa ja yhteiskuntatieteelliset puolestaan KTM:n toimintaa. Teknisten tutkimusten painopiste oli käytetyn ydinpolttoaineen geologisessa loppusijoituksessa eli tässä tapauksessa loppusijoituksessa syvälle suomalaiseen peruskallioon. Tekninen tutkimus sai noin 80 % rahoituksesta ja yhteiskuntatieteellinen tutkimus 20 %.

Teknis-luonnontieteelliset tutkimukset

Käytetyn ydinpolttoaineen loppusijoituksen tärkeimpiä geologisia tekijöitä ovat kallioperän ruhjeiden sijainti, käyttäytyminen ja ominaisuudet. Suomalaisen kallioperän rakenne on mosaiikkimainen, jossa kallioruhjeet rajaavat keskelleen ehjempiä lohkoja. Tutkimusten mukaan mahdolliset kallioliikunnot tapahtuvat näitä olemassa olevia ruhjeita pitkin, jolloin niiden sisällä oleva lohko jää ehjäksi. Jopa jääkauden lopun suurten kallioliikuntojen on havaittu keskittyneen vanhoihin ruhjeisiin, eikä uutta rakoilua ole havaittu ehjissä lohkoissa. Tämän perusteella loppusijoituksen turvallisuusarvioissa oletettu ääritilanne uusine, loppusijoitustilaa laajasti vaurioittavine ruhjeineen vaikuttaa erittäin pessimistiseltä. Merkittävä seisminen aktiivisuus Suomen leveysasteilla näyttää rajoittuneen jääkausien alku- ja loppuvaiheisiin. Tällä hetkellä ei ole kiistatonta näyttöä voimakkaasta seismisestä aktiivisuudesta muulta ajalta.

JYT2001-tutkimusohjelmassa saavutettiin merkittävää metodologista edistymistä paikkatutkimuksissa kerättävän hydrogeologisen ja hydrogeokemiallisen tutkimustiedon yhdistämisessä. Tästä huolimatta tietojen yhdistämisessä tarvitaan vielä jatkotyötä, sillä näin saatavan yhdistetyn mallin luotettavuus on yhä paljolti subjektiivista, toisin sanoen tekijästä riippuvaista. Jääkauden vaikutukset on otettava huomioon loppusijoitustilan turvallisuutta arvioitaessa. Tutkimuksissa on saatu geokemiallisia viitteitä, että kallioperässä on merkittäviä määriä jääkauden sulamisvesiä 100–300 metrin syvyydessä. On kuitenkin vielä epävarmaa, johtuvatko viitteet sulamisvesien sekoittumisesta muihin vesiin vai ikiroutavaiheen aiheuttamasta veden jäätymistä seuraavasta kemiallisesta erottumisesta. Uraani-

sarjatutkimuksilla on havaittu selviä merkkejä happipitoisten sulamisvesien tunkeutumisesta ainakin kallion pintakerroksiin.

Loppusijoitustilan lähialueen ilmiöitä mallinnetaan yleensä kytketysti ottamalla huomioon kulkeutumisilmiöt ja kemia. Näissä malleissa kulkeutuminen kuvataan useimmiten suhteellisen tarkasti, mutta kemiallisia reaktioita yksinkertaistetaan voimakkaasti. Mallinnuksen luotettavuus riippuu suoraan lähtötietojen luotettavuudesta, ja geokemiallisten lähtötietojen tarkastaminen on erittäin vaativaa ja työlästä. Kytketty mallinnus kuitenkin auttaa tärkeiden parametrien löytämisessä. Uraanidioksidimatriisin liukoisuus loppusijoitussyvyydessä vallitsevissa pelkistävissä oloissa on keskeinen parametri radioaktiivisten aineiden vapautumiselle käytetystä polttoaineesta. Kirjallisuudessa ilmoitetut parametrit vaihtelevat useita kertaluokkia. JYT2001-ohjelmassa suoritetut mittaukset viittaavat alhaisempaan uraanin liukoisuuteen kuin esimerkiksi OECD/NEAn tietopankki, mikä lisää tältä osin loppusijoituksen turvamarginaalia. Bentoniittitutkimuksia on tehty paljon vuosien varrella, mutta edelleen on tarvetta selvittää bentoniitin paisumismekanismeja ja niihin liittyviä prosesseja.

Radionuklidien kulkeutumista kallioperän vettäjohtavissa halkeamissa on tutkittu laboratoriokokein ja luonnonanalogioin. Laboratoriokokeet ovat olleet staattisia, joissa vesi ei virtaa, ja dynaamisia kolonnikokeita, joissa vesi virtaa. Joissain kolonnikokeissa on saavutettu koetyypin tekniset rajat. Näissä koe- ja mallinnustulosten yhteensovittamisen parantamiseksi on usein tarpeen olettaa kanavoitunut veden virtaus kolonnissa. Tämä on sinänsä perusteltua, mutta kokeesta ei saada riippumatonta tietoa kanavoituneen vesivirtauksen kuvaamiseksi. Luonnonanalogiatutkimuksissa on osoitettu, että radionukliden kallioperäkulkeutumisen tärkeimpinä pidetyt pidätysmekanismit, sorptio ja matriisidiffuusio, todella tapahtuvat luonnossa. Palmotun uraaniesiintymätutkimuksissa on havaittu, että kalliomatriisi vaikuttaa hapettomalta sisältäpäin, vaikka sitä rajaavissa halkeamissa virtaava vesi olisi voimakkaasti hapellista. Tämä viittaa kallion huomattavaan kykyyn kuluttaa happipitoisten vesien sisältämä happi.

Turvallisuusanalyysien kulkeutumistarkastelut perustuvat yksinkertaistettujen mallien käyttöön. Mallinnuksen realistisuuden lisäämiseksi tutkimusohjelmassa on selvitetty tarkempien kytkettyjen mallien käyttönäkymiä ottaen huomioon mahdollisuudet hankkia tarvittavat lähtötiedot. Tarkempien mallien tosiasiallista hyödyllisyyttä epävarmuuksien vähentämisessä tulee kuitenkin arvioida sitä taustaa vasten, että turvallisuusanalyysissa on aina joissain osakokonaisuuksissa merkittäviä epävarmuuksia, joita ei voida täysin poistaa. Näiden osakokonaisuuksien tarkastelussa on edelleenkin käytettävä pessimistisiä oletuksia.

Loppusijoitustilassa jätekapseli eristetään suorasta kosketuksesta kallioon bentoniittisaven avulla. Bentoniitin mekaanisen pitkäaikaisstabiilisuuden arvioimiseksi tarvitaan matemaattinen malli. Mallin tarvitsemista lähtötiedoista suurin osa voidaan saada tai laskea kirjallisuudessa esitettyjen kokeiden perusteella. Joidenkin parametrien kohdalla kirjallisuudessa on kuitenkin käytetty puutteellisia malleja. Prosessien hitaus asettaa omat rajoituksensa, ja esimerkiksi bentoniitin viskositeettiparametrien mittaaminen kokeellisesti ei onnistu käytännössä, koska se vaatisi epärealistisen pitkiä koeaikoja. Tutkimusohjelmassa kehitettyjen osamallien hyvyyttä testataan kansainvälisessä yhteisprojektissa.

Käytetyn polttoaineen kallioperään suunnitellun loppusijoituksen turvallisuusanalyysien metodiikkaa on JYT2001-ohjelmassa tutkittu kansainvälisenä yhteistyönä. Suomalaisittain merkittävin yhteistyöfoorumi on OECD/NEA, jonka alaisuudessa toimivassa asiantuntijaryhmässä vertailtiin yksityiskohtaisesti eri maissa tehtyjä turvallisuusanalyyseja sekä niistä laadittuja ulkopuolisia arviointeja.

Biosfäärimallinnusta tarvitaan loppusijoituksen turvallisuusanalyysissa, koska viranomaisten asettamat turvallisuuskriteerit perustuvat säteilyannosrajoihin. Näin ollen radionuklidien päästönopeudet on muunnettava annosnopeuksiksi. Kansainväliset biosfäärimallinnushankkeet ovat viime aikoina toimineet IAEA:n alaisuudessa. Biosfäärimallinnuksessa olisi merkittävää hyötyä kansainvälisesti hyväksytyistä tyyppibiosfääreistä, eli valmiiksi ajatelluista säteilyaltistusympäristöistä ja -tavoista, mutta toistaiseksi sellaisista ei ole päästy yhteisymmärrykseen edes yksinkertaisille kaivovesitapauksillekaan. Suomessa kaivotapaukselle on tehty Olkiluodon paikkakohtaisin tiedoin laimennusvesimäärien mallinnustarkastelu, jossa kävi ilmi laimennusvesimäärien suuri vaihtelu riippuen kaivon paikasta ja syvyydestä, mutta myös se, että eri paikoista loppusijoitustilaa vapautuvat radionuklidit purkautuvat biosfäärissä eri puolilla Olkiluotoa. Laimennusvesimäärät ovat tärkeitä, koska annoslaskennassa käytetään suoraan radionuklidipitoisuuksia biosfäärissä.

