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Swedish deep repository siting programme

Guide to the documentation of 25 years of geoscientific research (1976–2000)

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Abstract

Since the mid-1970s, the Swedish Nuclear Fuel and Waste Management Company (SKB) has been carrying out geoscientific research and feasibility studies aimed at identifying suitable sites for deep repositories in the Precambrian basement of the Baltic Shield. The documentation of this research effort forms an extensive body of material which is exceptionally wide-ranging and which is generally little known outside the Swedish nuclear waste community. This has now been compiled in the form of a "documentation guide" in order to make the research results more easily accessible to the scientific community at large, and to show how they relate to their "nearest surroundings", i.e. the relevant academic scientific literature and the documentation of similar research by other institutions, in Sweden and in other countries (Finland, Canada). The documentation covers the period 1976–2000 and contains ca. 850 citations, of which about half are technical reports published by SKB and its forerunners. In the main body of the guide (Chapters 2–9), the material is arranged thematically and the scope of the documentation in each theme is described and commented in short texts, showing the interrelationships between the individual reports and scientific papers, with appropriate cross-references. Early chapters (2–5, and 7) cover general themes: bedrock geology, fracturing, glaciation and crustal dynamics, deep groundwater, and geosphere transport, each subdivided into citation groups under headings which are of particular interest to the Swedish deep repository siting programme. Later chapters (6, and 8–9) include thumb-nail sketches of the Swedish study sites (Finnsjön, Fjällveden, Gideå, Kamlunge, Klipperås, Sternö), the underground laboratory sites of Stripa and Äspö, and comparable sites in Finland and Canada, as well as the complete documentation to the feasibility studies carried out in eight Swedish municipalities between 1993 and 2000 (Storuman, Malå, Nyköping, Östhammar, Oskarshamn, Tierp, Älvkarleby, Hultsfred). As added background, Chapter 10 contains a compilation of SKB conceptual studies and planning documents, and related material from other Swedish institutions. A complete bibliography is appended as the final chapter.

Sammanfattning

Sedan mitten av 1970-talet har Svensk Kärnbränslehantering AB (SKB) och dess föregångare genomfört geovetenskaplig forskning och förstudier, med målet att finna lämpliga områden för djupförvar i den svenska delen av Baltiska Sköldens prekambriska berggrund. Dokumentationen av denna forskning är omfattande och täcker ett mycket brett forskningsfält, men är i allmänhet föga känd utanför interessesfären kring svensk kärnavfallshantering. Materialet har nu sammanställts i denna "dokumentationsguide" för att därmed göra forskningsresultaten mera lättillgängliga för vetenskapssamhället i stort. Dessutom visas hur materialet anknyter till relevant vetenskaplig litteratur och dokumentation av likartad forskning utförd av andra institutioner i Sverige och andra länder (Finland och Kanada).

Dokumentationen täcker perioden 1976–2000 och innehåller cirka 850 referenser, av vilka ungefär hälften är tekniska rapporter publicerade av SKB eller dess föregångare. I guidens huvuddel (kapitlen 2–9) är materialet tematiskt organiserat och dokumentationens omfång inom varje tema beskrivs och kommenteras i korta texter. Dessutom förklaras inbördes samband mellan olika rapporter och vetenskapliga publikationer och relevanta korsreferenser ges. De inledande kapitlen (2–5 och 7) täcker generella teman: berggrundsgeologi, sprickbildning, nedisning och jordskorpans dynamik, djupt grundvatten och transport av radionuklider i geosfären. Varje tema är indelat i citeringsgrupper under rubriker som är av speciellt intresse för det Svenska djupförvarsprogrammet. De följande kapitlen (6 och 8–9) inkluderar korta beskrivningar av SKB:s typområden (Finnsjön, Fjällveden, Gideå, Kamlunge, Klipperås, Stenö), underjordslaboratorierna i Stripa och Äspö, och av jämförbara objekt i Finland och Kanada. Här ingår också den kompletta dokumentationen från de förstudier som utförts i åtta kommuner mellan 1993 och 2000 (Storuman, Malå, Nyköping, Östhammar, Oskarshamn, Tierp, Älvkarleby, Hultsfred). Som bakgrundmaterial ger kapitel 10 en sammanställning av SKB:s metodstudier och planeringsdokument och relaterat material från andra svenska institutioner. En komplett bibliografi bifogas i kapitel 11.

Contents

1 Introduction

Background

A deep repository is planned to be built at a depth of ca. 500 m in the bedrock as an important component in the Swedish system for the management of spent fuel from the nuclear power stations. As part of the siting programme for the deep repository, the Swedish Nuclear Fuel and Waste Management Company (SKB) has been carrying out feasibility studies ("Förstudier") in eight different municipalities, with a view to identifying suitable areas for more detailed investigation (including deep drilling). Two of the feasibility studies (Storuman and Malå) were completed in 1995 and 1997 respectively, and the remaining six (Östhammar, Nyköping, Oskarshamn, Hultsfred, Tierp, Älvkarleby) in year 2000. In December 2000, SKB published a report stating where they want to conduct more detailed investigations (site investigations) and how these investigations would be carried out. The report has later been subject to review by the safety authorities followed by a decision by the Swedish government, authorising SKB to proceed to site investigations. The process of obtaining permission by the municipalities concerned is currently under way. SKB expects to be able to commence the site investigations in 2002.

An important component in the feasibility studies consisted of a compilation of all available geoscientific information for the municipality in question and its interpretation in terms of favourable areas for carrying out further investigations. This interpretation, or expert judgement, as to where, from a geoscientific point of view, to carry out further investigations in the search for a safe deep repository, is itself based on the accumulated knowledge from about 25 years of problem-oriented research by SKB, as well as on the general geoscientific basis provided by the Geological Survey of Sweden (SGU) and Swedish academic institutions. The research supported and carried out by SKB since the mid-1970s forms an extensive body of material which is exceptionally wide-ranging and is generally little known outside the nuclear waste community. Hence, although the compilation of SKB's geoscientific documentation was carried out in support of the siting programme it was thought that it could also be of wider interest. For this reason, the material has been compiled in the form of the present "Documentation Guide", an attempt to make it more accessible to the geoscience community at large, and to make this specialised aspect of the siting process in Sweden more easily subjected to the necessary scientific scrutiny.

Content of report

The Documentation Guide itself is contained in Chapters 2–9 of this report. The geoscientific background material is arranged thematically and the scope of the documentation in each theme is commented in short texts, with appropriate cross-references. As a backcloth to this scientific work, documents concerned with the broader context of the siting process in Sweden – programmes, plans, reviews, etc., and reports of more general interest – are collected and grouped in Chapter 10. All documents are then listed alphabetically according to first author in the Bibliography (Chapter 11) in the conventional way. The material covered is as follows:

- All KBS, SKBF/KBS and SKB Technical Reports, and SKB reports in the Projektrapport and Rapport series, which fall within the area of geoscience in the broad sense, together with a selection of reports from the Stripa and Äspö HRL projects.
- Recent SKB-supported doctoral and licentiate theses of geoscientific nature.
- A selection of recent SKB and SKI reports of more general nature related to the siting process and site characterisation, including performance and safety assessment studies (e.g. Site-94, SR-97), and related studies by other Swedish institutions (SSI, KASAM, SKN, etc.).
- A selection of reports from the Finnish and Canadian programmes, where Precambrian crystalline rocks similar to those in the Swedish bedrock have also been studied as hosts for a deep repository.
- A selection of scientific papers on relevant aspects of Swedish geoscience, mostly published later than 1990 and including many papers based on SKB-supported research.

The SKB documentation itself has been worked through systematically, up to and including year 2000, whereas material from other sources has been more selective. A few SKB reports which were published in 2001 have been included, where they conclude and summarise long-standing projects. With regard to what has *not* been included, the lines have been drawn as follows. Most technical reports which are mainly of a theoretical nature, including numerical modelling which was not directly tied to the conditions at a particular site, have not been included. Similarly, most experimental studies in which the aim was to simulate supposed repository conditions or to develop methods related to repository design and construction were excluded. These limitations were introduced because the primary motivation behind the work was to provide a geoscientific background report in support of the siting process, not an overview of all SKB's scientific and technical work. Another limitation is that only reports of SKB's Technical Report, Projektrapport and Rapport series have been included, or equivalent publications of other institutions. All progress and working reports (e.g. SKB's Arbetsrapport series) have been omitted, although these are often cited in the Technical Reports and are therefore, in principle, publically available. This limitation was made in order to reduce the number of documents to manageable proportions, on the assumption that, in most cases, the results reported in the working documents were eventually published in some form in Technical Reports. Some exceptions have been made to this rule when this seems not to have been the case. Even with these limitations, the Bibliography contains about 850 citations, of which about half are publications of SKB and its forerunners.

Report structure

In the main body of the report, the documents are arranged in Chapters according to general themes, and the listings in each Chapter are arranged in Sections and Subsections according to content. A short text is included at the beginning of each Chapter (except Chapter 10), explaining the subdivision into Sections. A brief overview is given at the beginning of each Section and Subsection, describing the character of the documentation, outlining interrelationships between individual citations, and, perhaps most important, giving cross-references to other parts of the guide. The arrangement of the citations in the Section and Subsection lists corresponds to the order in which they are cited in these brief explanatory texts. In Chapters 2–10, the same document may be cited in more than one Section, reflecting its importance for different themes, whereas each citation only occurs once in the Bibliography. The content of the Chapters can be briefly summarised as follows:

Chapter 2: Bedrock
GEOTAB/SICADA data base, host rock characterisation, petrography, heterogeneity, etc., and reports/papers on the evolution and formation of the Precambrian crystalline basement in Sweden (Baltic Shield).

Chapter 3: Fracturing
Lineament analysis, block structure, fault patterns (onshore, offshore), fracture system and fracture zone characterisation, etc., and reports/papers on the post-cratonisation history of the Baltic Shield.

Chapter 4: Glaciation and crustal dynamics
Quaternary-Recent geology, climatic change, past and future glaciation of Scandinavia, neotectonics, seismicity, heat flow, *in situ* stress, etc., and reports/papers on glacio-isostasy and its relation to seismicity.

Chapter 5: Deep groundwater
Hydraulic conductivity of crystalline rocks, regional patterns of groundwater flow in Sweden, hydrogeochemistry, interface freshwater/seawater, microbiology of deep groundwater, etc., and reports/papers on the hydrogeological effects of glaciation, seismicity, etc.

Chapter 6: Underground conditions
Experience from SKB study sites, predicting underground relationships, deep drilling, seismic interpretation, etc., tunnelling and underground caverns, underground conditions in general (depth dependency, low-angle fracture zones, fracture hydrology, stress, etc.), Stripa and Äspö underground laboratories, etc.

Chapter 7: Transport of radionuclides in the geosphere
Reports on natural analogues of radioactive waste repositories (Oklo, Cigar Lake, Palmottu, etc.), and a selection of reports on the results of sorption/migration experiments in underground laboratories.

Chapter 8: SKB's siting programme
Historical overview, national/regional surveys, feasibility studies at county scale (SGU's "Länsstudier"), and feasibility studies at municipality scale ("Förstudier").

Chapter 9: Comparable programmes
Selection of reports from the Finnish and Canadian programmes, with particular emphasis on the siting process and site characterisation.

Chapter 10: Broader context
SKB conceptual and programmatic material relating to the KBS-3 concept, alternative concepts, site selection programme, scenario development, safety analysis (SR-97), etc., SKI's performance assessment project (SITE-94), SKI's and other reviews of SKB's activities and planning.

This report is in principle a guide to SKB-sponsored geoscientific research over the past 25 years. The main emphasis is on the arrangement of all geoscience-related technical reports published by SKB in a logical framework, and on showing how they are related to each other and to their "nearest surroundings" (scientific literature, Finland, Canada, SKI, etc.). In some traditional areas, SKB has relied heavily on research results published in the scientific literature, where geoscientists at the universities have been engaged in studies which are particularly relevant to SKB concerns. This is particularly the case for the first three themes (Chapters 2–4): in these cases, a list of "Selected scientific papers" and a brief commentary are added. The aim was to complement the problem-oriented research reported in the SKB documents with some coverage of the regional geological background to SKB research, as it appears in the scientific literature. In the remaining Chapters, relevant scientific papers, particularly those based on research sponsored by SKB, are entered together with the SKB documents in the appropriate categories.

Acknowledgments

Help has been received from many sides, for which I am very grateful. Bengt Leijon (SKB) initiated the project and kept it running on the right track, giving generously from his wide experience in numerous discussions and in his comments on various drafts. Sven Follin (GeoLogic SF), John Smellie (Conterra), and Rune Johansson and Michael Stephens (both SGU) made detailed comments on different parts of the texts and helped considerably with important literature which would otherwise have been missed. Others whose comments and added references were greatly appreciated include Fred Karlsson and Karl-Erik Almén (both SKB), Lars O Ericsson (Chalmers) and Lennart Ekman (LE Geokonsult). My thanks are due to all these colleagues for their invaluable contributions. I also thank Håkan Sjöström (Uppsala University) for translating the English abstract into Swedish.

2 Bedrock

The siting process in Sweden takes as its starting point the KBS-3 method of deep disposal – disposal of encapsulated spent nuclear fuel in rock caverns at ca. 500 m depth in the Swedish bedrock (Chapter 10). There seems to be some degree of consensus that "bedrock" in this context means crystalline rock of Precambrian age belonging to the Baltic Shield. At an early stage, however, certain areas adjacent to the Baltic Shield were excluded from further consideration (Chapter 8, Section 8.1). This concerns (1) the Precambrian basement covered by the Caledonian nappes in western Norrland, (2) the strongly faulted southern margin of the Baltic Shield in Skåne, and (3) the basement covered by a thick sequence of Palaeozoic rocks on the island of Gotland. At a later stage, also areas judged to be of high ore potential were excluded, on the basis of more detailed study (Chapter 8, Sections 8.2 and 8.3). For the present purposes, bedrock refers to Precambrian crystalline rocks lying outside the above areas.

A modern overview of the rock types and formation processes of the Swedish Precambrian are given in the volume "Berg och jord" of the Swedish National Atlas, in the chapter "Berggrunden", under the heading "Sveriges urberg – en del av den Baltiska skölden" (*Fredén (ed.) 1994*, p. 14–21 – in the present report, the Swedish edition will be referenced, rather than the English edition, which was also published in 1994 with the title "Geology"). Petrographical and geochemical descriptions of the different rock types in the bedrock are spread throughout the scientific literature, including numerous SGU publications, and occur in many diploma and doctoral theses. No attempt has been made by SKB to compile and summarise this enormous body of data. Rather, this published database is regarded as a general background of experience against which to set the detailed descriptions of individual objects, particularly individual outcrops, trenches, shorelines, drill cores and tunnels, at various sites and in various research areas. These detailed descriptions were originally stored in SKB's geodatabase, GEOTAB, which is described in the reports listed below (Section 2.1), and later in the data base SICADA (<u>Si</u>te <u>C</u>h<u>a</u>racterisation <u>Da</u>tabase), which was set up to store the site investigation data from Äspö HRL (Section 6.3).

"Crystalline rock" is the general name given to rocks similar to those occurring in Swedish bedrock, the geological environment in which the KBS-3-type repository for spent fuel in Sweden is to be built. "Crystalline" refers to the grained texture which most rocks in the Swedish bedrock show, independent of the different types of minerals (mainly silicates) they contain. The grained texture derives from the slow cooling of molten, semi-molten or highly tempered silicate rocks and minerals, formed deep in the Earth's crust during Precambrian times (Section 2.5) and subsequently uplifted and eroded to their present positions (cf. *Fredén (ed.) 1994*). Because of their crystallization and/or recrystallization under high temperatures and pressures, crystalline rocks typically show very low porosity and relatively high strength (positive attributes), a propensity to deform by fracturing when brought up to the Earth's surface (negative attribute), and complex, poorly predictable behaviour in relation to geological structure and migrating fluids (anatexis, ore deposits, hydrothermal alteration, deep groundwater, etc.).

Many bodies of crystalline rock complexes are compositionally heterogeneous and structurally complex features which can only be discussed in relation to detailed lithological characterisation of individual localities. However, the documentation in this category can be roughly subdivided into three groups based on first-order differences in composition and structure:

- **Massive felsic rock**: crystalline rock dominated by light silicate minerals such as feldspar, quartz and white mica (felsic minerals), usually without strong mineral alignment and usually without strong compositional banding (”massive” means lacking foliation and banding). These rocks are generally part of large and relatively homogeneous igneous intrusions (Section 2.2).
- **Foliated/banded felsic rock**: crystalline rocks with mineral alignment (foliation due to aligned micas, amphiboles, mineral aggregates, etc.) and/or compositional banding on different scales with a wide spectrum of lithologies (but dominantly felsic). These rocks are generally part of strongly folded, metamorphic and/or migmatitic complexes, whose original material (protolith) may be sedimentary or magmatic (volcanic or plutonic) in origin (Section 2.3).
- **Massive or foliated mafic rock**: crystalline rock characterized by lack of quartz and predominance of dark minerals such as pyroxene, amphibole and biotite (mafic minerals). These rocks generally occur in much smaller bodies than the above, and the massive and foliated occurrences are not separated in the citations below (Section 2.4).

Of these groups, the first two (Sections 2.2 and 2.3) are represented here by a selection of site descriptions, as examples of the variability of petrographic relationships which are found almost everywhere in Swedish bedrock (for complete documentation, see Chapter 6, and for further descriptions, see Chapter 8). The third group (Section 2.4) represents a special type of crystalline rock, which, although not as widespread as the others, was thought at one time to show special advantages. These did not turn out to be critical enough to justify abandoning felsic rock as a prospective host rock. At present, all crystalline rocks are regarded as potential hosts, depending on local conditions, particularly the degree of fracturing (see Chapter 3) and the extent to which fracturing is controlled by lithology and structure. This position is supported, at least for the felsic crystallines, by recent safety analyses for Precambrian bedrock sites (SR97 – Subsection 10.1.2; TILA-99 – Subsection 9.1.3), which seem to suggest that the different characteristics of the rock matrix have little influence on the outcome of the modelling.

The final group in Chapter 2, Section 2.5, gives a selection of scientific papers dealing with crustal processes and the formation of the bedrock in Precambrian times. This has been a central object of scientific research in Sweden since the early beginnings and is still the subject of heated discussion, even today. A selection of recent papers on the subject is therefore included, as background to the descriptions in the reports cited in Sections 2.2–2.4, and as general background to Chapters 2, 6 and 8.

Fredén, C. (ed.), 1994. **Berg och jord**. Sveriges Nationalatlas.

2.1 Data acquisition and storage

There are few specific reports on crystalline rocks as hosts for KBS-3-type repositories in the SKB documentation. This is presumably because generalities would be banal, and specifics have been treated *in extenso* in the large body of SGU and scientific literature on the Precambrian basement of Sweden. However, SKB has collected a huge amount of information, now incorporated in numerous published and unpublished reports, which is exceptionally comprehensive and would not have been available if it had not have been for SKB activities. Research at the SKB study sites, preceding the activities of the siting programme, alone yielded 39 000 m of rock core from a total of about 75 drillholes, in addition to detailed surface data (detailed geological mapping, e.g. of trenches, geophysical surveys, etc.), downhole geophysical logging, hydrogeological testing, etc.. In the northeastern part of Oskarshamn municipality (Subsection 8.3.5), the amount and depth of subsurface data acquired in connection with SKB activities (Kråkemåla, Laxemar, Ävrö, CLAB, Äspö HRL), including 15 000 m of rock core and more than 4 kilometres of tunnels and shafts, must be unique world-wide (Section 6.3, Subsection 6.1.7). Already during the 80s, it became clear that the storage and retrieval of such large quantities of data required a sophisticated electronic system, which developed into SKB's database GEOTAB (*Sehlstedt 1988, Stark 1988, Eriksson, E. et al 1992*). This was replaced in the earlier 90s with the more powerful SICADA system (Site Characterisation Database, e.g. *SKB 1999f*), to deal with the even stronger data flood which was expected to arise from the construction of the Äspö tunnel and underground laboratory, and all later site investigations. In addition to the electronic systems, however, it was deemed necessary to present regular overviews of the scope of activities, essentially to inform on what data the databases contained, how, why and when the data was acquired, and where the initial data processing was reported (mainly in the form of internal SKB reports). In the case of the study sites, these overviews were presented in 1991–1992 (*Ahlbom et al 1991a, 1991b, 1992a, 1992b, 1992c, 1992d*, see Section 6.1). A detailed overview of the Äspö investigations 1986–1995 is to be found in *Stanfors et al 1997a.*

Sehlstedt, S., 1988. **Description of geophysical data on the SKB database GEOTAB.** SKB TR 88-05, Svensk Kärnbränslehantering AB.

Stark, T., 1988. **Description of geological data in SKBs database GEOTAB**. SKB TR 88-06, Svensk Kärnbränslehantering AB.

Eriksson, E., Johansson, B., Gerlach, M., Magnusson, S., Nilsson, A.-C., Sehlstedt, S., Stark, T., 1992. **GEOTAB. Overview.** SKB TR 92-01, Svensk Kärnbränslehantering AB.

SKB 1999f. **Äspö Hard Rock Laboratory. Annual Report 1998.** SKB TR 99-10, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, J.-E., Nordqvist, R., Ljunggren, C., Tirén, S.A., Voss, C., 1991a. **Gideå study site. Scope of activities and main results.** SKB TR 91-51, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, J.-E., Nordqvist, R., Ljunggren, C., Tirén, S.A., Voss, C., 1991b. **Fjällveden study site. Scope of activities and main results.** SKB TR 91-52, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, J.-E., Nordqvist, R., Ljunggren, C., Tirén, S.A., Voss, C., 1992a. **Sternö study site. Scope of activities and main results.** SKB TR 92-02, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, J.-E., Andersson, P., Ittner, T., Ljunggren, C., Tirén, S.A., 1992b. **Kamlunge study site – Scope of activities and main results.** SKB TR 92-15, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, J.-E., Andersson, P., Ittner, T., Ljunggren, C., Tirén, S.A., 1992c. **Klipperås study site. Scope of activities and main results.** SKB TR 92-22, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, J.-E., Andersson, P., Ittner, T., Ljunggren, C., Tirén, S.A., 1992d. **Finnsjön study site. Scope of activities and main results.** SKB TR 92-33, Svensk Kärnbränslehantering AB.

Stanfors, R., Erlström, M., Markström, I., 1997a. **Äspö HRL – Geoscientific evaluation 1997/1. Overview of site characterisation 1986–1995.** SKB TR 97-02, Svensk Kärnbränslehantering AB.

2.2 Massive felsic rock (granite, etc.)

The usual name for massive felsic rock is "granite" or "granitoid", but many of the rock types under consideration are not granitic in the petrographic sense (too little quartz). The more general name "felsic" is preferred here because it can include all lithologies which are dominated by light minerals (feldspars + quartz), whether or not they are plutonic (as the name granite implies). Massive implies a lack of mineral orientation, although at many of the localities listed below, the rocks often show a vague alignment which may be magmatic or may be due to weak post-consolidation deformation. At some localities, the rock bodies are intersected by narrow high-strain (mylonitic) zones, although these are subsidiary compared to the large volume of massive rock (e.g. Äspö, Kivetty). It should also be noted that plutonic "granitoids" are generally intersected by aplitic to pegmatitic vein systems, which, because of their different reaction to fracturing, may locally be of hydrogeological significance. Some localities also show a significant number of later mafic dykes (e.g. Klipperås). As examples of localities dominated by "massive felsic rocks", six of the main Swedish and Finnish study sites are listed in the following table, with brief summaries of the dominant rock types, a key citation, and a cross-reference to their Subsection in this guide (where a complete list of citations will be found). Of these localities, Äspö (Aberg), Kivetty and Hästholmen have been the objects of safety analyses, with positive outcome.

Kamlunge	Lina granite (about 40% of map area), intruded into a metamorphic/migmatitic rock complex	*Ahlbom et al 1983b,* see Subsection 6.1.4
Klipperås	Småland granite, locally weakly foliated	*Olkiewicz & Stejskal 1986,* see Subsection 6.1.5
Stripa	Granite	*Olkiewicz et al 1978*, see Section 6.2
Äspö	Complex mixture of Småland granite, Äspö diorite and aplite, often weakly foliated (well-foliated in Äspö shear zone)	*Rhén et al 1997c,* see Section 6.3
Kivetty	Porphyritic and even-grained granite and granodiorite	*Anttila et al 1999b,* see Subsection 9.1.2
Hästholmen	Rapakivi granite, coarse-grained, often orbicular	*Anttila et al 1999a,* see Subsection 9.1.2

Ahlbom, K., Albino, B., Carlsson, L., Danielsson, J., Nilsson, G., Olsson, O., Sehlstedt, S., Stejskal, V., Stenberg, L., 1983b. **Evaluation of the geological, geophysical and hydrogeological conditions at Kamlunge.** SKBF/KBS TR 83-54, Svensk Kärnbränsleförsörjning AB.

Olkiewicz, A., Stejskal, V., 1986. **Geological and tectonical description of the Klipperås study site.** SKB TR 86-06, Svensk Kärnbränslehantering AB.

Olkiewicz, A., Hansson, K., Almén, K.-E., Gidlund, G., 1978. **Geologisk och hydrogeologisk grund-dokumentation av Stripa försöksstation.** KBS TR 63, Svensk Kärnbränslehantering AB.

Rhén, I., Gustafson, G., Stanfors, R., Wikberg, P., 1997c. **Äspö HRL – Geoscientific evaluation 1997/5. Models based on site characterisation 1986–1995. S**KB TR 97-06, Svensk Kärnbränslehantering AB.

Anttila, P., Ahokas, H., Front, K., Heikkinen, E., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M.V., Wikström, L., Öhberg, A., 1999b. **Final disposal of spent nuclear fuel in Finnish bedrock – Kivetty site report**. Posiva Oy, report 99-09.

Anttila, P., Ahokas, H., Front, K., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M.V., Wikström, L., Öhberg, A., 1999a. **Final disposal of spent nuclear fuel in Finnish bedrock – Hästholmen site**. Posiva Oy, report 99-08.

2.3 Foliated felsic rock (migmatite, metamorphite)

The rocks in this group are typically both anisotropic (showing well-developed mineral alignment) and heterogeneous (showing well-developed segregation of minerals into bands and bodies of different composition). This, together with the fact that they are mainly felsic (dominated by the light minerals feldspar + quartz), means that they are usually referred to as gneiss. They are mainly high-grade metamorphic rocks (subjected to high temperatures and pressures at depth under long periods of time) and migmatites (subjected to partial melting at even higher temperatures and pressures, or due to the availability of fluids). The anisotropy and compositional banding is due to strong ductile deformation before, during and/or after metamorphism and migmatization, which often leads to complex folding and interleaving of originally distinct rock types. The rock complexes are generally roughly classified according to these original rocks (protoliths), into sedimentary, volcanic or plutonic metamorphites and migmatites. In Sweden, metamorphic and migmatitic rocks of sedimentary and volcanic origin are called "ytbergarter" and those of plutonic origin are called "djupbergarter". These names refer to the protoliths – all rocks in this group were at a later stage drawn down to great depths and transformed into the crystalline rocks we see today. In the sites listed below, some are dominated by "ytbergarter" (Fjällveden, Gideå, Olkiluoto) and others are dominated by "djupbergarter" (Sternö, Finnsjön, Romuvaara). Common to all of them is that they have been little affected by deformation since the period of metamorphism and migmatization, and hence have retained their crystalline textures. As in the localities cited in Section 2.2, some of those below show a significant number of mafic dykes, intruded into the gneisses after consolidation (Sternö, Gideå, Romuvaara). As examples of localities dominated by "foliated felsic rocks", six Swedish and Finnish study sites are listed in the following table, with brief summaries of the dominant rock types, a key citation and a cross-reference. Of these localities, Gideå (Ceberg), Finnsjön (Beberg), Olkiluoto and Romuvaara have been the objects of safety analyses, with positive outcome.

Sternö	Blekinge Coastal Gneiss (foliated granodiorite)	*Ahlbom et al 1979,* see Subsection 6.1.6
Fjällveden	Migmatitic sedimentary gneiss with some granitic gneiss layers	*Ahlbom et al 1983d,* see Subsection 6.1.2
Gideå	Migmatitic sedimentary gneiss	*Ahlbom et al 1983a,* see Subsection 6.1.3
Finnsjön	Foliated granodiorite	*Ahlbom & Tirén 1991,* see Subsection 6.1.1
Olkiluoto	Migmatitic sedimentary gneiss with infolded tonalitic gneiss and some post-migmatitic granitoids	*Anttila et al 1999c,* see Section 9.1.2
Romuvaara	Archean migmatized tonalitic gneiss with sedimentary gneiss zone, some contacts mylonitized	*Anttila et al 1999d,* see Section 9.1.2

Ahlbom, K., Carlsson, L., Gidlund, G., Klockars, C.-E., Scherman, S., Thoregren, U., 1979. **Utvärdering av de hydrogeologiska och berggrundsgeologiska förhållandena på Sternö.** SKBF/KBS TR 79-09, Svensk Kärnbränsleförsörjning AB.

Ahlbom, K., Carlsson, L., Carlsten, L.-E., Duran, O., Larsson, N.-Å., Olsson, O., 1983d. **Evaluation of the geological, geophysical and hydrogeological conditions at Fjällveden.** SKBF/KBS TR 83-52, Svensk Kärnbränsleförsörjning AB.

Ahlbom, K., Albino, B., Carlsson, L., Nilsson, G., Olsson, O., Stenberg, L., Timje, H., 1983a. **Evaluation of the geological, geophysical and hydrogeological conditions at Gideå.** SKBF/KBS TR 83-53, Svensk Kärnbränsleförsörjning AB.

Ahlbom, K., Tirén, S.A., 1991. **Overview of geologic and geohydrologic conditions at the Finnsjön site and its surroundings.** SKB TR 91-08, Svensk Kärnbränslehantering AB.

Anttila, P., Ahokas, H., Front, K., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M.V., Wikström, L., Öhberg, A., 1999c. **Final disposal of spent nuclear fuel in Finnish bedrock – Olkiluoto site report**. Posiva Oy, report 99-10.

Anttila, P., Ahokas, H., Front, K., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M.V., Wikström, L., Öhberg, A., 1999d. **Final disposal of spent nuclear fuel in Finnish bedrock – Romuvaara site report**. Posiva Oy, report 99-11.

2.4 Massive or foliated mafic rock (gabbro, amphibolite)

Mafic rocks were for a period thought to show some advantages over the felsic rocks discussed above, from the point of view of favourability as a host rock for a KBS-3-type repository. In small bodies, they occur widely distributed throughout the Swedish Precambrian basement, as massive or layered gabbro or as foliated and metamorphosed amphibolite or greenstone. On general grounds, the advantages are related to the high proportion of dark minerals (pyroxene, amphibole, biotite), i.e. magnesium- and iron-rich minerals, from which the name "mafic" derives. These minerals are more susceptible to alteration in circulating groundwaters and hydrothermal fluids, forming chlorites and clay minerals which clog the channels (low hydraulic conductivity) and are strongly retarding for radionuclide migration. These features were largely confirmed in the investigations listed below (*Larson & Tullborg 1984, Gentzschein & Tullborg 1985, Smellie 1992, Liedholm 1992*), as well as the good geomechanical properties (*Leijon 1992*). However, the favourable features were offset by definitely unfavourable ones in a Swedish context (*Ahlbom et al 1992e*). Firstly, there are very few bodies of mafic rock that are potentially of sufficient size to host a repository, thereby offering little latitude as regards site selection. Secondly, mafic bodies are often intersected by felsic veins which are much more fractured and water-conducting than the host rock, hence reducing the suitability of the body as a whole. Because of this, the search for suitable repository sites continues to focus on the much more widespread felsic crystallines, without however excluding the possibility that under some conditions mafic crystallines may be equally favourable. In Canada, the research on the East Bull Lake mafic pluton (a layered gabbro) provides a basis for comparison (see Subsection 9.2.2).

Larson, S.Å., Tullborg, E.-L., 1984. **Fracture fillings in the gabbro massif of Taavinunnanen, northern Sweden.** SKBF/KBS TR 84-08, Svensk Kärnbränsleförsörjning AB.

Gentzschein, B., Tullborg, E.-L., 1985. **The Taavinunnanen gabbro massif. A compilation of results from geological, geophysical and hydrogeological investigations.** SKB TR 85-02, Svensk Kärnbränslehantering AB.

Smellie, J.A.T., 1992. **Gabbro: geological and hydrogeochemical features**. SKB PR 44-92-003, (tidigare nr LOK 92-03), Svensk Kärnbränslehantering AB.

Liedholm, M., 1992. **The hydraulic properties of different greenstone areas. A comparative study.** SKB PR 44-92-007, Svensk Kärnbränslehantering AB.

Leijon, B., 1992. **Geomechanical and rock engineering characteristics of gabbro**. SKB PR 44-92-001, (tidigare nr LOK 92-01), Svensk Kärnbränslehantering AB.

Ahlbom, K., Leijon, B., Liedholm, M., Smellie, J.A.T., 1992e. **Gabbro as a host rock for a nuclear waste repository**. SKB TR 92-25, Svensk Kärnbränslehantering AB.

2.5 Selected scientific papers

From the point of view of crust formation during the Precambrian, there is general agreement that to a first approximation, the Swedish bedrock can be subdivided into three main domains (e.g. *Park 1991, Gorbatschev & Bogdanova 1993*). In the north lies the “Archean” domain, the oldest part of the Baltic Shield (rocks generally older than 1,900 Ma and in part older than 2,500 Ma). In northern, central and south-eastern Sweden lies the Svecofennian domain (which attained its present architecture during the Svecokarelian orogeny, ca. 1,900–1,770 Ma ago), and to the southwest, the Sveconorwegian domain (structured during the Sveconorwegian orogeny, ca. 1,100–900 Ma ago, reworking crust formed during the Gothian orogeny, 1,700–1,590 Ma). Most of the SKB study sites cited above (Sections 2.2–2.4), all the Förstudie municipalities (Chapter 8), and three of the four Finnish sites (Section 9.1), lie within the Svecofennian domain, to which most of the papers cited below refer.

The papers have been subdivided into two subgroups, depending on whether they emphasize the geological history of the crust during its formative phases (dominated by the Svecokarelian orogeny), or whether they deal with later events of magmatic or ductile deformational character. The latter took place after the Svecokarelian crust had consolidated, but before it had cooled sufficiently to react in a brittle manner. Papers referring mainly to later brittle deformation of the crust in the Svecofennian domain are cited in Section 3.5.

Ideas on the process of crust formation before and during the Svecokarelian orogeny, which resulted in high grade metamorphism and migmatization of both ancient crust (Archean) and newly accreted sediments and volcanics (early Proterozoic) in the Svecofennian domain, are quite diverse and include both convergent and divergent plate tectonic models (cf. *Lawrie 1992, Korja A & Heikkinen 1995, Mansfeld 1996, Korja T 1997, Nironen 1997, Andersson 1997, Nironen et al 2000*). Some of these ideas revolve around the geochemistry and field relations of the late Svecokarelian belt of granites and porphyries which form the western limit of the Svecofennian domain in Småland ("Småland granite") and central Sweden, the so-called Transscandinavian Igneous Belt (TIB) (e.g. *Andersson 1991, Mansfeld 1995, Lundqvist & Persson 1999, Åhall & Larson 2000*). These are of particular interest to SKB because of their relevance to understanding the host rock at Äspö (Section 6.3) and in the Förstudie municipalities Oskarshamn and Hultsfred (Section 8.3) (e.g. *Kornfält et al 1997*).

With regard to later intrusive and ductile deformational events, some references have been selected to illustrate three main themes. First, the formation of subvertical ductile shear zones in the Svecofennian crust at a late stage in the Svecokarelian orogeny (partly coeval with TIB intrusions) or later, which have been observed in many parts of Sweden and Finland (e.g. *Kärki et al 1993, Stephens & Wahlgren 1993, 1996, Bergman & Sjöström 1994, Talbot & Sokoutis 1995, Bergman & Weihed 1997, Högdahl 2000, Beunk & Page 2001*). Such zones are suspected to be unfavourable for repository siting, because of their susceptibility to brittle reactivation, their often heterogeneous character and their local potential in the context of mineral exploration (see Section 3.5, and Sections 8.2 and 8.3). They are also of considerable academic interest. The second heading concerns so-called "anorogenic" intrusions, such as the large rapakivi granites in the Baltic Shield (e.g. *Elo & Korja 1993, Rämö & Haapala 1995, Ahl et al 1997, Puura & Flodén 1999, 2000*), in which, for instance, the Kråkemåla (Subsection 6.1.7) and Hästholmen (Finland, Subsection 9.2.2) sites lie. The third heading includes some recent papers on the "Protogine zone" or what is now more properly called the Sveconorwegian Frontal Deformation Zone, representing the ductile overprinting of the Svecofennian crust along the eastern margin of the Sveconorwegian orogen (e.g. *Andréasson & Rodhe 1990, Larson et al 1990, Wahlgren et al 1994, Andréasson & Dallmeyer 1995, Wahlgren & Stephens 1996, 2000, Page et al 1996, Juhlin et al 2000*).