Posivan periaatepäätöshakemuksen käsittelyssä valtioneuvosto ja eduskunta pohtivat ydinjätehuollon toteuttamiskelpoisiksi arvioituja strategioita. Tämän pohdinnan tueksi suoritettiin tutkimusohjelmassa katsaus kirjallisuudessa useimmin esitettyihin vaihtoehtoisiin teknisiin ratkaisuihin käytetyn polttoaineen huollolle. Erittäin pitkää välivarastointia ei katsauksessa pidetty ydinenergialain tarkoittamana 'pysyväksi katsottavana' ydinjätehuollon tapana. Transmutaation katsottiin olevan vielä niin varhaisessa tutkimusvaiheessa, että järkevää arviota sen teknisestä ja taloudellisesta käytettävyydestä tulevaisuudessa ei voitu antaa. Vaikka transmutaatio toteutuisikin tulevaisuudessa, se ei poista jäljelle jäävien jätteiden loppusijoitustarvetta. Transmutaatiotutkimus on suurissa ydinenergia-

maissa nykyisin kuitenkin suosittua, ja tämän tutkimuksen seuranta on Suomessakin hyödyllistä.

Yhteiskuntatieteelliset tutkimukset

Ydinenergialaki antaa ehdotetulle loppusijoitustilan sijaintikunnalle ehdottoman veto-oikeuden, mikä korostaa päätöksenteon alkuvaiheen paikallista luonnetta. Vivahteikkaan paikallisen päätöksentekovaiheen jälkeen valtioneuvosto teki joulukuussa 2000 myönteisen periaatepäätöksen loppusijoitustilan rakentamisesta Eurajoen Olkiluotoon. Posivan periaatepäätöshakemuksen taustamateriaalina oli ydinenergialain mukaisesti suomalaisittain varsin kattava loppusijoituslaitoksen ympäristövaikutusten arviointiraportti (YVA-raportti). Paikalliset vastustavat ryhmät olivat epäilleet YVA-menettelyä koko ajan, lähinnä Posivan keskeisen roolin takia. Eurajoen, Loviisan, Kuhmon ja Äänekosken ryhmät olivat kukin tahoillaan omaksuneet erilaisen toimintastrategian, joten kysymys oli paikallinen myös vastustajille.

Käytetyn ydinpolttoaineen huoltoon liittyvä päätöksenteko on varsin mutkikas prosessi monivaiheisine lupakäsittelyineen. Siksi erityisesti paikalliset ihmiset kytkivät YVAn suoraan päätöksentekoon, vaikka ydinergialain mukaisesti päätöksenteon ensimmäinen vaihe toteutuu periaatepäätöksessä (PAP), jossa YVA toki on tärkeänä osana. Eurajoen kunnallisvaltuuston jäsenet näkivät taloudelliset syyt tärkeimpänä yksittäisenä omaan päätökseensä vaikuttaneena tekijänä. Päätöksen kansallinen tärkeys, poliittiset näkökohdat sekä jo vuonna 1983 päätetty ydinjätehuollon perusstrategia tekivät asiayhteyden niin vaikeaksi, että YVAan kytketyt asiat koettiin osin epäolennaisina. Julkinen osallistuminen YVAan oli alhaista ja osallistuminen lisäksi keskittyi samoille yksilöille. Vastustajien tilanne oli hankala: yhtäällä YVAa piti yrittää hyödyntää, mutta toisaalta siihen ei oikein luotettu.

Jälkikäteen tarkastellen edellä mainitut YVA-ongelmat näyttäisivät johtuvan ydinjätehuollon päätoimijoiden puutteellisesta tai epäselvästä tiedottamisesta. Ensinnäkin kaikille keskusteluun osallistujille ei tullut selväksi, että nyt oli kyse tästä nimenomaisesta loppusijoituslaitoksesta, eikä enää ydinjätehuollon periaatteellisen linjan valinnasta. Toiseksi kaikki osallistujat eivät tulleet riittävän tietoisiksi siitä, että Posivan aktiivinen rooli YVA-prosessissa perustui itse asiassa ydinenergialakiin. Kolmanneksi kaikille ei tullut riittävän selväksi, että YVAssa ei tehdä päätöksiä. Toisaalta toimijat itse, mukaanlukien Eurajoen virkamiesjohto, ymmärsivät täysin paikallisen tuen saamisen tärkeyden loppusijoitushankkeelle.

Tutkimusohjelmassa seurattiin ydinjätehuollon mediakeskustelua hieman yli kahden vuoden ajan. Keskustelu oli verrattain runsasta, mutta jutut olivat yleensä rutiiniraportteja. Posivan periaatepäätöshakemus vuonna 1999 teki ydinjätehuollosta valtakunnallisen asian, mutta mediakeskustelu pysyi paikallisena vielä senkin jälkeen, kun Eurajoen kunnanvaltuusto oli tehnyt myönteisen päätöksen tammikuussa 2000. Valtakunnan tason poliitikot, tutkijat ja muut asiantuntijat eivät juurikaan osallistuneet mediakeskusteluun. Näkyvimmin mediassa olivat kansalaiset, kuntien edustajat ja Posiva, joka tosin ei itse hakeutunut sinne kovinkaan aktiivisesti. On ilmeistä, että myönteiseen periaatepäätökseen ovat vaikuttaneet mediajulkisuuden asemesta muut seikat, esimerkiksi luottamus Posivan ja viranomaisten ammattitaitoon sekä Posivan tiedotuksen asiasisältöön.

Suomalaisilla viranomaisilla on ollut kaikki mahdollisuudet vaikuttaa JYT2001-tutkimusohjelman sisältöön. On siis ilmeistä, että tutkimusohjelma on tukenut viranomaisia näiden toivomalla tavalla. Koska Suomen ydinjätehuollon ohjelma jatkuu vielä vuosikymmeniä, on tärkeätä nähdä tieteellisen asiantuntemuksen jatkuva tarve. Sitä tarvitsevat sekä viranomaiset että voimayhtiöt. JYT2001-tutkimusohjelman nyt päättyessä käynnissä on suunnittelutyö uuden tutkimusohjelman kehittämiseksi, jotta taattaisiin korkeatasoisen kotimaisen asiantuntemuksen jatkuvuus. Posivasta riippumattoman uskottavan JYT2001-tutkimusohjelman olemassaolo on omalta osaltaan lisännyt suomalaista ydinjätehuollon ohjelmaa kohtaan tunnettua luottamusta, joka ilmeni periaatepäätöksen käsittelyssä.

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Annex A: Project descriptions

Projects belonging to the Public Sector's Research Programme on Nuclear Waste Management in Finland JYT2001 (1997 - 2001)

1. Co-ordination and communication of the research programme
2. Safety and costs of nuclear waste management
3. Chemistry of transport phenomena
4. Hydrogeological and mechanical performance of nuclear waste repository
5. Transport of radionuclides in a natural flow system at Palmottu (EU Contract No FI4W-CT95-0010, DG 12-WSME)
6. Role of geological factors in disposal safety
7. Migration of radionuclides in fractured crystalline bedrock
8. Oxidation states of uranium and redox chemistry in groundwaters and on rock fracture surfaces
9. Stability of bentonite barrier
10. Geophysical characterisation of deep fractures
11. Material properties of bentonite
12. Long-term geologic interactions from natural analogues
13. Societal questions of Finnish nuclear waste management: EIA & social science research
14. Political decision making of final disposal of nuclear waste
15. Nuclear waste management issues in media
16. Image effects of a final disposal facility for spent nuclear fuel on local and regional economy
17. Socio-economic and environmental impacts of nuclear waste management in municipalities

NAME OF THE PROJECT
Co-ordination and communication of the research programme

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
VTT Energy	Seppo Vuori	1997 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
19	250				250

GENERAL AIMS

The aim of the project was to co-ordinate the implementation of the JYT2001-research programme and take care of the general communication with domestic and foreign co-operation partners. The specific responsibilities included in the co-ordination have included the preparation of general and annual research plans taking into account the planned activities in the individual projects on the basis of the annual recommendations by the steering group. One particularly important task has been the linking of the two main areas of the programme - namely technical/natural science and social science studies. This project has also taken care of the compilation of the annual reports of the whole programme as well as the compilation and editing of the midterm report and the present final report of the research programme. The communication activities have extended also to international fora, where the role of this programme has been described in the perspective of the whole nuclear waste management programme in Finland. The project has also taken care of the practical administration of the programme.

MAIN ACHIEVEMENTS

- preparation of the general plan of the research programme on the basis of the recommendations of the ad hoc expert group nominated by KTM and with the supervision of the steering group
- compilation of the annual research plans of the programme on the basis of the plans of individual projects and the recommendations of the steering group
- compilation of annual reports and follow-up summaries during each year and taking care of other practical administration tasks
- compilation, co-ordination and editing of mid-term and final reports
- participation in the communication activities in Finland and in reporting the experiences of the Finnish NWM-programme in international events

SCIENTIFIC STAFF

DTech	Seppo Vuori	leader of the research programme, secretary of the steering group
DTech	Kari Rasilainen	research co-ordinator, secretary of the technical/natural science co-operation group

NAME OF THE PROJECT
Safety and costs of nuclear waste management

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
VTT Energy	Kari Rasilainen	1997 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
123	760	30	160	70	1 020

GENERAL AIMS

The aim of the project was to develop expertise for technical and economic assessment of spent nuclear fuel management in support of Finnish authorities. The safety of geologic disposal of spent nuclear fuel was the main topic, with emphasis on groundwater flow and radionuclide migration modelling in fractured bedrock. The safety of spent fuel transportations was another topic. In addition, cost estimates of nuclear waste management were done and reviewed, and the related uncertainties were estimated. The project supported the communication efforts of the authorities in connection with the progress of Finnish spent nuclear fuel management programme (EIA and DiP processes).

MAIN ACHIEVEMENTS

- natural analogue studies in the area of migration and uranium-series disequilibria to test basic migration concepts used in performance assessments of an underground repository (10 joint publications and a doctoral thesis)
- participation in the EU-funded Palmottu Project to co-ordinate the migration related research (6 joint publications)
- participation in different laboratory studies of migration to test basic migration concepts used in performance assessments of an underground repository (4 joint publications)
- participation in relevant international working groups and research projects, e.g. OECD/NEA (RWMC, PAAG (later IGSC), CRPPH), BIOMASS Project, to develop Finnish performance assessment methodology and to communicate Finnish experiences
- review reports of the state-of-the-art in coupled migration modelling and retardation mechanism studies (2 reviews)
- annual reviews of the cost estimates of nuclear waste management by the nuclear energy producing power companies
- series of reports for a non-technical audience, e.g. decision-makers, about the whole spent fuel management chain (3 reports)

ACADEMIC DEGREES (1997 - 2001)

Doctor of Technology	Kari Rasilainen, 1997	Matrix diffusion model. In situ tests using natural analogues.
Licentiate of Technology	Henrik Nordman, 1998	Performance analysis of alternative immobilization methods and repository designs for low and medium level liquid waste (in Finnish)
Master of Science Technology	Vesa Tukiainen, 2000	Interpretation of tracer experiments with a computational model (in Finnish)

SCIENTIFIC STAFF

DTech	Kari Rasilainen	natural analogue studies, project manager
DTech	Seppo Vuori	performance assessment, fuel cycle & biosphere studies
DTech	Timo Vieno	performance assessment
LicTech	Henrik Nordman	migration modelling, performance assessment
MScTech	Vesa Tukiainen	migration modelling (1998 - 2001)
MScTech	Vesa Suolanen	biosphere modelling, transportation safety
MSc	Antti Poteri	groundwater flow modelling
MSc	Jari Löfman	groundwater flow modelling
MScTech	Eero Kattilakoski	groundwater flow modelling (1997 - 2001)
MScTech	Kurt Meling	groundwater flow modelling (1997 - 2001)
MScTech	Mikko Laitinen	groundwater flow modelling (1997 - 1999)
MScTech	Antti Lehtilä	cost analysis (1997 - 2001)
PhLic	Lasse Koskinen	groundwater flow modelling (1997)

NAME OF THE PROJECT
Chemistry of transport phenomena

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
VTT Chemical Technology	Matti Valkiainen (1997-2000) Torbjörn Carlsson (2001)	1997 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
100	680	-	295	-	975

GENERAL AIMS

The main objective of the project was to identify important chemical processes in the near-field of a repository for spent nuclear fuel and also to identify the possible interactions between these processes. Several topics were considered in the project: interactions in the near-field, bedrock matrix effects, the reliability of solubility-data, the coupling between surface reactions and diffusion and bentonite swelling. The results are relevant for the Finnish authorities in their assessment of the long-term safety of the Finnish spent fuel repository concept.

MAIN ACHIEVEMENTS

- deeper insight into the swelling mechanisms of compacted bentonite from the relation between clay microstructure and hydration.
- improved understanding of the physico-chemical interactions taking place in the repository environment.
- improved understanding of the difficulties associated with the evaluation of data in, e.g, thermodynamic databases.
- new solubility data for uranium under reducing conditions

SCIENTIFIC STAFF

MSc	Matti Valkiainen	matrix diffusion, project manager (1997-2000)
PhD	Torbjörn Carlsson	groundwater chemistry, project manager (2001)
MSc	Hannu Aalto	radiochemistry
MScTech	Heikki Kumpulainen	colloids, diffusion
MScTech	Jarmo Lehikoinen	surface complexation
DTech	Arto Muurinen	bentonite chemistry
MSc	Kaija Ollila	uranium chemistry
MSc	Ulla Vuorinen	colloid chemistry

NAME OF THE PROJECT
Hydrogeological and mechanical performance of nuclear waste repository

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
VTT Communities and Infrastructure[36]	Petteri Pitkänen	1997 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
57	315		125	65	505

GENERAL AIMS

The aim of the project was to develop expertise and methods for characterising and evaluating the hydrogeological, geochemical and mechanical performance of an underground nuclear waste repository. The requirement was to assess and model interaction between technical barriers, hydrogeological and mechanical properties in various expected conditions developed, for example, by construction of a repository or climate change. Consistency between geoscientific models was prioritised in evaluation process and therefore integration of hydrogeology and geochemistry was main topic during the programme.

MAIN ACHIEVEMENTS

- participation in the EU-funded Palmottu Project to co-ordinate the integrated evaluation of hydraulic and hydrogeochemical results (4 joint publications), and the geochemical interpretation and modelling of water-rock interaction with special emphasis in palaeohydrogeological changes (4 joint publications)
- use of hydrogeochemical and isotopic information in testing groundwater flow models (3 joint publications)
- developments of geochemical and statistical methods in prediction of site hydrogeochemistry and hydrogeology (4 joint publications)
- studies on coupled processes in hydromechanics (DECOVALEX) and hydrogeochemistry in underground repository and technical barriers (6 articles and reports)
- development of geophysical methods in interpretation of the structures and mechanical properties of bedrock (5 articles and reports, and a doctoral thesis)

ACADEMIC DEGREES (1997 - 2001)

Doctor of Technology	Olli Okko 1998	On the development in digital engineering-seismic studies in Finland
Master of Science	Mikael Kulikoff 2001	Prediction of hydraulic conductivity in rock using neural networks (in Finnish)

[36] Since 1.1.2001 VTT Building and transport.

SCIENTIFIC STAFF		
MSc	Petteri Pitkänen	geochemistry, project manager
PhLic	Kai Front	geology
MScTech	Juhani Korkealaakso	geophysics, hydrogeology
MSc	Mikael Kulikoff	geology
PhD	Ari Luukkonen	geochemistry, hydrogeology
DTech	Auli Niemi	hydrogeology (1997 - 1999)
DTech	Olli Okko	geophysics
MScTech	Tuomas Pantsar	information science
LicTech	Jukka Pöllä	rock mechanics (1997-1999)
LichTech	Tiina Vaittinen	geophysics (1997- 2000)
MScTech	Jaakko Vuopio	rock mechanics

NAME OF THE PROJECT
Transport of radionuclides in a natural flow system at Palmottu
(EU Contract No FI4W-CT95-0010, DG 12-WSME)

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
Geological Survey of Finland (Co-ordinator)	Runar Blomqvist	1996 - 1999

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	NATIONAL FUNDING OF PARTICIPANT COUNTRIES	EU FUNDING	TOTAL
406	2 420	1 450	3 870

GENERAL AIMS

The Palmottu U-Th mineralisation in southwestern Finland has been studied to increase the understanding of the mobilisation, transport and retardation of uranium in natural environment. The site has a number of analogous features to aspects being considered in the performance assessment of spent nuclear fuel repositories in crystalline bedrock. The Palmottu Natural Analogue Project consisted of two phases. Phase I assessed the processes connected with the flow of groundwater in the bedrock. Phase II identified and quantified the processes related to radionuclide mobilisation and transport. The work was divided in five workpackages: WP1 Understanding of natural flow system; WP2 Geochemical evolution of the water-rock system; WP3 Redox processes; WP4 Migration of radionuclides and WP5 Conclusions relevant to repository performance assessment.

MAIN ACHIEVEMENTS

The use of hydrogeochemical models in testing the various hydrogeological concepts proved to be a powerful tool to establish a reliable conceptual understanding of the groundwater system (chemistry and flow) at the site. Geochemical reactions and mixing processes governing the composition and evolution of the groundwater types were identified. The consistency of the different geochemical modelling results gave credibility to the proposed hydrogeochemical processes. An extensive data set of redox measurements in the crystalline bedrock was obtained from ground surface to 400 m. The modelling results of the redox controlling processes gave good credibility to the present understanding of redox controlling phenomena in crystalline bedrock regimes. This in turn has a strong impact on the behaviour of redox sensitive elements in the geosphere. Several model-testing exercises were included that provided information of interest to repository performance assessment, e.g. the applicability of conceptual models, geochemical codes and associated databases to describe the geochemical variability was tested via blind-predictive modelling exercise. It was also demonstrated that coupled migration models could be used satisfactorily to describe the evolution of the major chemical characteristics and the behaviour of dissolved uranium in an infiltration area.

PARTICIPATING ORGANISATIONS

Finland

Geological Survey of Finland
(co-ordinator)

Helium Gas Research Ltd

Helsinki University of Technology, Laboratory of Engineering Geology and Geophysics (HUT)

PRG-tec Ltd

Radiation and Nuclear Safety Authority (STUK),

University of Helsinki, Laboratory of Radiochemistry (UHRAD)

University of Jyväskylä, Department of Physics, Finland

VTT Communities and Infrastructure

VTT Energy

Sweden

Conterra AB

Geokema AB

Geosigma AB

Göteborg University

Intera KB

Kemakta Konsult AB

Royal Institute of Technology, (KTH)

Studsvik Radwaste

Svensk Kärnbränslehantering AB (SKB)

Terralogica AB

Spain

Centro de Investicationes Energéticas, Medioambientales y Tecnológicas (CIEMAT)

Empresa Nacional de Residuos Radioactivos S.A (ENRESA)

Institut de Ciencies de la Terra , (CSIC)

QuantiSci SL

Universitat Politècnica de Catalunya (UPC-DIT)

Universitat Politècnica de Catalunya, (UPC-DEQ)

University of Oviedo

France

Bureau de Recherches Géologiques et Minières (BRGM)

United Kingdom

Enterpris Ltd

Canada

University of Waterloo, Department of Earth Sciences

Switzerland

Paul Scherrer Institute (PSI)

University of Geneva

Germany

Bundesanstalt für Materialforschung und -prüfung (BAM)

NAME OF THE PROJECT
Role of geological factors in disposal safety

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
Geological Survey of Finland (GTK)	Paavo Vuorela	1997 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
78	410		135		545

GENERAL AIMS

The long-term behaviour of the bedrock as well as slow changes in groundwater conditions are factors which have to be taken in account in considering of the safety of the final disposal of spent nuclear fuel. The strongest changes in bedrock stability and in chemistry and movements of groundwater are related to ice ages. These long-term effects are indicated in traces of the last ice age. Present day bedrock movements and post-glacial faults have been studied in Finland and Russian Karelia. Signs of glacial melt water intrusions have been studied in Sukkulansalo fracture zone in eastern Finland and radionuclide migration and transport in Palmottu district around a small uranium ore deposit. Palmottu has been an international target for analogy studies.