Formation of Svecofennian crust, Svecokarelian orogeny

Park, A.F., 1991. **Continental growth by accretion: a tectonostratigraphic terrain analysis of the evolution of the western and central Baltic Shield, 3.50 to 1.75 Ga.** Geological Society of America Bulletin, 103, 522–537.

Gorbatschev, R., Bogdanova, S., 1993. **Frontiers in the Baltic Shield**. Precambrian Research, 64, 3–21.

Lawrie, K.C., 1992. **Geochemical characterisation of a polyphase deformed, altered, and high grade metamorphosed volcanic terrane: implications for the tectonic setting of the Svecofennides, south-central Finland.** Precambrian Research, 59, 171–205.

Korja, A., Heikkinen, P.J., 1995. **Proterozoic extensional tectonics of the central Fennoscandian Shield: results from the Baltic and Bothnian Echoes from the Lithosphere experiment.** Tectonics, 14, 504–517.

Mansfeld, J., 1996. **Geological, geochemical and geochronological evidence for a new Palaeoproterozoic terrane in southeastern Sweden**. Precambrian Research, 77, 91–103.

Korja, T., 1997. **Electrical conductivity of the lithosphere – implications for the evolution of the Fennoscandian Shield.** Geophysics, 33, 17–50.

Nironen, M., 1997. **The Svecofennian orogen: a tectonic model.** Precambrian Research, 86, 21–44.

Andersson, U.B., 1997. **Petrogenesis of some Proterozoic granitoid suites and associated basic rocks in Sweden (geochemistry and isotope geology).** Geological Survey of Sweden (SGU), report 91.

Nironen, M., Elliott, B.A., Ramo, O.T., 2000. **1.88–1.87 Ga post-kinematic intrusions of the Central Finland Granitoid Complex: a shift from C-type to A-type magmatism during lithospheric convergence.** Lithos, 53, 37–58.

Transscandinavian Igneous Belt (TIB)

Andersson, U.B., 1991. **Granitoid episodes and mafic/felsic magma interaction in the Svecofennian of the Fennoscandian Shield, with main emphasis on the 1.8 Ga plutonics**. Precambrian Research, 51, 127–149.

Mansfeld, J., 1995. **Crustal evolution in the southeastern part of the Fennoscandian Shield.** Doctoral thesis, Univ. Stockholm.

Lundqvist, T., Persson, P.-O., 1999. **Geochronology of porphyries and related rocks in northern and western Dalarna, south-central Sweden.** GFF, 121, 307–322.

Åhäll, K.-I., Larson, S.Å., 2000. **Growth-related 1.85–2.55 Ga magmatism in the Baltic Shield: a review addressing the tectonic characteristics of Svecofennian, TIB 1-related, and Gothian events.** GFF, 122, 193–206.

Kornfält, K.-A., Persson, P.-O., Wikman, H., 1997. **Granitoids from the Äspö area, southeastern Sweden – geochemical and geochronological data**. GFF, 119, 109–114.

Syn/post-Svecokarelian, pre-Sveconorwegian ductile shear zones

Kärki, A., Laajoki, K., Luukas, J., 1993. **Major Palaeoproterozoic shear zones of the central Fennoscandian Shield.** Precambrian Research, 64, 207–223.

Stephens, M.B., Wahlgren, C.-H., 1993. **Workshop. Ductile shear zones in the Swedish segment of the Baltic Shield. Abstracts and excursion guide.** Geological Survey of Sweden (SGU), report 76.

Bergman, S., Sjöström H., 1994. **The Storsjön-Edsbyn deformation zone, central Sweden**. Unpublished R&D report (SGU), 1–46.

Talbot, C.J., Sokoutis, D., 1995. **Strain ellipsoids from incompetent dykes: application to volume loss during mylonitization in the Singö shear zone, central Sweden**. Journal of Structural Geology, 17, 427–448.

Stephens, M.B., Wahlgren, C.-H., 1996. **Post-1.85 Ga tectonic evolution of the Svecokarelian orogen with special reference to central and SE Sweden**. GFF, 118, A26–A27.

Bergman, S., Weihed, J., 1997. **Regional deformation zones in the Skellefte and Arvidsjaur areas**. Unpublished R&D report (SGU), 1–35.

Högdahl, K., 2000. **Late-orogenic, ductile shear zones and protolith ages in the Svecofennian Domain, central Sweden**. Doctoral thesis, Stockholm University.

Beunk, F.F., Page, L.M., 2001**. Structural evolution of the accretional continental margin of the Paleoproterozoic Svecofennian orogen in southern Sweden.** Tectonophysics, 339, 67–92.

Post-Svecokarelian (”anorogenic”) intrusions

Elo, S., Korja, A., 1993. **Geophysical interpretation of the crustal and upper mantle structure in the Wiborg rapakivi granite area, southeastern Finland.** Precambrian Research, 64, 273–288.

Rämö, O.T., Haapala, I., 1995. **One hundred years of rapakivi granite.** Mineral. Petrol., 52, 129–185.

Ahl, M., Andersson, U.B., Lundqvist, T., Sundblad, K. (eds.), 1997. **Rapakivi granites and related rocks in central Sweden.** Geological Survey of Sweden (SGU), Series Ca, research paper 87.

Puura, V., Flodén, T., 1999. **Rapakivi-granite-anorthosite magmatism – a way of thinning and stabilisation of the Svecofennian crust, Baltic Sea Basin.** Tectonophysics, 305, 75–92.

Puura, V., Flodén, T., 2000. **Rapakivi-related basement structures in the Baltic Sea area**. GFF, 122, 257–272.

Sveconorwegian Frontal Deformation Zone (”Protogine Zone”)

Andréasson, P.-G., Rodhe, A., 1990. **Geology of the Protogine Zone south of Lake Vättern, southern Sweden: a reinterpretation.** GFF, 111, 107–125.

Larson, S.Å. Berglund, J., Stigh, J., Tullborg, E.-L., 1990. **The Protogine Zone, southwest Sweden: a new model – an old issue**. In: Mid-Proterzoic Laurentia-Baltica (Gower, C.F., et al., eds.), Geol. Assoc. Canada, Special Paper 38, 317–333.

Wahlgren, C.-H., Cruden, A.R., Stephens, M.B., 1994. **Kinematics of a major fan-like structure in the eastern part of the Sveconorwegian orogen, Baltic Shield, south-central Sweden**. Precambrian Research, 70, 67–91

Andréasson, P.-G., Dallmeyer, R.D., 1995. **Tectonothermal evolution of high-alumina rocks within the Protogine Zone, southern Sweden**. Jour. Metm. Geol.,13, 461–474.

Wahlgren, C.-H., Stephens, M.B., 1996. **Polyphase tectonometamorphic reworking in the Transscandinavian Igneous Belt, east of Lake Vänern – regional tectonic implications**. GFF, 118, A27–A28.

Wahlgren, C.-H., Stephens, M.B., 2000. **Structural and geochronological evolution of the northeastern part of the Sveconorwegian orogen, south-central Sweden**. Bulletin Geological Society Denmark, 46, 161–163.

Page, L.M., Stephens, M.B., Wahlgren, C.-H., 1996. **Ar40/Ar39 geochronological constraints on the tectonothermal evolution of the Eastern Segment of the Sveconorwegian Orogen, south-central Sweden**. In: Precambrian Crustal Evolution of the North Atlantic Region (T.S. Brewer, ed.), Geological Society (London), Special Publication 112, 315–330.

Juhlin, C., Wahlgren, C.-H., Stephens, M.B., 2000. **Seismic imaging in the frontal part of the Sveco-norwegian orogen, south-western Sweden.** Precambrian Research, 102, 135–154.

3 Fracturing

As indicated in Chapter 2, the crystalline rocks of the Baltic Shield were formed deep in the Precambrian crust by magmatic, metamorphic and metasomatic processes, and ductile deformation. Understanding these ancient crustal processes has been one of the main aims of Swedish researchers for over a century, driven by academic curiosity (universities) and the search for natural resources (SGU, mining companies, etc.). From the point of view of radioactive waste disposal, however, understanding how the crystalline rocks were formed takes second place to understanding their behaviour after consolidation and exhumation, i.e. after cooling and uplift to near-surface environments. This took place at different times and at different rates in different parts of the Baltic Shield, but as a rough generalization it can be considered as having been completed everywhere by late Precambrian times. This means that the rocks which build the present-day landscapes of the Baltic Shield have been at or close to the Earth' surface for hundreds of millions of years, during this time reacting by brittle deformation (fracturing) to any movements in the Earth's crust.

Since groundwater flow is confined to the fracture system, the fracturing of crystalline rocks is a central theme of research with respect to KBS-3-type repositories, and SKB has invested considerable effort in documenting and understanding fracture systems at all scales. Fracturing is a dominant theme in connection with all the SKB study sites (Chapter 6) and all the feasibility studies (Chapter 8). Not surprisingly, therefore, SKB has over the years commissioned numerous studies on various, more general, aspects of fracturing and brittle deformation in Swedish bedrock. The documentation of this theme fall naturally into four main groups:

- tectonic evolution of Baltic Shield after consolidation (Section 3.1),
- large-scale fracture pattern analyses (Section 3.2),
- geological characterisation of fracture zones and small-scale fracture patterns (Section 3.3),
- geomechanics and the geophysical identification of fracture zones (Section 3.4).

Geological evidence for the evolution of the Baltic Shield after the consolidation of the crystalline rocks is rather fragmentary, except for the evidence from the mountain region and Norway concerning the Caledonian orogeny (see *Fredén (ed.) 1994* – National Atlas of Sweden, "Berg och jord", p. 22–24). To fill this gap, and to provide the necessary background for more detailed studies, aspects of the regional setting of the Baltic Shield in Sweden in a wider context are treated in the first group of reports (Section 3.1). These are complemented by a series of earlier, and some contemporaneous, works dealing with the large-scale fracture patterns, both offshore and onshore (Section 3.2). Most of these are lineament analyses, i.e. studies of the patterns of linear morphological and other geophysically defined features which are assumed to represent major fracture zones in the Earth's crust, in contrast to geological studies, in which concrete evidence for the existence of fracturing and fault movement is required in the interpretation of morphological and submarine features.

With regard to geological characterisation of fracture zones and related small-scale fracturing (Section 3.3), the documentation listed in this Chapter is highly selective and represents only a fraction of the large amount of material which is available. The location and reconstruction of fracture zones at individual study sites, and the definition of fracture patterns in the rock blocks, is one of the main activities of site characterisation, since quantitative data are required for groundwater flow and rock engineering modelling. Extensive fracture data have been collected from all drill cores, outcrops, tunnels, etc.. These are stored in GEOTAB/SICADA database (see Section 2.1) and have been analysed in depth at each individual site or research area. Hence most of the fracture data is to be found in the reports listed in Chapters 6 and 8 (see also Chapter 9, for similar studies in Finland and Canada).

Similarly, the discussion around nomenclature and the geomechanical definition of fracture zones and rock quality (Section 3.4) is the subject of more intensive discussion than the list of SKB documents would imply, particularly in the scientific literature. One aspect, however, has been the subject of special attention in Sweden: the possibilities and limitations of using geophysical methods to identify fracture zones and to determine their orientation and lateral extent in the subsurface, using investigations on the Earth's surface and in boreholes and tunnels. The final group in this Chapter (Section 3.5) is a selection of published scientific papers, either scientific presentations of research material worked on under the auspices of SKB, or regional papers summarizing conditions in the Baltic Shield, which form an important background to SKB research.

Fredén, C. (ed.), 1994. **Berg och jord**. Sveriges Nationalatlas.

3.1 Tectonic evolution of Baltic Shield after consolidation

The tectonic evolution of the Baltic Shield after consolidation (i.e. after the phases of intrusion, migmatization, ductile deformation, etc., which led to the formation of the bedrock, see Chapter 2) is part of the general background required for understanding the fracturing observed at the different sites. This background data is mainly to be found in the scientific literature and SGU documents, but certain aspects have been treated by a number of authors under contract to SKB. As indicated above (Section 2.5), the Swedish Precambrian can be subdivided into 3 main domains: an "Archean" domain, in the north; a younger domain covering much of central Sweden, called the Svecofennian domain, which was mainly formed in the period 1,900–1,770 Ma and consolidated about 1,500 Ma ago; and the youngest domain, the Sveconorwegian domain, which mainly formed between 1,100 and 900 Ma before consolidating in latest Precambrian time.

The zone in which the Sveconorwegian deformation and metamorphism overprints the older Svecofennian structures, now called the Sveconorwegian Frontal Deformation Zone (SFDZ), is marked in southern Sweden by a system of major ductile shear zones which was formerly called the "Protogine Zone" (Section 2.5), and which is also an important zone of brittle reactivation (*Andréasson & Rodhe 1992*). Brittle reactivation (i.e. brittle fractures following older, ductile structures) is an element in all later periods involving crustal deformation, but also new fractures formed in many places, independently of earlier structures (*Larson & Tullborg 1993*). This occurred mainly in connection with the Caledonian orogeny, to the west and south (*Tullborg et al 1995*), and, later, with the formation of the Oslo Graben and early North Sea extensional tectonics, in the area around the lakes Vättern and Vänern (*Milnes et al 1998*). Even younger tectonic events have potentially affected the otherwise very stable Baltic Shield in the last 100 Ma (*Wannäs & Flodén 1994, Muir-Wood 1995*).

Most of the works cited here cover a wider time-range of the tectonic history than this short exposition would imply. They were intended to deepen knowledge in lesser known areas and, at the same time, to look at the problems from the point of view of nuclear waste disposal. The references in this group deal with *tectonic* events, i.e. crustal movements related to plate motion, as opposed to the *glacio-dynamic* events, i.e. movements related to ice loading/unloading during the Quaternary, which are discussed in Chapter 4. For comparative material from the Finnish part of the Baltic Shield and the Canadian Shield, see Chapter 9.

Andréasson, P.-G., Rodhe, A., 1992. **The Protogine Zone. Geology and mobility during the last 2.5 Ga**. SKB TR 92-01, Svensk Kärnbränslehantering AB.

Larson, S.Å., Tullborg, E.-L., 1993. **Tectonic regimes in the Baltic Shield during the last 1,200 Ma – A review.** SKB TR 94-05, Svensk Kärnbränslehantering AB.

E.-L., Larson, S.Å., Björklund, L., Samuelsson, L., Stigh, J., 1995. **Thermal evidence of Caledonide foreland, molasse sedimentation in Fennoscandia.** SKB TR 95-18, Svensk Kärnbränslehantering AB.

Milnes, A.G., Gee, D.G., Lund, C.-E., 1998. **Crustal structure and regional tectonics of SE Sweden and the Baltic Sea.** SKB TR 98-21, Svensk Kärnbränslehantering AB.

Wannäs, K.O., Flodén, T., 1994. **Tectonic framework of the Hanö Bay area, southern Baltic Sea.** SKB TR 94-09, Svensk Kärnbränslehantering AB.

Muir-Wood, R., 1995. **Reconstructing the tectonic history of Fennoscandia from its margins: The past 100 million years.** SKB TR 95-36, Svensk Kärnbränslehantering AB.

3.2 Large-scale fracture pattern analyses (lineaments)

From the point of view of siting, one of the most important factors is the avoidance of major fault and fracture zones. A well-known feature of most shield areas is the tendency to be subdivided into rock blocks bounded by morphologically identifiable lineaments, which are interpreted as the surface expression of steeply dipping fracture zones and/or major faults. Hence, regional surveys (e.g. *Röshoff & Lagerlund 1977, Flodén 1977, 1980, Röshoff 1989a*) assume, as a precautionary measure, that any straight or slightly curved linear topographic depression is potentially a zone of fracturing and therefore to be avoided in the siting process.

In connection with the pre-investigation phase for the Äspö Hard Rock Laboratory (see Section 6.3), analysis methods were refined and applied at different scales to provide both regional and site-scale structural models (in combination with other geoscientific data and methods), as outlined in the Äspö reports (e.g. *Wikberg et al 1991, Almén et al 1994,* see also Section 3.5 under the heading: lineament analysis and morphotectonics). As more detailed databases became available and increased computer capacity more accessible, so also the sophistication of the analysis methods increased (e.g. *Eriksson & Isaksson 1995*). Also, the methods have become more widely applicable, and are used as an important basis for evaluations within the framework of the Länsstudier (Section 8.2) and Förstudier (Section 8.3), and for studies of the potential effects of earthquakes on repository integrity (e.g. a recent Finnish study, *Kuivamäki 2000*).

Röshoff, K., Lagerlund, E., 1977. **Tektonisk analys av södra Sverige. Vättern – Norra Skåne.** KBS TR 20, Svensk Kärnbränslehantering AB.

Flodén, T., 1977. **Tectonic lineaments in the Baltic from Gävle to Simrishamn.** KBS TR 59, Svensk Kärnbränslehantering AB.

Flodén, T., 1980**. Seismic stratigraphy and bedrock geology of the Central Baltic.** Stockholm Contrib. in Geol., 35, 1–240.

Röshoff, K., 1989a. **Characterisation of the morphology, basement rock and tectonics in Sweden.** SKB TR 89-03, Svensk Kärnbränslehantering AB.

Wikberg, P., Gustafson, G., Rhén, I., Stanfors, R., 1991. **Äspö Hard Rock Laboratory. Evaluation and conceptual modelling based on the pre-investigations 1986–1990.** SKB TR 91-22, Svensk Kärnbränslehantering AB.

Almén, K.-E., Olsson, P., Rhén, I., Stanfors, R., Wikberg, P., 1994. **Äspö Hard Rock Laboratory. Feasibility and usefulness of site investigation methods. Experiences from the pre-investigation phase.** SKB TR 94-24, Svensk Kärnbränslehantering AB.

Eriksson, P., Isaksson, H., 1995. **Översiktsstudier. Texturanalys av flygmagnetiska data i Sverige.** SKB PR D-95-010, Svensk Kärnbränslehantering AB.

Kuivamäki, A., 2000. **Lineament database of the Finnish potential repository sites for the calculation of bedrock movements induced by earthquakes**. Posiva Oy, working report WR 2000-12.

3.3 Characterisation of fracture zones and fracture systems

In the previous group, the cited works assume, as a precautionary measure, that topographic lineaments and other types of lineament represent fracture zones. Here, we collect works which focus on the fracture zones as geologically defined elements, and on the small-scale fracturing associated with them and otherwise distributed within any volume of crystalline rock (*Bäckblom 1989*). The following list is highly selective, and by no means exhaustive, even of SKB material. Specific fracture zone studies have mainly been carried out at the Finnsjön study site (e.g. *Ahlbom et al 1986, 1989, Andersson Peter 1993*), in the Stripa mine (e.g. *Gale et al 1991*), on Äspö island (*Munier 1993a,b*), and in the Äspö tunnel (e.g. *Stanfors et al 1997b, Part I, Rhén et al 1997c, Chapter 5*). The descriptions in this selection are based on a large body of material in the corresponding SKB progress reports (Arbetsrapporter), and need to be complemented with data from, for instance, the Finnish study sites (e.g. *Front et al 1999*, see Section 9.1) and the published literature (Section 3.5, below). In general, one can say that the geological characterisation of fracture zones is an important theme because it shows how elusive "fracture zones" really are, and provides a necessary counter-balance to the concept of parallel-sided, sharply-bounded and planar structures which is built into most structural models (*Saksa & Nummela 1998*).

With regard to small-fracturing within blocks between fracture zones, the most detailed analyses have been carried out in the Stripa and Äspö underground laboratories (e.g. *Andersson & Dverstorp 1987, Bursey et al 1991, Martel 1992, Gale et al 1991*, *Bossart et al 2001*, see Sections 6.2 and 6.3), and form an integral part of discrete fracture network (DFN) modelling for geomechanical and geohydrological studies (e.g. *Black et al 1994, LaPointe et al 1995*). Small-scale fracturing has also been studied in the sedimentary cover of the crystalline basement in Småland (*Milnes & Gee 1992*).

Bäckblom, G., 1989. **Guidelines for use of nomenclature on fractures, fracture zones and other topics.** SKB Teknisk PM 25-89-007, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, P., Ekman, L., Gustafsson, E., Smellie, J.A.T., Tullborg, E.-L., 1986. **Preliminary investigations of fracture zones in the Brändan area, Finnsjön study site.** SKB TR 86-05, Svensk Kärnbränslehantering AB.

Ahlbom, K., Smellie, J.A.T., Tirén, S.A., Andersson, J.-E., Ekman, L., Nordqvist, R., Winberg, A., Gustafsson, E., Andersson, P., Wikberg, P., 1989. **Characterisation of fracture zone 2, Finnsjön study-site. Part 1: Overview of the fracture zone project at Finnsjön, Sweden. Part 2: Geological setting and deformation history of a low angle fracture zone at Finnsjön, Sweden. Part 3: Hydraulic testing and modelling of a low-angle fracture zone at Finnsjön, Sweden. Part 4: Groundwater flow conditions in a low angle fracture zone at Finnsjön, Sweden. Part 5: Hydrochemical investigations at Finnsjön, Sweden. Part 6: Effects of gas-lift pumping on hydraulic borehole conditions at Finnsjön, Sweden.** SKB TR 89-19, Svensk Kärnbränslehantering AB.

Andersson, Peter (ed.), 1993: **The Fracture Zone Project – Final report.** SKB TR 93-20, Svensk Kärnbränslehantering AB.

Gale, J., MacLeod, R., Bursey, G., Stråhle, A., Tirén, S.A., 1991. **Characterisation of the structure and geometry of the H fracture zone at the SCV site**. SKB TR 91-37, Svensk Kärnbränslehantering AB.

Munier, R., 1993a: **Segmentation, fragmentation and jostling of the Baltic Shield with time.** Doctoral thesis, Uppsala University.

Munier, R., 1993b: **Four-dimensional analysis of fracture arrays at the Äspö hard rock laboratory, SE Sweden**. Engineering Geology, 33, 159–175.

Stanfors, R., Olsson, P., Stille, H., 1997b. **Äspö HRL – Geoscientific evaluation 1997/3. Results from pre-investigations and detailed site characterisation. Geology and mechanical stability.** SKB TR 97-04, Svensk Kärnbränslehantering AB

Rhén, I., Gustafson, G., Stanfors, R., Wikberg, P., 1997c. **Äspö HRL – Geoscientific evaluation 1997/5. Models based on site characterisation 1986–1995.** SKB TR 97-06, Svensk Kärnbränslehantering AB.

Front, K., Paulamäki, S., Ahokas, H., Anttila, P., 1999. **Lithological and structural bedrock model of the Hästholmen study site, Loviisa, SE Finland**. Posiva Oy, report POSIVA 99-31.

Saksa, P., Nummela, J., 1998. **Geological-structural models used in SR-97. Uncertainty analysis.** SKB TR 98-12, Svensk Kärnbränslehantering AB.

Andersson, J., Dverstorp, B., 1987. **3-D migration experiment – Report 4. Fracture network modelling of the Stripa 3-D site.** SKB, Stripa Project TR 87-22, Svensk Kärnbränslehantering AB.

Bursey, C.G., Gale, J.E., MacLeod, R., Stråhle, A., Tirén, S.A., 1991. **Site Characterisation and Validation – validation drift fracture data, stage IV**. SKB AB, Stripa Project TR-91-19, Svensk Kärnbränslehantering AB.

Martel, S., 1992. **Geologic characterisation of fractures as an aid to hydrologic modelling of the SCV block at the Stripa mine.** SKB, Stripa Project TR-92-24, Svensk Kärnbränslehantering AB.

Gale, J., MacLeod, R., Bursey, G., Stråhle, A., Tirén, S.A., 1991. **Characterisation of the structure and geometry of the H fracture zone at the SCV site**. SKB, Stripa Project TR-91-37, Svensk Kärnbränslehantering AB.

Bossart, B., Hermanson, J., Mazurek, M., 2001. **Äspö Hard Rock Laboratory. Analysis of fracture networks based on structural and hydrogeological observations on different scales.** SKB TR 01-21, Svensk Kärnbränslehantering AB.

Black, J., Dershowitz, W., Axelsson, K.-L., Doe, T., Been, K., 1994. **Review of SKB Framework for the Geoscientific Characterisation of Sites for Deep Repositories with emphasis on the Testing and Numerical Representation of Fractured Crystalline Rock.** SKB PR 44-94-001, Svensk Kärnbränslehantering AB.

LaPointe, P.R., Wallmann, P., Follin, S., 1995. **Estimation of effective block conductivities based on discrete network analyses using data from the Äspö site.** SKB TR 95-15, Svensk Kärnbränslehantering AB.

Milnes, A.G., Gee, D.G., 1992. **Bedrock stability in southeastern Sweden. Evidence from fracturing in the Ordovician limestones of Northern Öland.** SKB TR 92–23, Svensk Kärnbränslehantering AB.

3.4 Geomechanics and applied geophysics

The degree and type of fracturing in crystalline rocks forms the basis of engineering geological evaluations of the design and layout of repositories and their access tunnels, shafts, etc.. Geomechanics and the definition of rock quality for deep excavation has been discussed in several SKB studies, (*Leijon & Ljunggren 1992, Leijon 1993, Almén et al 1996, Stanfors et al 1997b, Part II, Rhén et al 1997c, Chapter 6*), with particular reference to the geomechanical properties of fracture zones, and different aspects have been studied in a number of doctoral theses (*Li 1993, Hakami 1995, Kou 1996, Lindfors 1996, Tan 1996, Probert 1998, Olsson 1998, Sturk 1998*). The first part of the list ends with some more general references, focussed on the excavation damage zone which develops around underground cavities (*Emsley et al 1997*), on the possible effects of high pore pressures in fractured rocks (*Olsson 1997)*, and, for comparison, on the geomechanical stability of the four Finnish sites (*Johansson & Rautakorpi 2000*).

The second part of the list includes a selection of reports which focus on the application of geophysical methods (particularly reflection seismics and radar) to the identification of fracture zones ahead of tunnels and in the surroundings of boreholes (*Sehlstedt & Stenberg 1986, Carlsten et al 1987, 1989, Quanhong 1996,* and from the Finnish programme, *Labbas 1997*), as a complement to the physical description of fractures in the borehole and tunnel walls (see Section 3.3). In addition, the possibilities of identifying fracture zones in the subsurface from surface geophysical studies has been a particular concern of SKB (e.g. *Dahl-Jensen & Lindgren 1987, Sturgeon 1992, Cosma et al 1994, Juhlin & Palm 1997*).

The last part of this rather heterogeneous Section contains reports dealing with the geomechanical modelling of the long-term evolution of repository sites on different scales, including both SKB and SKI studies (*Stephansson 1987, Hansson et al 1995b, 1995c, Shen & Stephansson 1996a, 1996b*).

Geomechanics

Leijon, B., Ljunggren, C., 1992. **A rock mechanics study of Fracture Zone 2 at the Finnsjön site.** SKB TR 92-28, Svensk Kärnbränslehantering AB.

Leijon, B., 1993. **Mechanical properties of fracture zones.** SKB TR 93-19, Svensk Kärnbränslehantering AB.

Almén, K.-E., Stanfors, R., Svemar, C., 1996. **Nomenklatur och klassificering av geologiska strukturer vid platsundersökningar för SKB:s djupförvar.** SKB PR D-96-029, Svensk Kärnbränslehantering AB.

Stanfors, R., Olsson, P., Stille, H., 1997b. **Äspö HRL – Geoscientific evaluation 1997/3. Results from pre-investigations and detailed site characterisation. Geology and mechanical stability.** SKB TR 97-04, Svensk Kärnbränslehantering AB

Rhén, I., Gustafson, G., Stanfors, R., Wikberg, P., 1997c. **Äspö HRL – Geoscientific evaluation 1997/5. Models based on site characterisation 1986–1995.** SKB TR 97-06, Svensk Kärnbränslehantering AB.

Li, C., 1993. **Deformation and failure of brittle rocks under compression**. Doctoral thesis, Luleå University of Technology.

Hakami, E., 1995. **Aperture distribution of rock fractures**. Doctoral thesis, Royal Institute of Technology (KTH), Stockholm.

Kou, S., 1996. **Some basic problems in rock breakage by blasting and by indentation**. Doctoral thesis, Luleå University of Technology.

Lindfors, U., 1996. **Experimental study of the mechanics of rock joints**. Licentiate thesis, Luleå University of Technology.

Tan, X., 1996. **Modelling of drill string buckling and tool indentation in rock drilling and fragmentation**. Doctoral thesis, Luleå University of Technology.

Probert, T., 1998. **The underground storage facility. Modelling of nuclear waste repositories and aquifer thermal energy stores**. Doctoral thesis, Lund Institute of Technology.

Olsson, R., 1998. **Mechanical and hydromechanical behaviour of hard rock joints. A laboratory study**. Doctoral thesis, Chalmers University of Technology, Göteborg.

Sturk, R., 1998. **Engineering geological information – its value and impact on tunnelling**. Doctoral thesis, Royal Institute of Technology (KTH), Stockholm.

Emsley, S., Olsson, O., Stenberg, L., Alheid, H.-J., Falls, S., 1997. **ZEDEX – A study of damage and disturbance from tunnel excavation by blasting and tunnel boring.** SKB TR 97-30, Svensk Kärnbränslehantering AB.

Olsson, R., 1997. **The effective stress concept in a jointed rock mass. A literature survey.** SKB R-97-18, Svensk Kärnbränslehantering AB.

Johansson, E., Rautakorpi, J., 2000. **Rock mechanics stability at Olkiluoto, Hästholmen, Kivetty and Romuvaara**. Posiva Oy, report 2000-02.

Geophysical studies

Sehlstedt, S., Stenberg, L., 1986. **Geophysical investigations at the Klipperås study site.** SKB TR 86-07, Svensk Kärnbränslehantering AB.

Carlsten, S., Olsson, O., Sehlstedt, S., Stenberg, L., 1987. **Radar measurements performed at the Klipperås study site.** SKB TR 87-01, Svensk Kärnbränslehantering AB.

Carlsten, S., Lindqvist, L., Olsson, O., 1989. **Comparison between radar data and geophysical, geological and hydrological borehole parameters by multivariate analysis of data.** SKB TR 89-15, Svensk Kärnbränslehantering AB.

Quanhong, F., 1996. **Application of image processing to borehole logging**. Master thesis, Royal Institute of Technology (KTH), Stockholm.

Labbas, K., 1997. **Comparison of 3-D geological and geophysical investigation methods in boreholes KI-KR1 at Äänekoski Kivetty site and RO-KR3 at Kuhmo Romuvaara site**. Posiva Oy, report 97-03.

Dahl-Jensen, T., Lindgren, J., 1987. **Shallow reflection seismic investigation of fracture zones in the Finnsjö area, method evaluation**. SKB TR 87-13, Svensk Kärnbränslehantering AB.

Sturgeon, L., 1992. **Application of high resolution geophysical surveys for offshore site investigation.** SKB PR 44-92-005, (tidigare nr LOK 92-05), Svensk Kärnbränslehantering AB.

Cosma, C., Juhlin, C., Olsson, O., 1994. **Reassessment of seismic reflection data from the Finnsjön study site and prospectives for future surveys.** SKB TR 94-03, Svensk Kärnbränslehantering AB.

Juhlin, C., Palm, H., 1997. **Reflection seismic studies on the island of Ävrö.** SKB PR D-97-09, Svensk Kärnbränslehantering AB.

Geomechanical modelling

Stephansson, O., 1987. **Modelling of crustal rock mechanics for radioactive waste storage in Fennoscandia – Problem definition.** SKB TR 87-11, Svensk Kärnbränslehantering AB.

Hansson, H., Stephansson, O., Shen, B., 1995b. **Far-field rock mechanics modelling for nuclear waste disposal.** Statens kärnkraftinspektion, Report SKI 95:40.

Hansson, H., Shen, B., Stephansson, O., Jing, L., 1995c. **Rock mechanics modelling for the stability and safety of a nuclear waste repository. Executive summary (SITE-94).** Statens kärnkraftinspektion, Report SKI 95:41.

Shen, B., Stephansson, O., 1996a. **Near-field mechanical modelling for nuclear waste disposal.** Statens kärnkraftinspektion, Report SKI 96:17.

Shen, B., Stephansson, O., 1996b. **Modelling of rock fracture propagation for nuclear waste disposal.** Statens kärnkraftinspektion, Report SKI 96:18.

3.5 Selected scientific papers

The scientific literature on fracturing is very extensive. The selection in this group has been made in view of two themes which are of particular relevance to SKB interests. The first concerns the general geological evolution of the Baltic Shield after consolidation, which, as we have seen (Section 3.1), has been the object of several SKB studies. The second covers case studies, mainly focused on understanding the brittle tectonics of Swedish sites and areas, but including some other works thought to be of particular relevance, complementing, and in some cases based on, SKB-supported research. The citations are arranged under headings which reflect subdivisions made earlier in this chapter. From the point of view of regional tectonics, fracturing in Swedish bedrock is related to late Precambrian and Phanerozoic activity around the cratonic margins and to intracratonic processes.

The citations in the first part of the list are arranged under three headings – regional studies concerning: (1) activity along the southern margin of the Baltic Shield, mainly addressing the Palaeozoic and Mesozoic development of the Trans-European Suture Zone (*Franke 1993, Erlström et al 1997, Pharaoh 1999, Meissner & Krawczyk 1999*); (2) activity along the western margin of the shield during the Caledonian orogeny, particularly the discovery of, and controversy surrounding, the now completely denuded Devonian foreland basin in Sweden (*Tullborg et al 1995,1996, Middleton et al 1996, Cederbom 1997, Tullborg 1997, Garfunkel & Greiling 1998, Greiling et al 1998, Samuelsson & Middleton 1998, Larson et al 1999, Cederbom et al 2000*); and (3) the sporadic late Precambrian and Palaeozoic deformation of the internal parts of the craton, as exemplified by the early history of the Vättern graben in Sweden, the evolution of the Dnieper-Donets rift in Ukraine and the post-consolidaion deformation in the Gulf of Finland (*Vidal & Moczydlowska 1995, Bogdanova et al 1996, Nikishin et al 1996, Starostenko et al 1999, Puura et al 1996*). Added to the latter group are some references on the detailed structural geology of the Vättern graben, as an example of the question of brittle reactivation of earlier (ductile) structures (*Andréasson & Rodhe 1990, 1994, Månsson* 1996), which has been a recurring theme in the SKB feasibility studies (Chapter 8).

The Vättern papers lead over to a collection of recent papers dealing specifically with fracturing at Swedish sites and areas. A first group contains papers which deal with lineament analysis and the interpretation of the morphology of the bedrock surface in terms of fault and fracture zones. Some of these use digital terrain models as a basis for delineating rock blocks (*Tirén & Beckholmen 1989, 1990, 1992*), whilst the others approach morphotectonics from the point of view of identifying and dating changes in level in ancient peneplains to identify later faulting (*Lidmar-Bergström 1993, 1996, 1999, Lidmar-Bergström et al 1997, Johansson et al 1999;* see also Lindmar-Bergström in *Fredén (ed.) 1994,* p. 44–53).

The second group contains a collection of papers on fracturing at different sites in Sweden (*Tirén 1991, Munier 1993, Line et al 1997, Tirén et al 1999*) and more generally, on the use of geophysical methods to identify subsurface structures, particularly zones which could be interpreted as fracture zones (*Juhlin 1990, Juhlin et al 1991, Juhlin 1995, Papasikas & Juhlin 1997, Juhlin & Palm 1999, Ormo 1999, Wänstedt et al*

2000). Much of this research has been supported by SKB, since the development of non-destructive methods for site investigations is an area of prime importance (see Section 3.4).

Trans-European Suture Zone (southern margin of Baltic Shield)

Franke, D., 1993. **The southern border of Baltica – a review of the present state of knowledge**. Precambrian Research, 64, 419–430.

Erlström, M., Thomas, S.A., Deeks, N., Sivhed, U., 1997. **Structure and tectonic evolution of the Tornquist Zone and adjacent sedimentary basins in Scania and the southern Baltic Sea area**. Tectonophysics, 271, 191–215.