MAIN ACHIEVEMENTS

- Natural analogue studies in the EU-funded Palmottu project. Modelling of geometry, flow and transport around a small U-deposit in SW-Finland in cooperation of 6 countries and number of native research institutes. (more than 20 joint publications and a doctoral thesis).
- Bedrock movements have been followed in cooperation with geodetic institute. Precise levelling network and GPS has been used for stability studies of the bedrock. Postglacial faults have been studied and also drilled by the GSF. PG-fault studies have been made in North Finland and Russian Karelia where cooperation exsists with the Russian Academy of Science. Review report.
- Search for signs of glacial melt water in the known fracture zone of Sukkulansalo. Research report and general report of ice ages related to long-term disposal of the spent nuclear fuel.
- Studies of mineralogy and microstructures for sorption and diffusion experiments. Joint papers.
- Participation in international working groups, OECD/ NEA (SEDE), IC-NF natural analogy working group of EU com., European Environm. Agency.

ACADEMIC DEGREES (1997 - 2001)

Doctor of Technology	Runar Blomqvist	Hydrogeochemistry of deep ground-waters in the central part of the Fenno-scandian Shield

SCIENTIFIC STAFF		
PhLic	Paavo Vuorela	project manager, engineering and structural geology
DTech	Runar Blomqvist	natural analogue studies, hydrogeochemistry
PhD	Lasse Ahonen	hydrogeochemistry, chemical balances
MSc	Veikko Hakkarainen	quaternary geology
MSc	Juha Kaija	hydrogeology
MSc	Aimo Kuivamäki	structural geology, stability
MSc	Antero Lindberg	mineralogy and microstructures
LicTech	Markku Paananen	geophysical interpretation and 3D modelling
MSc	Seppo Paulamäki	bedrock geology, mineralogy
MSc	Timo Ruskeeniemi	paleohydrology, U-mineralogy

NAME OF THE PROJECT
Migration of radionuclides in fractured crystalline bedrock

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
University of Helsinki Laboratory of Radio-chemistry	Timo Jaakkola (1997-2000) Jukka Lehto (2001)	1997 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
74	295	70			365

GENERAL AIMS

The aim of the project was to gain a better understanding of the transport and retardation behaviour of radionuclides and to test the transferability of laboratory data to field conditions. The aim was also to improve the understanding of basic transport processes in crystalline rock matrices at corescale considering the heterogeneous system of pores with a wide variability in size and shape. The main objective was to provide Finnish authorities with research results relevant for the long-term safety of geologic disposal of spent nuclear fuel regarding in radionuclide migration in fractured bedrock.

MAIN ACHIEVEMENTS

- different laboratory scale studies to measure the interaction between radionuclides and rock matrix and to test basic radionuclide transport and retardation concepts used in performance assessments of an underground repository (6 publications)
- development and testing PMMA method to characterize rock matrix structures using different materials (8 publications).
- participation in natural analogue studies in the area of physical rock matrix characterization (3 publications).
- co-operations with Chalmers University of Technology and University of Poitiers in linking rock structure and diffusion modelling (3 publications).
- review report of the state-of-the-art in retardation mechanism studies

ACADEMIC DEGREES (1997 - 2001)

Doctor of Philosophy	Juhani Suksi 2001	Natural uranium as a tracer in radionuclide geosphere transport studies.
Doctor of Philosophy	Marja Siitari-Kauppi 2002	Development of ^{14}C-polymethylmeth-acrylate method for the characterisation of low porosity media.
Doctor of Philosophy	Pirkko Hölttä (thesis to be completed in 2002)	Laboratory scale methods for the determination of radionuclide transport and retardation on crystalline rock

SCIENTIFIC STAFF

Prof	Timo Jaakkola	project manager (1997-2000)
Prof	Jukka Lehto	project manager (2001)
MSc	Pirkko Hölttä	radionuclide migration
MSc	Marja Siitari-Kauppi	radionuclide migration
MSc	Maarit Kelokaski	radionuclide migration
MSc	Esa Oila	radionuclide migration

NAME OF THE PROJECT

Oxidation states of uranium and redox chemistry in groundwater and on rock fracture surfaces

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
University of Helsinki Laboratory of Radio-chemistry	Timo Jaakkola (1997-2000) Jukka Lehto (2001)	1997 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
18	85				85

GENERAL AIMS

The aim of the project was to further develop the method for determination of uranium oxidation states in solid phases. Especially the effect of different iron containing minerals during the dissolution of a geological sample material required more attention. In addition, it was important to find possible reagents and better experimental conditions to minimize interfering effects due to iron. The project supported the Finnish nuclear waste disposal safety assessments.

MAIN ACHIEVEMENTS

- validation of the method for determination of uranium oxidation states in solid phases
- broadening the knowledge of the possible uncertainty factors during the analysis
- improvements to the experimental procedure of complex geological materials
- licentiate in Philosophy publication

ACADEMIC DEGREES (1997 - 2001)

Licentiate in Philosophy	Heini Ervanne	Determination of uranium oxidation states in groundwater and natural solid phases.

SCIENTIFIC STAFF

Prof	Timo Jaakkola	project manager (1997-2000)
Prof	Jukka Lehto	project manager (2001)
PhLic	Heini Ervanne	oxidation state of uranium

NAME OF THE PROJECT
Stability of bentonite barrier

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
HUT Laboratory of Theoretical and Applied Mechanics[37]	Antti Lempinen	1998 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
49	200	4	2		205

GENERAL AIMS

The aim of the project was to examine computationally the mechanical performance of the bentonite barrier around the nuclear waste canisters. The critical question was: does the canister remain inside the buffer. Because the nuclear waste canister is much heavier than the compacted the bentonite, which in addition creates significant swelling pressure in contact with the groundwater, the question is not at all trivial. To answer this question a mathematical model had to be developed, since the swelling behaviour prevents from using the conventional models for porous materials. The validation of the mathematical and computational models was done within the international DECOVALEX III project. The long-time behaviour of the barrier after saturation with water was studied as worst case scenarios with inadequate experimental information.

MAIN ACHIEVEMENTS

- modelling of the thermo-hydro-mechanical behaviour of compacted bentonite and determination of the THM parameters of bentonite (3 publications)
- participation in the international DECOVALEX III-project on thermo-hydro-mechanical simulations of HLW repositories (2 publications to appear in 2002)
- developing of numerical methods on solving the THM-model of bentonite (2 publications)
- modelling of the long-time behaviour of the bentonite buffer and determination of the relevant materials properties from inadequately short laboratory measurements (1 publication and one Masters Thesis)

SCIENTIFIC STAFF

DTech, Prof	Martti Mikkola	bentonite modelling
MScTech	Antti Lempinen	project manager; bentonite modelling, numerical calculations
MScTech	Petri Jussila	analytical solutions (2001)
MScTech	Juha Hartikainen	permafrost calculations (DECOVALEX III, 2001)
BScTech	Tuukka Lahtinen	long-time behaviour of bentonite (2001)

[37] Since 1.9.2001 HUT Institute of Mathematics.

NAME OF THE PROJECT
Geophysical characterisation of deep fractures

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
HUT Engineering Geology and Geophysics	Markku Peltoniemi	1997

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
9	21		16		37

GENERAL AIMS

The aim of the project was to apply numerical modelling methods for the geophysical detection and characterisation of deep fracture zones in crystalline bedrock. Such fracture zones are of primary importance for rock stability, groundwater flow and geodynamic behaviour of bedrock. Modelling methods were used in order to find out the minimum contrasts in petrophysical and structural properties of fractured and intact rock volumes at depth that can be detected by geophysical measurements made at the Earth's surface. Results for three-dimensional fracture zones were modelled for Earth gravity, magnetic and electromagnetic methods. Different representative model structures were analysed: a single fracture zone, two adjacent zones, a fracture zone in the contact of two lithological units, and the screening effects from glacial overburden. Combinations of different model parameters for the fracture zone were varied: the width, the depth extent, the dip angle, the strike length, the depth of burial, the strike azimuth, and the contrasts in density, magnetic susceptibility and electrical conductivity for fractured vs. intact rock.

MAIN ACHIEVEMENTS

- numerical results of quantitative modelling of deep fracture zones for the estimation of depth penetration and resolving power of geophysical measurements made at the Earth's surface (2 publications)
- technical reports, posters and presentations about the geophysical detectability of deep bedrock fractures (2 reports, 3 posters and 3 presentations at international meetings)

SCIENTIFIC STAFF

Prof	Markku Peltoniemi	project manager
MSc	Juha Mursu	geophysical modelling

NAME OF THE PROJECT
Material properties of bentonite

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
HUT Engineering Geology and Geophysics	Heikki Niini (1997-1998) Markku Peltoniemi (1999)	1997-1999

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 1999

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
29	90		60		150

GENERAL AIMS

The aim of the project was to study bentonite as a technical barrier material in the final disposal of spent nuclear fuel. The studies in this project have focused on the following three subjects: on the study of bentonite occurrences and deposits as a natural analogue to the long-term mechanical behaviour of the bentonite barrier; on chemical and petrophysical properties of bentonite as a means of displaying the changes in its compaction and porosity *in situ*; and on microstructural studies of bentonite as a means of predicting its behaviour and properties on a macroscopic scale. Finally, mineralogical and geological expertise was provided for the preparation of bentonite samples used in the swelling-pressure measurements.

In the natural analogue studies, occurrences in Almeria (Spain) and Wyoming (USA) were investigated with special emphasis on their structure and deformation histories *in situ* during geological time, to offer a long-term analogue for the experimental swelling tests in laboratory conditions. A limited set of laboratory measurements was performed for the determination of relations between electrolyte saturation, porosity and electrical conductivity of bentonite samples. In the microstructural studies, the physico-chemical conditions on the microscopic scale were used to model the spatial and temporal variation of bentonite on a macroscopic scale by using simulation and geostatistical estimation methods.

MAIN ACHIEVEMENTS

- the study of bentonite occurrences gave useful information about the temporal and weathering behaviour of bentonite *in situ*, and at one of the localities studied it could be concluded that bentonite has retained its swelling capability throughout the whole 17 Ma geological history of the occurrence (1 publication, 2 reports and 1 presentation)
- significant change of electrical resistivity as a function of porosity and compaction was observed in the laboratory measurements of bentonite samples (2 publications, 1 report and 2 presentations)
- results from the microstructural modelling were found useful for the prediction of the bentonite aggregation process at microscopic level, and this will improve modelling possibilities for the physico-chemical processes of groundwater flow on a macroscopic scale (1 publication and 2 reports)

ACADEMIC DEGREES (1997 - 1999)

Doctor of Tecnology	Eevaliisa Laine 1998	Geostatistical, geological and geophysical modelling of subsurface structures of the Precambrian bedrock in Finland
Doctor of Technology	Heikki Vanhala 1997	Laboratory and field studies of environmental and exploration applications of the spectral induced polarization (SIP) method
Licentiate of Technology	Markku Paananen 1997	Mise-à-la-masse method in structure investigations of crystalline bedrock (in Finnish)
Master of Science	Paula Keto 2000	Bentonite deposits as a natural analogue to long-term barriers in a final repository of nuclear waste (in Finnish; University of Helsinki)

SCIENTIFIC STAFF

Prof	Heikki Niini	project manager (1997-1998)
Prof	Markku Peltoniemi	project manager (1999)
DTech	Eevaliisa Laine	bentonite microstructure & simulation
MSc	Nuria Marcos	bentonite petrophysics, mineralogy & geology
MSc	Paula Keto	bentonite deposit study (1999)

NAME OF THE PROJECT
Long-term geologic interactions from natural analogues

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
HUT Engineering Geology and Geophysics[38]	Markku Peltoniemi	2000 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
6	34		3		37

GENERAL AIMS

The aim of the project was to study the geochemical processes that occur at the bedrock-groundwater interface with special emphasis in the behaviour or uranium, thorium and rare-earth elements (REE). The project aimed to link the physical and chemical properties of the bedrock as a means of predicting and testing the interactions and migration models used in performance assessment. Both natural analogue and laboratory studies were performed to investigate the retardation mechanisms and the physico-chemical reactions within and across the bedrock-groundwater interfaces.

MAIN ACHIEVEMENTS

- natural analogue studies in the area of migration and uranium-series disequilibria, with results indicating that fracture bentonite (smectite) may form a long-term sink for natural radionuclides and may result in long-term chemical stability of uranium in smectite (3 joint publications)
- studies on the influence of groundwater flow in the release of U, Th, and REE, suggesting that the leaching rate of these radioelements in stagnant groundwater can be different from leaching rates measured in flowing groundwater (1 publication)

ACADEMIC DEGREES

Doctor of Technology	Nuria Marcos (thesis to be completed in 2002)	Study of geochemical transport and groundwater flow phenomena with REEs

SCIENTIFIC STAFF

Prof	Markku Peltoniemi	project manager
MSc	Nuria Marcos	geochemistry & natural analogue studies

[38] Since 1.3.2001 HUT Rock Engineering (Geology).

NAME OF THE PROJECT

Societal questions of Finnish nuclear waste management: EIA & Social Science Research

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
University of Jyväskylä	Tapio Litmanen	1997 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	YM	OWN FUNDING	OTHER, e.g. EU	TOTAL
28	84	12			96

GENERAL AIMS

The aim of the project was to study societal questions of Finnish nuclear waste management in order to increase the overall comprehension of the complex issue. Project's studies were aimed to support both national and municipal authorities in their decision-making about the issue. The project had three main research tasks. Firstly developed evaluation criteria for Posiva's EIA by carrying out a large survey in the possible host communities of nuclear waste facility. Secondly it produced a summary of all social science research and results related to nuclear waste management. Thirdly it analysed the role of social science in the Finnish nuclear waste management by interviewing municipal authorities of Eurajoki and national nuclear waste management experts and citizen activist.

MAIN ACHIEVEMENTS

- developing evaluation criteria for Posiva's EIA by carrying out a large survey in the possible host communities of nuclear waste facility. (1 publication)
- review report of the state-of-the-art in Finnish social science research (1 publication)
- analysing the experiences of both local decision-makers and national nuclear waste management experts about the role of social science research (2 publications)
- participation in the research networks (University of Tampere: Department of Political Science and International Relations & Journalism Research and Development Centre; VTT Communities and Infrastructure), which concentrated to study societal questions of Finnish nuclear waste management (2 joint publication)
- participation in international working group (OECD/NEA Forum on Stakeholder Confidence to develop understanding of Finnish nuclear waste management and to communicate Finnish experiences (1 conference proceedings publication)

ACADEMIC DEGREES (1997 - 2001)

Doctor of Social Sciences	Tapio Litmanen, 2001	The struggle over risk. Spatial, temporal and cultural dimensions of protest against nuclear technology

SCIENTIFIC STAFF		
DSocSci	Tapio Litmanen	citizen's attitudes, surveys, sociology of knowledge, quantitative and qualitative methodology, project manager
MSocSci	Minna Heikka	analyses of the experiences of decision-makers and experts, qualitative methodology, sociology of knowledge
MSocSci	Martti Kaunismaa	reviews of social science research, analyses of qualitative data

NAME OF THE PROJECT
Political decision making of final disposal of nuclear waste

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
University of Tampere Department of Political Science	Pekka Hokkanen	1997 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	YM	OWN FUNDING	OTHER, e.g. EU	TOTAL
102	340	20	-	-	360

GENERAL AIMS

The principal goal of the research project was to evaluate the citizen participation in the environmental impact assessment process (EIA) of the final disposal of nuclear waste. From the research point of view the EIA was primarily seen as a political process. EIA-process was divided into three research subject of public participation: 1) public hearings, 2) written opinions for contact authority and 3) EIA-contact persons of candidate municipalities. Other aims of the project were to study

1. the political system of research municipalities,
2. local association institution and protest history,
3. attitudes of local ruling actors,
4. interaction networks of local ruling actors,
5. suitability of the consultative municipal referendum,
6. political styles of local civic movements,
7. preparation and implementation of the decision in principle (DiP) and
8. ratification of the DiP in the Parliament

MAIN ACHIEVEMENTS

- systematic observation of the EIA-process, main actors and public participation (2 publications and 4 reports)
- examination of local association field, roles of civic movements (5 publications and a master thesis)
- survey based study of the attitudes of local decision makers, study for the suitability of the consultative municipal referendum, overview for political systems in research municipalities, study of local policy networks (5 publications and 2 reports)
- study for the formation of Finnish nuclear waste policy, the observation of the reparation and implementation of the DiP, examination of the ratification of DiP in the Parliament, review of the role of social sciences in nuclear waste management in Finland (5 publications)
- co-operation with the Department of sociology at University of Jyväskylä and The Journalism Research and Development Centre at University of Tampere (3 articles)
- participation in the making of the half-way report and the final report of JYT2001 (2 joint publications)

ACADEMIC DEGREES (1997 - 2001)		
Master of Social Sciences	Matti Kojo, 1998	Activited by the nuclear waste question. The interests, statements, influence possibilities, and action repertoire of the local association field in the possible candidate sites
SCIENTIFIC STAFF		
PhD	Ilkka Ruostetsaari	head of project
MSocSc	Pekka Hokkanen	project manager, EIA-process, public participation, DiP
MSocSc	Matti Kojo	researcher, civic movements, EIA process, local political decision making
MSocSc	Petteri Suominen	researcher, civic movements, ratification of the DiP
LSocSc	Jouni Ponnikas	researcher, attitudes of local decision makers
DSc	Marja Sutela	researcher, the consultative municipal referendum

NAME OF THE PROJECT
Nuclear waste management issues in media

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
University of Tampere Department of Journalism and Mass Communication	Pentti Raittila	1999 - 2001

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
29	130	-	-	-	130

GENERAL AIMS

The aim of this study was to systematically follow how nuclear waste disposal issue was discussed in the Finnish media in 1999-2001. Articles were analyzed both from the viewpoint of content and way of presentation. Special attention was given to how different interest groups got their voices heard in the media and what kind of interaction they had in these articles. Furthermore, attention was given to the manner of argumentation in connection with the DiP process in the parliament. One part of the project was to interview journalists in order to analyze the journalistic working processes.