Pharaoh, T.C., 1999. **Palaeozoic terranes and their lithospheric boundaries within the Trans-European Suture Zone (TESZ): a review.** Tectonophysics, 314, 17–41.

Meissner, R., Krawczyk, C.H., 1999. **Caledonian and Proterozoic terrane accretion in the southwest Baltic Sea.** Tectonophysics, 314, 255–267.

Caledonian foreland basin (western margin of Baltic Shield)

Tullborg, E.-L., Larson, S.Å., Björklund, L., Samuelsson, L., Stigh, J., 1995. **Thermal evidence of Caledonide foreland, molasse sedimentation in Fennoscandia.** SKB TR 95-18, Svensk Kärnbränslehantering AB.

Tullborg, E.-L., Larson, S.Å., Stiberg, J.-P., 1996. **Subsidence and uplift of the present land surface in the southeastern part of the Fennoscandian Shield**. GFF, 118, 126–128.

Middleton, M.F., Tullborg, E.-L., Larson, S.Å., Björklund, L., 1996. **Modelling of a Caledonian fore-land basin in Sweden: petrophysical constraints.** Marine and Petroleum Geology, 13, 407–415.

Tullborg, E.-L., 1997. **Recognition of low-temperature processes in the Fennoscandian shield**. Doctoral thesis, Göteborg University.

Cederbom, C., 1997. **Fission track thermochronology applied to Phanerozoic thermotectonic events in central and southern Sweden**. Licentiate thesis, Göteborg University.

Garfunkel, Z., Greiling, R.O., 1998. **A thin orogenic wedge upon thick foreland lithosphere and the missing foreland basin.** Geologische Rundschau, 87, 314–325.

Greiling, R.O., Garfunkel, Z., Zachrisson, E., 1998. **Evolution of the orogenic wedge in the central Scandinavian Caledonides and its interaction with the foreland lithosphere.** GFF, 120, 181–190.

Samuelsson, J., Middleton, M.F., 1998. **The Caledonian foreland basin in Scandinavia: constrained by the thermal maturation of the Alum Shale.** GFF, 120, 307–314.

Larson, S.Å., Tullborg, A.-L., Cederblom, C., Stiberg, J.-P., 1999. **Sveconorwegian and Caledonian foreland basins in the Baltic Shield revealed by fission-track thermochronology.** Terra Nova, 11, 210–215.

Cederbom, C., Larson, S.Å. Tullborg, E.-L., Stiberg, J.-P., 2000. **Fission track thermochronology applied to Phanerozoic thermotectonic events in central and southern Sweden.** Tectonophysics, 316, 153–167.

Intracratonic events

Vidal, G., Moczydlowska, M., 1995. **The Neoproterozoic of Baltica – stratigraphy, palaeobiology and general geological evolution**. Precambrian Research, 73, 197–216.

Bogdanova, S.V., Pashkevich, I.K., Gorbatschev, R., Orlyuk, M.I., 1996. **Riphean rifting and major Palaeoproterozoic crustal boundaries in the basement of the East European Craton: geology and geophysics**. Tectonophysics, 268, 1–21

Nikishin, A.M., Ziegler, P.A., Stephenson, R.A., Cloetingh, S.A.P.L., Furne, A.V., Fokin, A., Ershov, A.V., Bolotov, S.N., Korotaev, M.V., Alekseev, A.S., Gorbachev, V.I., Shipilov, E.V., Lankreijer, A., Bembinova, E.Y., Shalimov, I.V., 1996. **Late Precambrian to Triassic history of the East European Craton: dynamics of sedimentary basin evolution**. Tectonophysics, 268, 23–63.

Puura, V., Amantov, A., Tikhomirov, S., Laitakari, I., 1996. **Latest events affecting the Precambrian basement, Gulf of Finland and surrounding areas.** In: Explanation to the Map of Precambrian Basement of the Gulf of Finland and Surrounding Areas, 1:1 mill. (Koistinen, T., ed.), Geological Survey of Finland, Special Paper 21, 115–125.

Starostenko, V.I., Danilenko, V.A., Vengrovitch, D.B., Kutas, R.I., Stovba, S.M., Stephenson, R.A., Kharitonov, O.M., 1999. **A new geodynamical-thermal model of rift evolution with application to the Dnieper-Donets Basin, Ukraine.** Tectonophysics, 313, 29–40.

Andréasson, P.-G., Rodhe, A., 1990. **Geology of the Protogine Zone south of Lake Vättern, southern Sweden: a reinterpretation**. GFF, 112, 107–125.

Andréasson, P.-G., Rodhe, A., 1994. **Ductile and brittle deformation within the Protogine Zone, southern Sweden: a discussion**. GFF, 116, 115–117.

Månsson, A.G.M., 1996. **Brittle reactivation of ductile basement structures; a tectonic model for the Lake Vättern basin, southern Sweden**. GFF, 118, A19.

Lineament analysis, morphotectonics

Tirén, S.A., Beckholmen, M. 1989 **Block faulting in southeastern Sweden interpreted from digital terrain models**. Geol. Fören. Förh. (Stockholm), 111, 171–179.

Tirén, S.A., Beckholmen, M., 1990. **Rock block configuration in southern Sweden and crustal deformation**. Geol. Fören. Förh. (Stockholm), 112, 361–364.

Tirén, S.A., Beckholmen, M., 1992. **Rock block map analysis of southern Sweden**. Geol. Fören. Förh. (Stockholm), 114, 253–269.

Lidmar-Bergström, K., 1993. **Denudation surfaces and tectonics in the southernmost part of the Baltic Shield**. Precambrian Research, 64, 337–345.

Lidmar-Bergström, K., 1996. **Long term morphotectonic evolution in Sweden**. Geomorphology, 16, 33–59.

Lidmar-Bergström, K., 1999. **Uplift histories revealed by landforms of the Scandinavian domes.** Geological Society (London), Special Publication 162, 85–91.

Lidmar-Bergström, K., Olsson, S., Olvmo, M., 1997. **Palaeosurfaces and associated saprolites in southern Sweden.** Geological Society (London), Special Publication 120, 95–124.

Johansson, M., Olvmo, M., Söderström, M., 1999. **Application of digital elevation and geological data in studies of morphotectonics and relief – a case study of the sub-Cambrian peneplain in south-western Sweden.** Zeitschrift der Geomorphologie, N.F., 43, 505–520.

Fredén, C. (ed.), 1994. **Berg och jord.** Sveriges Nationalatlas. (English version: Fredén, C. (ed.), 1994. **Geology.** National Atlas of Sweden.)

Swedish sites – characterisation, geophysical methods

Tirén, S.A., 1991. **Geological setting and deformation history of a low-angle fracture zone at Finnsjön, Sweden.** Journal of Hydrology, 126, 17–43.

Tirén, S.A., 1993. **Planning of infrastructures and the role of remote analysis of structural elements in the bedrock.** GFF, 115, 275–277.

Munier, R., 1993. **Four-dimensional analysis of fracture arrays at the Äspö hard rock laboratory, SE Sweden**. Engineering Geology, 33, 159–175.

Line, C.E.R., Snyder, D.B., Hobbs, R.W., 1997. **The sampling of fault populations in dolerite sills of Central Sweden and implications for resolution of seismic data**. Journal of Structural Geology, 19, 687–701.

Tirén, S.A., Askling, P., Wänstedt, S., 1999. **Geologic site characterisation for deep nuclear waste disposal based on 3D data visualization.** Engineering Geology, 52, 319–346.

Juhlin, C., 1990. **Interpretation of the reflections in the Siljan Ring area based on results from the Gravberg-1 borehole.** Tectonophysics, 173, 345–360.

Juhlin, C., Lindgren, J., Collini, B., 1991. **Interpretation of seismic reflection and borehole data from Precambrian rocks in the Dala Sandstone area, central Sweden.** First Break, 9, 24–36.

Juhlin, C., 1995. **Imaging of fracture zones in the Finnsjön area, central Sweden, using the seismic reflection method.** Geophysics, 60, 66–75.

Papasikas, N., Juhlin, C., 1997. **Interpretation of reflections from the central part of the Siljan Ring impact structure based on results from the Stenberg-1 borehole.** Tectonophysics, 269, 237–245.

Juhlin, C., Palm, H., 1999. **3-D structure below Ävrö island from high-resolution reflection seismic studies, southeastern Sweden.** Geophysics, 64, 662–667.

Ormo, J., 1999. **Mutually constrained geophysical data for the evaluation of a proposed impact structure: Lake Hummeln, Sweden.** Tectonophysics, 311, 155–177.

Wänstedt, S., Carlsten, S., Tirén, S.A., 2000. **Borehole radar measurements aid structure geological interpretations.** Journal of Applied Geophysics, 43, 227–237.

4 Glaciation and crustal dynamics

Much of the fracturing in Swedish bedrock (Chapter 3) may have been affected by, possibly even caused by, crustal movements related to the advances and retreats of the continental ice sheets which covered Sweden intermittently during the last 2 million years (*Fredén (ed.) 1994*, p. 102–153). It seems probable that a number of similar glaciations will take place in the next 2 million years, possibly adversely affecting the integrity of a KBS-3-type repository. This raises a number of closely connected issues which cross the traditional boundaries between several branches of geoscience. It has been attempted here to pull together the mechanical aspects of these issues in the present chapter; the hydrogeological aspects, which may be equally important and partly overlap the points raised here, are treated in Chapter 5 (Section 5.4). The question of glaciation and crustal dynamics was brought into sharp focus in Sweden, in the early days of radioactive waste research, by the discovery of evidence for major postglacial movement on faults in northern Sweden, and related evidence for major earthquake activity, in the 1970s. Because of its obvious relevance to question of long-term safety, this quickly became an area of considerable SKB-supported research, whose results are to be found in the reports cited in Section 4.1. More controversial was the evidence for postglacial faulting in southern and central Sweden, and particularly how this evidence was interpreted by one geoscientist to question the viability of the KBS-3 project as a whole, as indicated below.

These results, and the controversy surrounding them, showed that the question of postglacial fault movement needed to be viewed in a wider context, causing SKB to be increasingly involved in issues of more general significance for the relation between continental glaciation and bedrock stability. The corresponding documentation has been subdivided into two groups. Section 4.2 concerns the prediction and modelling of future glaciations, which involves the whole question of global climatic change, based on the results of marine and terrestrial Pleistocene geology, on the evidence for orbital control of glacial and interglacial periods, and on present understanding of ice sheet dynamics. Connected with this issue is the geological record of shoreline displacement and lake tilting, which has been widely studied in Scandinavia, and the reconstruction of land/sea changes during the retreat of the last ice sheet.

The other general aspect concerns the present state of the Earth's crust in Sweden, particularly with respect to the mechanical imbalance caused by the down-flexuring and subsequent rebound of the lithosphere due to ice sheet growth and disappearance, reflected today as continued uplift rates of up to 9 mm per year (Section 4.3). In addition to the results of academic research (see Section 4.5), SKB has supported a whole spectrum of work in areas such as seismicity, *in situ* stress, heat flow and space geodetics, to complement the scientific database in areas of interest.

The data from Sections 4.2 and 4.3 (and the corresponding scientific literature, see Section 4.5) form the background to the fourth group of SKB reports in this chapter

(Section 4.4), those concerned with interpreting the data in terms of “bedrock stability” and geodynamic models. This includes general discussions of crustal deformation and stress systems (large-scale geomechanics, in contrast to the engineering-type geomechanics of Section 3.4), as well as modern risk analyses of the seismic activity to be expected from future crustal movement. Since all the issues addressed in this chapter are of considerable academic interest, there is a large body of scientific literature, a selection of which being given in Section 4.5.

The reports and papers cited in this chapter concern the *mechanical* effects of glacial loading and unloading on the Earth's crust. A further issue of concern for radioactive waste disposal is the change in hydrogeological regime brought about by glaciation – reports and papers on this theme are collected in the following chapter (Section 5.4).

Fredén, C. (ed.), 1994. **Berg och jord**. Sveriges Nationalatlas.

4.1 Postglacial faulting and paleoseismicity

As indicated above, this theme touches on a central and problematic area of SKB activities. Here, we list only works dealing with the geological evidence for postglacial fault movement and related earthquake activity, which was associated with the retreat and disappearance of the last (Weichselian) ice sheet about 10,000 years ago. The first group of references concerns postglacial faulting in northern Sweden, where such faulting is well developed. Evidence for neotectonic activity in northern Scandinavia was recognized in the 1970’s and, because of its obvious relevance to repository siting and safety, became the subject of a very early KBS study (*Lagerbäck & Henkel 1977*). This study, based mainly on air photo interpretation was followed up by more detailed geological studies (air photo interpretation, photogrammetry, outcrop description) and a high resolution aeromagnetic survey (*Lagerbäck & Witshard 1983, Henkel et al 1983*). Later, SKB launched what became known as the Lansjärv Project, after the most easily accessible fault, the Lansjärv fault, which was chosen for more detailed study (*Bäckblom & Stanfors 1989*). The first phase of this project (1986–1988) consisted of both regional and detailed field studies, including the drilling of a 500 m cored borehole, hydrogeological testing in the borehole, and the mapping of trenches through the fault zone (e.g. *Talbot 1986, Henkel 1988, Lagerbäck 1988*). The second phase (1989–1991) confirmed and consolidated the conclusions of the first phase (*Lagerbäck 1990, 1991*), and provided an opportunity for review by an international group of experts in June 1991 (*Stanfors & Ericsson 1993*). The main conclusions were that the postglacial faulting in the Lansjärv area was guided by pre-existing zones of weakness in the bedrock and that the cause of the movement was a combination of tectonic and glacio-isostatic forces. The Lansjärv Project was an interdisciplinary effort which included other activities, such as seismological monitoring (see Section 4.3).

In southern Sweden, the existence of postglacial faults and their relation to glacial retreat and unloading, is less obvious, and has been a matter of controversy, since it was first suggested in the late 1970s and early 1980s (*Mörner 1977, 1979, Mörner et al 1981, Björkman & Trädgårdh 1982, Mörner 1985*). Later, it was maintained that many of the fractures on the island of Äspö (Section 6.3) were faults which formed and/or reactivated immediately after the retreat of the last ice sheet, about 9,000 years ago (*Mörner 1989*), but most geoscientists, after scrutinising the evidence, remain unconvinced (*SKB 1990*). However, although the faults remain elusive, evidence is accumulating from the study of the late Quaternary sedimentary deposits and other surface features (*Sjöberg 1994, Tröften 1997, 2000, Tröften & Mörner 1997, Mörner 1995, 1996, 1999, Mörner & Tröften 1993, Mörner et al 1989, 2000*) that the retreat of the ice sheets was accompanied by a level of seismicity which is higher than at the present time. The subject of deglaciation seismotectonics is documented further in Section 4.5, since it is world-wide a matter of concern and scientific interest. Be that as it may, the Swedish controversy focusses today, not so much on its occurrence, as on its effects, which most researchers maintain can be reduced to insignificance, with regard to the safety of a nuclear waste repository at ca. 500 m depth in bedrock after the *next* glaciation (about 60,000 years hence), by careful site selection. That earthquakes did occur in the late Pleistocene seems to have been confirmed by the above studies. The question is whether they would be the main hazard to a deep repository considering all the other potential effects of a future glaciation (see Sections 4.4 and 5.4, and *Talbot 1999*).

Northern Sweden

Lagerbäck, R., Henkel, H., 1977. **Studier av neotektonisk aktivitet i mellersta och norra Sverige, flygbildsgenomgång och geofysisk tolkning av recenta förkastningar.** KBS TR 19, Svensk Kärnbränslehantering AB.

Henkel, L., Hult, K., Eriksson, L., Johansson, L., 1983. **Neotectonics in northern Sweden – geophysical investigations.** SKBF/KBS TR 83-57. Svensk Kärnbränsleförsörjning AB.

Lagerbäck, R., Witshard, F., 1983. **Neotectonics in northern Sweden – geological investigations.**, SKBF/KBS TR 83-58, Svensk Kärnbränsleförsörjning AB.

Talbot, C.J., 1986. **A preliminary structural analysis of the pattern of post-glacial fault in northern Sweden.** SKB TR 86-20, Svensk Kärnbränslehantering AB.

Henkel, H., 1988. **Tectonic studies in the Lansjärv region.** SKB TR 88-07, Svensk Kärnbränslehantering AB.

Lagerbäck, R., 1988. **Postglacial faulting and paleoseismicity in the Lansjärv area, northern Sweden.** SKB TR 88-25, Svensk Kärnbränslehantering AB.

Bäckblom, G., Stanfors, R. (eds.), 1989. **Interdisciplinary study of post-glacial faulting in the Lansjärv area Northern Sweden 1986–1988.** SKB TR 89-31, Svensk Kärnbränslehantering AB.

Lagerbäck, R., 1990. **Late Quaternary faulting and paleoseismicity in northern Fennoscandia with particular reference to the Lansjärv area, northern Sweden.** GFF, 112, 333–335.

Lagerbäck, R., 1991. **Seismically deformed sediments in the Lansjärv area, Northern Sweden.** SKB TR 91-17, Svensk Kärnbränslehantering AB.

Stanfors, R., Ericsson, L.O. (eds.), 1993. **Post-glacial faulting in the Lansjärv area, Northern Sweden. Comments from the expert group on a field visit at the Molberget post-glacial fault area, 1991.** SKB TR 93-11, Svensk Kärnbränslehantering AB.

Southern and central Sweden

Mörner, N.-A., 1977. **Rörelser och instabiliteter i den svenska berggrunden.** KBS TR 18, Svensk Kärnbränsleförsörjning AB.

Mörner, N.-A., 1979**. Earth movements in Sweden 20,000 BP to 20,000 AP: recorded and expected.** Geol. Fören. Stockholm Föhandl., 100, 279–286.

Mörner, N.-A., Lagerlund, E., Björck, S., 1981**. Neotectonics in the Province of Blekinge.** Zeitschrift für Geomorphologie, N.F. Suppl. 40, 55–60.

Björkman, H., Trädgårdh, J., 1982. **Differential uplift in Blekinge indicating late-glacial neotectonics.** Geol. Fören Stockholm Förh., 104, 75–79.

Mörner, N.-A., 1985. **Paleoseismicity and geodynamics in Sweden.** Tectonophysics, 117, 139–153.

Mörner, N.-A., 1989. **Postglacial faults and fractures on Äspö.** SKB PR 25-89-24, Svensk Kärnbränslehantering AB.

SKB 1990. **Granskning av Nils-Axel Mörners arbete avseende postglaciala strukturer på Äspö**. SKB AR 90-18, Svensk Kärnbränslehantering AB.

Sjöberg, R., 1994. **Bedrock caves and fractured rock surfaces in Sweden. Occurrence and origin**. Doctoral thesis, Univ. Stockholm.

Tröften, P.E., 1997. **Neotectonics and paleoseismicity in southern Sweden, with emphasis on sedimentological criteria**. Doctoral thesis, Univ. Stockholm.

Tröften, P.E., 2000. **The use of varved clay chronology for dating paleoseismic events: the Erstavik record in the Stockholm area, southern Sweden.** Sedimentary Geology, 130, 167–181.

Tröften, P.E., Mörner, N.-A., 1997**. Varved clay chronology as a means of recording paleoseismic events in southern Sweden.** Journal of Geodynamics, 24, 249–258.

Mörner, N.-A., 1995**. Paleoseismicity – the Swedish case.** Quaternary International, 25, 75–79.

Mörner, N.-A., 1996. **Liquefaction and varve disturbance as evidence of paleoseismic events and tsunamis; the autumn 10,430 BP event in Sweden.** Quaternary Science Reviews, 15, 939–948.

Mörner, N.-A., 1999. **Paleo-tsunamis in Sweden.** Physics and Chemistry of the Earth, 24, 443–448.

Mörner, N.-A., Tröften, P.E., 1993**. Paleoseismotectonics in glaciated cratonal Sweden.** Zeitschrift für Geomorphologie, N.S., 94, 107–117.

Mörner, N.-A., Somi, E., Zuchiewicz, W., 1989. **Neotectonics and paleoseismicity within the Stockholm intracratonic region in Sweden.** Tectonophysics, 163, 289–303.

Mörner, N.-A., Tröften, P.E., Sjöberg, R., Grant, D., Dawson, S., Bronge, C., Kvamsdal, O., Sidén, A., 2000. **Deglacial paleoseismicity in Sweden: the 9663 BP Iggesund event.** Quaternary Science Reviews, 19, 1461–1468.

Talbot, C.J., 1999. **Ice ages and nuclear waste isolation.** Engineering Geology, 52, 177–193.

4.2 Quaternary geology, climatic change, future glaciations

The references in this group relate to Quaternary geology in its widest sense. They reflect the enormous strides which have been made over the past 20 years in studying and understanding climatic change, and the causes of the "Ice Ages" which dominate the youngest epoch of Earth history, the Pleistocene (the last 3.5 Ma). SKB contract studies form, of course, only a minute part of the total scientific literature (see selection of references in Section 3.5). Nevertheless, important reviews have been produced (*Ahlbom et al 1991c, Björck & Svensson 1992, Holmgren & Karlén 1998, Westman et al 1999, Boulton et al 2001a*), focussed on Swedish conditions and on one of the main concerns of SKB research, the prediction of future processes and events which may adversely affect a deep repository. Particularly important in this respect is the advance and retreat of continental ice sheets and their effects on the Earth's crust (isostasy) and the worldwide sea-level regime (eustacy). The relative importance of isostasy and eustacy, which determines past and future displacements of the shoreline and hence the evolution of hydrogeological conditions at any coast-near site, has been the focus of a particular series of SKB-supported studies (*Påsse 1996a, 1996b, 1997, 2001 Brydsten 1999, Brunberg & Blomqvist 2000, Morén & Påsse 2001*), as well as corresponding ones in Finland (e.g. *Miettinen et al 1999*) and numerous recent scientific publications (see Section 3.5).

Based on studies such as these, and the whole body of relevant geoscientific research, attempts can be made to reconstruct the dimensions and dynamics of the last (Weichselian) Ice Age in Sweden and to make predictions about the occurrence and effects of future glacial periods. This type of modelling, based on such wide-ranging data as the projected changes in the Earth's orbit around the Sun, the maximum extent of the Weichselian ice sheet, and Pleistocene sea surface temperature fluctuations in the NE Atlantic, has for obvious reasons received considerable SKB support (*Boulton & Payne 1993, King-Clayton et al 1997, Boulton et al 1999*).

Ahlbom, K., Äikäs, T., Ericsson, L., 1991c. **SKB/TVO Ice age scenario.** SKB TR 91-32, Svensk Kärnbränslehantering AB.

Björck, S., Svensson, N.-O., 1992. **Climatic changes and uplift patterns – past, present and future.** SKB TR 92-38, Svensk Kärnbränslehantering AB.

Holmgren., K., Karlén, W., 1998. **Late Quaternary changes in climate.** SKB TR 98-13, Svensk Kärnbränslehantering AB.

Westman, P., Wastegård, S., Schoning, K., Gustafsson, B., Omstedt, A., 1999. **Salinity change in the Baltic Sea during the last 8,500 years: evidence, causes and models**. SKB TR 99-38, Svensk Kärnbränslehantering AB.

Boulton, G.S., Kautsky, U., Morén, L., Wallroth, T., 2001a. **Impact of long-term climate change on a deep geological repository for spent nuclear fuel.** SKB TR 99-05, Svensk Kärnbränslehantering AB.

Påsse, T., 1996a. **Lake-tilting investigations in southern Sweden.** SKB TR 96-10, Svensk Kärnbränslehantering AB.

Påsse, T., 1996b. **A mathematical model of the shore level displacement in Fennoscandia.** SKB TR 96-24, Svensk Kärnbränslehantering AB.

Påsse, T., 1997. **A mathematical model of past, present and future shore level displacement in Fennoscandia.** SKB TR 97-28, Svensk Kärnbränslehantering AB.

Påsse, T., 2001. **An empirical model of glacio-isostatic movements and shore-level displacement in Fennoscandia.** SKB TR 01-41, Svensk Kärnbränslehantering AB.

Brydsten, L., 1999. **Shore line displacement in Öregrundsgrepen.** SKB TR 99-16, Svensk Kärnbränslehantering AB.

Brunberg, A.-K., Blomqvist, P., 2000. **Post-glacial, land rise-induced formation and development of lakes in the Forsmark area, central Sweden.** SKB TR 00-02, Svensk Kärnbränslehantering AB.

Morén, L., Påsse, T., 2001**. Climate and shoreline in Sweden during Weichsel and the next 150,000 years.** SKB TR 01-19, Svensk Kärnbränslehantering AB.

Miettinen, A., Eronen, M., Hyvärinen, H., 1999. **Land uplift and relative sea-level changes in the Loviisa area, southeastern Finland, during the last 8,000 years.** Posiva Oy, report 99-28.

Boulton, G.S., Payne, A., 1993. **Simulation of the European ice sheet through the last glacial cycle and prediction of future glaciation.** SKB TR 93-14, Svensk Kärnbränslehantering AB.

King-Clayton, L., Chapman, N., Ericsson, L.O., Kautsky, F., 1997. **Glaciation and hydrogeology: proceedings of a workshop on the impact of climate change and glaciations on rock stresses, groundwater flow and hydrochemistry – past, present and future**. SKI Report 97:13.

Boulton, G.S., Caban, P., Hulton, N., 1999. **Simulations of the Scandinavian ice sheet and its sub-surface conditions**. SKB R-99-73, Svensk Kärnbränslehantering AB.

4.3 Present crustal conditions

The depression and rebound of the Earth's crust due to glacial loading and unloading (glacio-isostatic movements) can be the cause of brittle deformation, including fracturing, fault movement and earthquake activity, and numerous related effects. The post-glacial faulting and paleoseismicity in Sweden (Section 4.1), temporally correlated with the retreat of the Weichselian ice sheet, is thought to be partly due to this, although there is evidence that tectonic forces (i.e. forces due to lithospheric plate motion, unrelated to glaciation) also played a significant role. Some authors have suggested that the crust became exceptionally unstable during Weichselian retreat, and that, at that time, major earthquakes were common (e.g. *Mörner 1977*).

These controversial views at an early stage in the development of the Swedish nuclear waste disposal programme caused much concern (for details, see Section 4.1) and led also to numerous detailed studies of present-day seismicity, financially supported by SKB and its forerunners. Early compilations (*Kulhánek & Wahlström 1977, Kulhánek et al 1980*) were followed by the installation of special seismograph networks in some areas – in northern Sweden (in connection with the Lansjärv Project, *Kim et al 1988, Wahlström et al 1988, 1989, Slunga 1989*, see Section 4.1), in southern Sweden (*Slunga & Nordgren 1987*), and on a national basis (*Sundqvist 1995*). Because of the low seismicity in Sweden (giving few and weak signals), and because of the wide spacing of the recording network (except for the special networks mentioned above), the interpretation of the distribution of focal depths, source characteristics and fault mechanisms in terms of causes is the subject of continuing discussion. This, together with the fragmentary nature of other types of evidence related to postglacial and present-day crustal deformation, means that there is still no consensus on the relative importance of tectonic versus glacio-isostatic forces (compare *Slunga 1990, Muir-Wood 1993*).

In addition to seismicity, SKB has been involved in the compilation of other types of geophysical data with a bearing on present-day crustal conditions and "bedrock stability" (see Section 4.4), including *in situ* stress, heat flow and space geodetics (*Bergman 1977, Stephansson et al 1991, Ljunggren & Persson 1995, Ahlbom et al 1995, Sundberg 1995, Scherneck et al 1996*).

Mörner, N.-A., 1977. **Rörelser och instabiliteter i den svenska berggrunden.** KBS TR 18, Svensk Kärnbränslehantering AB.

Kulhánek, O., Wahlström, R., 1977. **Earthquakes of Sweden 1891–1957, 1963–1972.** KBS TR 21, Svensk Kärnbränslehantering AB.

Kulhánek, O., Norris, J., Meyer, K., van Eck, T., Wahlström, R., 1980. **The Bergshamra earthquake sequence of December 23, 1979.** SKBF/KBS TR 80-09, Svensk Kärnbränsleförsörjning AB.

Kim, W.Y., Skordas, E., Zhou, Y. P., Kulhanek, O., 1988. **Source parameters of major earthquakes near Kiruna, Northern Sweden, deduced from synthetic seismogram computation.** SKB TR 88-12, Svensk Kärnbränslehantering AB.

Wahlström, R., Linder, S.-O., Holmqvist, C., 1988. **Near-distance seismological monitoring of the Lansjärv neotectonic fault region.** SKB TR 88-12, Svensk Kärnbränslehantering AB.

Wahlström, R., Linder, S.-O., Holmqvist, C., Mårtensson, H.-E., 1989. **Near-distance seismological monitoring of the Lansjärv neotectonic fault region. Part II: 1988.** SKB TR 89-01, Svensk Kärnbränslehantering AB.

Slunga, R., 1989. **Earthquake mechanisms in Northern Sweden Oct 1987–Apr 1988.** SKB TR 89-28, Svensk Kärnbränslehantering AB.

Slunga, R., Nordgren, L., 1987. **Earthquake measurements in southern Sweden, Oct 1, 1986–Mar 31, 1987.** SKB TR 87-27, Svensk Kärnbränslehantering AB.

Sundqvist, S., 1995. **Near-surface seismic events in Sweden, 1980–1993.** SKB PR D-95-015, Svensk Kärnbränslehantering AB.

Slunga, R., 1990. **The earthquakes of the Baltic shield.** SKB TR 90-30, Svensk Kärnbränslehantering AB.

Muir-Wood, R., 1993. **A review of the seismotectonics of Sweden.** SKB TR 93-13, Svensk Kärnbränslehantering AB.

Bergman, S.G.A., 1977. **Spänningsmätingar i skandinavisk berggrund – förutsättningar, resultat och tolkning.** KBS TR 64, Svensk Kärnbränsleförsörjning AB.

Stephansson, O., Ljunggren, C., Jing, L., 1991**. Stress measurements and tectonic implication for Fennoscandia.** Tectonophysics, 189, 317–322.

Ljunggren, C., Persson, M., 1995. **Beskrivning av databas – Bergspänningsmätningar i Sverige.** SKB PR D-95-017, Svensk Kärnbränslehantering AB.

Ahlbom, K., Olsson, O., Sehlstedt, S., 1995. **Temperature conditions in the SKB study sites**. SKB TR 95-16, Svensk Kärnbränslehantering AB.

Sundberg. J., 1995. **Termiska egenskaper för kristallint berg i Sverige – Kartor över värmekonduktivitet, värmeflöde och temperatur på 500 m djup.** SKB PR D-95-018, Svensk Kärnbränslehantering AB.

Scherneck, H.-G., Johansson, J.M., Elgered, G., 1996. **Application of space geodetic techniques for the determination of intraplate deformations and movements in relation with the postglacial rebound of Fennoscandia.** SKB TR 96-19, Svensk Kärnbränslehantering AB.

4.4 Bedrock stability, large-scale geomechanics, risk estmation

Based on an early controversy (*Bjerhammar 1977, Mörner 1977*), SKB and its forerunners have been continuously concerned about what has become known in Sweden as "bedrock stability". Geologists are agreed that when the present-day crust was formed, at different times in the Precambrian, conditions at the contemporary surface were most likely anything but stable (widespread volcanism, major faulting, earthquakes, formation of Himalaya-type mountain chains and Dead Sea-like rifts, etc.). However, they also agree that for 100s of millions of years, the Baltic Shield has remained one of the most stable parts of the Earth's crust – up to the last few million years, when it was subjected to loading and unloading by successive continental ice sheets.

The question of stability during this latest period of geologic time then becomes controversial. The retreat and disappearance of the last ice sheet, which took place between 20,000 and 7,000 years ago, left Sweden and Finland at the centre of a crustal depression. Since then, the crust has been slowly recovering, with a present uplift rate in the centre (Gulf of Bothnia) of up to 9 mm per year. This is a relatively rapid uplift rate, geologically speaking, exceeding, for instance, uplift rates measured in the present-day Alps. Also, there is evidence of significant postglacial faulting and paleoseismicity (Section 4.1) and some authors believe that also present-day seismicity is related to the glacio-isostatic rebound (Section 4.3). In addition, most researchers agree that at least one Ice Age similar to the last one is to be expected long before the contents of a radioactive waste repository can be considered harmless (Section 4.2). Does all this mean that the Swedish bedrock is, or can be expected to become, unstable, and is therefore unsuitable for radioactive waste disposal? Although most geoscientists would, from worldwide comparisons and general experience, negate this question, the problems raised are clearly to be taken seriously. The reports cited below belong to SKB-supported research which attempts to come to grips with some of these problems in a numercal/probabilistic way. They treat two particular areas of concern:

1) **Large-scale geomechanics** (*Stephansson 1987, Rosengren & Stephansson 1990, Stephansson & Hudson 1994, Israelsson et al. 1992, Hansson et al 1995b, Milnes et al 1998*).

These are attempts to provide the necessary data for modelling the effects of future glacial loading of the Earth's crust, in a general way, as well as specifically with reference to a particular site.

2) **Risk estimation** (*Båth 1979, Röshoff 1989b, VBB 1992, King-Clayton et al 1997, LaPointe et al 1997, 1999, 2000*, see also *Coppersmith & Youngs 1999, and for Finland, LaPointe & Cladouhos 1999, Saari 2000*).

These are attempts to estimate the effects of earthquakes of different sizes on repository construction and contents, and to quantify statistically the occurrence of earthquake-related movement on fractures using site-specific data.

Bjerhammar, A., 1977. **The gravity field in Fennoscandia and postglacial crustal movements.** KBS TR 17, Svensk Kärnbränsleförsörjning AB.

Mörner, N.-A., 1977. **Rörelser och instabiliteter i den svenska berggrunden.** KBS TR 18, Svensk Kärnbränsleförsörjning AB.

Large-scale geomechanics

Stephansson, O., 1987. **Modelling of crustal rock mechanics for radioactive waste storage in Fennoscandia – Problem definition.** SKB TR 87-11, Svensk Kärnbränslehantering AB.

Rosengren, L., Stephansson, O., 1990. **Distinct element modelling of the rock mass response to glaciation at Finnsjön, Central Sweden.** SKB TR 90-40, Svensk Kärnbränslehantering AB.

Stephansson, O., Hudson, J.A., 1994. **RES approach for scenario development: with the methodology applied to a 'large rock movement' perturbation.** SKB AR 94-43, Svensk Kärnbränslehantering AB.

Israelsson, J., Rosengren, L., Stephansson, O., 1992. **Sensitivity study of rock mass response to glaciation at Finnsjön, central Sweden.** SKB TR 92-34, Svensk Kärnbränslehantering AB.

Hansson, H., Stephansson, O., Shen, B., 1995b. **Far-field rock mechanics modelling for nuclear waste disposal.** Statens kärnkraftinspektion, Report SKI 95:40.

Milnes, A.G., Gee, D.G., Lund, C.-E., 1998. **Crustal structure and regional tectonics of SE Sweden and the Baltic Sea.** SKB TR 98-21, Svensk Kärnbränslehantering AB.

Risk estimation

Båth, M., 1979. **Fracture risk estimation for Swedish earthquakes.** SKBF/KBS TR 79-27, Svensk Kärnbränsleförsörjning AB.

Röshoff, K., 1989b. **Seismic effects on bedrock and underground constructions. A literature survey of damage on constructions; changes in ground-water levels and flow; changes in chemistry in groundwater and gases.** SKB TR 89-30, Svensk Kärnbränslehantering AB.

VBB 1992. **Project SEISMIC SAFETY. Characterisation of seismic ground motions for probabilistic safety analyses of nuclear facilities in Sweden. Summary Report.** Statens kärnkraftinspektion, SKI report 92:3.

King-Clayton, L., Chapman, N., Ericsson, L.O., Kautsky, F., 1997. **Glaciation and hydrogeology: proceedings of a workshop on the impact of climate change and glaciations on rock stresses, groundwater flow and hydrochemistry – past, present and future**. SKI Report 97:13.

LaPointe, P.R., Wallmann, P., Thomas, A., Follin, S., 1997. **A methodology to estimate earthquake effects on fractures intersecting canister holes.** SKB TR 97-07, Svensk Kärnbränslehantering AB.

LaPointe, P.R., Cladouhos, T., Follin, S., 1999. **Calculation of displacement on fractures intersecting canisters induced by earthquakes: Aberg, Beberg and Ceberg examples.** SKB TR 99-03, Svensk Kärnbränslehantering AB.

LaPointe, P.R., Cladouhos, T.T., Outters, N., Follin, S., 2000. **Evaluation of the conservativeness of the methodology for estimating earthquake-induced movements of fractures intersecting canisters.** SKB TR 00-08, Svensk Kärnbränslehantering AB.