MAIN ACHIEVEMENTS

- publishing the results of media follow-up: two interim reports and the final report (in Finnish, 3 publications)
- participation in the making of the half-way report and the final report of JYT2001 (2 joint publications)
- co-operation with the Department of Political Science at University of Tampere and the Department of sociology at University of Jyväskylä (2 articles)
- presentation of the results of the media research in scientific seminars and in JYT2001 seminar (4 reports)

ACADEMIC DEGREES (1997 - 2001)

Master of Social Sciences	Laura Häkli 2000	Making business with nuclear waste. The discursive interpretation of the news coverage of the agreements between Posiva and Eurajoki municipality in the newspapers in Eurajoki and in other candidate locations (in Finnish)
Master of Social Sciences	Anna Tommola 2001	Journalists and nuclear waste. Journalists´ conceptions of the Finnish discussion on the final disposal and of the parties of that discussion. Interview research (in Finnish)

SCIENTIFIC STAFF		
LicSocSc	Pentti Raittila	researcher, project manager
MSocSc	Tommi Kutilainen	researcher (1999-2000)
BSc (Admin.)	Susanna Vehmas	researcher (2001)
MSocSc	Laura Häkli	researcher (2000)
MSocSc	Anna Tommola	researcher (2000-2001)
MSocSc	Risto Suikkanen	researcher (1999)
BSocSc	Michael Karlsson	research assistant (2000-2001)
BSocSc	René Lindqvist	research assistant (1999)
StudSocSc	Timo Lilja	research assistant (1999)

NAME OF THE PROJECT

Image effects of a final disposal facility for spent nuclear fuel on local and regional economy

ORGANISATION	**PROJECT MANAGER**	**PROJECT DURATION**
University of Tampere Department of Local Government Studies	Veli Karhu	1998 - 2000

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
28	67				67

GENERAL AIMS

The main purpose of the project was to study the long run effects of a final disposal facifility for spent nuclear fuel on the alternative location municipalities - Eurajoki, Kuhmo, Loviisa and Äänekoski – and their industries. The special interest was to study the potential image effects of the facility on the long run development of different industries such as agriculture, tourism, commerce and other industries, and local public economy. Earlier the effects have not been studied sufficiently.

MAIN ACHIEVEMENTS

- Negative image effects on the long run development of industries were bigger in Kuhmo and Äänekoski than Loviisa and Eurajoki, because in Kuhmo and Äänekoski there were more such kind of industries which are nature-sensitive. When the final disposal facility will probably be located at Eurajoki, other municipalities will manage to avoid these threatening negative externalities.
- The image of Eurajoki will become emphasized as the municipality of radiative high-tech industry. This means that in the future Eurajoki would specialize in big industries and intensive farming.
- The results of project have reported in the joint publication of project members. On the study results we have given a lecture in four seminars.

SCIENTIFIC STAFF

PhD (Economics)	Veli Karhu	project manager
MSc (Admin.)	Pasi Rentola	researcher
MSc (Admin.)	Matti Soronen	researcher

NAME OF THE PROJECT
Socio-economic and environmental impacts of nuclear waste management in municipalities

ORGANISATION	PROJECT MANAGER	PROJECT DURATION
VTT Communities and Infrastructure	Irmeli Harmaajärvi	1997 - 1999

VOLUME (person-months) AND FUNDING (1000 €) IN 1997 - 2001

VOLUME	KTM	STUK	OWN FUNDING	OTHER, e.g. EU	TOTAL
15	147[39]				147

GENERAL AIMS

The aim of the project was to define the most important socio-economic and environmental impacts and assess generally socio-economic impacts of locating a nuclear waste disposal plant in the possible location municipalities Eurajoki, Kuhmo, Loviisa and Äänekoski.

MAIN ACHIEVEMENTS

- supporting the work of the authorities and the EIA process in the municipalities
- promoting wide and open discussion
- definition of the most important socio-economic and environmental impacts in localities
- a general assessment of socio-economic impacts in the possible location municipalities
- participation in conferences in the Nordic countries
- a wide inquiry for the inhabitants about importance of possible impacts of a nuclear waste disposal plant (together with the University of Jyväskylä)
- participation in revising the series of reports for a non-technical audience, e.g. decision-makers, about the whole spent fuel management chain (VTT Energy)

SCIENTIFIC STAFF

MScTech	Irmeli Harmaajärvi	socio-economic and environmental impacts, project manager
MSc	Kimmo Koski	municipal economics
MPolSc	Heimo Tolsa	social impacts

[39] Part of the work (7 k€) was subcontracted to the University of Jyväskylä during 1997.

Annex B: List of most important publications

Technical studies

Nuclear waste managment and performance assessment methodology

Anttila, M., Björnberg, M. & Vuori, S. 1999. Alternatives for management of spent nuclear fuel in Finland. Continued long-term interim storage and nuclide transmutation. Helsinki: Ministry of Trade and Industry. 64 p. (Ministry of Trade and Industry, Studies and reports 10/1999). (in Finnish).

Broden, K., Carugati, S., Brodersen, K., Carlsson, T., Harmaajärvi, I., Viitanen, P., Vuori, S., Walderhaug, T., Boroddsson, B., Sneve, M., Hornkjol, S. & Backe, S. 1997. Safety in the final disposal of radioactive waste. Final report on the Nordic Safety Project AFA-1. NKS(97)FR3, 71 p. + app. 14 p. ISBN 87-7893-023-5

Broden, K., Carugati, S., Vuori, S., Walderhaug, T. & Sneve, M. 1998. Nordic project on disposal of radioactive waste. Valencia. TOPSAFE'98. TSE-3. Decontamination and Waste Treatment Techniques. 7 p.

Pescatore, C., Vieno, T. & Andersson, J. 1998. Deep geological disposal — Lessons learnt from recent performance assessment studies. NEA Newsletter. Vol. 16, no. 1, pp. 25 - 26.

Rasilainen, K. & Vuori, S. 1999. The management of spent nuclear fuel. Basic features of the Finnish plan. Espoo: Technical Research Centre of Finland. 50 p. + app. 7 p. (VTT Tiedotteita 1953. (in Finnish).

Rasilainen, K., Kattilakoski, E., Suolanen, V., Vieno, T. & Vuori, S. 2001. Some viewpoints on reference biospheres in Finnish performance assessments. IAEA Specialists' Meeting to Resolve Issues Related to the Preparation of Safety Standards on the Geological Disposal of Radioactive Waste. Vienna 18 – 22 June 2001. Proceedings. (in print).

Rasilainen, K., Luukkonen, A., Niemi, A., Olin, M., & Pöllä, J. 1999. The feasibility of modelling coupled processes in safety analysis of spent nuclear fuel disposal. Espoo: Technical Research Centre of Finland. 83 p. + app. 4 p. (VTT Research Notes 1973).

Rasilainen, K., Suolanen, V. & Vuori, S. 2000. The management of spent nuclear fuel. Basics of performance assessments. Espoo: Technical Research Centre of Finland. 57 p. (VTT Tiedotteita 2033). (in Finnish).

Rasilainen, K., Suolanen, V. & Vuori, S. 2001. The management of spent nuclear fuel. Illustration of radiation impacts calculated in performance assessments. Espoo: Technical Research Centre of Finland. 58 p. + app. 5 p. (VTT Tiedotteita 2080). (in Finnish).

Suolanen, V., Vuori, S. & Pöllänen, L. 1999. Risk analysis of spent fuel transportation related to EIA for repository site evaluation. Nuclear Europe Worldscan, no. 5 - 6, pp. 42 - 43.

Vuori, S. & Rasilainen K. 2001. Role of public sector's research programme in supporting the authorities and in building confidnce on the saftey of spent fuel disposal. Extended summary. NEA Forum on Stakeholder (FSC), 2nd FSC Workshop, Stakeholder Involvement and Confidence in the Process of Decision Making for the Disposal of Spent Nuclear Fuel in Finland. Turku, Finland, November 14 - 16. 2001. Proceedings. (in print).

Vuori, S. & Rasilainen, K. 2000. Public sector's research programme of spent fuel management in Finland supporting the authorities. In: Proceedings of an International Conference on Safety of Radioactive Waste Management. Córdoba, Spain, 13 - 17 March 2000. Vienna: IAEA. 5. p. Paper 25 in contributed papers.

Vuori, S. 1999. Present status and plans of the Finnish spent fuel management program and the ongoing environmental impact assessment for repository siting. Spent Fuel Management Seminar XVI. Washington, DC, 13 - 15 Jan. 1999. Washington: Institute of Nuclear Materials Management 1999. 15 p.

Vuori, S., Rasilainen, K. 1999. Finnish nuclear waste management programme. In: Litmanen, T., Hokkanen, P. & Kojo, M. (eds.) Nuclear waste in our hands. The Finnish nuclear waste management and the Finnish society. Jyväskylä: SoPhi. Pp. 238 - 249. (in Finnish).

Role of bedrock in disposal safety

Kuivamäki, A., Vuorela, P. & Paananen, M., 1998. Indications of postglacial and recent bedrock movements in Finland and Russian Karelia. Espoo: Geological Survey of Finland. 92 p. (Report YST-99).

Kuivamäki, A. Paananen, M. & Vuorela P. 2001. Postglacial faults and bedrock movements in Finland. Final report of investigations in 1987–2001. Espoo: Geological Survey of Finland. (Report YST-106). (under prep.)

Kukkonen, I. T., Suppala, I., Sulkanen, K., Lindberg, A., Hautojärvi, A., Raiko, H. & Johansson, E. 2001. Investigations on thermal properties of rocks at test sites for final disposal of spent nuclear fuel in Finland. In: Särkkä, P. & Eloranta, P. (eds.) Rock mechanics : a challenge for society : proceedings of the ISRM regional symposium EUROCK 2001. Espoo, Finland, 4 - 7 June 2001. A. A. Balkema, Lisse. Pp. 757 – 762.

Laine, E. 1998. Geostatistical, geological and geophysical modelling of subsurface structures of Precambrian bedrock in Finland. Espoo: Helsinki University of Technology, Laboratory of Engineering Geology and Geophysics. (Research Report TKK-IGE-A-23). (Doctoral Thesis).

Lindberg, A. & Hellmuth, K-H., 2001. On the nature of groundwater flow paths: observations at fractures and fracture coatings at road-cuts. Espoo: Geological Survey of Finland. 11 p. + 1 app. (Report YST-104).

Marcos, N,, Kivekäs, L. & Vanhala, H. 1998. Electrical properties of bentonite. In: Proceedings of the IV Meeting of Environmental and Engineering Geophysical Society. European Section. Albert Casas (ed.) Pp. 449 - 452. ISBN:84-8497-817-6.

Mursu, J. 1998. Modelling of gravity and magnetic anomalies related to fracture zones. Espoo: Helsinki University of Technology, Laboratory of Engineering Geology and Geophysics. 125 p. (Research Report TKK-IGE A19).

Niini, H. 1997. Mining and sustainable development. In: Papunen, H. (ed.) Mineral Deposits: Research and Exploration, Where do They Meet? Proceedings of the Fourth Biennial SGA Meeting. Turku, Finland 11 - 13 August 1997. Rotterdam: Balkema. Pp. 915 - 917 .

Niini, H. 1999. Exploration for deep disposal of high-level radioactive waste. Proceedings of the Nordic Mining and Mineral Processors Meeting. Askersund, Sweden, 25 - 27 August 1999. 7 p.

Niini, H. & Tuokko, T. 1998. Topography as an indicator for bedrock instabilities. Espoo: Helsinki University of Technology, Laboratory of Engineering Geology and Geophysics. 11 p. (Report IGE-JYT-7-98). (in Finnish).

Okko, O. & Front, K. 1999. Acoustic logs in the structural interpretation of the Hästholmen Rapakivi granite site. European Association of Geoscientists & Engineers 61st Conference and Technical Exhibition, EAGE´99. Helsinki, Finland 7 - 11 June 1999. Poster P055. Vol. 2. EAGE. Houten. 4 p.

Okko, O. 1998. On the development in digital engineering-seismic studies in Finland. Espoo: Technical Research Centre of Finland. 57 p. (VTT Publications 349). (Doctoral Thesis).

Paananen, M. 1997. Mise-à-la-masse method in structure investigations of crystalline rock. Espoo: Geological Survey of Finland. (Report YST-96). (Licentiate Thesis). (in Finnish).

Peltoniemi, M. & Mursu, J. 1999. Gravity and magnetic anomalies of deep fracture zones. European Association of Geoscientists and Engineers (EAGE). 61st Meeting. Helsinki, Finland. 6 – 11 June 1999. Extended Abstracts. Volume 2, p. 115. 4 p.

Peltoniemi, M. 1998. Depth of penetration of frequency-domain airborne electromagnetics in resistive terrains. Exploration Geophysics. Vol 29. no. 1 & 2, pp 12 - 15.

Hydrogeology and geochemistry

Ahonen, L., Luukkonen, A., Pitkänen, P., Rasilainen, K. & Ruskeeniemi, T. 2001. Ice ages and final disposal of nuclear waste (in Finnish) (in prep.).

Bath, A., Boulton, G., Marivoet, J. & Blomqvist, R. 2000. What approach and tools do we have for understanding the past evolution of groundwater systems as a guide to future evolution for repository performance assessment? In: Davies, C. (ed.) Euradwaste 1999: radioactive waste management strategies and issues: Fifth European Commission Conference on Radioactive Waste Management and Disposal and Decommissioning. Luxembourg 15 - 18 November 1999. Luxembourg: Office for Official Publications of the European Communities. (EUR 19143 EN). Pp. 257 - 273.

Blomqvist, R. 1999. Hydrogeochemistry of deep groundwaters in the central part of the Fennoscandian Shield. Espoo: Geological Survey of Finland. 41 pages, 11 figs. (Report YST-101). (Doctoral Thesis).

Blomqvist, R., Kaija, J., Lampinen, P., Paananen, M., Ruskeeniemi, T., Korkealaakso, J., Pitkänen, P., Ludvigson, J.-E., Smellie, J., Koskinen, L., Floria, E., Turrero, M., Galarza, G., Jakobson, K., Laaksoharju, M., Casanova, J., Grundfelt, B. & Hernan, P. 1998. The Palmottu natural analogue project Phase I: Hydrogeological evaluation of the site. Luxembourg: European Commission, Nuclear science and technology. 96 p. (EUR 18202 EN).

Blomqvist, R., Paananen, M., Korkealaakso, J., Pitkänen, P., Kattilakoski, E., Smellie, J. & Ludvigson J-E. 1998. Evaluation of local groundwater flow conditions at the Palmottu natural analogue site. In: Use of hydrogeochemical information in testing groundwater flow models. Workshop Proceedings. Borgholm, Sweden 1 – 3 September 1997. Paris: OECD NEA. Pp. 271 – 280.

Blomqvist, R., Ruskeeniemi, T., Kaija, J., Ahonen, L., Paananen, M., Smellie, J., Grundfelt, B., Bruno, J., Pérez del Villar, L., Rasilainen, K., Pitkänen, P., Suksi, J., Casanova, J., Read, D. & Frape, S. 2000. The Palmottu natural analogue project. Phase II: Transport of radionuclides in a natural flow system at Palmottu. Luxembourg: European Commission, Nuclear Science and Technology Series. 192 p. (EUR 19611 EN).

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Annex C: Organisation of the JYT2001 research programme

Steering group, and Co-operation groups for technical and social science studies of the Public Sector's Research Programme on Nuclear Waste Management JYT2001 (1997 - 2001)

Steering group of the JYT2001 research programme

Director	Tero Varjoranta	STUK	**chair**
Professor	Olavi Borg	TaY	member
Senior government secretary	Päivi Janka	KTM/E	member
Professor	Ullamaija Kivikuru	University of Helsinki, Swedish school of social science	member
Docent	Helena Mussalo-Rauhamaa	HYKS	member
Environmental consellor	Olli Pahkala	YM	member
Professor	Rainer Salomaa	TKK/TF	member
Professor	Jaakko Siivola	HYGL	member
Research scientist	Helena Valve	SYKE	member
Head of Nuclear Waste Section	Esko Ruokola	STUK	permanent expert
Managing director	Veijo Ryhänen	Posiva Oy	permanent expert
Senior adviser	Jorma Sandberg	KTM/E	permanent expert (1997-1999)
Senior adviser	Anne Väätäinen	KTM/E	permanent expert (1999-2001)
Chief research scientist	Seppo Vuori	VTT/ENE	**secretary,** programme leader

Co-operation group for the technical studies of the JYT2001 research programme

Head of unit	Paavo Vuorela	GTK	**chair**, project manager
Senior research scientist	Runar Blomqvist	GTK	project manager (1997-1999)
Professor	Timo Jaakkola	HYRL	project manager (1997-2000)
Professor	Jukka Lehto	HYRL	project manager (2001)
Senior research scientist	Antti Poteri	VTT/ENE	project manager (1997-2000)
Professor	Heikki Niini	TKK/IGE	project manager (1997-1998)
Professor	Markku Peltoniemi	TKK/IGE	project manager
Assistant	Antti Lempinen	TKK/MEK	project manager (1998-2001)
Senior research scientist	Petteri Pitkänen	VTT/YKI	project manager
Senior research scientist	Kari Rasilainen	VTT/ENE	**secretary**, project manager
Senior research scientist	Matti Valkiainen	VTT/KET	project manager (1997-2000)
Senior research scientist	Torbjörn Carlsson	VTT/KET	project manager (2001)
Chief research scientist	Seppo Vuori	VTT/ENE	programme leader, project manager
Senior adviser	Jorma Sandberg	KTM/E	contact person (1997-1999)
Senior adviser	Anne Väätäinen	KTM/E	contact person (1999-2001)
Head of Nuclear Waste Section	Esko Ruokola	STUK	contact person
Senior research scientist	Esko Eloranta	STUK	contact person
Senior research scientist	Karl-Heinz Hellmuth	STUK	contact person
Senior inspector	Kaj Jakobsson	STUK	contact person
Inspector	Kaisa-Leena Hutri	STUK	contact person (2000-2001)
Senior inspector	Risto Paltemaa	STUK	contact person
Senior inspector	Kirsti-Liisa Sjöblom	STUK	contact person (2000-2001)
Research director	Juhani Vira	Posiva Oy	observer

Co-operation group for the social science studies of the JYT2001 research programme