Coppersmith, K.J., Youngs, R.R., 1999. **Data needs for probabilistic fault displacement hazard analysis.** Journal of Geodynamics, 29, 329–343.

LaPointe, P.R., Cladouhos, T.T., 1999**. An overview of a possible approach to calculate rock movements due to earthquakes at Finnish nuclear waste repository sites.** Posiva Oy, report POSIVA 99-02.

Saari, J., 2000**. Seismic activity parameters of the Finnish potential repository sites.** Posiva Oy, report POSIVA 2000-13.

4.5 Selected scientific papers (Fennoscandia)

Pleistocene climatic change, the growth and decay of continental ice sheets and the reaction of the Earth's crust and mantle to glacial loading are not only key areas in SKB-sponsored research, they have long been the focus of considerable academic (and in the case of seismicity, societal) interest. In this Section, we list a selection of the most recent scientific papers on these themes, as a complement to the SKB reports, focussed particularly on Fennoscandia as a classical area of Pleistocene studies and a renowned example of glacio-isostasy. The first heading collects some very recent papers on Pleistocene climates and climatic change, emphasizing the correlation and integration of different data sets, both marine and terrestrial (*Baumann et al 1995, Andrén et al 1999, Isarin 1999, Petit et al 1999, Chapman 2000, Renssen 2000, Sejrup et al 2000, Stroeven 2000*). No claim is made here that this list (or the others in this Section) is representative or complete – the hope is that the citations may, through their lists of references, provide a quick entry into the literature.

Understanding climatic change is a prerequisite for understanding the growth and decay of continental ice-sheets, which is in turn the basis for assessing the mechanical effects of continental glaciation on the Earth's crust, and hence, in Fennoscandia, for understanding present-day crustal dynamics. The crustal dynamics of Fennoscandia has been studied in great detail, for instance within the framework of the European Geotraverse project (e.g. *Gregersen et al 1991, Müller et al 1992. Blundell et al 1992*). These and numerous other publications describe historical and present-day seismicity, complementing the large number of SKB reports (e.g. *Slunga 1991, Ahjos & Uski 1992, Gregersen 1992, Kulhánek & Wahlström 1992, 1996, Wahlström & Grünthal 1994*, see Section 4.3), and recent developments in space geodetics to measure directly crustal movements (*Scherneck et al 1998, Pan et al 1999*).

Of particular interest for plate tectonic theory are the insights which the Fennoscandian data give into crustal and mantle processes. In the first instance, these are based on increased understanding of the thermal structure of the lithosphere based on interpretations of surface heat flow and radiogenic heat production (*Balling 1995, Kukkonen 1995, 1998, Nyblade 1999, Kukkonen & Peltonen 1999*). This leads to interpretations of the rheological properties of the lithosphere and their variation with depth on a very long time scale (*Dragoni et al 1993, Cloetingh & Burov 1996, Kaikkonen et al 2000*).

The same data base is important for the shorter term crustal movements associated with glacio-isostasy. Fennoscandia is a well known region for glacial rebound, since the crustal deformation resulting from the retreat of the last ice-sheet is still observable (e.g. *Ekman 1996, Kakkuri 1997, Gudmundsson 1999, Lambeck & Johnston 1998, Lambeck et al 1998a, 1998b,*). The good observation base has lead to numerous attempts to model the effects of glacial loading and unloading in terms of the mechanical properties of crust and upper mantle (*Mörner 1978, 1990, 1991, Johnston et al 1998, Lambeck 1999, Poudjom Djomani 1999, Klemann & Wolf 1999*), some directly related to nuclear waste disposal (*Johnston 1987, Stephansson & Shen 1991*, *Rosengren & Stephansson 1993,* see also *Talbot 1999*). All this research is also relevant to the problem of deglaciation seismotectonics, which is a controversial theme in Sweden (see Section 4.1) and which is currently under debate internationally (e.g. *Fjeldskaar et al 2000, Muir-Wood 2000, Stewart et al 2000*).

Pleistocene climates and climatic change

Baumann, K.-H., Lackschewitz, K.S., Mangerud, J., Spielhagen, R.F., Wolf-Welling, T.C.W., Henrich, R., Kassens, H., 1995. **Reflections of Scandinavian ice sheet fluctuations in Norwegian Sea sediments during the past 150 000 years.** Quaternary Research, 43, 185–197.

Andrén, T., Björck, J., Johnsen, S., 1999. **Correlation of Swedish glacial varves with the Greenland (GRIP) oxygen isotope record.** Journal of Quaternary Science, 14, 361–371.

Isarin, R.F.B., 1999. **Reconstructing and modelling late Weichselian climates : the Younger Dryas in Europe as a case study.** Earth Science Reviews, 48, 1–38.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barbola, J.-M., Basile, I., Bender, M., Chappelaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., Stievenard, M., 1999. **Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica**. Nature, 399, 429–436.

Chapman, M.R., 2000. **Sea surface temperature variability during the last glacial-interglacial cycle: Assessing the magnitude and pattern of climate change in the North Atlantic.** Palaeogeography, Palaeoclimatology, Palaeoecology, 157, 1–25.

Renssen, H., 2000. **Permafrost as a critical factor in palaeoclimate modelling: the Younger Dryas case in Europe.** Earth and Planetary Science Letters, 176, 1–5.

Sejrup, H.P., Larsen, E., Landvik, J., King, E.L., Haflidason, H., Nesje, A., 2000. **Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region.** Quaternary Science Reviews, 19, 667–685.

Stroeven, A.P., 2000. **Age of Sirius Section on Mount Feather, McMurdo Dry Valleys, Antarctica, based on glaciological inferences from the overridden mountain range of Scandinavia.** Global and Planetary Change, 23, 231–247.

Crustal dynamics

Gregersen, S., Korhonen, H., Husebye, E.S., 1991. **Fennoscandian dynamics: present-day earthquake activity.** Tectonophysics, 189, 333–344.

Müller, B., Zoback, M.L., Fuchs, K., Mastin, L., Gregersen, S., Pavoni, N., Stephansson, O., Ljunggren, C., 1992. **Regional patterns of tectonic stress in Europe**. Jour. Geophys. Research, 97, B8, 11783–11803.

Blundell, D., Freeman, R., Müller, S., eds., 1992. **A Continent Revealed – the European Geotraverse**. Cambridge Univiversity Press (Cambridge, UK).

Slunga, R., 1991. **The Baltic Shield earthquakes.** Tectonophysics, 189, 323–331.

Gregersen, S., 1992. **Crustal stress regime in Fennoscandia from focal mechanisms**. Jour. Geophys. Research, 97, 11821–11827.

Ahjos, T., Uski, M., 1992. **Earthquakes in northern Europe in 1375–1989.** Tectonophysics, 207, 1–23.

Kulhánek, O., Wahlström, R., 1992. **Macroseismic observations in Sweden, 1984–1990.** Geological Survey of Sweden (SGU), Series C, research paper 825.

Kulhánek, O., Wahlström, R., 1996. **Macroseismic observations in Sweden, 1991–1995.** Geological Survey of Sweden (SGU), Series C, research paper 829.

Wahlström, R., Grünthal, G., 1994. **Seismicity and seismotectonic implications in the southern Baltic Sea area**. Terra Nova, 6, 149–157.

Pan, M., Sjöberg, L.E., Talbot, C.J., Asenjo, E., 1999. **GPS measurements of crustal deformation in Skåne, Sweden, between 1989 and 1996.** GFF, 121, 67–80.

Scherneck, H.-G., Johansson, J.M., Mitrovica, J.X., Davis, J.L., 1998. **The BIFROST project: GPS de termined 3-D displacement rates in Fennoscandia from 800 days of continuous observations in the SWEPOS network.** Tectonophysics, 294, 305–321.

Thermal regime, rheology

Balling, N., 1995. **Heat flow and thermal structure of the lithosphere across the Baltic Shield and northern Tornquist Zone.** Tectonophysics, 244, 13–50.

Kukkonen, I.T., 1995. **Thermal aspects of groundwater circulation in bedrock and its effect on crustal geothermal modelling in Finland, the central Fennoscandian Shield**. Tectonophysics, 244, 119–136.

Kukkonen, I.T., 1998. **Temperature and heat flow density in a thick cratonic lithosphere: the SVEKA transect, central Fennoscandian Shield.** Journal of Geodynamics, 26, 111–136.

Nyblade, A.A., 1999. **Heat flow and the structure of Precambrian lithosphere**. Lithos, 48, 81–91.

Kukkonen, I.T., Peltonen, P., 1999. **Xenolith-controlled geotherm for the central Fennoscandian Shield: implications for lithosphere-asthenosphere relations.** Tectonophysics, 304, 301–315.

Dragoni, M., Pasquale, V., Verdoya, M., Chiozzi, P., 1993. **Rheological consequences of the lithospheric thermal structure in the Fennoscandian Shield.** Global Planetary Change, 8., 113–126.

Cloetingh, S., Burov, E.B., 1996. **Thermomechanical structure of European continental lithosphere: constraints from rheological profiles and EET estimates.** Geophysical Journal International, 124, 695–723.

Kaikkonen, P., Moisio, K., Heeremans, M., 2000. **Thermomechanical lithospheric structure of the central Fennoscandian Shield.** Physics of the Earth and Planetary Interiors, 119, 209–235.

Glacio-isostasy, glacial rebound, geomechanics of continental glaciation

Ekman, J., 1996. **A consistent map of the postglacial uplift of Fennoscandia.** Terra Nova, 8, 158–165.

Kakkuri, J., 1997. **Postglacial deformation of the Fennoscandian crust.** Geophysics, 33, 99–109.

Gudmundsson, A., 1999. **Postglacial crustal doming, stresses and fracture formation with application to Norway.** Tectonophysics, 307, 407–419.

Lambeck, K., Johnston, P., 1998. **The viscosity of the mantle: evidence from analyses of glacial-rebound phenomena.** In: "The Earth's Mantle; Composition, Structure and Evolution" (Jackson, I., ed.), Cambridge Univ. Press (Cambridge), 461–502.

Lambeck, K., Smither, C., Ekman, M., 1998a. **Tests of glacial rebound models for Fennoscandinavia based on instrumented sea- and lake-level records.** Geophysical Journal International, 135, 375–387.

Lambeck, K., Smither, C., Johnston, P., 1998b. **Sea-level change, glacial rebound and mantle viscosity in northern Europe.** Geophysical Journal International, 134, 102–144.

Davis, J.L., Mitrovica, J.X., Scherneck, H.-G., Fan, H., 1999. **Investigations of Fennoscandian glacial isostatic adjustment using modern sea level records.** Journal of Geophysical Research, 104, B2, 2653–3034.

Mörner, N.-A., 1978. **Faulting, fracturing and seismic activity as a function of glacial-isostasy in Fennoscandia.** Geology, 6, 41–45

Mörner, N.-A., 1990. **Glacial isostasy and long-term crustal movements in Fennoscandia with respect to lithospheric and asthenospheric processes and properties.** Tectonophysics, 176, 13–24.

Mörner, N.-A., 1991**. Intense earthquakes and seismotectonics as a function of glacial isostasy.** Tectonphysics, 188, 407–410.

Johnston, P., Wu, P., Lambeck, K., 1998. **Dependence of horizontal stress magnitude on load dimension in glacial rebound models.** Geophysical Journal International, 132, 41–60.

Lambeck, K., 1999. **Shoreline displacements in southern-central Sweden and the evolution of the Baltic Sea since the last maximum glaciation.** Journal Geol. Soc. London, 156, 465–486.

Poudjom Djomani, Y.H., 1999. **The flexural rigidity of Fennoscandia: reflection of the tectonothermal age of the lithospheric mantle.** Earth and Planetary Science Letters, 174, 139–154.

Klemann, V., Wolf, D., 1999. **Implications of a ductile crustal layer for the deformation caused by the Fennoscandian ice sheet.** Geophysical Journal International, 139, 216–226.

Johnston, A.C., 1987. **Suppression of earthquakes by large continental ice sheets.** Nature, 330, 467–469.

Stephansson, O., Shen, B., 1991. **Modelling of faulted mass response to glaciation, thermal loading and seismicity**. Quart. Jour. Engineering Geology, 24, 355–362.

Rosengren, L., Stephansson, O., 1993**. Modelling of rock mass response to glaciation at Finnsjön, central Sweden.** Tunnelling and Underground Space Technology, 8, 75–82.

Talbot, C.J., 1999. **Ice ages and nuclear waste isolation.** Engineering Geology, 52, 177–193.

Fjeldskaar, W., Lindholm, C., Dehls, J.F., Fjeldskaar, I., 2000. **Postglacial uplift, neotectonics and seismicity in Fennoscandia.** Quaternary Science Reviews, 19, 1413–1422.

Muir-Wood, R., 2000**. Deglaciation seismotectonics: a principle influence on intraplate seismogenesis at high latitudes.** Quaternary Science Reviews, 19, 1399–1411.

Stewart, I.S., Sauber, J., Rose, J., 2000. **Glacio-seismotectonics: ice sheets, crustal deformation and seismicity.** Quaternary Science Reviews, 19, 1367–1389.

5 Deep groundwater

The understanding of deep groundwater flow, chemical evolution and microbial content of groundwater, and its interaction with the minerals lining the rock fractures – in a word, the hydrogeology of a site – is obviously an important key to evaluating the performance of KBS-3-type repositories. Since a KBS-3 repository lies at ca. 500 m depth in crystalline bedrock, where the deep groundwater circulates mainly in a complex system of fractures and fracture zones, performance assessment can only be based on subsurface hydrogeological investigations in boreholes and underground excavations. The hydrogeological conditions at depth can only to a very limited extent be evaluated from observations at, or at shallow depths below, the Earth's surface – many geoscientists would argue that they cannot be evaluated at all on the basis of surface data alone.

This leads to a major problem in the search for suitable KBS-3-type repository sites, what we have here called the siting process. After following some general rules, such as avoiding major fracture zones and areas of high local relief, large areas of crystalline rock remain, which experience suggests will be hydrogeologically “good enough” at depth, but this impression can only be confirmed or negated by in-depth investigation, including deep drilling. The hydrogeological work in connection with the siting process, as set out in the Länsstudier and Förstudier (Chapter 8), is confined to compiling surface and near-surface data on groundwater conditions and to judging whether they are “normal” in the general context of what is known about the relation between surface and deep subsurface conditions in Swedish bedrock. In this process, the results of hydrogeological investigations at the SKB study sites and underground laboratories (Chapter 6) have provided an invaluable body of experience.

From the above discussion, it is clear that most hydrogeological data from the deeper levels of Swedish bedrock is site-specific, and most SKB reports deal with conditions at particular sites, especially the SKB study sites and the Stripa and Äspö underground laboratories (Chapter 6). These reports are not cited in this chapter, unless they are judged to be of more general significance. Similarly, the hydrogeological reports which form part of the Förstudie are only listed under the different municipalities in Chapter 8. However, since this is such an important subject, SKB and its contractors have been involved in a whole range of activities of a more general nature (development and testing of methods and instrumentation, hydrogeological modelling, etc.), and in comparing results from different sites. Reports on these aspects are the main emphasis in the present chapter. These have been subdivided into four groups:

Section 5.1: Geohydrology
Reports dealing with groundwater flow on a regional scale, and the measurement of large-scale hydraulic parameters.

Section 5.2: Hydrogeochemistry
Reports on chemical conditions in deep groundwater, and their interpretation in terms of age, chemical evolution and rock/water interaction.

Section 5.3: Microbiology of groundwater
Reports treating the microbiology of groundwater in Sweden and the deep biosphere in general, and its relation to hydrogeochemistry.

Section 5.4: Hydrogeology and glaciation
Reports on the problem of understanding and predicting changes in geohydrology and hydrogeochemistry caused by advancing and retreating continental ice sheets.

For the hydrogeology of specific sites and areas, consult the citations in Chapters 6 and 8.

5.1 Geohydrology

Geohydrology is the name given to those aspects of hydrogeology which concern groundwater flow. It is one of the most important aspects of the safety analysis of any site, and, in fractured crystalline rocks, it is one of the most difficult to treat quantitatively, because of the extreme heterogeneity of water flow patterns at the small scale (centimetres to metres to tens of metres). This problem is critical for site-scale investigations (Chapter 6), but at a larger scale (tens of metres to kilometres to hundreds of kilometres) the heterogeneities can be treated statistically and it becomes meaningful to assign average hydraulic properties ("effective" values) to rock volumes above a certain size. If this can be done, it also becomes meaningful to model large-scale (regional) groundwater flow patterns. Hence, the references in this Section have been collected under two headings.

In the first, the reports listed treat the methods used for defining the effective hydraulic conductivity of fractured crystalline rocks and the processing of the results, as well as methods for characterising groundwater flow in 3D fracture systems. For near-surface hydraulic parameters, the data in the SGU well archive can be used to study regional variations (*Carlsson & Carlstedt 1977, Wladis et al 1977,* see also the Länsstudier and Förstudier, Sections 8.2 and 8.3). For depths greater than 100 m, however, the data is derived from different types of hydrogeological testing in deep boreholes (single- and double-packer, cross-hole, difference flow, etc.), combined with a spectrum of other core and borehole logging methods (e.g. *Magnusson & Duran 1984, LaPointe 1994, Follin et al 2000,* see also site lists, Chapter 6). Other methods are based on detailed underground knowledge of the 3D fracture network in addition to hydrological data, as becomes available in underground excavations, such as Stripa mine and Äspö HRL (*Lindblom & Granemo 1979, Winberg 1991, Andersson, Peter, et al 1993, LaPointe et al 1995, Rhén et al 1997b, Svensson 1999c, Bossart et al 2001*).

The remaining works under this heading are more oriented towards the results obtained with different methods and towards comparisons between different locations (*Lindblom & Hahn 1979, Ericsson & Ronge 1986, Liedholm 1992, Walker et al 1997*), including the effect of dissolved gasses on transmissivity (*Geller & Jarsjö 1995, Jarsjö & Destouni 1998*). SKB has been involved in testing the Finnish difference flow measurement technique (*Öhberg & Rouhiainen* 2000) and has supported a number of post-graduate theses in the area of geohydrology (e.g. *Järsjö 1998, Vidstrand 1999*).

Under the second heading, SKB reports describing the methods and results of regional groundwater flow modelling in different parts of the country are listed. In this group, models for the region around the Finnsjön site (Beberg, in SR97, see Subsection 6.1.1) are particularly prominent (*Lindbom & Boghammar 1992, Boghammar et al 1993, Hartley et al 1998*), but other SR97 sites are also represented (*Rehbinder et al 1997, Boghammar et al 1997*, see Subsection 6.1.3 and Section 6.3). In this connection, it is important to note a series of reports dealing with the particularities of the geohydrology at coastal sites and the geohydrological implications of interacting freshwater and salt-water systems (*Voss & Andersson 1993, Follin 1995, Svensson 1997, 1999a, Engqvist 1997*).

Methodology

Carlsson, L., Carlstedt, A., 1977. **Estimation of transmissivity and permeability in Swedish bedrock.** Nordic Hydrology, 8, 103–116.

Wladis, D., Jönsson, P., Wallroth, T., 1997. **Regional characterisation of hydraulic properties of rock using well test data.** SKB TR 97-29, Svensk Kärnbränslehantering AB.

Magnusson, K.-Å., Duran, O., 1984: **Comparative study of geological, hydrological and geophysical borehole investigations**. SKBF/KBS TR 84-09, Svensk Kärnbränsleförsörjning AB.

LaPointe, P.R., 1994. **Evaluation of stationary and non-stationary geostatistical models for inferring hydraulic conductivity values at Äspö.** SKB TR 94-22, Svensk Kärnbränslehantering AB.

Follin, S., Askling, P., Carlsten, S., Stråhle, A., 2000. **Smålandsgranitens vattengenomsläpplighet. Jämförelse av borrhålsdata från Äspö, Laxemar och Klipperås.** SKB R-00-46, Svensk Kärnbränslehantering AB.

Lindblom, U., Granemo, J.J., 1979. **Beräkning av permeabilitet i stor skala vid bergrum i Karlshamns hamn.** SKBF/KBS TR 79-16, Svensk Kärnbränsleförsörjning AB.

Winberg, A., 1991. **Analysis of spatial correlation of hydraulic conductivity data from the Stripa mine**. SKB TR 91-28, Svensk Kärnbränslehantering AB.

Andersson, Peter, Andersson, J.-E., Gustafssson, E., Nordqvist, R., Voss, C., 1993. **Site characterisation in fractured crystalline rock. A critical review of geohydraulic measurement methods.** Statens kärnkraftinspektion, Report SKI 93:23.

LaPointe, P., Wallmann, P., Follin, S., 1995. **Estimation of effective block conductivities based on discrete network analyses using data from the Äspö site.** SKB TR 95-15, Svensk Kärnbränslehantering AB.

Rhén, I., Gustafson, G., Wikberg, P., 1997b. **Äspö HRL – Geoscientific evaluation 1997/4. Results from pre-investigations and detailed site characterisation. Comparison of predictions and observations.**

Hydrogeology, groundwater chemistry and transport of solutes. SKB TR 97-05, Svensk Kärnbränslehantering AB.

Svensson, U., 1999c. **Representation of fracture networks as grid cell conductivities.** SKB TR 99-25, Svensk Kärnbränslehantering AB.

Bossart, B., Hermanson, J., Mazurek, M., 2001. **Äspö Hard Rock Laboratory. Analysis of fracture networks based on structural and hydrogeological observations on different scales.** SKB TR 01-21, Svensk Kärnbränslehantering AB.

Lindblom, U., Hahn, T., 1979. **Hydraulisk konduktivitet bestämd i stor skala i ytliga partier av Blekinge kustgnejs.** SKBF/KBS TR 79-20, Svensk Kärnbränsleförsörjning AB.

Ericsson, L.O., Ronge, B., 1986. **Correlation between tectonic lineaments and permeability values of crystalline bedrock in the Gideå area.** SKB TR 86-19, Svensk Kärnbränslehantering AB.

Liedholm, M., 1992. **The hydraulic properties of different greenstone areas. A comparative study.** SKB PR 44-92-007, (tidigare nr LOK 92-07), Svensk Kärnbränslehantering AB.

Walker, D., Rhén, I., Gurban, I., 1997. **Summary of hydrogeologic conditions at Aberg, Beberg and Ceberg**. SKB TR 97-23, Svensk Kärnbränslehantering AB.

Geller, J.T., Jarsjö. J., 1995. **Groundwater degassing and two-phase flow: Pilot hole test report.** SKB ICR 95-03, Svensk Kärnbränslehantering AB.

Jarsjö, J., Destouni, G., 1998. **Groundwater degassing in fractured rock. Modelling and data comparison.** SKB TR 98-17, Svensk Kärnbränslehantering AB.

Öhberg, A., Rouhiainen, P., 2000. **Posiva groundwater flow measuring techniques.** Posiva Oy, report POSIVA 2000-12.

Järsjö, J., 1998. **Hydraulic conductivity relations in soil and fractured rock: Fluid component and phase interaction effects**. Doctoral thesis, Royal Institute of Technology (KTH), Stockholm.

Vidstrand, P., 1999. **Hydrogeological scale effects in crystalline rocks**. Licentiate thesis, Chalmers University of Technology, Göteborg.

Regional geohydrology

Lindbom, B., Boghammar, A., 1992. **Numerical groundwater flow calculations at the Finnsjön study site – extended regional area.** SKB TR 92-03, Svensk Kärnbränslehantering AB.

Boghammar, A., Grundfelt, B., Widén, H., 1993. **Analysis of the regional groundwater flow in the Finnsjön area.** SKB TR 93-15, Svensk Kärnbränslehantering AB.

Hartley, L., Boghammar, A., Grundfelt, B., 1998. **Investigation of the large scale regional hydrogeological situation at Beberg.** SKB TR 98-24, Svensk Kärnbränslehantering AB.

Rehbinder, G., Follin, S., Isaksson, A., 1997. **On regional flow in Baltic Shield rock. An application of an analytical solution using hydrogeologic conditions at Aberg, Beberg and Ceberg of SR 97.** SKB R-97-17, Svensk Kärnbränslehantering AB.

Boghammar, A., Grundfelt, B., Hartley, L., 1997. **Investigation of the large scale regional hydrogeologi-cal situation at Ceberg.** SKB TR 97-21, Svensk Kärnbränslehantering AB.

Voss, C., Andersson, J., 1993. **Regional flow in the Baltic Shield during Holocene coastal regression.** Ground Water, 31, 989–1006.

Follin, S., 1995. **Geohydrological simulation of a deep coastal repository.** SKB TR 95-33, Svensk Kärnbränslehantering AB.

Svensson, U., 1997. **A regional analysis of groundwater flow and salinity distribution in the Äspö area.** SKB TR 97-09, Svensk Kärnbränslehantering AB.

Engqvist, A., 1997. **Water exchange estimates derived from forcing for the hydraulically coupled basins surrounding Äspö island and adjacent coastal water.** SKB TR 97-14, Svensk Kärnbränslehantering AB.

Svensson, U., 1999a. **A laboratory scale analysis of groundwater flow and salinity distribution in the Äspö area.** SKB TR 99-24, Svensk Kärnbränslehantering AB.

5.2 Hydrogeochemistry

Hydrogeochemical studies are generally thought to have a special significance for safety assessments. The reason is that analyses of the chemical and isotopic composition of groundwater can be used to interpret its past evolution and hence the possibility of understanding a site's long-term development from a hydrogeological perspective. Apart from some early reports on the occurrence of naturally radioactive groundwater and springs in Sweden (*Aastrup 1981, Ek et al 1982*), most of the SKB- supported work on hydrogeochemistry refers to the problems of sampling, analysing and interpreting groundwaters from the deep boreholes at the study sites and from deep underground excavations (cf. Chapter 6). Because hydrogeochemistry gives possibilities of evaluating the long-term evolution of deep repository sites in terms of rock/water interaction, it is of particular importance for safety considerations, together with geochemical results from natural analogues (see references in Section 7.1).

With regard to date of publication, the reports listed below fall into two main periods. The earlier group were published between 1977 and 1990, and give a broad overview over deep groundwater chemistry in Sweden, based mainly on results from the study sites (*Rennerfelt 1977, Gidlund 1978, Laurent 1982, Wikberg et al 1983, Smellie et al 1985, Nordström & Puigdomènech 1986, Pettersson et al 1990,* for references to individual sites, see Chapter 6). However, they also revealed that major problems with sample collection, and in some cases sample analysis, existed, which reduced confidence in any conclusions. In the last decade, however, the scientific basis of geochemical work on deep groundwaters in Sweden and Finland has been strengthened considerably and the quality of the results from the Swedish/Finnish cooperation in this area has reached internationally recognised standards (*Grenthe et al 1992, Romero 1993, Laaksoharju et al 1993, 1995a, 1998, Banwart et al 1999, Smellie et al 1999, Blomqvist 1999*). This has enabled the development of a new hydrogeochemical model which takes into account both rock/water interactions and mixing history, whilst new sampling and analysis techniques reduce the acquisition and processing uncertainties (*Laaksoharju 1999, Gurban et al 1999*). A list SKB-supported post-graduate these is appended, which includes those works focussed on hydrogeochemistry and transport processes (*Nordén 1994, Östhols 1994, Byegård 1995, Christiansen-Sätmark 1995, Romero 1995, Wen 1995, Daquing Cui, 1996, Malmström 1996, Selroos 1996, Johansson 2000*).

Aastrup, M., 1981. **Naturligt förekommande uran-, radium- och radonaktiviteter i grundvatten.** SKBF/KBS TR 81-08, Svensk Kärnbränsleförsörjning AB

Ek, J., Evans, S., Ljungqvist, L., 1982. **Variation in radioactivity, uranium and radium-226 contents in three radioactive springs and along their out-flows, Northern Sweden.** SKBF/KBS TR 82-13, Svensk Kärnbränsleförsörjning AB.

Early methodology

Rennerfelt, J., 1977. **Sammansättning av grundvatten på större djup i granitisk berggrund.** KBS TR 36, Svensk Kärnbränsleförsörjning AB.

Gidlund, G., 1978. **Analyser och åldersbestämningar av grundvatten på stora djup.** KBS TR 62, Svensk Kärnbränsleförsörjning AB.

Laurent, S., 1982. **Analysis of groundwater from deep boreholes in Kråkemåla, Sternö and Finnsjön**. SKBF/KBS TR 82-23, Svensk Kärnbränsleförsörjning AB.

Wikberg, P., Grenthe, I., Axelsen, K., 1983. **Redox conditions in groundwaters from Svartboberget, Gideå, Fjällveden and Kamlunge**. SKBF/KBS TR 83-40, Svensk Kärnbränsleförsörjning AB.

Smellie, J.A.T., Larsson, N.-Å., Wikberg, P., Carlsson, L., 1985. **Hydrochemical investigations in crystalline bedrock in relation to existing hydraulic conditions. Experience from the SKB test-sites in Sweden.** SKB TR 85-11, Svensk Kärnbränslehantering AB.

Nordstrom, D K., Puigdomènech, I., 1986. **Redox chemistry of deep groundwaters in Sweden.** SKB TR 86-03, Svensk Kärnbränslehantering AB.

Pettersson, C., Ephraim, J., Allard, B., Borén, H., 1990. **Characterisation of humic substances from deep groundwaters in granitic bedrock in Sweden.** SKB TR 90-29, Svensk Kärnbränslehantering AB.

Improved methodology

Grenthe, I., Stumm, W., Laarksoharju, M., Nilsson, A.-C., Wikberg, P., 1992. **Redox potentials and redox reactions in deep groundwater systems**. Chemical Geology, 98, 131–150.

Romero, L., 1993. **Evolution of redox fronts around a repository for high-level nuclear waste**. Licentiate thesis, Royal Institute of Technology (KTH), Stockholm.

Laaksoharju, M., Smellie, J.A.T., Ruotsalainen, P., Snellman, M.V., 1993. **An approach to quality classification of deep groundwaters in Sweden and Finland.** SKB TR 93-27, Svensk Kärnbränslehantering AB.

Laaksoharju, M., Degeuldre, C., Skårman, C., 1995a. **Studies of colloids and their importance for repository performance assessment.** SKB TR 95-24, Svensk Kärnbränslehantering AB.

Laaksoharju, M., Gurban, I., Skårman, C., 1998. **Summary of hydrochemical conditions at Aberg, Beberg and Ceberg.** SKB TR 98-03, Svensk Kärnbränslehantering AB.

Banwart, S.A., Wikberg, P., Puigdomènech, I., 1999. **Protecting the redox stability of a deep repository: concepts, results and experience from the Äspö hard rock laboratory.** In: "Chemical Containment of Waste in the Geosphere" (Metcalfe, R., Rochelle, C.A., eds.), Geol. Soc. London, Special Publ. 157, 85–99.

Smellie, J.A.T., Laaksoharju, M., Snellman, M.V., Ruotsalainen, P.H., 1999. **Evaluation of the quality of groundwater sampling: Experience derived from radioactive waste disposal programmes in Sweden and Finland during 1980–1992.** Posiva Oy, report 99-29.

Blomqvist, R., 1999. **Hydrogeochemistry of deep groundwaters in the central part of the Fenno-scandian Shield.** Geological Survey of Finland, Nuclear Waste Disposal Research, Report 101.

Laaksoharju, M., 1999. **Groundwater characterisation and modelling: problems, facts and possibilities.** SKB TR 99-42, Svensk Kärnbränslehantering AB.

Gurban, I., Laaksoharju, M., Made, B., Ledoux, E., 1999. **Uranium transport around the reactor zone at Okelobondo (Oklo). Data evaluation with M3 and HYTEC**. SKB TR 99-36, Svensk Kärnbränslehantering AB.

SKB-supported post-graduate research

Nordén, M., 1994. **The complexation of some radionuclides with natural organics – implications for radioactive waste disposal**. Doctoral thesis, Linköping University.

Östhols, E., 1994. **Some processes affecting the mobility of thorium in natural groundwaters**. Doctoral thesis, Royal Institute of Technology (KTH), Stockholm.

Byegård, J., 1995. **Developments of some in situ tracer techniques applied in groundwater research**. Doctoral thesis, Chalmers University of Technology, Göteborg.

Christiansen-Sätmark, B., 1995. **Transport of radionuclides and colloid through quartz sand columns**. Doctoral thesis, Chalmers University of Technology, Göteborg.

Romero, L., 1995. **The near-field transport in a repository for high-level nuclear waste**. Doctoral thesis. Royal Institute of Technology (KTH), Stockholm.

Wen, X.-H., 1995. **Geostatistical methods for prediction of mass transport in groundwater**. Doctoral thesis, Royal Institute of Technology (KTH), Stockholm.

Daquing Cui, 1996. **Sorption processes and solubilities of radionuclides in deep granitic fracture systems.** Doctoral thesis, Royal Institute of Technology, Stockholm.

Malmström, M., 1996. **The weathering kinetics and dissolution stoichiometry of biotite: implications for the geochemistry of granitic aquifers.** Doctoral thesis, Royal Institute of Technology (KTH), Stockholm.

Selroos, J.-O., 1996. **Contaminant transport by groundwater: Stochastic traveltime analysis and probabilistic safety assessment**. Doctoral thesis, Royal Institute of Technology (KTH), Stockholm.

Johansson, H., 2000. **Retardation of tracers in crystalline rock. Sorption and matrix diffusion of alkali metal and alkaline earth metal tracers in laboratory and field experiments.** Doctoral thesis, Chalmers University of Technology, Göteborg.

5.3 Microbiology of groundwater

The hydrochemistry and the microbiology of groundwater are traditionally treated separately, but are now known to be intimately entwined. The possible importance of bacteria and other microbes for KBS-3 repository performance and canister corrosion became clear in the 80s, when microbial ecosystems were discovered in deep aquifers under reducing conditions. This prompted SKB to initiate and support a long-term programme of research into the subterranean biosphere of the Baltic Shield. Already at an early stage, this showed that such ecosystems existed to depths exceeding 1,000 m (*Pedersen*

1989, Pedersen & Ekendahl 1990), and later, the possibly of a deep biosphere down to several kilometres in Swedish bedrock has been proposed (*Gold 1999*). The results of SKB-supported research have been published in a long series of Technical Reports, doctoral theses and scientific publications (*Pedersen et al 1991, Pedersen & Ekendahl 1992a, Pedersen & Karlsen 1995, Ekendahl 1996, Pedersen 1996, Pedersen (ed.) 1996, 1997, Kotelnikova & Pedersen 1999, Motamedi 1999, Pedersen 1999, 2000*). Similar research, but less extensive, has been carried out within the Canadian and Finnish programmes (*Stroes-Gascoyne et al 1996, Haveman et al 2000*). Much of this research has relevance to the controversy about the possibly biogenic origin of the methane gas which occurs in regionally extensive and volumetrically significant accumulations in the Canadian and Baltic Shields (*Sherwood Lollar et al 1993a, 1993b*), a phenomenon which may have wider significance (earthquake genesis, cf. *Gold op cit*).

Pedersen, K., 1989. **Deep ground water microbiology in Swedish granitic rock and it's relevance for radionuclide migration from a Swedish high level nuclear waste repository.** SKB TR 89-23, Svensk Kärnbränslehantering AB.

Pedersen, K., Ekendahl, S., 1990. **Distribution and activity of bacteria in deep granitic groundwaters of southeastern Sweden.** Microbial Ecology, 20, 37–52.

Gold, T., 1999. **The Deep Hot Biosphere.** Springer-Verlag (New York, etc.).

Pedersen, K., Ekendahl, S., Arlinger, J., 1991. **Microbes in crystalline bedrock. Assimilation of CO2 and introduced organic compounds by bacterial populations in groundwater from deep crystalline bedrock at Laxemar and Stripa.** SKB TR 91-56, Svensk Kärnbränslehantering AB.

Pedersen, K., Ekendahl, S., 1992a. **Assimilation of CO_2 and introduced organic compounds by bacterial communities in groundwater from southeastern Sweden deep crystalline bedrock.** Microbial Ecology, 23, 1–14.

Pedersen, K., Karlsson, F., 1995. **Investigations of subterranean microorganisms. Their importance for performance assessment of radioactive waste disposal.** SKB TR 95-10, Svensk Kärnbränslehantering AB.

Ekendahl, S., 1996. **Deep subsurface ecosystems – numbers, activity and diversity of groundwater bacteria in Swedish granitic rock**. Doctoral thesis, Göteborg University.

Pedersen, K., 1996. **Investigations of subterranean bacteria in deep crystalline rock.** Canadian Journal of Microbiology, 42, 382–391.

Pedersen, K. (ed.), 1996. **Bacteria, colloids and organic carbon in groundwater at the Bangombé site in the Oklo area.** SKB TR 96-01, Svensk Kärnbränslehantering AB.

Pedersen, K., 1997. **Investigations of subterranean microorganisms and their importance for performance assessment of radioactive waste disposal. Results and conclusions achieved during the period 1995 to 1997.** SKB TR 97-22, Svensk Kärnbränslehantering AB.

Kotelnikova, S., Pedersen, K., 1999. **The Microbe-REX project. Microbial O_2 consumption in the Äspö tunnel.** SKB TR 99-17, Svensk Kärnbränslehantering AB.

Motamedi, M., 1999. **The survival and activity of bacteria in compacted bentonite clay in conditions relevant to high level radioactive waste (HLW) repositories**. Doctoral thesis, Göteborg University.

Pedersen, K., 1999. **Subterranean microorganisms and radioactive waste disposal in Sweden.** Engineering Geology, 52, 163–176.

Pedersen, K., 2000. **Microbial processes in radioactive waste disposal.** SKB TR 00-04, Svensk Kärnbränslehantering AB.

Stroes-Gascoyne, S., Pedersen, K., Daumas, S., Hamon, C.J., Haveman, S.A., Delaney, T.L., Ekendahl, S., Jahromi, N., Arlinger, J., Hallbeck, L., Dekeyser, K., 1996. **Microbial analysis of the buffer/-container experiment at AECL's Underground Research Laboratory.** SKB TR 96-02, Svensk Kärnbränslehantering AB.

Haveman, S.A., Nilsson, E.L., Pedersen, K., 2000. **Regional distribution of microbes in groundwater from Hästholmen, Kivetty, Olkiluoto and Romuvaara, Finland.** Posiva Oy, report POSIVA 2000-06.

Sherwood Lollar, B., Frape, S.K., Fritz, P., Macko, S.A., Welhan, J.A., Blomqvist, R., Lahermo, P.W., 1993a. **Evidence for bacterially generated hydrocarbon gas in Canadian Shield and Fennoscandian Shield rocks.** Geochim. Cosmochim Acta, 57, 5073–5085.

Sherwood Lollar, B., Frape, S.K., Wiese, S.M., Fritz, P., Macko, S.A., Wehlan, J.A., 1993b. **Abiogenic methanogenesis in crystalline rocks.** Geochim. Cosmochim. Acta, 57, 5087–5097.

5.4 Hydrogeology and glaciation

Some of the possible effects of a future continental glaciation in Sweden and associated crustal movements on a deep repository have been outlined and documented in Chapter 4. The emphasis there was on geomechanical effects, for instance, on estimating the risk of earthquake-triggered movement on fractures intersecting the deposition holes and breaching the canisters. However, the main problem with future glaciations and related crustal deformation is that they will radically change the hydrogeological regime (e.g. *Talbot 1999*). Coupled hydromechanical processes may lead to a variety of adverse effects, such as:

- Changes in the stress field may cause fractures to open or close, and become either more or less water-conducting.
- Meltwater incursion, seismic pumping and changing freshwater/marine conditions at the surface may lead to strongly varying geochemical conditions in the deep groundwater.
- Glacial action at the surface may change the local topography by piling up morainic materials and/or creating glacial incisions, altering markedly the driving forces for groundwater flow.
- The permafrost cap may lead to abnormal fluid pressures at repository level, favouring fracture reactivation in the bedrock and possibly making the backfill/buffer weaker and more brittle.

Reports which treat the general problem of glaciation-related changes in the deep hydrogeological environment, and some which treat some of the specific effects listed above, have been collected in this group to indicate the spectrum of possibilities (*Pusch 1978, Röshoff 1989b, Lindbom & Boghammar 1991, Wallin 1995, Provost et al 1996, Wallroth 1997, Guimerá et al 1999, Svensson 1999b, Rohr-Torp 2000*).

The modelling of a future continental ice sheet and its effects on hydrogeological conditions has been the task of an Edinburgh research group, partly financed by SKB

(*Boulton et al 1993, 1995, Boulton & Caban 1995, Boulton et al 1999, Boulton et al 2001a, 2001b*). Glaciation and hydrogeology was also the theme of a major international workshop funded jointly by SKB and SKI in April 1996 (*King-Clayton et al 1997*), and of other reviews (e.g. *Gascoyne 2000*).

Talbot, C.J., 1999. **Ice ages and nuclear waste isolation.** Engineering Geology, 52, 177–193.

Pusch, R., 1978. **Inverkan av glaciation på deponeringsanläggning belägen i urberg 500 m under markytan.** KBS TR 89, Svensk Kärnbränslehantering AB.

Röshoff, K., 1989b. **Seismic effects on bedrock and underground constructions. A literature survey of damage on constructions; changes in ground- water levels and flow; changes in chemistry in groundwater and gases**. SKB TR 89-30, Svensk Kärnbränslehantering AB.

Lindbom, B., Boghammar, A., 1991. **Exploratory calculations concerning the influence of glaciation and permafrost on the groundwater flow system, and an initial study of permafrost influences at the Finnsjön site – an SKB 91 study.** SKB TR 91-58, Svensk Kärnbränslehantering AB.

Wallin, B., 1995. **Palaeohydrological implications in the Baltic area and its relation to the groundwater at Äspö, south-eastern Sweden – A literature study.** SKB TR 95-06, Svensk Kärnbränslehantering AB.

Provost, A., Voss, C., Neuzil, C., 1996. **Glaciation and regional groundwater flow in the Fennoscandian shield.** Statens kärnkraftinspektion, Report SKI 96:11.

Ates, Y., Bruneau, D., Ridgway, W.R., 1997. **Continental glaciation and its potential impact on a used-fuel disposal vault in the Canadian shield.** Atomic Energy of Canada Ltd., report AECL-10140.

Wallroth, T., 1997. **Vad betyder en istid för djupförvaret?** SKB R-97-11, Svensk Kärnbränslehantering AB.

Guimerà, J., Duro, L., Jordana, S., Bruno, J., 1999. **Effects of ice melting and redox front migration in fractured rocks of low permeability.** SKB TR 99-19, Svensk Kärnbränslehantering AB.

Svensson, U., 1999b. **Subglacial groundwater flow at Äspö as governed by basal melting and ice tunnels.** SKB R-99-38, Svensk Kärnbränslehantering AB.

Rohr-Torp, E., 2000. **Postglacial isostatic uplift and groundwater potential in Norwegian hard rocks**. In: Hardrock Hydrogeology of the Fennoscandian Shield (G. Knutsson, ed.), Nordic Hydrological Programme, NHP report 45, 157–164.

Boulton, G.S., Slot, T., Blessing, K., Glasbergen, P., Leijnse, T., van Gijssel, K., 1993. **Deep circulation of groundwater in overpressured subglacial aquifers and its geological consequences**. Quaternary Science Reviews, 12, 739–745.

Boulton, G.S., Caban, P.E., Gijssel, K., 1995. **Groundwater flow beneath ice sheets: Part I – Large scale patterns**. Quaternary Science Reviews, 14, 545–562.

Boulton, G.S., Caban, P.E., 1995. **Groundwater flow beneath ice sheets: Part II – Its impact on glacier tectonic structures and moraine formation**. Quaternary Science Reviews, 14, 563–587.

Boulton, G.S., Caban, P., Hulton, N., 1999. **Simulations of the Scandinavian ice sheet and its subsurface conditions**. SKB R-99-73, Svensk Kärnbränslehantering AB.

Boulton, G.S., Kautsky, U., Morén, L., Wallroth, T., 2001a. **Impact of long-term climate change on a deep geological repository for spent nuclear fuel.** SKB TR 99-05, Svensk Kärnbränslehantering AB.

Boulton, G.S., Zatsepin, S., Maillot, B., 2001b. **Analysis of groundwater flow beneath ice sheets.** SKB TR 01-06, Svensk Kärnbränslehantering AB.

King-Clayton, L., Chapman, N., Ericsson, L.O., Kautsky, F., 1997. **Glaciation and hydrogeology: proceedings of a workshop on the impact of climate change and glaciations on rock stresses, groundwater flow and hydrochemistry – past, present and future**. SKI Report 97:13.

Gascoyne, M., 2000. **A review of published literature on the effects of permafrost on the hydro-geochemistry of bedrock.** Posiva Oy, report 2000-09.

6 Underground conditions

Investigations carried out on or very near the Earth's surface are only of limited use in predicting relationships at the depths envisaged for a KBS-3 type repository (ca. 500 m), particularly in crystalline complexes of the types found over most of Sweden. Geological mapping of natural outcrops, road cuts, quarries, etc. allows hypotheses to be made and models to be built, based on modern geological knowledge and experience, but the same knowledge and experience warns against a too great faith in the correctness of the results. Geophysical surveying on the surface (reflection seismics, aeromagnetics, gravity, etc.) often produces invaluable clues and indications, in combination with the geological data, but rarely with the resolution and confidence which would be necessary to lift subsurface reconstructions out of the realm of qualified speculation. In general, one can say that the elucidation of underground conditions in Swedish bedrock requires physical probing, which in the first instance means the drilling of a number of boreholes, at different positions and with different inclinations, with downhole geophysical logging, hydrogeological testing and sampling, and the extraction and description of rock cores. Since it is clearly impossible to carry out such investigations everywhere, the aim of surface geology and geophysics (e.g. the aim of the Förstudier, see Section 8.3) is to enable geoscientific experience and expert judgement to suggest where the drilling should be carried out to the greatest chance of success.

At the start of what is now called the siting process, in the mid-1970s, it became clear that the necessary basis for interpreting underground conditions from surface data was too weak, and SKB and its forerunners started drilling at numerous sites throughout Sweden with a view to building up a body of problem-oriented experience. Some of these sites were studied in great detail over a number of years, whereas others were not fully developed, but all contributed enormously to our knowledge of conditions at depth in Swedish bedrock. Reports referring to these so-called “study sites” (”Typområden”) are collected together in Section 6.1.

Most of the drilling, logging, testing and sampling at the study sites was carried out during the 1980s, parallel with the development of a different type of underground investigation, the Stripa Project. This international project, sponsored by the OECD Nuclear Energy Agency, used extensions of an abandoned iron mine at Stripa, in central Sweden, as an underground laboratory for many different experiments, as outlined below (Section 6.2). The reports cited here focus on the site characterisation aspects of the Stripa Project, particularly the description of the bedrock structure and hydrogeology of the site at the surface and in tunnels at ca. 350 m depth, and particularly the results of what became known as the Site Characterisation and Validation (SCV) experiment.

The Stripa Project ran from 1980 to 1991. Long before its termination, and clearly encouraged by its results, SKB embarked on an even more ambitious programme of underground investigation – the siting and construction of a special Hard Rock Laboratory (HRL) at a site undisturbed by previous mining activity. Interest focussed on the region around the Oskarshamn nuclear power station, and the island of Äspö was chosen as the site for the facility in 1988 (Section 6.3). Detailed surface-based studies were carried out in the period 1986–1990 with the specific intention of testing the accuracy of predictions concerning underground relationships, when the excavations were completed (after the construction period, 1990–1995). The reports in Section 6.3 have been selected to document the results of pre-construction, surface-based studies, in relation to the underground conditions actually encountered in the access tunnel and laboratory tract.

The chapter closes with a group of references to other sources of underground information (Section 6.4), from other underground excavations in Sweden (tunnels, caverns, mines) and from ultradeep boreholes in Sweden and at other European localities.

6.1 SKB study sites

As indicated above, it became clear at an early stage in the history of radioactive waste research in Sweden, that conditions at several hundred metres depth in the Precambrian basement could not be satisfactorily deduced from data collected at the surface. Because of this, the forerunner organization of SKB (KBS, later SKBF/division KBS) and, independently, a governmental institution (AKA, later PRAV) started programmes of site investigations involving deep core drilling. The sites were chosen on the basis of preliminary local studies, as outlined later (cf. Section 8.1). Out of these early studies, which were in some cases the focus of controversy and local opposition, there developed a more systematic programme of research which became focussed on six main sites, referred to here as SKB study sites. These represent a spectrum of different geographical locations and geological conditions. At each SKB study site, a complete range of surface-based and borehole-based investigations were carried out in the period 1977–1987, including detailed surface mapping and core description, fracture logging, surface and borehole geophysical surveying, hydrogeological testing and hydrochemical sampling. A selection of SKB Technical Reports which have appeared on each study site are listed in separate Subsections below. The scope of activities and main results from each site were described in a series of final reports in 1991–1992, as follows:

6.1.1 Finnsjön – *Ahlbom et al 1992d*
6.1.2 Fjällveden – *Ahlbom et al 1991b*
6.1.3 Gideå – *Ahlbom et al 1991a*
6.1.4 Kamlunge – *Ahlbom et al 1992b*
6.1.5 Klipperås – *Ahlbom et al 1992c*
6.1.6 Sternö – *Ahlbom et al 1992a*

These final reports contain full details of the basic documents relating to each site, which include both SKB Technical Reports (TR series) and SKB Progress Reports (Arbetsrapporter – AR series). In the present listings, only a selection from the TR-series are cited, chosen to contain the main information of importance for the siting process: site characterisation studies (reports outlining results from a range of geoscientific investigations), bedrock structure and geomechanics, and hydrogeology.

After the six main Subsections, a list of reports on other sites at which deep drilling has been carried out is added (Subsection 6.1.7). This includes two sites (Svartboberget, Taavinunnanen) for which site characterisation reports are available but which otherwise do not have a comparable data base to the “official” study sites.

6.1.1 Finnsjön (”Beberg”)

The Finnsjön study site lies in northern Uppland (Tierp municipality, Uppsala län, central Sweden). The site lies in an area of very low relief (0–60 m a.s.l.) and moderate exposure (ca. 15%). The bedrock of the site consists of foliated granodiorite (see Section 2.3), intruded 1890–1880 Ma ago and deformed and metamorphosed during the Svecokarelian orogeny (ca. 1850–1780, see Section 2.5). The bedrock is intersected by younger pegmatitic, aplitic and mafic veins and dykes, and is locally sheared and hydrothermally altered. The granodiorite forms part of a tectonic lens within a broad belt of ductile shearing. A total of 11 cored drillholes were sunk at the site, 7 to depths of 500 m or more, yielding a total length of core of about 6,000 m. The main period of site investigation was 1977–1983, but further detailed studies were carried out in the period 1985–1992 (including the Fracture Zone Project, see below). The Finnsjön site provided the data base for SKB's safety assessment SKB-91, and, later, as the hypothetical site “Beberg”, for the SR-97 safety analysis (see Subsection 10.1.2).

The regional geological setting of the Finnsjön study site is given in the Uppsala Länsstudie (*Antal et al 1998f,* see also Subsections 8.3.4 and 8.3.6). The scope of activities and the main results of the investigations, as documented in 49 Technical Reports and 46 Progress Reports, are summarised in the final site report of 1992 (*Ahlbom et al 1992d,* see also Beberg site description in *SKB 1999c*). The selection listed here consists, in the first instance, of general overviews of the site characteristics from both the early phase of investigation (*Almén et al 1978, Olkiewicz et al 1979, Magnusson & Duran 1984*) and later phases (*Ahlbom & Tirén 1991, Ageskog & Sjödin 1991*). The Finnsjön site served particularly for the development of concepts and methods for fracture system and fracture zone analysis (*Ahlbom et al 1986, Geier et al 1992*, *Saksa & Nummela 1998*, see also Fracture Zone Project, below), including the seismic imaging of fracture zones (*Dahl-Jensen & Lindgren 1987, Cosma et al 1994*), the geomechanical properties of rock, rock masses and fracture zones (*Swan 1977, Rosengren & Stephansson 1990, Leijon & Ljunggren 1992*), and studies of fracture mineralization (*Tullborg & Larsson 1982*).

Hydraulic testing and monitoring was also a major component of Finnsjön activities, consisting of water injection tests, interference tests, groundwater head measurements and various types of tracer tests, over a long period of time (*Carlsson et al 1983a, 1983b, Andersson et al 1991, Boghammar et al 1993*). As noted above, these data became the basis for the geohydrological model of the hypothetical Beberg site in SR 97 (*Walker et al 1997, Hartley et al 1998, Gylling et al 1999*). The hydrogeological studies were complemented by groundwater sampling in the deep drillholes and subsequent hydrogeochemical modelling (*Laurent 1982, Puigdomènech & Nordstrom 1987, Smellie & Wikberg 1991, Laaksoharju et al 1998*). All these different data acquisition and processing techniques – structural, geohydrological and hydrogeochemical – were eventually focussed on a special feature of the Finnsjön site, the gently dipping fracture zone 2, located at 100–240 m depth. The “Fracture Zone Project” yielded uniquely detailed insights into the structure and hydrogeological significance of a particular fracture zone and paved the way for more general understanding of an important aspect of performance assessment (*Ahlbom et al 1989, Andersson, Peter, 1993*).

Antal, I., Bergman, S., Gierup, J., Persson, C., Thunholm, B., Stephens, M., Johansson, R., 1998f. **Översiktsstudie av Uppsala län. Geologiska förutsättningar.** SKB R-98-32, Svensk Kärnbränslehantering AB

Site characterisation

Ahlbom, K., Andersson, J.-E., Andersson, P., Ittner, T., Ljunggren, C., Tirén, S.A., 1992d. **Finnsjön study site. Scope of activities and main results.** SKB TR 92-33., Svensk Kärnbränslehantering AB.

SKB 1999c: **SR-97. Waste, repository design and sites.** SKB TR 99-08, Svensk Kärnbränslehantering AB.

Almén, K.-E., Ekman, L., Olkiewicz, A., 1978. **Försöksområdet vid Finnsjön.** SKBF/KBS TR 79-02, Svensk Kärnbränsleförsörjning AB.

Olkiewicz, A., Scherman, S., Kornfält, K.-A., 1979. **Kompletterande berggrundsundersökningar inom Finnsjö- och Karlshamnsområdena**. SKBF/KBS TR 79-05, Svensk Kärnbränsleförsörjning AB.

Magnusson, K.-Å., Duran, O., 1984. **Comparative study of geological, hydrological and geophysical borehole investigations**. SKBF/KBS TR 84-09, Svensk Kärnbränsleförsörjning AB.

Ahlbom, K., Tirén, S.A., 1991. **Overview of geologic and geohydrologic conditions at the Finnsjön site and its surroundings.** SKB TR 91-08, Svensk Kärnbränslehantering AB.

Ageskog, L., Sjödin, K., 1991. **Tentative outline and siting of a repository for spent nuclear fuel at the Finnsjön site. SKB 91 reference concept.** SKB TR 91-36, Svensk Kärnbränslehantering AB.

Bedrock structure, geomechanics

Ahlbom, K., Andersson, P., Ekman, L., Gustafsson, E., Smellie, J.A.T., Tullborg, E.-L., 1986. **Preliminary investigations of fracture zones in the Brändan area, Finnsjön study site.** SKB TR 86-05, Svensk Kärnbränslehantering AB.

Geier, J.E., Axelsson, C.-L., Hässler, L., Benabderrahmane, A., 1992. **Discrete fracture modelling of the Finnsjön rock mass: phase 2.** SKB TR 92-07, Svensk Kärnbränslehantering AB.

Saksa, P., Nummela, J., 1998. **Geological-structural models used in SR-97. Uncertainty analysis**. SKB TR 98-12, Svensk Kärnbränslehantering AB.

Dahl-Jensen, T., Lindgren, J., 1987. **Shallow reflection seismic investigation of fracture zones in the Finnsjö area, method evaluation**. SKB TR 87-13, Svensk Kärnbränslehantering AB.

Cosma, C., Juhlin, C., Olsson, O., 1994. **Reassessment of seismic reflection data from the Finnsjön study site and prospectives for future surveys.** SKB TR 94-03, Svensk Kärnbränslehantering AB.

Swan, G., 1977. **The mechanical properties of the rocks in Stripa, Kråkemåla, Finnsjön and Blekinge.** KBS TR 48, Svensk Kärnbränsleförsörjning AB.

Rosengren, L., Stephansson, O., 1990. **Distinct element modelling of the rock mass response to glaciation at Finnsjön, Central Sweden**. SKB TR 90-40, Svensk Kärnbränslehantering AB.

Leijon, B., Ljunggren, C., 1992. **A rock mechanics study of Fracture Zone 2 at the Finnsjön site.** SKB TR 92-28, Svensk Kärnbränslehantering AB.

Tullborg, E.-L., Larson, S.Å., 1982. **Fissure fillings from Finnsjön and Studsvik, Sweden. Identification, chemistry and dating**. SKBF/KBS TR 82-20, Svensk Kärnbränsleförsörjning AB.

Hydrogeology

Carlsson, L., Winberg, A., Grundfelt, B., 1983a. **Model calculations of the groundwater flow at Finnsjön, Fjällveden, Gideå and Kamlunge.** SKB TR 83-45, Svensk Kärnbränslehantering AB.

Carlsson, L., Gidlund, G., Hesselström, B., 1983b. **I: Evaluation of the hydrogeological conditions at Finnsjön; II: Supplementary geophysical investigations of the Sternö peninsula**. SKBF/KBS TR 83-56, Svensk Kärnbränsleförsörjning AB.

Andersson, J.-E., Nordqvist, R., Nyberg, G., Smellie, J.A.T., Tirén, S.A., 1991. **Hydrogeological conditions in the Finnsjön area. Compilation of data and conceptual model.** SKB TR 91-24, Svensk Kärnbränslehantering AB.

Boghammar, A., Grundfelt, B., Widén, H., 1993. **Analysis of the regional groundwater flow in the Finnsjön area**. SKB TR 93-15, Svensk Kärnbränslehantering AB.

Walker, D., Rhén, I., Gurban, I., 1997. **Summary of hydrogeologic conditions at Aberg, Beberg and Ceberg**. SKB TR 97-23, Svensk Kärnbränslehantering AB.

Hartley, L., Boghammar, A., Grundfelt, B., 1998. **Investigation of the large scale regional hydrogeological situation at Beberg.** SKB TR 98-24, Svensk Kärnbränslehantering AB.

Gylling, B., Walker, D., Hartley, L., 1999. **Site-scale groundwater flow modelling of Beberg.** SKB TR 99-18, Svensk Kärnbränslehantering AB.

Laurent, S., 1982. **Analysis of groundwater from deep boreholes in Kråkemåla, Sternö and Finnsjön**. SKBF/KBS TR 82-23, Svensk Kärnbränsleförsörjning AB.

Puigdomènech, I., Nordstrom, D.K., 1987. **Geochemical interpretation of groundwaters from Finnsjön, Sweden**. SKB TR 87-15, Svensk Kärnbränslehantering AB.

Smellie, J.A.T., Wikberg, P., 1991. **Hydrochemical investigations at Finnsjön, Sweden.** Journal of Hydrology, 126, 129–158.

Laaksoharju, M., Gurban, I., Skårman, C., 1998. **Summary of hydrochemical conditions at Aberg, Beberg and Ceberg.** SKB TR 98-03, Svensk Kärnbränslehantering AB.

Fracture Zone Project

Ahlbom, K., Smellie, J.A.T., Tirén, S.A., Andersson, J.-E., Ekman, L., Nordqvist, R., Winberg, A., Gustafsson, E., Andersson, P., Wikberg, P., 1989. **Characterisation of fracture zone 2, Finnsjön study-site. Part 1: Overview of the fracture zone project at Finnsjön, Sweden. Part 2: Geological setting and deformation history of a low angle fracture zone at Finnsjön, Sweden. Part 3: Hydraulic testing and modelling of a low-angle fracture zone at Finnsjön, Sweden. Part 4: Groundwater flow conditions in a low angle fracture zone at Finnsjön, Sweden. Part 5: Hydrochemical investigations at Finnsjön, Sweden. Part 6: Effects of gas-lift pumping on hydraulic borehole conditions at Finnsjön, Sweden.** SKB TR 89-19, Svensk Kärnbränslehantering AB.

Andersson, Peter, 1993. **The Fracture Zone Project – Final report.** SKB TR 93-20, Svensk Kärnbränslehantering AB.

6.1.2 Fjällveden

The Fjällveden study site lies in eastern Sörmland (Nyköping municipality, Södermanlands län, central Sweden). The site lies on an undulating inland plateau (50–60 m a.s.l.), where the bedrock exposure is relatively good. The bedrock of the site is dominated by a rather homogeneous, gneissic metasedimentary rock with some layers of weakly foliated granodiorite ("granite gneiss", see Section 2.3), both groups metamorphosed and deformed during the Svecokarelian orogeny (ca. 1,850–1,780 Ma ago, see Section 2.5). This rock matrix locally contains greenstone layers, granitic and pegmatitic veins, and mafic dykes. The site lies between two fracture zones which belong to a set of regional, SE-NW striking structures with a regular spacing of 2–3 km. A total of 15 cored drillholes were sunk at the site, 8 to depths of 500 m or more, yielding a total length of core of about 7500 m. With the exception of some groundwater sampling, all activities at the site took place between 1981 and 1983.

The regional geological setting of the Fjällveden site is given in the Södermanland Länsstudie (*Antal et al 1998d,* see also Subsection 8.3.3). The scope of activities and the main results of the investigations, as documented in 10 Technical Reports and 11 Progress Reports, are summarised in the final site report of 1991 (*Ahlbom et al 1991b*). The site characterisation results were evaluated and published immediately after the investigation period (*Ahlbom et al 1983d*), together with model calculations of groundwater flow and hydrogeochemical analyses (*Carlsson et al 1983a, Laurent 1983b, Wikberg et al 1983*). A special feature of the Fjällveden site is the very low hydraulic conductivity of the gneissic metasedimentary rocks below ca. 200 m, significantly lower than any of the other study sites. This feature was confirmed in a later study of the regional characterisation of hydraulic properties at different study sites (*Wladis et al 1997*).

Antal, I., Bergman, T., Persson, C., Stephens, M., Thunholm, B., Åsman, M., Johansson, R., 1998d. **Översiktsstudie av Södermanlands län. Geologiska förutsättningar.** SKB R-98-28, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, J.-E., Nordqvist, R., Ljunggren, C., Tirén, S.A., Voss, C., 1991b. **Fjällveden study site. Scope of activities and main results.** SKB TR 91-52, Svensk Kärnbränslehantering AB.

Ahlbom, K., Carlsson, L., Carlsten, L.-E., Duran, O., Larsson, N.-Å., Olsson, O., 1983d. **Evaluation of the geological, geophysical and hydrogeological conditions at Fjällveden.** SKBF/KBS TR 83-52, Svensk Kärnbränsleförsörjning AB.

Carlsson, L., Winberg, A., Grundfelt, B., 1983a. **Model calculations of the groundwater flow at Finnsjön, Fjällveden, Gideå and Kamlunge.** SKB TR 83-45, Svensk Kärnbränslehantering AB.

Laurent, S., 1983b. **Analysis of groundwater from deep boreholes in Fjällveden.** SKBF/KBS TR 83-19, Svensk Kärnbränsleförsörjning AB.

Wikberg, P., Grenthe, I., Axelsen, K., 1983. **Redox conditions in groundwaters from Svartboberget, Gideå, Fjällveden and Kamlunge**. SKBF/KBS TR 83-40, Svensk Kärnbränsleförsörjning AB.

Wladis, D., Jönsson, P., Wallroth, T., 1997. **Regional characterisation of hydraulic properties of rock using well test data.** SKB TR 97-29, Svensk Kärnbränslehantering AB.

6.1.3 Gideå (”Ceberg”)

The Gideå study site is situated near the coast in central Norrland (northeastern corner of Västernorrlands län, northern Sweden). The site lies in an area of significant relief (0–300 m a.s.l.) and moderate exposure (ca. 25%). The bedrock of the site consists of migmatites (veined gneisses) and granitic gneisses derived from a metasedimentary protolith (see Section 2.3), formed during the Svecokarelian orogeny, ca. 1,850–1,780 Ma ago (see Section 2.5). The site is intersected by a set of E-W striking mafic dykes, and was possibly affected by the intrusion of a 100–300 m thick mafic sill, now eroded away from above the present site surface. These mafic bodies were intruded 1,270–1,215 Ma ago. A total of 13 cored drillholes were sunk at the site, 11 to depths of 500 m or more, yielding a total length of core of around 8,000 m. The main period of site investigation was from 1981 to 1983, but the site has been used intermittently since, mainly for small R&D projects and for testing new equipment. The Gideå site provided the data base for the hypothetical site "Ceberg" in the SR-97 safety analysis (see Subsection 10.1.2).

The regional geological setting of the Gideå study site is given in the Västernorrland Länsstudie (*Antal et al 1998h*). The scope of activities and the main results of the investigations, as documented in 18 Technical Reports and 11 Progress Reports, are summarised in the final site report of 1991 (*Ahlbom et al 1991a*, see also CEBERG site summary in *SKB 1999c*). The list below contains the original site characterisation report (*Ahlbom et al 1983a*) and a selection of other Technical Reports from the original list, plus a series of later reports, particularly those connected with SR-97. The first part of the list concerns the geological modelling of the site and the resulting uncertainties (*Hermansen et al 1997, Saksa & Nummela 1998*), together with geomechanical data (*Ljunggren et al 1985, Bjarnason & Stephansson 1986*). The rest of the citations are hydrogeological, dealing with the following themes:

- characterisation of hydraulic properties of bedrock and fracture zones (*Ericsson & Ronge 1986, Wladis et al 1997*),
- modelling of groundwater flow (*Carlsson et al 1983a, Walker & Gylling 1999*),
- hydrogeochemistry of deep groundwater (*Laurent 1983a, Wikberg et al 1983*),
- fracture mineralization (*Tullborg & Larsson 1983*).

The final citations give overall summaries of the hydrogeology and hydrochemistry of the site (Ceberg) and compare the relationships at Gideå with the other sites used as a basis for SR-97 (*Walker et al 1997, Laaksoharju et al 1998*).

Antal, I., Fredén, C., Gierup, J., Stølen, L.K., Thunholm, B., Stephens, M., Johansson, R., 1998h. **Översiktsstudie av Västernorrlands län. Geologiska förutsättningar.** SKB R-98-36, Svensk Kärnbränslehantering AB.

Site characterisation

Ahlbom, K., Andersson, J.-E., Nordqvist, R., Ljunggren, C., Tirén, S.A., Voss, C., 1991a. **Gideå study site. Scope of activities and main results.** SKB TR 91-51, Svensk Kärnbränslehantering AB.

SKB 1999c. **SR-97. Waste, repository design and sites.** SKB TR 99-08, Svensk Kärnbränslehantering AB.

Ahlbom, K., Albino, B., Carlsson, L., Nilsson, G., Olsson, O., Stenberg, L., Timje, H., 1983a. **Evaluation of the geological, geophysical and hydrogeological conditions at Gideå.** SKBF/KBS TR 83-53, Svensk Kärnbränsleförsörjning AB.

Bedrock structure, geomechanics

Hermanson, J., Hansen, L.M., Follin, S., 1997. **Update of the geological models of the Gideå study site.** SKB R-97-05, Svensk Kärnbränslehantering AB.

Saksa, P., Nummela, J., 1998. **Geological-structural models used in SR-97. Uncertainty analysis**. SKB TR 98-12, Svensk Kärnbränslehantering AB.

Ljunggren, C., Stephansson, O., Alm, O., Hakami, H., Mattila, U., 1985. **Mechanical properties of granitic rocks from Gideå, Sweden.** SKB TR 85-06, Svensk Kärnbränslehantering AB.

Bjarnason, B., Stephansson, O., 1986. **Hydraulic fracturing rock stress measurements in borehole Gi-1, Gideå Study Site, Sweden.** SKB TR 86-11, Svensk Kärnbränslehantering AB.

Hydrogeology

Ericsson, L.O., Ronge, B., 1986. **Correlation between tectonic lineaments and permeability values of crystalline bedrock in the Gideå area.** SKB TR 86-19, Svensk Kärnbränslehantering AB.

Wladis, D., Jönsson, P., Wallroth, T., 1997. **Regional characterisation of hydraulic properties of rock using well test data.** SKB TR 97-29, Svensk Kärnbränslehantering AB.

Carlsson, L., Winberg, A., Grundfelt, B., 1983a. **Model calculations of the groundwater flow at Finnsjön, Fjällveden, Gideå and Kamlunge.** SKB TR 83-45, Svensk Kärnbränslehantering AB.

Walker, D., Gylling, B., 1999. **Site-scale groundwater flow modelling of Ceberg.** SKB TR 99-13, Svensk Kärnbränslehantering AB.

Laurent, S., 1983a. **Analysis of groundwater from deep boreholes in Gideå.** SKBF/KBS TR 83-17, Svensk Kärnbränsleförsörjning AB.

Wikberg, P., Grenthe, I., Axelsen, K., 1983. **Redox conditions in groundwaters from Svartboberget, Gideå, Fjällveden and Kamlunge**. SKBF/KBS TR 83-40, Svensk Kärnbränsleförsörjning AB.

Tullborg, E.-L., Larson, S.Å., 1983. **Fissure fillings from Gideå, central Sweden.** SKBF/KBS TR 83-74, Svensk Kärnbränsleförsörjning AB.

Walker, D., Rhén, I., Gurban, I., 1997. **Summary of hydrogeologic conditions at Aberg, Beberg and Ceberg**. SKB TR 97-23, Svensk Kärnbränslehantering AB.

Laaksoharju, M., Gurban, I., Skårman, C., 1998. **Summary of hydrochemical conditions at Aberg, Beberg and Ceberg.** SKB TR 98-03, Svensk Kärnbränslehantering AB.

6.1.4 Kamlunge

The Kamlunge study site lies in northern Norrland (northeastern corner of Norrbottens län, northern Sweden). The site lies on a plateau across the top of an uplifted block which stands about 100 m above the surrounding lowland. On the plateau, the bedrock is well exposed. It consists of a heterogeneous complex of metasedimentary rocks (biotite gneiss, quartzitic gneiss), intruded by a fine to medium grained granite (Lina granite, see Section 2.2), with associated pegmatites, and other igneous rocks (diorite-granodiorite, gabbro/amphibolite). All rocks are affected by the Svecokarelian orogeny (ca. 1,850–1,780 Ma ago, see Section 2.5), although the Lina granite (intrusion age ca. 1,800 Ma) only shows a relatively weak foliation. A total of 16 cored drillholes were sunk at the site, 8 of them to depths of 500 m or more, yielding a total length of core of about 7,750 m. The main period of site investigation, including all the core drilling, was 1982–1983, with little activity since (one small research project, some tests of methods and instruments).

The regional geological setting of the Kamlunge study site is given in the Norrbotten Länsstudie (*Bergman et al 1998b*). The scope of activities and the main results of the investigations, as documented in 13 Technical Reports and 17 Progress Reports, are summarised in the final site report of 1992 (*Ahlbom et al 1992b*). The original documentation includes a site evaluation report (*Ahlbom et al 1983b*) and three hydrogeological reports (*Carlsson et al 1983a, Laurent 1983d, Wikberg et al 1983*). The documentation of the later investigation of uranium series disequilibrium in one of the cores is found in *Smellie 1984a*.

Bergman, S., Gierup, J., Kübler, L., Lagerbäck, R., Thunholm, B., Stephens, M., Johansson, R., 1998b. **Översiktsstudie av Norrbottens län. Geologiska förutsättningar.** SKB R-98-40, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, J.-E., Andersson, P., Ittner, T., Ljunggren, C., Tirén, S.A., 1992b. **Kamlunge study site – Scope of activities and main results.** SKB TR 92-15, Svensk Kärnbränslehantering AB.

Ahlbom, K., Albino, B., Carlsson, L., Danielsson, J., Nilsson, G., Olsson, O., Sehlstedt, S., Stejskal, V., Stenberg, L., 1983b. **Evaluation of the geological, geophysical and hydrogeological conditions at Kamlunge.** SKBF/KBS TR 83-54, Svensk Kärnbränsleförsörjning AB.

Carlsson, L., Winberg, A., Grundfelt, B., 1983a. **Model calculations of the groundwater flow at Finnsjön, Fjällveden, Gideå and Kamlunge.** SKB TR 83-45, Svensk Kärnbränslehantering AB.

Laurent, S., 1983d. **Analysis of groundwater from deep boreholes in Kamlunge.** SKBF/KBS TR 83-70, Svensk Kärnbränsleförsörjning AB.

Wikberg, P., Grenthe, I., Axelsen, K., 1983. **Redox conditions in groundwaters from Svartboberget, Gideå, Fjällveden and Kamlunge**. SKBF/KBS TR 83-40, Svensk Kärnbränsleförsörjning AB.

Smellie, J.A.T., 1984a. **Uranium series disequilibrium studies of drillcore KM3 from the Kamlunge test-site, northern Sweden.** SKBF/KBS TR 84-06, Svensk Kärnbränsleförsörjning AB.