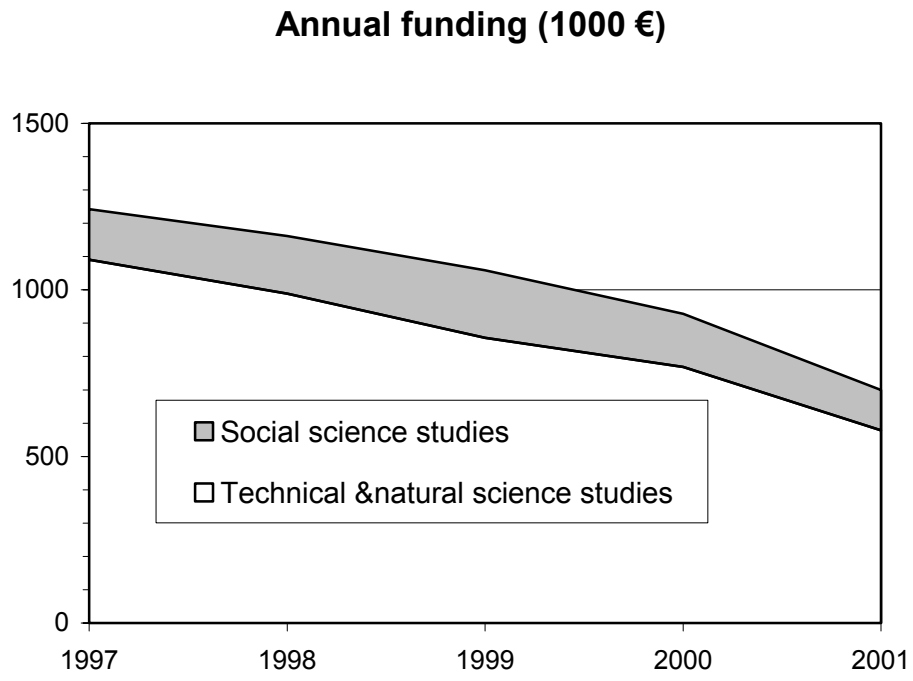
Docent	Ilkka Ruostetsaari	TaY	**chair**
Municipal manager	Juhani Niinimäki	Eurajoki municipality	member
City engineer	Hannu Huotari	Kuhmo city	member
Member of city board	Mikael Hafrén	Loviisa city	member
Mayor	Arto Lepistö	Äänekoski city	member
Information officer	Risto Isaksson	STUK	member
Senior adviser	Jorma Sandberg	KTM/E	contact person (1997-1999)
Senior adviser	Anne Väätäinen	KTM/E	contact person (1999-2001)
Research scientist	Helena Valve	SYKE	member
Chief research scientist	Seppo Vuori	VTT/ENE	member, programme leader
Senior research scientist	Irmeli Harmaajärvi	VTT/YKI	project manager (1997-1999)
Research scientist	Pekka Hokkanen	TaY	**secretary**, project manager
Senior assistant	Pentti Raittila	TaY	project manager (1999-2001)
Professor	Veli Karhu	TaY	project manager (1999)
Research scientist	Tapio Litmanen	JY	project manager

GTK	Geological Survey of Finland
HYGL	University of Helsinki, Department of Geology
HYKS	Helsinki University Central Hospital
HYRL	University of Helsinki, Laboratory of Radiochemistry
JY	University of Jyväskylä
KTM/E	Ministry of Trade and Industry, Department of Energy
STUK	Radiation and Nuclear Safety Authority
SYKE	Finnish Environment Institute
TaY	University of Tampere
TKK/IGE	Helsinki University of Technology, Laboratory of Engineering Geology and Geophysics
TKK/MEK	Helsinki University of Technology, Laboratory of Theoretical and Applied Mechanics
TKK/TF	Helsinki University of Technology, Department of Engineering Physics and Mathematics
VTT	Technical Research Centre of Finland
VTT/ENE	VTT Energy
VTT/KET	VTT Chemical Technology
VTT/YKI	VTT Communities and Infrastructure
YM	Ministry of Environment

Annex D: Funding of the JYT2001 research programme

The annual funding of the JYT2001 research programme is depicted in the diagram below. The Ministry of Trade and Industry (KTM) has provided the largest share (3.9 M€) of the funding. The Radiation and Nuclear Safety Authority (STUK) has funded the programme and related research topics by about 1 M€. The funding by STUK to the research programme was mostly directed to the Palmottu Natural Analogue Project, which was co-ordinated by the Geological Survey of Finland and partially funded by the Commission of the European Union. Roughly about 1 M€ of budget funding by the participating institutions was devoted for the support of this research programme.

The annual total research volume was at its maximum in the beginning of the research programme around 190 person-months and around 100 person-months at the end.



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Julkaisusarjan nimi ja tunnus
Tutkimuksia ja raportteja

Tekijät (toimielimestä: nimi, puheenjohtaja, sihteeri)
Kari Rasilainen (toim.)

Julkaisuaika
Toukokuu 2002

Toimeksiantaja(t)
Kauppa- ja teollisuusministeriö

Toimielimen asettamispäivä

Julkaisun nimi
Ydinjätehuolto Suomessa. Julkishallinnon ydinjätetutkimusohjelman JYT2001 (1997–2001) loppuraportti

Tiivistelmä
Ydinenergialain mukaan ydinjätteiden tuottajat ovat vastuussa jätteiden turvallisesta huollosta ja aiheutuvista kustannuksista. Ydinjäteyhtiö Posiva, jonka omistavat ydinenergiaa tuottavat voimayhtiöt, on vastuussa käytetyn ydinpolttoaineen huollosta Suomessa. Viranomaiset valvovat toimintaa ja antavat asiaan liittyviä määräyksiä. Julkishallinnon ydinjätetutkimusohjelma käynnistettiin viranomaisten tueksi tässä vaativassa työssä.

Tutkimusohjelman tavoitteena on ollut antaa viranomaisten käyttöön riippumatonta asiantuntemusta ja tutkimustuloksia, joita nämä tarvitsevat toiminnassaan. Painopiste oli käytetyn ydinpolttoaineen geologisessa loppusijoituksessa. Tutkimusalue jaettiin (1) loppusijoituksen turvallisuutta selvittäviin teknisiin tutkimuksiin ja (2) yhteiskuntatieteellisiin tutkimuksiin. Tekniset tutkimukset kattoivat kallioperän geologisen käyttäytymisen, kallioperän hydrogeologian ja geokemian, bentoniittipäästöesteen stabiilisuuden ja radionuklidien leviämisen kallioperässä. Näiden lisäksi tutkittiin ydinjätehuollon turvallisuusanalyysimetodiikkaa, käytetyn polttoaineen huollon vaihtoehtoisia tekniikoita sekä ydinjätehuollon kustannuksia. Yhteiskuntatieteelliset tutkimukset keskittyivät periaatepäätösprosessin (PAP) ja siihen kuuluvan ympäristövaikutusten arvioinnin (YVA) seurantaan sekä mielikuva- ja mediakysymyksiin.

JYT2001-tutkimusohjelma on tukenut viranomaisia merkittävällä tavalla sekä turvallisuusteknisissä että yhteiskunnallisissa kysymyksissä. Eduskunta vahvisti toukokuussa 2001 valtioneuvoston periaatepäätöksen käytetyn polttoaineen loppusijoituslaitoksen rakentamiseksi Eurajoen Olkiluotoon; Posiva oli jättänyt PAP-hakemuksensa vuonna 1999. Posivasta riippumattoman ja uskottavan JYT2001-tutkimusohjelman olemassaolo on osaltaan edistänyt suomalaista ydinjätehuoltoa kohtaan tunnettua luottamusta.

Ydinjätehuollon ohjelman mukaan seuraavat merkittävät osatavoitteet Suomessa ovat loppusijoituslaitoksen rakentamisluvan käsittely noin vuonna 2010 ja käyttölupakäsittely noin vuonna 2020. Tavoitteiden saavuttaminen edellyttää kuitenkin merkittävää tutkimuspanosta jatkossakin.

KTM:n yhdyshenkilö: Energiaosasto/Anne Väätäinen, puh. (09) 1606 4836

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Titel
Kärnavfallshanteringen i Finland. Slutrapport om den offentliga sektorns forskningsprogram JYT2001 (1997–2001)

Referat
Enligt kärnenergilagen är producenterna av kärnavfall ansvariga för alla åtgärder föranledda av kärnavfallshanteringen och kostnaderna för dessa. Bolaget Posiva, som ägs av kärnkraftbolagen, är ansvarigt för hanteringen av använt kärnbränsle i Finland. Myndigheterna övervakar kärnavfallshanteringen och ger ut bestämmelser för detta syfte. Den offentliga sektorns forskningsprogram för kärnavfall grundades för att ge stöd för myndigheterna i deras krävande arbete.

Huvudsyftet med forskningsprogrammet var att förse myndigheterna med oberoende expertis och relevanta forskningsresultat. Tyngdpunkten låg på geologisk slutförvaring av använt kärnbränsle. Forskningsprogrammet indelades i (1) tekniska studier rörande säkerhetsaspekterna kring avfallshanteringen och (2) samhällsvetenskapliga studier. De tekniska studierna täckte berggrundens geologiska beteende, berggrundens hydrogeologi och geokemi, bentonitbarriärens stabilitet och radionuklidernas spridning i berggrunden. Därtill studerades slutförvarets säkerhetsanalysmetodik, alternativa tekniska metoder för hanteringen av använt kärnbränsle, och kostnadsfrågor. De samhällsvetenskapliga studierna omfattade observation av principbeslutsprocessen, inkluderande förfarandena i slutförvarsanläggningens miljökonsekvensbedömning, samt media- och imagefrågor.

JYT2001 har kunnat ge myndigheterna betydande stöd i säkerhetstekniska och samhälleliga frågor. Riksdagen bekräftade i maj 2001 statsrådets principbeslut beträffande Posivas ansökan om slutförvarsanläggning för använt kärnbränsle i Olkiluoto i Euraåminne kommun. Det faktum, att det fanns ett trovärdigt forskningsprogram JYT2001, oberoende av Posiva, har sannolikt medverkat till att skapa det höga förtroendet för det finska hanteringsprogrammet för kärnavfall.

Enligt nuvarande planer är nästa betydande etapper i den finska kärnavfallshanteringen byggtillståndsansökan för slutförvarsanläggningen i Olkiluoto ungefär 2010 och drifttillståndsansökan ungefär 2020. Det behövs dock mycket forskning också i framtiden för att nå dessa ambitiösa mål.

Nyckelord
kärnavfallshantering, använt kärnbränsle, slutförvaring, säkerhet, miljökonsekvensbedömning

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