6.1.5 Klipperås

The Klipperås study site is situated in southern Småland (Kalmar län, southern Sweden). The area in which the site lies is characterized by an extremely low relief (very low hydraulic gradients) and an almost complete lack of bedrock exposures (no surface expression of fracture zones). The bedrock of the site, as it appears in the drillcores, is composed of a relatively homogeneous granite (Småland granite, see Section 2.2), with associated aplitic veins and porphyrite dykes, intersected by a number of younger N-S trending mafic dykes. The Småland granite belongs to the Transscandinavian Igneous Belt (see Section 2.5), intruded about 1,800 Ma years ago, and the mafic dykes are thought to be about 900 Ma old. A total of 14 cored drillholes were sunk at the site, 7 to depths of 500 m or more, one to 940 m, yielding a total length of core of about 6935 m. The main period of site investigation, including all the drilling, was 1984–1985. Later, the only new investigation was a borehole radar study, but the site data base continued to be used for a number of further studies.

The regional geological setting of the Klipperås study site is given in the Kalmar Länsstudie (*Antal et al 1998b*). The scope of activities and the main results of the investigations, as documented in 21 Technical Reports and 10 Progress Reports, are summarised in the final site report of 1992 (*Ahlbom et al 1992c*). The original site characterisation report (*Olkiewicz & Stejskal 1986*) was accompanied by a series of more detailed reports on different aspects of the site investigations (*Sehlstedt & Stenberg 1986, Gentzschein 1986a, Tullborg 1986, Sundblad et al 1985, Laurent 1986*). The hydrogeological investigations were followed up by specialized methodological studies in geohydrology (*Andersson & Lindqvist 1989, Follin et al 2000*) and hydrogeochemistry (*Smellie et al 1987, Possnert & Tullborg 1989, Wersin et al 1994*). The borehole radar study carried out at Klipperås and other sites (*Carlsten et al 1987, Carlsten et al 1989*) showed good correlations between radar intensity and fractured rock, leading to an increased usage of this new technique in site investigations.

Antal, I., Bergman, T., Gierup, J., Rudmark, L., Thunholm, B., Wahlgren, C.-H., Stephens, M., Johansson, R., 1998b. **Översiktsstudie av Kalmar län. Geologiska förutsättningar.** SKB R-98-24, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, J.-E., Andersson, P., Ittner, T., Ljunggren, C., Tirén, S.A., 1992c. **Klipperås study site. Scope of activities and main results.** SKB TR 92-22, Svensk Kärnbränslehantering AB.

Olkiewicz, A., Stejskal, V., 1986. **Geological and tectonical description of the Klipperås study site.** SKB TR 86-06, Svensk Kärnbränslehantering AB.

Sehlstedt, S., Stenberg, L., 1986. **Geophysical investigations at the Klipperås study site.** SKB TR 86-07, Svensk Kärnbränslehantering AB.

Gentzschein, B., 1986a. **Hydrogeological investigations at the Klipperås study site.** SKB TR 86-08, Svensk Kärnbränslehantering AB.

Tullborg, E.-L., 1986. **Fissure fillings from the Klipperås study site.** SKB TR 86-10, Svensk Kärnbränslehantering AB.

Sundblad, B., Landström, O., Axelsson, R., 1985. **Concentration and distribution of natural radionuclides at Klipperåsen and Bjulebo, Sweden**. SKB TR 85-09, Svensk Kärnbränslehantering AB.

Laurent, S., 1986. **Analysis of groundwater from deep boreholes in Klipperås.** SKB TR 86-17, Svensk Kärnbränslehantering AB.

Andersson, J.-E., Lindqvist, L., 1989. **Prediction of hydraulic conductivity and conductive fracture frequency by multivariate analysis of data from the Klipperås study site.** SKB TR 89-11, Svensk Kärnbränslehantering AB.

Follin, S., Askling, P., Carlsten, S., Stråhle, A., 2000. **Smålandsgranitens vattengenomsläpplighet. Jämförelse av borrhålsdata från Äspö, Laxemar och Klipperås.** SKB R-00-46, Svensk Kärnbränslehantering AB.

Smellie, J.A.T., Larsson, N.-Å., Wikberg, P., Puigdomènech, I., Tullborg, E.-L., 1987. **Hydrochemical investigations in crystalline bedrock in relation to existing hydraulic conditions: Klipperås test-site, Småland, Southern Sweden.** SKB TR 87-21, Svensk Kärnbränslehantering AB.

Possnert, G., Tullborg, E.-L., 1989. **14C-Analyses of calcite coatings in open fractures from the Klipperås study site, Southern Sweden.** SKB TR 89-36, Svensk Kärnbränslehantering AB.

Wersin, P., Bruno, J., Laaksoharju, M., 1994. **The implications of soil acidification on a future HLW repository. Part II: Influence on deep granitic groundwater. The Klipperås study site as test case.** SKB TR 94-31, Svensk Kärnbränslehantering AB.

Carlsten, S., Olsson, O., Sehlstedt, S., Stenberg, L., 1987. **Radar measurements performed at the Klipperås study site.** SKB TR 87-01, Svensk Kärnbränslehantering AB.

Carlsten, S., Lindqvist, L., Olsson, O., 1989. **Comparison between radar data and geophysical, geological and hydrological borehole parameters by multivariate analysis of data.** SKB TR 89-15, Svensk Kärnbränslehantering AB.

6.1.6 Sternö

The Sternö study site is situated on the coast of Blekinge (Blekinge län, southern Sweden). The area is characterized by low relief and moderate bedrock exposure. The bedrock consists mainly of fine grained felsic gneiss (ca. 1,700 Ma old) and foliated granodiorite (Blekinge gneiss, see Section 2.3), with numerous aplitic and pegmatitic veins. The veining is probably related to a large 1,450 Ma old granitic intrusion (Karlshamn granite) which lies to the south of the site and probably underneath it, at depth. The eastern side of the site is marked by a ca. 300 m thick mafic dyke, intruded ca. 930 Ma ago. A total of 5 cored drillholes were sunk at the site, all of them to depths in excess of 500 m, and about 3,300 m of core were retrieved. The main period of site investigation, including all the drilling, was 1977–1979, and, with the exception of two small projects (fracture mapping, geophysical determination of mafic dyke orientation), there has been no further activity.

The regional setting of the Sternö study site is given in the Blekinge Länsstudie (*Antal et al 1998a*). The scope of activities and the main results of the site investigations, as documented in 17 Technical Reports and 4 progress Reports, are summarised in the final site report of 1992 (*Ahlbom et al 1992a*). The site investigations are described in the original site characterisation report (*Ahlbom et al 1979*) and only a few supplementary studies have since appeared (*Ekman & Gentzschein 1980, Laurent 1982, Carlsson et al 1983*).

Antal, I., Bergman, T., Gierup, J., Persson, M., Thunholm, B., Wahlgren, C.-H., Stephens, M., Johansson, R., 1998a. **Översiktsstudie av Blekinge län. Geologiska förutsättningar.** SKB R-98-22, Svensk Kärnbränslehantering AB.

Ahlbom, K., Andersson, J.-E., Nordqvist, R., Ljunggren, C., Tirén, S.A., Voss, C., 1992a. **Sternö study site. Scope of activities and main results.** SKB TR 92-02, Svensk Kärnbränslehantering AB.

Ahlbom, K., Carlsson, L., Gidlund, G., Klockars, C.-E., Scherman, S., Thoregren, U., 1979. **Utvärdering av de hydrogeologiska och berggrundsgeologiska förhållandena på Sternö.** SKBF/KBS TR 79-09, Svensk Kärnbränsleförsörjning AB.

Ekman, L., Gentzschein, B., 1980. **Komplettering och sammanfattning av geohydrologiska undersökningar inom Sternöområdet, Karlshamn.** SKBF/KBS TR 80-01, Svensk Kärnbränsleförsörjning AB.

Laurent, S., 1982. **Analysis of groundwater from deep boreholes in Kråkemåla, Sternö and Finnsjön**. SKBF/KBS TR 82-23, Svensk Kärnbränsleförsörjning AB.

Carlsson, L., Gidlund, G., Hesselström, B., 1983b. **I: Evaluation of the hydrogeological conditions at Finnsjön; II: Supplementary geophysical investigations of the Sternö peninsula**. SKBF/KBS TR 83-56, Svensk Kärnbränsleförsörjning AB.

6.1.7 Other SKB drill sites

In addition to the six "official" study sites, above, several other sites have been drilled and investigated by SKB. The SKB reports referring to the most important of these are collected in this Subsection. The area of most intensive activity lies in the northeastern part of Oskarshamn municipality (Subsection 8.3.5), in the surroundings of the Äspö Hard Rock Laboratory (Section 6.3). A description of these investigations is given in one of the background reports to the Oskarshamn feasibility study (*Bergman et al 1999a*). Three sites in the surroundings of Äspö HRL have been drilled – Ävrö, Kråkemåla and Laxemar. In addition to drilling, the island of Ävrö has been used as a test for the identification of fracture zones using reflection seismic methods (*Juhlin & Palm 1997*). The Kråkemåla site was originally planned as a study site, in the particularly homogeneous and coarse grained Götemar granite pluton ("anorogenic" granite, see Section 2.5), but was later abandoned. However, information from Kråkemåla is contained in a number of site comparison studies, concerning geomechanics, geohydrology and hydrogeochemistry (*Swan 1977, Magnusson & Duran 1984, Laurent 1982*). At Laxemar, two cored drillholes were sunk, one down to over 1,700 m depth (*Andersson 1994, Laaksoharju et al 1995, Ekman 2001*) and the hydrogeological data has been used in a more regional study of the hydraulic properties of Småland granite (*Follin et al 2000*).

The two reports under the second heading below concern the Forsmark site (Östhammar municipality, Subsection 8.3.4), which encompasses the Forsmark nuclear power stations and the SFR low to medium radioactive waste repository (shallow underground caverns). Forsmark lies ca. 15 km east of the Finnsjön study site (Subsection 6.1.1, above). The geological information collected at the site from 3 cored drillholes and from the construction of several tunnels and the SFR caverns are summarised in *Bergman et al 1996* and *Axelsson & Hansen 1998*.

Under the third heading of this Subsection, the citations refer to other SKB or related sites from which underground information is available. From two of these, Svartboberget and Taavinunnanen, site characterisation reports are available (*Ahlbom et al 1983c, Gentzschein & Tullborg 1985*), in addition to some reports on special themes (*Wikberg et al 1983, Laurent 1983c, Larsson & Tullborg 1984*). Information is also available from deep drilling near the Forsmark nuclear power station, close to the existing underground repository for low-active nuclear waste, SFR (*Bergman et al 1996*, see Section 8.3.4). The final citations (*Bergman & Isaksson 1996, Tullborg & Larsson*

1982) refer to the Studsvik nuclear research site in Nyköping municipality (Subsection 8.3.3), where an early series of field migration experiments were carried out (Section 7.2).

Sites near Äspö – Ävrö, Kråkemåla, Laxemar

Bergman, T., Johansson, R., Lindén, A.H., Rudmark, L., Wahlgren, C.-H., Follin, S., Isaksson, H., Lindroos, H., Stanfors, R., 1999a. **Förstudie Oskarshamn. Erfarenheter från geovetenskapliga undersökningar i nordöstra delen av kommunen.** SKB R-99-04, Svensk Kärnbränslehantering AB.

Juhlin, C., Palm, H., 1997. **Reflection seismic studies on the island of Ävrö.** SKB PR D-97-09, Svensk Kärnbränslehantering AB.

Swan, G., 1977. **The mechanical properties of the rocks in Stripa, Kråkemåla, Finnsjön and Blekinge.** KBS TR 48, Svensk Kärnbränsleförsörjning AB.

Magnusson, K.-Å., Duran, O., 1984. **Comparative study of geological, hydrological and geophysical borehole investigations**. SKBF/KBS TR 84-09, Svensk Kärnbränsleförsörjning AB.

Laurent, S., 1982. **Analysis of groundwater from deep boreholes in Kråkemåla, Sternö and Finnsjön**. SKBF/KBS TR 82-23, Svensk Kärnbränsleförsörjning AB.

Andersson, O., 1994. **Deep drilling KLX02. Drilling and documentation of a 1,700 m deep borehole at Laxemar, Sweden**. SKB TR 94-19, Svensk Kärnbränslehantering AB.

Laaksoharju, M., Smellie, J.A.T., Nilsson, A.-C., Skårman, C., 1995b. **Groundwater sampling and chemical characterisation of the Laxemar deep borehole KLX02.** SKB TR 95-05, Svensk Kärnbränslehantering AB.

Ekman, L., 2001. **Project Deep Drilling KLX02 – Phase 2. Methods, scope of activities and results. Summary report.** SKB TR 01-11, Svensk Kärnbränslehantering AB.

Follin, S., Askling, P., Carlsten, S., Stråhle, A., 2000. **Smålandsgranitens vattengenomsläpplighet. Jämförelse av borrhålsdata från Äspö, Laxemar och Klipperås.** SKB R-00-46, Svensk Kärnbränslehantering AB.

Site near Finnsjön – Forsmark

Bergman, T., Ekblad, L., Isaksson, H., Larsson, H., Leijon, B., 1996. **Förstudie Östhammar. Samlingsrapport avseende: bergtekniska erfarenheter i regionen, sammanställning av geoinformation vid Forsmarksverket och data från kärnborrhål KF001 vid Forsmark.** SKB PR D-96-025, Svensk Kärnbränslehantering AB.

Axelsson, C.-L., Hansen, L.M., 1998. **Update of structural models at SFR nuclear waste repository, Forsmark, Sweden.** SKB R-98-05, Svensk Kärnbränslehantering AB.

Other drill sites

Ahlbom, K., Carlsson, L., Gentzschein, B., Jämtlid, A., Olsson, O., Tirén, S.A., 1983c. **Evaluation of the geological, geophysical and hydrogeological conditions at Svartboberget.** SKBF/KBS TR 83-55, Svensk Kärnbränsleförsörjning AB.

Wikberg, P., Grenthe, I., Axelsen, K., 1983. **Redox conditions in groundwaters from Svartboberget, Gideå, Fjällveden and Kamlunge**. SKBF/KBS TR 83-40, Svensk Kärnbränsleförsörjning AB.

Laurent, S., 1983c. **Analysis of groundwater from deep boreholes in Svartboberget.** SKBF/KBS TR 83-41, Svensk Kärnbränsleförsörjning AB.

Gentzschein, B., Tullborg, E.-L., 1985. **The Taavinunnanen gabbro massif. A compilation of results from geological, geophysical and hydrogeological investigations.** SKB TR 85-02, Svensk Kärnbränslehantering AB.

Larson, S.Å., Tullborg, E.-L., 1984. **Fracture fillings in the gabbro massif of Taavinunnanen, northern Sweden.** SKBF/KBS TR 84-08, Svensk Kärnbränsleförsörjning AB.

Bergman, T., Ekblad, L., Isaksson, H., Larsson, H., Leijon, B., 1996. **Förstudie Östhammar. Samlingsrapport avseende: bergtekniska erfarenheter i regionen, sammanställning av geoinformation vid Forsmarksverket och data från kärnborrhål KF001 vid Forsmark.** SKB PR D-96-025, Svensk Kärnbränslehantering AB.

Bergman, T., Isaksson, H., 1996. **Förstudie Nyköping. Sammanställning av geoinformation vid Studsvik.** SKB PR D-96-026, Svensk Kärnbränslehantering AB.

Tullborg, E.-L., Larsson, S.Å., 1982. **Fissure fillings from Finnsjön and Studsvik, Sweden. Identification, chemistry and dating**. SKBF/KBS TR 82-20, Svensk Kärnbränsleförsörjning AB.

6.2 Stripa mine

From the late 70s to the early 90s, numerous important underground tests and experiments were carried out within the framework of an international project, the Stripa Project, managed by SKB. The underground rock laboratory was situated in tunnels and cavities driven into unmined parts of the Stripa granite from levels 360 m and 410 m depth in the abandoned Stripa iron mine (Örebro län, central Sweden). The research, financed jointly by radwaste institutions in Canada, Finland, France (Phases 1 and 2), Japan, Spain (Phase 2), Sweden, Switzerland, United Kingdom (Phases 2 and 3) and United States, took place in three overlapping phases, each subdivided into projects concerned with natural barriers, and projects concerned with engineered barriers. The reports cited below derive from the natural barrier research, and, for this branch of the investigations, the contents of the three phases can be briefly summarised as:

- ***Phase 1 (1980–1985)***: investigation of the limitations and possibilities of existing site characterisation methods (fracture system analysis and determination of hydraulic conductivity of fractured rocks from borehole data; hydrogeochemical methods; tracer experiments for understanding the migration of dissolved components in groundwater).

- ***Phase 2 (1983–1988)***: development of improved characterisation methods and techniques ("cross-hole" methods of identifying hydraulically significant fracture zones using borehole radar, borehole seismics, hydrology; migration properties of non-sorbing tracers).

- ***Phase 3 (1986–1992)***: major "Site Characterisation and Validation" (SCV) experiment using the improved measuring and modelling techniques to successively characterise, model and evaluate the structure and hydrogeology of a previously undisturbed rock block (dimensions 125 x 125 x 50 m), with repeated comparison of observations and predictions (validation), first with the initial 5 cored drillholes into the block, then with an additional 3 boreholes to test the preliminary model, and finally with the construction of a tunnel into the block (the SCV drift) to test the refined model.

The International Stripa Project resulted in over 170 technical reports, many of them published by SKB in a special report series (cited below as Stripa Project Technical. Reports), as well as numerous scientific publications. The Stripa project, and particularly the results of the SCV experiment, has received international scientific acclaim for the major advance in the understanding of the hydrogeology of fractured rocks which it produced. Summaries of the organization, execution and main results of the Stripa Project are to be found in *SKB 1992a, 1992b, 1993a* (for a more recent and personal view, see also *Witherspoon 2000*).

The early reports on conditions at the Stripa site appeared in the regular KBS Technical Report series (e.g. *Swan 1977, Carlsson 1977, Olkiewicz et al 1978*) and in reports of the Swedish-American Cooperative programme (SAC reports, not included here). With the initiation of the Stripa project proper (1980), however, results were documented in a separate series of reports, as noted above. A selection of these from the first two phases of the project are given below – for details of the different tests and experiments, see the Stripa Project Annual Reports, which appeared in the same series but are not cited here. Hydrogeological aspects of the Phase I investigations are summarised in *Carlsson & Olsson 1985* and *Andersson & Klockars 1985*, whilst the results of their continuation in Phase 2 are to be found in *Gale et al 1987* and *Andrews et al 1988*. From the large number of individual reports, some have been selected to illustrate the scope of the cross-hole experiments (*Pihl et al 1986, Black et al 1987, Olsson et al 1987a, 1987b*), the 3D migration experiment (*Abelin et al 1987, Andersson & Dverstorp 1987*) and the tests with borehole radar to study flow distribution (*Andersson, Per, et al 1989*).

The main results of the Site Characterisation and Validation (SCV) experiment, which concluded the natural barrier studies at Stripa, are outlined in the final report of the project (*Olsson 1992*). Several other reports have been selected which are partly or wholly based on the results of the SCV project, mainly those dealing with the use of the techniques developed and experience collected. These deal with the processing and interpretation of lithological and structural data (*Triumf 1992, Gale et al 1991, Olsson 1993*), the characterisation of fracture/fracture systems for hydrogeological studies (*Doe & Geier 1991, Martel 1992*), the results of hydraulic and hydrochemical modelling (*Winberg 1991, Davis & Nordström 1992*), and some geomechanical modelling (*Barton et al 1992*).

SKB 1992a. **Stripa Project. Annual Report 1991.** SKB TR-92-26, Svensk Kärnbränslehantering AB.

SKB 1992b. **FUD-Program 92. Kärnkraftavfallets behandling och sluförvaring. 13. Stripa-projektet.** Svensk Kärnbränslehantering AB.

SKB 1993a. **SKB Annual Report 1992. Part III. Summary of the International Stripa Project 1980–1992.** SKB TR 92-46, Svensk Kärnbränslehantering AB.

Witherspoon, P.A., 2000. **The Stripa project.** International Journal of Rock Mechanics and Mining Sciences, 37, 385–396.

Original site characterisation

Swan, G., 1977. **The mechanical properties of the rocks in Stripa, Kråkemåla, Finnsjön and Blekinge.** KBS TR 48, Svensk Kärnbränsleförsörjning AB.

Carlsson, H., 1977. **Bergspänningsmätningar i Stripa gruva.** KBS TR 49, Svensk Kärnbränsleförsörjning AB.

Olkiewicz, A., Hansson, K., Almén, K.-E., Gidlund, G., 1978. **Geologisk och hydrogeologisk grunddokumentation av Stripa försöksstation.** KBS TR 63, Svensk Kärnbränsleförsörjning AB.

Phases 1 and 2 (Methods and techniques)

Carlsson, L., Olsson, T., 1985. **Hydrogeological and hydrochemical investigations in boreholes – Final report.** SKB TR 85-10, Svensk Kärnbränslehantering AB.

Andersson, Peter, Klockars, C.-E., 1985. **Hydrogeological investigations and tracer tests in a well-defined rock mass in the Stripa mine.** SKB TR 85-12, Svensk Kärnbränslehantering AB.

Gale, J., Macleod, R., Welhan, J., Cole, C., Vail, L., 1987. **Hydrogeological characterisation of the Stripa site**. SKB TR 87-15, Svensk Kärnbränslehantering AB.

Andrews, J., Fontes, J.-C., Fritz, P., Nordstrom, D.K., 1988. **Hydrogeochemichal assessment of crystalline rock for radioactive waste disposal: The Stripa experience**. SKB TR 88-05, Svensk Kärnbränslehantering AB.

Pihl, J., Hammarström, M., Ivansson, S., Morén, P., 1986. **Crosshole investigations – Results from seismic borehole tomography.** SKB TR 87-06, Svensk Kärnbränslehantering AB.

Black, J., Holmes, D., Brightman, M., 1987. **Crosshole investigations – Hydrogeological results and interpretations.** SKB TR 87-18, Svensk Kärnbränslehantering AB.

Olsson, O., Falk, L., Lundmark, L., Sandberg, E., 1987a. **Crosshole investigations – Results from borehole radar investigations.** SKB TR 87-11, Svensk Kärnbränslehantering AB.

Olsson, O., Black, J., Cosma, C., Pihl, J., 1987. **Crosshole investigations – Final report.** SKB TR 87-16, Svensk Kärnbränslehantering AB.

Abelin, H., Birgersson, L., Gidlund, J., Moreno, L., Neretnieks, I., Widén, H., Ågren, T., 1987. **3-D migration experiment – Report 3. Performed experiments, results and evaluation.** SKB TR 87-21, Svensk Kärnbränslehantering AB.

Andersson, J., Dverstorp, B., 1987. **3-D migration experiment – Report 4. Fracture network modelling of the Stripa 3-D site.** SKB TR 87-22, Svensk Kärnbränslehantering AB.

Andersson, Per, Andersson, Peter, Gustafsson, E., Olsson, O., 1989. **Investigation of flow distribution in a fracture zone at the Stripa mine, using the radar method, results and interpretation.** SKB TR 89-33, Svensk Kärnbränslehantering AB.

Phase 3 (Site Characterisation and Validation experiment)

Olsson, O. (ed.), 1992. **Stripa Project. Site Characterisation and Validation – Final Report**. SKB TR-92-22, Svensk Kärnbränslehantering AB.

Triumf, C.-A., 1992. **Classification of lithological units based on geophysical borehole logging – Data from the Stripa mine**. SKB TR 92-18, Svensk Kärnbränslehantering AB.

Gale, J., MacLeod, R., Bursey, G., Stråhle, A., Tirén, S.A., 1991. **Characterisation of the structure and geometry of the H fracture zone at the SCV site**. SKB TR-91-37, Svensk Kärnbränslehantering AB.

Olsson, O., 1993. **How to build structural models of a site – the Stripa experience.** SKB PR 44-93-007, Svensk Kärnbränslehantering AB.

Doe, T.W., Geier, J.E., 1991. **Interpretation of fracture system geometry using well test data**. SKB TR-91-03, Svensk Kärnbränslehantering AB.

Martel, S., 1992. **Geologic characterisation of fractures as an aid to hydrologic modeling of the SCV block at the Stripa mine.** SKB TR-92-24, Svensk Kärnbränslehantering AB.

Winberg, A., 1991. **Analysis of spatial correlation of hydraulic conductivity data from the Stripa mine**. SKB TR 91-28, Svensk Kärnbränslehantering AB.

Davis, S.N., Nordstrom, D.K. (eds.), 1992. **Hydrogeochemical investigations in boreholes at the Stripa mine. Final report by the Hydrochemical Advisory Section and their associates**. SKB TR 92-19, Svensk Kärnbränslehantering AB.

Pedersen, K., Ekendahl, S., 1992b. **Incorporation of CO_2 and introduced organic compounds by bacterial populations in groundwater from the deep crystalline bedrock of the Stripa mine.** Journal of Genetics and Microbiology, 138, 369–376.

Barton, N., Makurat, A., Monsen, K., Vik, G., Tunbridge, L., 1992. **Rock mechanics characterisation and modelling of the disturbed zone phenomena at Stripa**. SKB TR-92-12, Svensk Kärnbränslehantering AB

6.3 Äspö Hard Rock Laboratory (”Aberg”)

Plans for the construction of an underground research laboratory in a previously undisturbed part of Swedish bedrock were launched in 1986. The Hard Rock Laboratory (HRL) was intended to provide a research, development and demonstration base for the KBS-3 disposal concept, at the depth planned for the future deep repository. After an extensive site selection and preliminary site characterisation process, and subsequent governmental review, the location of the facility on Äspö, an island near the Oskarshamn nuclear power plant, was accepted, and construction started in 1990. This earliest phase of surface-based studies became known as the "pre-investigation phase" (1986–1990). The following "construction phase" (1990–1995) was accompanied by continued surface-based investigations, but attention focussed on investigations underground, in the ca. 2 km long access tunnel and in the spiral tunnel under Äspö (total tunnel length ca. 3600 m). The main part of the tunnel was excavated using conventional drill and blasting methods, whereas the last 400 m were excavated using a 5 m diameter Tunnel Bore Machine. From 1995 onwards, the facility has been in the "operating phase", and major experiments have been started at various locations in the deepest parts of the facility, within the framework of an international project. The aims of the Äspö HRL have been formulated in terms of Stage Goals (*SKB 1996b*):

- Goal 1: verification of pre-investigation methods
- Goal 2: finalization of detailed investigation methodology
- Goal 3: testing of models for groundwater flow and radionuclide migration

- Goal 4: demonstration construction and handling methods
- Goal 5: testing of important parts of the repository system (in *SKB 1999f* included in Goal 4)

From the point of view of the siting process, the important research is that directed towards Goals 1-3. The reports cited in the list below refer mainly to Goals 1 and 2, i.e. the development, application and validation of site characterisation methods. A selection of documents on the experimental and modelling studies, many of them ongoing and focussed on radionuclide migration (Goal 3), are included in Section 7.2 They form part of the Äspö operating phase and are being carried out within an international research programme.

In the following, the Äspö documentation has been arranged in three subgroups. Subsection 6.3.1 contains site characterisation reports documenting the 10 years of research between the start of site selection and the end of construction. The second subgroup (Subsection 6.3.2) encompasses technical reports on individual themes related to site geology, published successively from the pre-investigation phase to the use of Äspö as one of the model sites in the SR-97 safety analysis (hypothetical site "Aberg", see Subsection 10.1.2). Finally, the use of the Äspö data as a basis for a performance assessment exercise by the Swedish regulatory body, SKI, is documented in Subsection 6.3.3. It is fair to say that the construction and operation of Äspö HRL has made a major impact on radioactive waste research, worldwide, and will provide an exceptional scientific database for many different types of geoscientific study for years to come.

6.3.1 Site characterisation and validation

The Site Characterisation and Validation (SCV) experiment at Stripa (Section 6.2) was a small-scale version of what has been attempted on a large scale at Äspö – the research directed at Goals 1 and 2 (see above). The reports summarising this major site characterisation effort are collected in this subgroup under two headings below, depending on whether they refer to results and predictions of the pre-investigation phase alone (surface-based studies preceding the start of construction), or whether they include results from underground investigations (during and after the construction phase) and comparisons with the pre-investigation predictions (validation). The geoscientific studies in the pre-investigation phase included detailed geological and structural mapping (including continuous trench profiles), gravity and aeromagnetic surveying, core drilling (14 deep boreholes, mostly down to at least 500 m depth), percussion drilling (20 holes), extensive borehole geophysics (conventional logging, radar, VSP, etc.) and extensive hydrogeological observation, sampling and testing (*Gustafson et al 1988, 1989*). At a later stage, the data were used to make first predictions of conditions at 500 m depth and these were published as a major series of related reports (*Stanfors et al 1991, Almén & Zellman 1991, Wikberg et al 1991, Gustafson et al 1991, Almén et al 1991*). A report on hydrogeochemical conditions at the site closes the documentation of this preconstruction site characterisation effort (*Smellie et al 1992*).

The entries under the second heading constitute a second major series of related documents detailing the work carried out during the construction phase (detailed site characterisation: *Stanfors et al 1997a, 1997b, Rhén et al 1997a,* see also *Stanfors et al 1999*), including a critical evaluation of the relation between pre-construction predictions and post-construction results (*Rhén et al 1997b*), and a report the development of improved models and predictions (*Rhén et al 1997c*). The relation between prediction (from surface-based data) and observation (in the tunnel) was judged to be satisfactory in general, but poor in some specific areas (minor fracture zones <5 m thick, granitic veins, greenstone screens, fracture and fracture zone hydrology). For engineering purposes, unexpected conditions were not encountered which required changes in layout, or changes in construction method or specifications (*SKB 1996b*).

SKB 1996b. **Äspö Hard Rock Laboratory. 10 Years of Research.** Svensk Kärnbränslehantering AB.

SKB 1999f. **Äspö Hard Rock Laboratory. Annual Report 1998.** SKB TR 99-10, Svensk Kärnbränslehantering AB.

Pre-investigation phase (surface-based studies) 1986–1990

Gustafson, G., Stanfors, R., Wikberg, P., 1988. **Swedish Hard Rock Laboratory. First evaluation of preinvestigations 1986–87 and target area characterisation.** SKB TR 88-16, Svensk Kärnbränslehantering AB.

Gustafson, G., Stanfors, R., Wikberg, P., 1989. **Swedish Hard Rock Laboratory. Evaluation of 1988 year preinvestigations and description of the target area, the island of Äspö.** SKB TR 89-16, Svensk Kärnbränslehantering AB.

Stanfors, R., Erlström, M., Markström, I., 1991. **Äspö Hard Rock Laboratory. Overview of the investigations 1986–1990.** SKB TR 91-20, Svensk Kärnbränslehantering AB.

Almén, K.-E., Zellman, O., 1991. **Äspö Hard Rock Laboratory. Field investigation methodology and instruments used in the pre-investigation phase, 1986–1990.** SKB TR 91-21, Svensk Kärnbränslehantering AB.

Wikberg, P., Gustafsson, G., Rhén, I., Stanfors, R., 1991. **Äspö Hard Rock Laboratory. Evaluation and conceptual modelling based on the pre-investigations 1986–1990.** SKB TR 91-22, Svensk Kärnbränslehantering AB.

Gustafson, G., Liedholm, M., Rhén, I., Stanfors, R., Wikberg, P., 1991. **Äspö Hard Rock Laboratory. Predictions prior to excavation and the process of their validation.** SKB TR 91-23, Svensk Kärnbränslehantering AB.

Almén, K.-E., Olsson, P., Rhén, I., Stanfors, R., Wikberg, P., 1994. **Äspö Hard Rock Laboratory. Feasibility and usefulness of site investigation methods. Experiences from the pre-investigation phase.** SKB TR 94-24, Svensk Kärnbränslehantering AB.

Smellie, J.A.T., Laaksoharju, M., 1992. **The Äspö Hard Rock Laboratory: Final evaluation of the hydrogeochemical pre-investigations in relation to existing geologic and hydraulic conditions.** SKB TR 92-31, Svensk Kärnbränslehantering AB.

Construction phase – detailed site characterisation, 1990–1995 and later

Stanfors, R., Erlström, M., Markström, I., 1997a. **Äspö HRL – Geoscientific evaluation 1997/1. Overview of site characterisation 1986–1995.** SKB TR 97-02, Svensk Kärnbränslehantering AB.

Rhén, I., Bäckblom, G., Gustafson, G., Stanfors, R., Wikberg, P., 1997a. **Äspö HRL – Geoscientific evaluation 1997/2. Results from pre-investigations and detailed site characterisation. Summary report.** SKB TR 97-03, Svensk Kärnbränslehantering AB.

Stanfors, R., Olsson, P., Stille, H., 1997b. **Äspö HRL – Geoscientific evaluation 1997/3. Results from pre-investigations and detailed site characterisation. Geology and mechanical stability.** SKB TR 97-04, Svensk Kärnbränslehantering AB.

Stanfors, R., Rhén, I., Tullborg, E., Wikberg, P., 1999. **Overview of geological and hydrogeological conditions of the Äspö hard rock laboratory.** Applied Geochemistry, 14, 819–834.

Rhén, I., Gustafson, G., Wikberg, P., 1997b. **Äspö HRL – Geoscientific evaluation 1997/4. Results from pre-investigations and detailed site characterisation. Comparison of predictions and observations. Hydrogeology, groundwater chemistry and transport of solutes.** SKB TR 97-05, Svensk Kärnbränslehantering AB.

Rhén, I., Gustafson, G., Stanfors, R., Wikberg, P., 1997c. **Äspö HRL – Geoscientific evaluation 1997/5. Models based on site characterisation 1986–1995.** SKB TR 97-06, Svensk Kärnbränslehantering AB.

6.3.2 Thematic reports, and Äspö as Aberg in SR-97

The Äspö HRL is constructed in granitoids of the Transscandinavian Igneous Belt (see Section 2.5) at a coastal site in southeastern Sweden. The main rock types encountered were medium grained quartz monzonites (”Äspö diorite”) and adamellites (”Ävrö granite”), intersected by fine grained Småland granites, which occur as irregular intrusions, dykes, veins and patches (*Wikman & Kornfält 1995, Kornfält et al 1997*). Other lithologies occurring as xenoliths in the granitoids include metavolcanite and greenstone, concentrated in a foliated NE-SW striking zone across the centre of the island (”Äspö shear zone”). The age of the granitoids is ca. 1,800 Ma.

With regard to bedrock structure and stability, the Äspö rocks are intersected by a number of fracture zones in different orientations which can be distinguished in the surface morphology, in cores and by various geophysical techniques. The SKB surface-based models and the changes which were occasioned by observations in the tunnel are found in the site characterisation reports above (Subsection 6.4.1). However, there is still considerable disagreement on the number, orientation and location of the main fracture zones and their hydraulic significance, due to nomenclature problems and different weightings to different data sets (*Tirén 1996,* cf. Aberg site summary in *SKB 1999c*). The different stages of brittle deformation in the Äspö area has been studied in some detail, but many problems remain (*Munier 1993, Maddock et al 1993, Poteri 1995, Sirat 1999, Bossart et al 2001,* and SKB Progress Reports cited therein). One worker in the Äspö area has maintained that many of the fractures on Äspö were formed during the retreat of the last ice sheet, about 9,000 years ago (*Mörner 1989*), but most geoscientists remain unconvinced by the evidence presented (*SKB 1990*) – this in contrast to the convincing evidence for postglacial faulting and paleoseismicity in northern Sweden (Section 4.1).

The remaining reports in this Subsection concern hydrogeology in its widest meaning. These are grouped under three headings: geohydrology and hydrogeochemistry, dealing with the site conditions themselves, and, a more general heading, coastal hydrology and glaciation. With regard to geohydrology, work has been heavily concentrated on the modelling of groundwater flow in fractured rock, starting with the characterisation of the observed water-conducting features (*Mazurek et al 1997, Bossart et al 2001*), continuing with the geostatistical modelling of fracture arrays and hydraulic parameters (*LaPointe 1994, LaPointe et al 1995, Vidstrand 1999*), and ending with reports on modelling in connection with the pre-construction LPT2 experiment and the post-construction drawdown experiment. These experiments were modelled by different international groups. The groundwater flow modelling for the LPT2 experiment was based on tests performed in the numerous deep boreholes sunk before construction began, and was attacked by several groups within the international Äspö Task Force, using different modelling approaches (*Billaux et al 1994, Gylling et al 1994, Gylling 1995, 1997, Uchida et al 1994, Holton & Milický 1997*). Similarly, a multinational approach was used in the drawdown experiment, which attempted to model the hydraulic impact of the tunnel itself, once excavated (*Tanaka et al 1996, Uchida et al 1997, Mahara et al 1998,* see also *Axelsson & Follin 2000*). The final citations under this heading refer to the modelling of the Aberg site in the safety assessment SR-97 (see Subsection 10.2.2), which used the hydraulic data from the cored boreholes of the pre-investigation phase and from probeholes drilled during tunnel construction (*Walker et al 1997, Walker & Gylling 1998,* see also *Outters & Shuttle 2000*), and a special study of the hydraulic properties of Småland granite over a wider area (*Follin et al 2000*).

The reports collected under hydrogeochemistry include, in the first instance, some entries describing specific aspects of chemical conditions in Äspö groundwater (*Landström & Tullborg 1995, Laaksoharju (ed.), 1995, Banwart (ed.), 1995*). These and other aspects are summarised in the corresponding Aberg report for SR-97 (*Laaksoharju et al 1998*), but perhaps even more extensively, and subjected to peer review, in the special issue of the journal Applied Geochemistry on the geochemistry of the Äspö site (*Gascoyne & Wikberg, eds., 1999*). Finally, under coastal hydrology and glaciation, there are collected a series of reports which treat more general aspects of the hydrogeology of the Äspö site, as a coastal site with a past (and presumably future) history of glaciation (*Wallin 1995, Engqvist 1997, Svensson 1999a, 1999b,* see also Section 5.4).

Wikman, H., Kornfält, K.-A., 1995. **Updating of a lithological model of the bedrock of the Äspö area.** SKB PR 25-89-06, Svensk Kärnbränslehantering AB.

Kornfält, K.-A., Persson, P.-O., Wikman, H., 1997. **Granitoids from the Äspö area, southeastern Sweden – geochemical and geochronological data**. GFF, 119, 109–114.

Bedrock structure and stability

Tirén, S.A., 1996. **Comparison of the SKI, SKB and SKN geological and structural models of the Äspö area.** Statens kärnkraftinspektion, Report SKI 96:19.

SKB 1999c. **SR-97. Waste, repository design and sites.** SKB TR 99-08, Svensk Kärnbränslehantering AB.

Munier, R., 1993. **Four-dimensional analysis of fracture arrays at the Äspö hard rock laboratory, SE Sweden**. Engineering Geology, 33, 159–175.

Maddock, R.H., Hailwood, E.A., Rhodes, E.J., Muir-Wood, R., 1993. **Direct fault dating trials at the Äspö Hard Rock Laboratory.** SKB TR 93-24, Svensk Kärnbränslehantering AB.

Poteri, A., 1995. **Analysis of bedrock fracturing at Äspö.** SKB ICR 96-01, Svensk Kärnbränslehantering AB.

Sirat, M., 1999. **Structural and neural network analyses of fracture systems at the Äspö Hard Rock Laboratory, SE Sweden.** Doctoral thesis, Uppsala University.

Bossart, B., Hermanson, J., Mazurek, M., 2001. **Äspö Hard Rock Laboratory. Analysis of fracture networks based on structural and hydrogeological observations on different scales.** SKB TR 01-21, Svensk Kärnbränslehantering AB.

Mörner, N.-A., 1989. **Postglacial faults and fractures on Äspö.** SKB PR 25-89-24, Svensk Kärnbränslehantering AB.

SKB 1990. **Granskning av Nils-Axel Mörners arbete avseende postglaciala strukturer på Äspö**. SKB AR 90-18, Svensk Kärnbränslehantering AB.

Geohydrology

Mazurek, M., Bossart, P., Eliasson, T., 1997. **Classification and characterisation of water-conducting features at Äspö: results of investigations on the outcrop scale.** SKB ICR 92-39, Svensk Kärnbränslehantering AB.

Bossart, B., Hermanson, J., Mazurek, M., 2001. **Äspö Hard Rock Laboratory. Analysis of fracture networks based on structural and hydrogeological observations on different scales.** SKB TR 01-21, Svensk Kärnbränslehantering AB.

LaPointe, P.R., 1994. **Evaluation of stationary and non-stationary geostatistical models for inferring hydraulic conductivity values at Äspö.** SKB TR 94-22, Svensk Kärnbränslehantering AB.

LaPointe, P.R., Wallmann, P., Follin, S., 1995. **Estimation of effective block conductivities based on discrete network analyses using data from the Äspö site.** SKB TR 95-15, Svensk Kärnbränslehantering AB.

Vidstrand, P., 1999. **Hydrogeological scale effects in crystalline rocks**. Licentiate thesis, Chalmers University of Technology, Göteborg.

Billaux, D., Guérin, F., Wendling, J., 1994. **Hydrodynamic modelling of the Äspö Hard Rock Laboratory. Discrete fracture model.** SKB ICR 94-14, Svensk Kärnbränslehantering AB.

Gylling, B., Moreno, L., Neretnieks, I., Birgersson, L., 1994. **Analysis of LPT2 using the channel network model.** SKB ICR 94-05, Svensk Kärnbränslehantering AB.

Gylling, B., 1995. **Simulation of fluid flow and transport of solutes in fractured rock using a channel network model – application to field experiments**. Licentiate thesis, Royal Institute of Technology (KTH), Stockholm.

Gylling, B., 1997. **Development and applications of the Channel Network Model for simulations of flow and solute transport in fractured rock**. Doctoral thesis, Royal Institute of Technology (KTH), Stockholm.

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Axelsson, C.-L., Follin, S., 2000. **Grundvattensänkning och dess effekter vid byggnation och drift av ett djupförvar.** SKB R-00-21, Svensk Kärnbränslehantering AB.

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Walker, D., Gylling, B., 1998. **Site-scale groundwater flow modelling of Aberg.** SKB TR 98-23, Svensk Kärnbränslehantering AB.

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Landström, O., Tullborg, E.-L., 1995. **Interactions of trace elements with fracture filling minerals from the Äspö Hard Rock Laboratory.** SKB TR 95-13, Svensk Kärnbränslehantering AB.

Laaksoharju, M. (ed.), 1995. **Sulphate reduction in the Äspö HRL tunnel.** SKB TR 95-25, Svensk Kärnbränslehantering AB.

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Laaksoharju, M., Gurban, I., Skårman, C., 1998. **Summary of hydrochemical conditions at Aberg, Beberg and Ceberg.** SKB TR 98-03, Svensk Kärnbränslehantering AB.

Gascoyne, M., Wikberg, P. (eds.), 1999. **Geochemistry of the Äspö Hard Rock Laboratory, Sweden.** Applied Geochemistry, 14.

Coastal hydrology and glaciation

Svensson, U., 1999a. **A laboratory scale analysis of groundwater flow and salinity distribution in the Äspö area.** SKB TR 99-24, Svensk Kärnbränslehantering AB.

Svensson, U., 1999b. **Subglacial groundwater flow at Äspö as governed by basal melting and ice tunnels.** SKB R-99-38, Svensk Kärnbränslehantering AB.

Wallin, B., 1995. **Palaeohydrological implications in the Baltic area and its relation to the groundwater at Äspö, south-eastern Sweden – A literature study**. SKB TR 95-06, Svensk Kärnbränslehantering AB.

Engqvist, A., 1997. **Water exchange estimates derived from forcing for the hydraulically coupled basins surrounding Äspö island and adjacent coastal water**. SKB TR 97-14, Svensk Kärnbränslehantering AB.

6.3.3 SKI project SITE-94

The SKI performance assessment project SITE-94 (see Section 10.2) is based on data from the pre-investigation phase of the Äspö site characterisation project, with the addition of some later SKB data (up to 1992). Some of these reports contributed significantly to the understanding of the Äspö site, and, since the models were developed by a completely independent group of geoscientists, also provided a means of judging the uncertainties inherent in site models. The data base used in SITE-94 is summarised in a special report (*Geier et al 1996*) and the development of an independent geological and structural model for the site is described in detail, together with detailed background information, in *Tirén et al 1996* and *Tirén (ed.) 1997*. Other site characterisation aspects are treated in a number of individual reports, for example, borehole geostatistics (*LeLoc'h & Osland 1996*), hydrogeology (*Voss et al 1996*), groundwater flow modelling (*Tsang 1996*), and hydrogeochemistry (*Glynn & Voss 1996*). For a more complete list of the SITE-94 technical reports, see Section 10.2.

Geier, J.E., Tirén, S.A., Dverstorp, B., Glynn, P., 1996. **Site-specific base data for the performance assessment (SITE-94).** Statens kärnkraftinspektion, Report SKI 96:10.

Tirén, S.A., Beckholmen, M., Voss, C., Askling, P., 1996. **Development of a geological and structural model of Äspö, southeastern Sweden.** Statens kärnkraftinspektion, Report SKI 96:16.

Tirén, S.A. (ed.), 1997. **Background information and data used in development of the SITE-94 geological and structural models of Äspö.** Statens kärnkraftinspektion, Report SKI 97:7.

LeLoc'h, G., Osland, R., 1996. **Preliminary analysis of geostatistical structure of Äspö borehole data.** Statens kärnkraftinspektion, Report SKI 96:15.

Voss, C., Tirén, S.A., Glynn, P., 1996. **Hydrogeology of Äspö Island, Simpevarp, Sweden.** Statens kärnkraftinspektion, Report SKI 96:13.

Tsang, Y.W., 1996. **Stochastic continuum hydrological model of Äspö.** Statens kärnkraftinspektion, Report SKI 96:9.

Glynn, P., Voss, C., 1996: **Geochemical characterisation of Simpevarp ground waters near the Äspö Hard Rock Laboratory.** Statens kärnkraftinspektion, Report SKI 96:29.

6.4 Other underground data

In addition to the problem-orientated investigations outlined above, underground conditions have been studied and reported from many different situations, although not always in a form which makes the data easily useable for the problem at hand. In this Section, a selection of reports and papers are collected, without any claim to representativeness or even, in the first instance, usefulness. The first heading concerns experience from deep mines. Potentially, there is considerable information on underground conditions in Swedish bedrock, at least in the Bergsdalen mining province (in which Stripa is situated, Section 6.2) and in the Norrland mining districts (Skellefte, Kiruna, etc.), where the deepest mines go down to almost 1000 m. However, there seems to be no synthesis of this experience in Sweden, as, for instance, has been made for Canadian mines (*Raven & Gale 1986, Raven & Clark 1993,* see also *Röshoff 1989b*), although some information is found in one of the Östhammar Förstudie reports (*Bergman et al*

1996) and in a report on Swedish experience with water table draw-down around underground excavations (*Axelsson & Follin 2000*).

In contrast, there has been considerable interest in experience from Swedish tunnels, as indicated by the number of SKB Technical Reports on different examples (see *Bergman et al 1996* and other Förstudie reports, Section 8.3, as well as *Andersson et al 1987, Stanfors 1987, Palmqvist & Stanfors 1987, Olsson & Palmqvist 1989, Hakami et al 1991, Axelsson & Hansen 1997, Axelsson & Follin 2000*). The final group of citations are reports and papers describing investigations in ultradeep boreholes, i.e. deeper than 1000 m (for overview of European localities, see *Juhlin et al 1998*). This contains a selection of documents on the Laxemar deep borehole (*Ekman 2001*), on the deep gas drilling project in the Siljan area, Dalarna län (*Juhlin 1990, Juhlin et al 1991, Juhlin & Pedersen 1993, Gold 1999*), on the Russian deep hole on the Kola peninsula (*Moiseyenko 1986, Kazansky 1992, NEDRA 1992*), and on the continental deep borehole, KTB, in the Hercynian basement of Germany (*Emmermann et al 1995, Emmermann & Lauterjung 1997, Kohl & Rybach 1996*). For further references on this theme, consult the SKB reports on the Very Deep Hole (VDH) alternative disposal system (Subsection 10.2.3).

Mines

Raven, K.G., Gale, J.E., 1986. **A study of the surface and subsurface structural and groundwater conditions at selected underground mines and excavations.** Atomic Energy of Canada Ltd., report AECL TR-177.

Raven, K.G., Clark, I.D., 1993. **Survey of geoscientific data on deep underground mines in the Canadian Shield.** Atomic Energy Control Board (Canada), report AECB 92-012.

Röshoff, K., 1989b. **Seismic effects on bedrock and underground constructions. A literature survey of damage on constructions; changes in ground-water levels and flow; changes in chemistry in groundwater and gases.** SKB TR 89-30, Svensk Kärnbränslehantering AB.

Bergman, T., Ekblad, L., Isaksson, H., Larsson, H., Leijon, B., 1996. **Förstudie Östhammar. Samlingsrapport avseende: bergtekniska erfarenheter i regionen, sammanställning av geoinformation vid Forsmarksverket och data från kärnborrhål KF001 vid Forsmark.** SKB PR D-96-025, Svensk Kärnbränslehantering AB.

Axelsson, C.-L., Follin, S., 2000. **Grundvattensänkning och dess effekter vid byggnation och drift av ett djupförvar.** SKB R-00-21, Svensk Kärnbränslehantering AB.

Tunnels

Andersson, J.-E., Andersson, P., Carlsten, S., Falk, L., Olsson, O., Stråhle, A., 1987. **Combined interpretation of geophysical, geological, hydrogeological and radar investigations in the boreholes ST1 and ST2 at the Saltsjötunnel**. SKB TR 87-14, Svensk Kärnbränslehantering AB.

Stanfors, R., 1987. **The Bolmen Tunnel project. Evaluation of geophysical site investigation methods**. SKB TR 87-25, Svensk Kärnbränslehantering AB.

Palmqvist, K., Stanfors, R., 1987. **The Kymmen power station. TBM tunnel. Hydrogeological mapping and analysis**. SKB TR 87-26, Svensk Kärnbränslehantering AB.

Olsson, O., Palmqvist, K., 1989. **Radar investigations at the Saltsjötunnel – predictions and validation**. SKB TR 89-18, Svensk Kärnbränslehantering AB.

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Ultradeep boreholes

Juhlin, C., Wallroth, T., Smellie, J.A.T., Eliasson, T., Ljunggren, C., Leijon, B., Beswick, J., 1998. **The Very Deep Hole Concept: Geoscientific appraisal of conditions at great depth**. SKB TR 98-05, Svensk Kärnbränslehantering AB.

Ekman, L., 2001. **Project Deep Drilling KLX02 – Phase 2. Methods, scope of activities and results. Summary report.** SKB TR 01-11, Svensk Kärnbränslehantering AB.

Juhlin, C., AlDahan, A.A., Castano, J., Collini, B., Gorody, T., Sandstedt, H., 1991. **Scientific summary report of the deep gas drilling project in the Siljan ring impact structure.** Vattenfall RD&D report U(G) 1991/14.

Juhlin, C., 1990. **Interpretation of the reflections in the Siljan Ring area based on results from the Gravberg-1 borehole.** Tectonophysics, 173, 345–360.

Juhlin, C., Pedersen, L.B., 1993. **Further constraints on the formation of the Siljan impact crater from seismic reflection studies.** GFF, 115, 151–158.

Gold, T., 1999. **The Deep Hot Biosphere.** Springer-Verlag (New York, etc.).

Moiseyenko, F.S., 1986. **The Kola superdeep drillhole and some problems of interpreting deep-level geophysical interpretations.** International Geological Reviews, 28, 1021–1030.

Kazansky, V.I., 1992. **Deep structure and metallogeny of Early Proterozoic mobile belts in the light of superdeep drilling in Russia.** Precambrian Research, 58, 289–303.

NEDRA, 1992. **Characterisation of crystalline rocks in deep boreholes. The Kola, Krivoy Rog and Tyrnauz boreholes**. SKB TR 92-39, Svensk Kärnbränslehantering AB.

Emmermann, R., Althaus, E., Giese, P., Stöckhert, B., 1995. **KTB Hauptbohrung. Results of geoscientific investigation in the KTB field laboratory. Final report: 0 – 9101 m.** Geological Survey of Lower Saxony, German Continental Deep Drilling Programme, report KTB 95-2.

Emmermann, R., Lauterjung, J., 1997. **The German Continental Deep Drilling Program KTB: overview and major results.** Journal of Geopysical Research, 102 (B8), 18179–18201.

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7 Transport of radionuclides in the geosphere

One of the main aims of the siting of KBS-3-type repositories is to identify locations at depth in a geological environment which can be expected to prevent or retard the transport of radionuclides from the repository to the biosphere, should they, at some future time, be released from the system of artificial barriers which the KBS-3 concept envisages. Hence, considerable effort has been put into understanding how such migration would take place, what physical and geochemical processes would be involved, and how to acquire quantitative information which could be used with confidence in a performance assessment or safety analysis. Because of the complexity and heterogeneity of the geosphere, and because of the enormously long time-scales involved, it has long been recognized that confidence cannot be built up on the basis of laboratory tests, or very simple field experiments, alone. Hence, two further lines of investigation have been followed intensively during the past two decades. The first, as documented in Section 7.1 below, involves the search for, and detailed investigation of, natural geological systems which are analogous to the whole or some part of the artificial situation created by the repository and its contents. These have become known as natural analogues, and can be thought of as natural field experiments which have been allowed to proceed over geological timescales, and whose end results can be studied today. The second line of investigation, Section 7.2 below, consists of field experiments on different scales, carried out in underground rock laboratories. Although these are limited by the, geologically, very short time of observation, they allow insights into the behaviour of radioactive and non-radioactive tracers in the natural environment and the effects of natural heterogeneity and complexity. This chapter is relatively short, and the documentation is highly selective, especially in Section 7.2. This is because the material is not directly related to the siting process and therefore lies mainly outside the scope of the present compilation.

7.1 Natural analogues

Applied natural analogues studies related to radionuclide transport around KBS-3-type repositories are subject to one basic requisite: they should include, as quantitatively as possible, both spatial and temporal data. Put simply, interest centres on how far a given radionuclide, or other element, has moved in a measurable time interval. For instance, in an early Swedish study, we read: “ (The data) indicated U migration along distances of 40 cm or more on a time scale of 1 million years, in conjunction with Th immobility under the same conditions.” (*Smellie et al 1986*). This is the essence: the whole story is that it is an extremely complicated task to obtain such data, involving intensive field work, sophisticated analytical procedures, complicated numerical modelling and specialized geological knowledge, particularly in the areas of geochemistry, isotope geology, geochronology and hydrogeology.

In Sweden, small inroads in the early 1980s (*Smellie 1982, 1984b, Smellie & Rosholt 1984, Smellie & Stuckless 1985, Smellie 1985*) quickly led to the recognition of the enormous potential of such work for building confidence in the conclusions of assessments of long-term safety, and for revealing potentially, on the long term deleterious, natural conditions (e.g. *Chapman et al 1984, McKinley & Alexander 1992, 1996, Brandenberg et al 1993, Miller et al 1994, Smellie et al 1997, Smellie & Karlsson 1999, Wronkiewicz et al 1999, Miller et al 2000*). Particularly the latter point, identification of potentially deleterious conditions, has important implications for the siting process, and for site characterisation in general. The tremendous upswing in research activity in the 1980s took place within a wide international context, with some degree of scientific coordination channelled through the "Natural Analogue Working Section" (NAWG), under the general auspices of the European Commission. This research led to major co-operative projects, in which SKB and its consultants were actively represented, such as the Pocos de Caldas Project, in Brazil (*Chapman et al 1989, Chapman et al 1992, Nordström et al 1992, Romero et al 1992*), the Cigar Lake Analog Study, in Canada (*Cramer & Smellie 1994a,b, Liu 1995, Smellie & Karlsson 1996*), and the Maqarin project in Jordan (*Khoury et al 1992, Alexander et al 1992, Clark et al 1994, Smellie (ed.) 1998, 2000*).

Internationally, since the 1970s, analogue studies have focussed particularly on a series of unique geological occurrences in and around the Oklo/Okélobondo uranium mine, in Gabon, where the "fossilized" remains of several natural fission reactors were found. These are locations within the ore body which "went critical" about 2,000 Ma ago, and afterwards became natural spent fuel "repositories". This interest is illustrated by the number of SKB Technical Reports which have treated different aspects of this African locality (*e.g. Curtis & Gancarz 1983, Curtis 1985, Pedersen (ed.) 1996, Oversby 1996, Gurban et al 1998, 1999, Zetterström 2000,),* and by the enormous volume of published scientific literature, of which only a minute selection are added here (e.g. *Curtis et al 1989, Hidaka et al 1992,1999, Hidaka 1999, Menet et al 1992, Smellie 1995, Gauthier-Lafaye et al 1996, Janeczek 1999, Gauthier-Lafaye et al 2000*).

Nearer to home, and perhaps more directly relevant to Swedish conditions, is the uranium deposit of Palmottu, in SW Finland, which has been subjected to detailed investigation from the point of view of natural analogues since the early 1980s (*Jaakola et al 1989, Blomqvist et al 1991*), most recently within the framework of EU-supported research projects (*Blomqvist et al 1995, Casanova et al 1999, Kaija et al 2000, Blomqvist et al 2000*). However, natural analogue research has not only been in the form of international large-scale, interdisciplinary and multiprocess projects. Restricted, small-scale localities representing special circumstances which can throw light on various aspects of nuclear waste disposal, bringing in the long-term perspective, are, geologically speaking, all around us, and have resulted in numerous, more modest, but nevertheless extremely useful, studies (e.g. *Hallberg et al 1987, Pusch & Karnland 1988, Finch & Ewing 1989, Marcos & Ahonen 1999, Milodowski et al 2000*).

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Palmottu

Jaakola, T., Suksi, J., Suutarinen, R., Niini, H., Ruskeeniemi, T., Söderholm, B., Vesterinen, M., Blomqvist, R., Halonen, S., Lindberg, A., 1989. **The behaviour of natural radionuclides in and around uranium deposits. 2. Results of investigations at the Palmottu analogue study site, SW Finland.** Geological Survey of Finland, report YST-64.

Blomqvist, R., Jaakola, T., Niini, H., Ahonen, L., eds., 1991. **The Palmottu Analogue Project. Progress Report 1990.** Geological Survey of Finland, Nuclear Waste Disposal Research, report YST-73.

Blomqvist, R., Suksi, J., Ruskeeniemi, T., Ahonen, L., Niini, H., Vuorinen, U., Jakobsson, K., 1995. **The Palmottu natural analogue project. The behaviour of natural radionuclides in and around uranium deposits.** Finnish Centre for Radiation and nuclear Safety (STUK), report STUK-YTO-TR 84.

Casanova, J., Négrel, P., Frape, S.K., Kaija, J., Blomqvist, R., 1999. **Multi-isotope geochemistry of the Palmottu hydrosystem, Finland.** In “Geochemistry of the Earth's Surface (Ármannson, H., ed.), Balkema (Rotterdam), 483–486.

Kaija, J., Blomqvist, R., Suksi, J., Rasilainen, K., 2000. **The Palmottu Natural Analogue Project. Progress Report 1999**. Geological Survey of Finland, Nuclear Waste Disposal Research, Report YST-103.

Blomqvist, R., Ruskeeniemi, T., Kaija, J., Paananen, M., Ahonen, L., Smellie, J., Grundfelt, B., Bruno, J., Pérez del Villar, L., Rasilainen, K., Pitkänen, P., Casanova, J., Suksi, J., 2000. **Final Report: The Palmottu natural analogue project. Phase II: Transport of radionuclides in a natural flow system at Palmottu.** European Commission (in press).

Other analogues

Hallberg, R.O., Östlund, P. and Wadsten, T., 1987. **A 17th century cannon as an analogue for radio-active waste disposal.** In: B. Côme, and N.A Chapman, (Eds.), CEC Radioactive Management Series, Commission of the European Communities. EUR 11037 EN, Luxemburg. p.135–139.

Pusch, R. and Karnland, O., 1988. **Geological evidence of smectite longevity: The Sardinian and Gotland cases.** SKB TR 88-26, Svensk Kärnbränslehantering AB.

Finch, R.J., Ewing, R.C., 1989. **Alteration of natural UO2 under oxidizing conditions from Shinkolobwe, Katanga, Zaire: A natural analogue for the corrosion of spent fuel.** SKB TR 89-37, Svensk Kärnbränslehantering AB.

Marcos, N., Ahonen, L., 1999. **New data on the Hyrkkölä U-Cu mineralization: the behaviour of native copper in a natural environment.** Posiva Oy, report POS 99-23.

Milodowski, A.E., Styles, M.T., Hards, V.L., 2000. **A natural analogue for copper waste canisters: The copper-uranium mineralised concretions in the Permian mudrocks of south Devon, United Kingdom**. SKB TR 00-11, Svensk Kärnbränslehantering AB.

7.2 Field experiments

Although all experiments lack the geological time perspective, field experiments, for instance in underground research laboratories, have an advantage over normal laboratory experiments on radionuclide transport in that they must learn to deal with natural heterogeneity and complexity. That is, in fact, the point – to simulate actual conditions in and around an underground repository. In the context of the present report, no attempt is made to treat this theme exhaustively, since it is more relevant to performance assessment. However, it is an important corollary to natural analogue research, and SKB is, and has been, heavily involved in this type of research from the earliest days.

The earliest “*in situ*” migration experiments were carried out on the site of the nuclear research facility at Studsvik (*Landström et al 1977, Landström et al 1978, Klockars et al 1980, Landström 1980, Klockars et al 1982, Landström et al 1983*). Later, parts of the underground laboratories at Stripa and Äspö were used for similar field experiments, within projects with international participation. Experimentation started in tunnels driven from various levels of the Stripa mine (Section 6.2) in the 1980s, particularly aimed at understanding the processes of matrix diffusion (*Birgersson & Neretnieks 1988*) and tracer migration on single fractures and in 3D fracture networks

(*Abelin et al 1985, Abelin et al 1987, Herbert & Lanyon 1992, Birgersson et al 1992b,1992c, Long & Karasaki 1992, Hodgkinson & Cooper 1992a,1992b*). More sophisticated experiments are at present underway, organized as international collaborative projects managed by SKB, in the Äspö HRL (Section 6.3). The first of these projects, TRUE-1 (Tracer Retention Understanding Experiments, Stage 1) has recently been completed (*Winberg (ed.) 1996, Winberg et al 2000, SKB 2001b*), whilst two other major experiments related to radionuclide transport are at present underway, the TRUE Block Scale and the Long-Term Diffusion experiments (*Winberg 1996b, Byegård et al 1999,* see *SKB 2000d*). Many of the theses cited under hydrogeochemistry (Section 5.2) contain results from field experiments relevant to radionuclide transport in the geosphere.

Studsvik

Landström, O., Klockars, C.-E., Holmberg, K.-E., Westerberg, S., 1977. **Fältförsök rörande spårämnens transport med grundvatten i sprickförande berggrund.** PRAV, Rapport 4.7.

Landström, O., Klockars, C.-E., Holmberg, K.-E., Westerberg, S., 1978. **In situ experiments on nuclide migration in fractured crystalline rocks.** SKBF/KBS TR 110, Svensk Kärnbränsleförsörjning AB.

Klockars, C.-E., Persson, O., Carlsson, L., Duran, O., Lindström, D., Magnusson, K.-Å., Scherman, S., 1980. **Preparatory hydrogeologic investigations for in situ migration experiments in Studsvik.** PRAV, Rapport 4.17.

Landström, O., 1980. **Preparatory work on in situ migration experiments at Studsvik.** PRAV, Rapport 4.18

Klockars, C.-E., Persson, O., Landström, O., 1982. **The hydraulic properties of fracture zones and tracer tests with non-reactive elements at Studsvik.** SKBF/KBS TR 82-10, Svensk Kärnbränsleförsörjning AB.

Landström, O., Klockars, C.-E., Persson, O., Tullborg, E.-L., Larson, S.-Å., Andersson, K., Allard, B., Torstenfelt, B., 1983. **Migration experiments at Studsvik.** SKBF/KBS TR 83-18, Svensk Kärnbränsleförsörjning AB.

Stripa

Birgersson, L., Neretnieks, I., 1988. **Diffusion in the matrix of granitic rock. Field test in the Stripa mine. Final report.** SKB TR 88-08, Svensk Kärnbränslehantering AB.

Abelin, H., Neretnieks, I., Tunbrant, S., Moreno, L., 1985. **Final report of the migration in a single fracture – Experimental results and evaluation.** SKB TR 85-03, Svensk Kärnbränslehantering AB.

Abelin, H., Birgersson, L., Gidlund, J., Moreno, L., Neretnieks, I., Widén, H., Ågren, T., 1987. **3-D migration experiment – Report 3. Performed experiments, results and evaluation.** SKB TR 87-21, Svensk Kärnbränslehantering AB.

Herbert, A.W., Lanyon, G.W., 1992. **Modelling tracer transport in fractured rock at Stripa.** SKB TR 92-01, Svensk Kärnbränslehantering AB.

Birgersson, L., Widén, H., Ågren, T., Neretnieks, I., Moreno, L., 1992b. **Site characterisation and validation – Tracer migration experiment in the validation drift. Part 1: Performed experiments, results and evaluation**. SKB TR 92-03, Svensk Kärnbränslehantering AB.

Birgersson, L., Widén, H., Ågren, T., Neretnieks, I., 1992c. **Tracer migration experiments in the Stripa mine 1980–1991**. SKB TR 92-25, Svensk Kärnbränslehantering AB.

Long, J., Karasaki, K., 1992. **Simulation of tracer transport for the site characterisation and validation site in the Stripa mine.** SKB TR 92-06, Svensk Kärnbränslehantering AB.

Hodgkinson, D.P., Cooper, N.S., 1992a. **A comparison of measurements and calculations for the Stripa Validation Drift Inflow Experiment**. SKB TR 92-07, Svensk Kärnbränslehantering AB.

Hodgkinson, D.P., Cooper, N.S., 1992b. **A comparison of measurements and calculations for the Stripa tracer experiments**. SKB TR 92-20, Svensk Kärnbränslehantering AB.

Äspö HRL

Winberg, A. (ed.), 1996. **The first TRUE stage Tracer Retention Understanding Experiments. Descriptive structural-hydraulic models on block and detailed scales of the TRUE-1 site**. SKB ICR 96-04, Svensk Kärnbränslehantering AB.

Winberg, A., Andersson, P., Hermanson, J., Byegård, J., Cvetkovic, V., Birgersson, L., 2000. **Äspö Hard Rock Laboratory. Final report of the first stage of the tracer retention understanding experiments**. SKB TR 00-07, Svensk Kärnbränslehantering AB.

SKB 2001b**. First TRUE Stage – Transport of solutes in an interpreted single fracture.** Proceedings from the 4th International Seminar, Äspö, September 9–11, 2000. SKB TR-01-16, Svensk Kärnbränslehantering AB.

Winberg, A., 1996b. **Tracer Retention Understanding Experiments (TRUE). Test plan for the TRUE Block Scale experiment**. SKB ICR 97-02, Svensk Kärnbränslehantering AB.

Byegård, J., Johansson, J., Andersson, P., Hansson, K., Winberg, A., 1999: **Test plan for the long-term diffusion experiment.** SKB IPR 99-36, Svensk Kärnbränslehantering AB.

SKB 2000d. **Äspö Hard Rock Laboratory. Annual Report 1999**. SKB TR 00-10, Svensk Kärnbränslehantering AB.

8 SKB's siting programme

Under this theme, we draw together all the material which is directly related to the siting process, i.e. the process of screening and selection of favourable sites for KBS-3-type repositories in Sweden. Although this process must take into account a whole spectrum of non-geoscientific considerations, there is general agreement that screening in the first instance must be based on attempting to identify favourable geoscientific conditions, using the presently available data on the geology of Swedish bedrock. This data, and the expertise to synthesize and interpret it, mainly lies with the Geological Survey of Sweden (SGU), and the work documented in this Chapter was mainly carried out by SGU, under contract to SKB. The siting programme studies fall naturally into three groups:

Section 8.1: Country-wide and regional studies

The main emphasis here is on the numerous syntheses of different types of data, covering large parts of the country, which SKB has sponsored since the early days in connection with the siting process. These are grouped under three headings corresponding to the three phases of the history of siting efforts in Sweden, as outlined below. A key document in this category, however, is not the result of an SKB contract, but rather of the need to synthesize country-wide geoscientific data for all types of societal activity. It is the volume "Berg och jord" (in the English version, "Geology") of the Swedish National Atlas (*Fredén (ed.) 1994*), which was mainly written by geoscientists from SGU and Swedish academic institutions. This superb compilation laid a solid foundation for the later feasibility studies (Länsstudier and Förstudier, see below), which had been lacking during the earlier phases of the siting process.

Section 8.2: "Länsstudier" (feasibility studies at county scale)

After the publication of the SNA "Berg och jord" volume (*Fredén (ed.) 1994*), and SKB's own national overview report (*SKB 1995b*), SGU was contracted to carry out problem-oriented compilations of bedrock conditions in each Swedish "county" (called "län" in Swedish). These desk studies were called "Länsstudier", which can best be described as: feasibility studies at county scale, and were completed between 1997 and 1999.

Section 8.3: "Förstudier" (feasibility studies at municipality scale)

Partly before, partly parallel with, and partly after completion of the Länsstudier, SGU was also involved in the compilation of geoscientific data in those municipalities which consented to be considered as potential hosts for a KBS-3-type repository. The aim was to defining area within the municipal boundaries which, from a geoscientific viewpoint, would be most favourable for carrying out detailed studies with respect to siting a deep repository. These problem-oriented desk studies, followed by field control of the areas selected by SKB on the basis of primarily geological and environmental considerations, were called "Förstudier" (literally "pre-studies"), which can best be described as: feasibility studies at municipality scale. The Förstudier were carried out between 1993 and

2000. In the list below, the order of the municipalities is chronological, according to when the feasibility study was initiated.

Fredén, C. (ed.), 1994. **Berg och jord**. Sveriges Nationalatlas.

SKB 1995b. **General Siting Study 95 – Siting of a deep repository for spent nuclear fuel.** SKB TR 95-34, Svensk Kärnbränslehantering AB.

8.1 Country-wide and regional studies

At the national level, the search for suitable KBS-3-type repository sites can be regarded as taking place in three phases:

Phase 1: mid-1970s to 1985

Nuclear power and its future became one of the main political themes in the mid 1970s. In 1977, the "Stipulation Law" was passed, which coupled the further development of nuclear power to the demonstration of how and where "an absolutely safe final storage of high level waste – – – can be effected". As a consequence, the forerunner of SKB initiated the KBS project, the first results being published in December 1977 (KBS-1) and June 1978 (KBS-2), with the results of additional geological investigations published in February 1979 (KBS-Supplement). Some of this geological work was aimed at synthesizing geoscientific data on a national scale as a preliminary to screening the country for suitable repository sites (e.g. *Kulhánek & Wahlström 1977, Röshoff & Lagerlund 1977, Larsson et al 1977, Flodén 1977, Bergman 1977, Scherman 1978*).

KBS-1 and KBS-Supplement were used to support licence applications for subsequent nuclear reactors, starting with Ringhals 3. But controversy continued, compounded by an international review which came to the conclusion that a suitable site could probably be found, but that it had not yet been identified. At the same time, preliminary work relevant to siting was continuing, and studies in varying degrees of detail were carried out at several sites by various bodies (AKA, PRAV, KBS). This work, however, tended to provoke local nuclear opposition and helped to create the polarized atmosphere which culminated in the 1984 referendum on the future of nuclear power in Sweden. Nevertheless, the geoscientific work carried out in this period and contributed to the KBS-3 report, which was completed in May 1983 and laid the basis for the present programme. In 1985, radioactive waste management in Sweden was reorganised, resulting in the founding of SKB. From that point on, all work related to radioactive waste disposal was collected under one roof and there was a clear separation between SKB, as the implementing organization, and governmental control bodies (SKI, SSI, etc.), as the regulators.

Phase 2: 1985–1992

The siting concept which had evolved during the earlier years, and which was embedded in KBS-3, was that Sweden could be subdivided into geological provinces which were more favourable or less favourable for a deep KBS-3-type repository. The provinces which were considered less favourable were those in which the basement was covered by thick sedimentary sequences (Gotland, Skåne), those in which it was involved in intensive, especially geological young, faulting (Skåne), and dominated by Caledonian nappes (Fjällregionen). A consensus developed that these should be excluded from further consideration. This left the Precambrian basement complex of the Baltic Shield, a vast area of "crystalline rocks" (plutonic and high-grade metamorphic rocks, see Chapter 2), as potentially suitable for a deep repository. Phase 2 is characterised by the detailed investigation of individual study sites at different locations within this basement complex, as detailed in Chapter 6. Final reports on all investigations which had been carried out at six of the study sites were published in 1991–1992 (see Section 6.1). In addition, there was eventually a large amount of problem-oriented information from several other localities – Studsvik, Svartboberget, Forsmark, Ävrö, Laxemar, Kråkemåla, etc.. The main importance of the results from all these sites is that they consider not only surface conditions but also – and primarily – conditions at repository depth (several hundred meters below the surface). At the same time, the lack of clarity of the early period was removed – it was specifically stated that none of these localities were under consideration as a potential repository site. It was emphasised that the investigations were purely for testing and developing techniques, equipment, concepts, assessment methods, etc. (see SKB Annual Reports 1985–1990).

In addition to the work at the SKB study sites and at Stripa and Äspö (Chapter 6), country-wide surveys of relevant data continued to be commissioned and published in the Technical Report series, as listed below (e.g. *Nordström & Puigdomènech 1986, Kornfält & Larsson 1987, Slunga & Nordgren 1987, Röshoff 1989a, Pettersson et al 1990, Slunga 1990. Muir-Wood 1993, Laaksoharju et al 1993*).

Phase 3: 1992 onwards

Did the KBS-3 concept "stand up to the test" at the study sites? SKB maintains that it did, for instance, in the following quote from the R&D plan published in 1992 (*SKB 1992b*, p.67):

"De flesta av de undersökta områdena duger förmodligen för ett djupförvar, men det finns skillnader som gör områdena mer eller mindre lämpliga. En viktig observation är att lämpliga, resp. mindre lämpliga, områden inte kan hänföras till någon speciell landsdel eller någon speciell geologisk miljö. I stället är det de lokala förhållandena i området, och i den omgivande regionen, som avgör ett områdes lämplighet."

In a supplementary study to the 1992 R&D programme (*SKB 1994*), which had been requested by the Government, SKB specified in detail the planned scope and content of the siting programme, including the technical and other requirements on which site selection would be based. This strategy was later accepted by the Government and has since been the basis of the siting process in Sweden.

The siting strategy which has been followed since1992 uses the conclusion quoted above, which is essentially geoscientific in nature, as its basic premise. The starting point is that nowhere within the Swedish Precambrian basement province can be excluded from consideration on general grounds, and that there is no way of distinguishing more favourable and less favourable areas without carrying out local investigations (feasibility studies). This standpoint was qualified by two general exclusion criteria within the Precambrian basement at the national scale: the avoidance of major deformation zones, and the avoidance of areas judged to be of high ore potential, criteria were also applied at the county and municipality scales (Sections 8.2 and 8.3). However, these do not affect the basic rationale behind SKB's "strategy of consent". Local acceptance and local cooperation at the municipal level was taken as a prerequisite for carrying out a feasibility study.

In addition to the SGU compilation in SNA "Berg och jord" (*Fredén (ed.) 1994,* see also *Stephens et al 1994*), the most important report in Phase 3 is the 1995 General Siting Study (*SKB 1995b*), together with the later comparison of siting factors in inland v. coastal and northern v. southern areas (*Leijon 1998*), against the background of a more general review (*McEwen & Balch 1993*). Otherwise, regional and country-wide studies and compilations of relevant data were continuously carried out in connection with specific problems or knowledge gaps. They concern mainly tectonic conditions (*Larsson & Tullborg 1993, Wannäs & Flodén 1994, Muir-Wood 1995, Eriksson & Isaksson 1995, Scherneck et al 1996, Milnes et al 1998*), rock stresses (*Ljunggren & Persson 1995*), and geothermal conditions (*Sundberg 1995, Ahlbom et al 1995*).

During Phase 3, work started on the feasibility studies (Sections 8.2 and 8.3), according to the new siting strategy. At the same time, the development of a definitive set of geoscientific suitability indicators, criteria and requirements began (*Andersson et al 1997, Ström et al 1998, 1999, Andersson et al 2000a, 2000b, SKB 2000k, 2000l*), These were eventually applied to the evaluation of the potentially favourable areas identified in the Förstudie, although the final decisions were based also on non-geoscientific criteria (see Section 8.3).

Phase 1

Kulhánek, O., Wahlström, R., 1977. **Earthquakes of Sweden 1891–1957, 1963–1972.** SKBF/KBS TR 21, Svensk Kärnbränsleförsörjning AB.

Röshoff, K., Lagerlund, E., 1977. **Tektonisk analys av södra Sverige. Vättern – Norra Skåne.** SKBF/KBS TR 20, Svensk Kärnbränsleförsörjning AB.

Larsson, I., Lundgren, T., Wiklander, U., 1977. **Blekinge kustgnejs. Geologi och hydrogeologi.** SKBF/KBS TR 25, Svensk Kärnbränsleförsörjning AB.

Flodén, T., 1977. **Tectonic lineaments in the Baltic from Gävle to Simrishamn.** SKBF/KBS TR 59, Svensk Kärnbränsleförsörjning AB.

Bergman, S.G.A., 1977. **Spänningsmätingar i skandinavisk berggrund – förutsättningar, resultat och tolkning.** SKBF/KBS TR 64, Svensk Kärnbränsleförsörjning AB.

Scherman, S., 1978. **Förarbeten till platsval, berggrundsundersökningar.** SKBF/KBS TR 60, Svensk Kärnbränsleförsörjning AB.

Phase 2

Nordstrom, D K., Puigdomènech, I., 1986. **Redox chemistry of deep groundwaters in Sweden.** SKBF/SKB TR 86-03, Svensk Kärnbränsleförsörjning AB.

Kornfält, K.-A., Larsson, K., 1987. **Geological maps and cross-sections of Southern Sweden.** SKBF/SKB TR 87-24, Svensk Kärnbränsleförsörjning AB.

Slunga, R., Nordgren, L., 1987. **Earthquake measurements in southern Sweden, Oct 1, 1986–Mar 31, 1987.** SKB TR 87-27, Svensk Kärnbränslehantering AB.

Röshoff, K., 1989a. **Characterisation of the morphology, basement rock and tectonics in Sweden**. SKB TR 89-03, Svensk Kärnbränslehantering AB.

Pettersson, C., Ephraim, J., Allard, B., Borén, H., 1990. **Characterisation of humic substances from deep groundwaters in granitic bedrock in Sweden.** SKB TR 90-29, Svensk Kärnbränslehantering AB.

Slunga, R., 1989. **The earthquakes of the Baltic shield.** SKB TR 90-30, Svensk Kärnbränslehantering AB.

Muir-Wood, R., 1993. **A review of the seismotectonics of Sweden.** SKB TR 93-13, Svensk Kärnbränslehantering AB.

Laaksoharju, M., Smellie, J.A.T., Ruotsalainen, P., Snellman, M.V., 1993. **An approach to quality classification of deep groundwaters in Sweden and Finland.** SKB TR 93-27, Svensk Kärnbränslehantering AB.

Phase 3

SKB 1992b. **FUD-Program 92. Kärnkraftavfallets behandling och slutförvaring.** Svensk Kärnbränslehantering AB.

SKB 1994. **FUD-Program 92. Kompletterande Redovisning.** Svensk Kärnbränslehantering AB.

Fredén, C. (ed.), 1994. **Berg och jord**. Sveriges Nationalatlas.

Stephens, M.B., Wahlgren, C.-H., Weihed, P., 1994. **Geological map of Sweden, scale 1:3 million.** Geological Survey of Sweden, Series Ba, 52.

SKB 1995b. **General Siting Study 95 – Siting of a deep repository for spent nuclear fuel.** SKB TR 95-34, Svensk Kärnbränslehantering AB.

Leijon, B., 1998. **Nord-syd/Kust/inland. Generella skillnader i förutsättningar för lokalisering av djupförvar mellan olika delar av Sverige.** Svensk Kärnbränslehantering AB, Rapport SKB R-98-16.

McEwen, T., Balch, C., 1993. **Review of the status of siting radioactive waste repositories.** SKB PR 44-93-001, Svensk Kärnbränslehantering AB.

Larson, S.Å., Tullborg, E.-L., 1993. **Tectonic regimes in the Baltic Shield during the last 1200 Ma – A review.** SKB TR 94-05, Svensk Kärnbränslehantering AB.

Wannäs, K.O., Flodén, T., 1994. **Tectonic framework of the Hanö Bay area, southern Baltic Sea.** SKB TR 94-09, Svensk Kärnbränslehantering AB.

Muir-Wood, R., 1995. **Reconstructing the tectonic history of Fennoscandia from its margins: The past 100 million years.** SKB TR 95-36, Svensk Kärnbränslehantering AB.

Eriksson, P., Isaksson, H., 1995. **Översiktsstudier. Texturanalys av flygmagnetiska data i Sverige.** SKB PR D-95-010, Svensk Kärnbränslehantering AB.

Scherneck, H.-G., Johansson, J.M., Elgered, G., 1996. **Application of space geodetic techniques for the determination of intraplate deformations and movements in relation with the postglacial rebound of Fennoscandia.** SKB TR 96-19, Svensk Kärnbränslehantering AB.

Milnes, A.G., Gee, D.G., Lund, C.-E., 1998. **Crustal structure and regional tectonics of SE Sweden and the Baltic Sea.** SKB TR 98-21, Svensk Kärnbränslehantering AB.

Ljunggren, C., Persson, M., 1995. **Beskrivning av databas – Bergspänningsmätningar i Sverige.** SKB PR D-95-017, Svensk Kärnbränslehantering AB.

Sundberg. J., 1995. **Termiska egenskaper för kristallint berg i Sverige – Kartor över värmekonduktivitet, värmeflöde och temperatur på 500 m djup.** SKB PR D-95-018, Svensk Kärnbränslehantering AB.

Ahlbom, K., Olsson, O., Sehlstedt, S., 1995. **Temperature conditions in the SKB study sites.** SKB TR 95-16, Svensk Kärnbränslehantering AB.

Andersson, J., Almén, K.-E., Ericsson, L.O., Frederiksson, A., Karlsson, F., Stanfors, R., Ström, A., 1997. **Parametrar att bestämma vid geovetenskaplig platsundersökning.** SKB R-97-03, Svensk Kärnbränslehantering AB.

Ström, A., Almén, K.-E., Andersson, J., Ericsson, L.O., Svemar, C., 1998. **Geovetenskapliga värderingsfaktorer och kriterier för lokalisering och platsutvärdering. Lägesredovisning.** SKB R-98-20, Svensk Kärnbränslehantering AB.

Ström, A., Almén, K.-E., Ericsson, L.O., Svemar, C., 1999. **Geoscientific evaluation factors and criteria for siting and site evaluation.** SKB R-99-07, Svensk Kärnbränslehantering AB.

Andersson, J., Ström, A., Svemar, C., Almén, K.-E., Ericsson, L.O., 2000a. **Vilka krav ställer djupförvaret på berget? Geovetenskapliga lämplighetsindikatorer och kriterier för lokalisering och platsvärdering.** SKB R-00-15, Svensk Kärnbränslehantering AB.

Andersson, J., Ström, A., Svemar, C., Almén, K.-E., Ericsson, L.O., 2000b. **What requirements does a KBS-3 repository make on the host rock? Geoscientific suitability indicators and criteria for siting and site evaluation.** SKB TR 00-12, Svensk Kärnbränslehantering AB.

SKB 2000k. **Geovetenskapligt inriktat program för undersökning och utvärdering av platser för djupförvaret.** SKB R-00-30, Svensk Kärnbränslehantering AB.

SKB 2000l. **Geoscientific programme for investigation and evaluation of sites for the deep repository.** SKB TR 00-20, Svensk Kärnbränslehantering AB.

8.2 ”Länsstudier” (feasibility studies at county scale)

SGU geoscientists carried out the work of compiling the data for the Länsstudier during 1997 and 1998. This resulted first in a series of reports dealing with the counties adjoining the east coast, published in late 1998, and then a second series encompassing the remaining counties, published in mid-1999. As noted above, the Länsstudier were focussed on a particular problem, the search for a deep repository for spent nuclear fuel, and culminated in an assessment of which areas within the Precambrian basement were considered “favourable for further investigation” or “less favourable for further investigation” in every county in Sweden.

Because of their problem-orientated focus, the Länsstudier have made a valuable contribution to the geoscientific background material for the siting process. It is important to note, however, that they are desk studies. They are built on a broad and solid foundation of data, much of it publicly available as SGU maps and reports before the Länsstudier were started. As emphasised above, national coverage of Swedish geoscience is provided in the volume “Berg och Jord” in Sveriges Nationalatlas, written by SGU and other Swedish researchers (*Fredén (ed.) 1994*). This was published in 1994, and formed one of the main sources for the material presented in SKB's General Siting Study (*SKB 1995b*). Additionally, hydrogeological maps, bedrock maps and explanatory texts existed for many of the counties, normally at scales of 1:200,000 or 1:250,000, before the siting process started in 1992. These are sometimes more detailed than the ones used in the Länsstudier (which are often copies of the relevant parts of the Geological Map of Sweden 1:1 250 000, from *Fredén (ed.) 1994*). With the exception of Norrbotten and Västerbotten, they were all published in the 1980s and early1990s.

It is important to note, however, that the Länsstudier made accessible a considerable amount of information which had previously been available only as raw data. Much background material appeared in them for the first time and cannot be easily extracted from earlier documentation. The problem in focus raised new questions which required new answers, new ways of looking at the available data, and new compilations. These include the following:

- An up-to-date view of geological map coverage and the area covered by aerial geophysics, including on-going work (Fig. 2 in each Länsstudie).
- The definition of areas of high ore potential (Fig. 10 in each Länsstudier), i.e. areas to be avoided because of conflicts of interest and the possibility of future human intrusion.
- A structural map showing the extent of brittle and ductile deformation zones (Fig. 13 in each Länsstudie), to be avoided because of presumed adverse underground conditions.
- A synthesis of hydrological data from wells penetrating bedrock, the data being stored in SGU's extensive well archive (Fig. 21 or 22 or 23, in different Länsstudier), showing variations in bedrock permeability.
- Compilations of available data on the thickness of the Quaternary deposits in each county (i.e. depth to bedrock), and on the chemistry of bedrock groundwaters.

An excellent summary of the main results of the Länstudier and the Förstudie (Section 8.3) from a geological point of view is given in *Stephens & Bergman 1999.*

The citations below are geographically arranged, from north to south.

Northern Sweden: Norrbotten (*Bergman et al 1998b*), Västerbotten (*Antal et al 1998i*), Jämtland (*Antal et al 1999b*), Västernorrland (*Antal et al 1998h*), Dalarna (*Gierup et al 1999c*), Gävleborg (*Antal et al 1998g*).

Central Sweden: Värmland (*Fredén et al 1999*), Örebro (*Bergman et al 1999d*), Västmanland (*Bergman et al 1999e*), Uppsala (*Antal et al 1998f*), Västra Götaland (*Antal et al 1999c*), Östergötland (*Antal et al 1998c*), Södermanland (*Antal et al 1998d*), Stockholm (*Antal et al 1998e*).

Southern Sweden: Halland (*Antal et al 1999a*), Jönköping (*Gierup et al 1999d*), Kalmar (*Antal et al 1998b*), Skåne (*Gierup et al 1999b*), Kronoberg (*Gierup et al 1999a*), Blekinge (*Antal et al 1998a*).

Many of the Länsstudier reports form the most convenient source for information on the regional geological setting of the SKB study sites (Section 6.1) and the Förstudie municipalities (Section 8.3), as indicated under each site/municipality.

Fredén, C. (ed.), 1994. **Berg och jord**. Sveriges Nationalatlas.

SKB 1995b. **General Siting Study 95 – Siting of a deep repository for spent nuclear fuel.** SKB TR 95-34, Svensk Kärnbränslehantering AB.

Stephens, M.B., Bergman, T., 1999. **På spaning efter en plats för djupförvar av använt kärnbränsle**. Geologisk forum, 23, 13–17.

Northern Sweden

Bergman, S., Gierup, J., Kübler, L., Lagerbäck, R., Thunholm, B., Stephens, M., Johansson, R., 1998b. **Översiktsstudie av Norrbottens län. Geologiska förutsättningar.** SKB R-98-40, Svensk Kärnbränslehantering AB.

Antal, I., Stølen, L.K., Sundh, M., Thunholm, B., Åsman, M., Stephens, M., Johansson, R., 1998i. **Översiktsstudie av Västerbottens län. Geologiska förutsättningar.** SKB R-98-38, Svensk Kärnbränslehantering AB.

Antal, I., Bergman, S., Fredén, C., Gierup, J., Stølen, L.K., Thunholm, B., Stephens, M., Johansson, R., 1999b. **Översiktsstudie av Jämtlands län (urbergsdelen). Geologiska förutsättningar.** SKB R-99-25, Svensk Kärnbränslehantering AB.

Antal, I., Fredén, C., Gierup, J., Stølen, L.K., Thunholm, B., Stephens, M., Johansson, R., 1998h: **Översiktsstudie av Västernorrlands län. Geologiska förutsättningar.** SKB R-98-36, Svensk Kärnbränslehantering AB.

Gierup, J., Kübler, L., Lindén, A., Ripa, M., Stephens, M., Stølen, L.K., Thunholm, B. Johansson, R., 1999c. **Översiktsstudie av Dalarnas län (urbergsdelen). Geologiska förutsättningar.** SKB R-99-29, Svensk Kärnbränslehantering AB.

Antal, I., Bergman, S., Fredén, C., Gierup, J., Thunholm, B., Stephens, M., Johansson, R., 1998g. **Översiktsstudie av Gävleborgs län. Geologiska förutsättningar.** SKB R-98-34, Svensk Kärnbränslehantering AB.

Central Sweden

Fredén, C., Gierup, J., Johansson, R., Stølen, L.K., Thunholm, B., Wahlgren, C.-H., Stephens, M., 1999. **Översiktsstudie av Värmlands län. Geologiska förutsättningar.** SKB R-99-21, Svensk Kärnbränslehantering AB.

Bergman, T., Fredén, C., Gierup, J., Kübler, L., Stephens, M., Stølen, L.K., Thunholm, B., Johansson, R., 1999d. **Översiktsstudie av Örebro län. Geologiska förutsättningar.** SKB R-99-23, Svensk Kärnbränslehantering AB.

Bergman, T., Gierup, J., Kübler, L., Lindén, A., Stephens, M., Stølen, L.K., Thunholm, B., Johansson, R., 1999e. **Översiktsstudie av Västmanlands län. Geologiska förutsättningar.** SKB R-99-31, Svensk Kärnbränslehantering AB.

Antal, I., Bergman, S., Gierup, J., Persson, C., Thunholm, B., Stephens, M., Johansson, R., 1998f. **Översiktsstudie av Uppsala län. Geologiska förutsättningar.** SKB R-98-32, Svensk Kärnbränslehantering AB.

Antal, I., Berglund, J., Eliasson, T., Gierup, J., Hilldén, A., Stølen, L.K., Thunholm, B., Stephens, M., Johansson, R., 1999c. **Översiktsstudie av västra Götalands län. Geologiska förutsättningar.** SKB R-99-33, Svensk Kärnbränslehantering AB.

Antal, I., Bergman, T., Gierup, J., Lindén, A., Stephens, M., Thunholm, B., Johansson, R., 1998c. **Översiktsstudie av Östergötlands län. Geologiska förutsättningar.** SKB R-98-26, Svensk Kärnbränslehantering AB.

Antal, I., Bergman, T., Persson, C., Stephens, M., Thunholm, B., Åsman, M., Johansson, R., 1998d. **Översiktsstudie av Södermanlands län. Geologiska förutsättningar.** SKB R-98-28, Svensk Kärnbränslehantering AB.

Antal, I., Bergman, T., Persson, C., Stephens, M., Thunholm, B., Åsman, M., Johansson, R., 1998e. **Översiktsstudie av Stockholms län. Geologiska förutsättningar.** SKB R-98-30, Svensk Kärnbränslehantering AB.

Southern Sweden

Antal, I., Berglund, J., Gierup, J., Lundqvist, I., Påsse, T., Stølen, L.K., Thunholm, B., Stephens, M., Johansson, R., 1999a. **Översiktsstudie av Hallands län. Geologiska förutsättningar.** SKB R-99-17, Svensk Kärnbränslehantering AB.

Gierup, J., Johansson, R., Pamnert, M., Persson, M., Thunholm, B., Wahlgren, C.-H., Wikman, H., Stephens, M., Johansson, R., 1999d. **Översiktsstudie av Jönköpings län. Geologiska förutsättningar.** SKB R-99-35, Svensk Kärnbränslehantering AB.

Antal, I., Bergman, T., Gierup, J., Rudmark, L., Thunholm, B., Wahlgren, C.-H., Stephens, M., Johansson, R., 1998b. **Översiktsstudie av Kalmar län. Geologiska förutsättningar.** SKB R-98-24, Svensk Kärnbränslehantering AB.

Gierup, J., Kübler, L., Pamnert, M., Persson, M., Thunholm, B., Wahlgren, C.-H., Wikman, H., Stephens, M., Johansson, R., 1999b. **Översiktsstudie av Skåne län (urbergsdelen). Geologiska förutsättningar.** SKB R-99-27, Svensk Kärnbränslehantering AB.

Gierup, J., Johansson, R., Persson, M., Stølen, L.K., Thunholm, B., Wahlgren, C.-H., Wikman, H., Stephens, M., 1999a. **Översiktsstudie av Kronobergs län. Geologiska förutsättningar.** SKB R-99-19, Svensk Kärnbränslehantering AB.

Antal, I., Bergman, T., Gierup, J., Persson, M., Thunholm, B., Wahlgren, C.-H., Stephens, M., Johansson, R., 1998a. **Översiktsstudie av Blekinge län. Geologiska förutsättningar.** SKB R-98-22, Svensk Kärnbränslehantering AB.

8.3 ”Förstudier” (feasibility studies at municipality scale)

As pointed out above, SKB has taken as its starting point for site selection that no location within the Swedish Precambrian basement, with the exception of those defined in the General Siting Study (see Section 8.1), can be excluded from consideration on general grounds, and that there is no way of distinguishing more favourable and less favourable areas without carrying out local investigations. The necessity of local investigations is also emphasized by SGU in the Länsstudier (Section 8.2). In 1992, SKB decided that these local investigations, called Förstudier (feasibility studies at municipality scale, aimed at compiling and assessing all pre-existing information), would only be carried out if there existed “a mutual interest from the municipality and SKB to study the issue further" (SKB Annual Report 1992, p. 85). Within such feasibility studies, the investigations would include, in addition to geoscientific data compilations and evaluations, all environmental and societal aspects of importance for siting, such as land use, nature conservancy, transport, tourism, industrial development, etc., and they would be carried out in close interaction with the local population and other interested parties. Subsequently, between 1993 and 2000, eight Förstudier were completed. In two of the municipalities concerned, Storuman and Malå, decisions were made, by local referendum after the Förstudier had been completed, not to allow further investigation. For the remaining six municipalities, Nyköping, Östhammar, Oskarshamn, Tierp, Älvkarleby, and Hultsfred, SKB compiled all information and conducted an integrated evaluation of siting alternatives that had been preliminary identified. In November 2000, SKB presented a number of sites which were judged promising enough to justify site investigations, and suggested that three of them should be retained for such investigations. After comprehensive review organised by the safety authorities, SKB's proposal was approved by the government. Following this, the municipalities concerned (Östhammar, Oskarshamn, Tierp and Älvkarleby) are to decide on whether or not they accept site investigations.

In the following, the final reports and the geoscientific background documentation of each feasibility study are listed. After Storuman and Malå, the background reports were structured similarly and themes which appeared as separate reports in the first two became combined into two or three main geoscientific documents, with the following content:

1) Quaternary deposits, bedrock geology and deformation zones.
2) Groundwater flow and chemistry, including possible long-term changes.
3) Ores and minerals (in later studies included in 1)).
4) Engineering geology experience in the municipality (later included in a background report on construction and transport, not cited here).
5) Reports on special subjects (different from municipality to municipality).

After the geoscientific background reports and the accompanying reports on environmental and societal aspects had been completed, SKB published a preliminary evaluation ("Preliminär slutrapport") in which the areas within the municipality which were considered most favourable for further investigation were defined. The procedure followed was, first, to define the areas most favourable from a purely geoscientific point of view (based on the reports listed here), and then, to use the results of the environmental/societal studies (not cited here) to prioritise them or exclude them. The result was a provisional definition of so-called candidate areas within the municipality.

After the publication of the "Preliminär slutrapport", two further activities took place: (1) a period of field work in the candidate areas to check that the geoscientific conclusions reached in the desk studies were valid – this was documented immediately afterwards in a report on "Kompletterande arbeten", (2) intensive discussions between SKB and the interested parties in the municipality (politicians, civil servants, general public) on all problems arising out of the preliminary conclusions. In some cases, the "Preliminär slutrapport" was also subjected to independent review, on the initiative of the municipalities, by review groups recruited from Swedish academic institutions and other organizations. The results of these activities were incorporated in SKB's definitive evaluation ("Slutrapport"), which represents the final result of the feasibility study and the definition of the candidate areas most promising for further investigation. The geoscientific reports, SKB's preliminary evaluation report, the supplementary work report and SKB's final evaluation report are cited below in the sequence described here, except for Storuman and Malå, which did not follow the later established pattern. An English summary of the results of the last six Förstudier has been published as a SKB Technical Report (*SKB 2001a*).

In the following, the Förstudier are listed in chronological order, according to the starting date of the investigations.

SKB 2001a. **Feasibility Studies – Östhammar, Nyköping, Oskarshamn, Tierp, Hultsfred and Älvkarleby. Summary Report.** SKB TR 01-16, Svensk Kärnbränslehantering AB.

8.3.1 Storuman

The regional geological setting of Storuman municipality is given in the earliest Förstudie report (*Eliasson & Lundqvist* 1994) and in the Västerbotten Länsstudie (*Antal et al 1998i*). The geoscientific part of the feasibility study consists of reports on bedrock geology (*Lindroos 1994b*), ore potential (*Lindroos 1994a*), geophysics (*Isaksson & Johansson 1994*), Quaternary deposits (*Johansson et al 1994*) and hydrogeology (*Nyberg & Jönsson 1994, Jönsson & Nõmtak 1994a*). Special reports describe geological and hydrological data from the Juktan power station and general rock engineering experience from the area (*Axelsson et al 1994, Leijon 1994*). No preliminary evaluation report was published for Storuman, but some geological field work and re-interpretation of geophysical data was carried out (*Lindroos et al 1994*), before the final evaluation was made (*SKB 1995a*).

Eliasson, T., Lundqvist, T., 1994. **Storumans kommun i ett regional-geologiskt sammanhang.** SKB PR 44-94-003, Svensk Kärnbränslehantering AB.

Antal, I., Stølen, L.K., Sundh, M., Thunholm, B., Åsman, M., Stephens, M., Johansson, R., 1998i. **Översiktsstudie av Västerbottens län. Geologiska förutsättningar.** SKB R-98-38, Svensk Kärnbränslehantering AB.

Lindroos, H., 1994b. **Förstudie Storuman, Beskrivning till berggrundskarta över urberget i Storumans kommun.** SKB PR 44-94-009, Svensk Kärnbränslehantering AB.

Lindroos, H., 1994a. **Förstudie Storuman, Malmer och mineral inom Storumans kommun.** SKB PR 44-94-008, Svensk Kärnbränslehantering AB.

Isaksson, H., Johansson, R., 1994. **Förstudie Storuman, Geofysisk dokumentation och tolkning.** SKB PR 44-94-010, Svensk Kärnbränslehantering AB.

Johansson, K., Ranged, G., Rodhe, L., 1994. **Förstudie Storuman, Beskrivning till jordartskarta över Storumanområdet.** SKB PR 44-94-004, Svensk Kärnbränslehantering AB.

Nyberg, G., Jönsson, S., 1994. **Förstudie Storuman, Storumans kommun, geohydrologisk beskrivning.** SKB PR 44-94-005, Svensk Kärnbränslehantering AB.

Jönsson, R., Nömtak, V., 1994a. **Förstudie Storuman, Vattenkemiska förhållanden.** SKB PR 44-94-006, Svensk Kärnbränslehantering AB.

Axelsson, C.-L., Hansen, L., Olsson, T., 1994. **Juktans pumpkraftverk. Sammanställning av geologisk och hydrologisk information.** SKB PR 44-94-007, Svensk Kärnbränslehantering AB.

Leijon, B., 1994. **Förstudie Storuman, Bergbyggnadstekniska erfarenheter i regionalt och lokalt perspektiv.** SKB PR 44-94-011, Svensk Kärnbränslehantering AB.

Lindroos, H., Isaksson, H., Johansson, R., 1994. **Förstudie Storuman, Geologiska fältkontroller och geofysisk tolkning av intressanta områden – samlingsrapport.** SKB PR 44-94-035, Svensk Kärnbränslehantering AB.

SKB 1995a: **Feasibility study for siting of a deep repository within the Storuman municipality.** SKB TR 95-08, Svensk Kärnbränslehantering AB.

8.3.2 Malå

For the regional geological setting of Malå municipality, consult the Västerbotten Länsstudie (*Antal et al 1998i*). The geoscientific part of the feasibility study consists of reports on bedrock geology (*Lindroos 1994c*), ore potential (*Lindroos 1994d*), geophysics (*Isaksson et al 1994*), Quaternary deposits (*Ransed et al* 1994) and hydrogeology (*Jönsson & Nõmtak 1994b, Axelsson & Ekstav 1995*), together with a survey of rock engineering experience in the area (*Leijon 1995*). Only a final evaluation report was published for Malå (*SKB 1996a*).

Antal, I., Stølen, L.K., Sundh, M., Thunholm, B., Åsman, M., Stephens, M., Johansson, R., 1998i. **Översiktsstudie av Västerbottens län. Geologiska förutsättningar.** SKB R-98-38, Svensk Kärnbränslehantering AB.

Lindroos, H., 1994c. **Förstudie Malå, Beskrivning till berggrundskarta över Malå kommun.** SKB PR 44-94-027, Svensk Kärnbränslehantering AB

Lindroos, H., 1994d. **Förstudie Malå, Malmer och mineral inom Malå kommun.** SKB PR 44-94-028, Svensk Kärnbränslehantering AB.

Isaksson, H., Johansson, R., Triumf, C.-A., 1994. **Förstudie Malå, Geofysisk dokumentation och tolkning.** SKB PR 44-94-028, Svensk Kärnbränslehantering AB.

Ransed, G., Rodhe, L., Sundh, M., 1994. **Förstudie Malå, Jordarter i Malå-området.** SKB PR 44-94-030, Svensk Kärnbränslehantering AB.

Jönsson, R., Nömtak, V., 1994b. **Förstudie Malå, Vattenkemiska förhållanden.** SKB PR 44-94-031, Svensk Kärnbränslehantering AB.

Axelsson, C.-L., Ekstav, A., 1995. **Förstudie Malå. Hydrogeologisk beskrivning.** SKB PR 44-95-003, Svensk Kärnbränslehantering AB.

Leijon, B., 1995. **Förstudie Malå. Bergbyggnadstekniska data och erfarenheter.** SKB PR 44-95-011, Svensk Kärnbränslehantering AB.

SKB 1996a. **Feasibility study for siting of a deep repository within the Malå municipality.** SKB TR 96-22, Svensk Kärnbränslehantering AB.

8.3.3 Nyköping

The regional geological setting of Nyköping municipality is described in the Södermanlands Länsstudie (*Antal et al 1998d*). The geoscientific part of the feasibility study consists of reports on bedrock and Quaternary geology, with special emphasis on deformation zones (*Isaksson et al 1996*), ore potential (*Lindroos 1996a*), and hydrogeology (*Jacks et al 1996a*). Special reports consist of reports on geological information from the area surrounding industrial and nuclear research complex at Studsvik (*Bergman & Isaksson 1996*), on the possible significance of the existence of a meteorite impact crater offshore from Studsvik (*Juhlin & Tullborg 1996*), and on general rock engineering experience from the municipality (*Windelhed et al 1996*). The publication of the preliminary evaluation report (*SKB 1997a*) was followed by field control of geological conditions in the candidate areas (*Bergman et al 1999c*), before the publication of the final evaluation (*SKB 2000e*). It should be noted that the SKB study site Fjällveden (Subsection 6.1.2) lies within the municipality. An English summary of the results of the Nyköping feasibility study is given in *SKB 2001a*.

Antal, I., Bergman, T., Persson, C., Stephens, M., Thunholm, B., Åsman, M., Johansson, R., 1998d. **Översiktsstudie av Södermanlands län. Geologiska förutsättningar.** SKB R-98-28, Svensk Kärnbränslehantering AB.

Isaksson, H., Bergman, T., Johansson, R., Persson, C., Lindén, A., Stephens, M., 1996. **Förstudie Nyköping. Jordarter, bergarter och deformationszoner.** SKB PR D-96-013, Svensk Kärnbränslehantering AB.

Lindroos, H., 1996a. **Förstudie Nyköping. Malmer och mineral inom Nyköpings kommun.** SKB PR D-96-008, Svensk Kärnbränslehantering AB.

Jacks, G., Follin, S., Årebäck, M., 1996a. **Förstudie Nyköping. Grundvattnets rörelse, kemi och långsiktiga förändringar.** SKB PR D-96-014, Svensk Kärnbränslehantering AB.

Windelhed, K., Leijon, B., Ekman, L., 1996. **Förstudie Nyköping. Erfarenheter från berganläggningar i regionen samt undersökningsresultat från Björksund.** SKB PR D-96-023, Svensk Kärnbränslehantering AB.

Bergman, T., Isaksson, H., 1996. **Förstudie Nyköping. Sammanställning av geoinformation vid Studsvik.** SKB PR D-96-026, Svensk Kärnbränslehantering AB.

Juhlin, C., Tullborg, E.-L., 1996. **Förstudie Nyköping. Meteoritnedslaget i havsfjärden Tvären vid Studsvik.** SKB PR D-96-015, Svensk Kärnbränslehantering AB.

SKB 1997a. **Förstudie Nyköping. Preliminär Slutrapport**. Svensk Kärnbränslehantering AB, June 1997.

Bergman, T., Johansson, R., Lindén, A., Lundström, I., Stephens, M., Isaksson, H., 1999c. **Förstudie Nyköping. Fältkontroll av berggrunden inom potentiellt gynnsamma områden.** SKB R-99-61, Svensk Kärnbränslehantering AB.

SKB 2000e. **Förstudie Nyköping. Slutrapport**. Svensk Kärnbränslehantering AB, October 2000.

SKB 2001a. **Feasibility Studies – Östhammar, Nyköping, Oskarshamn, Tierp, Hultsfred and Älvkarleby. Summary Report.** SKB TR 01-16, Svensk Kärnbränslehantering AB.

8.3.4 Östhammar

The regional geological setting of Östhammar municipality is described in the Uppsala Länsstudie (*Antal et al 1998f*). The geoscientific part of the feasibility study consists of reports on bedrock and Quaternary geology, with special emphasis on deformation zones (*Bergman S et al 1996*), ore potential (*Lindroos 1996b*), and hydrogeology (*Jacks et al 1996b*). A special report consists of a review of general rock engineering experience from the municipality, particularly in the nearby deep mines and from core-drilling and tunnelling at the Forsmark nuclear power station and the Forsmark low active radioactive waste repository, SFR (*Bergman et al 1996*). The publication of the preliminary evaluation report (*SKB 1997b*) was followed by field control of geological conditions in the candidate areas (*Bergman et al 1998a*), before the publication of the final evaluation (*SKB 2000f*). It should be noted that the SKB study site Finnsjön, or "Beberg" (Subsection 6.1.1) lies just outside the municipal boundary. An English summary of the results of the Östhammar feasibility study is given in *SKB 2001a*.

Antal, I., Bergman, S., Gierup, J., Persson, C., Thunholm, B., Stephens, M., Johansson, R., 1998f. **Översiktsstudie av Uppsala län. Geologiska förutsättningar.** SKB R-98-32, Svensk Kärnbränslehantering AB.

Bergman, S.,Isaksson, H., Johansson, R., Lindén, A.H., Persson, C., Stephens, M., 1996. **Förstudie Östhammar. Jordarter, bergarter, och deformationszoner.** SKB PR D-96-016, Svensk Kärnbränslehantering AB.

Jacks, G., Follin, S., Årebäck, M., 1996b. **Förstudie Östhammar. Grundvattnets rörelse, kemi och långsiktiga förändringar.** SKB PR D-96-017, Svensk Kärnbränslehantering AB.

Lindroos, H., 1996b. **Förstudie Östhammar. Malmer och mineral inom Östhammars kommun.** SKB PR D-96-012, Svensk Kärnbränslehantering AB.

Bergman, T., Ekblad, L., Isaksson, H., Larsson, H., Leijon, B., 1996. **Förstudie Östhammar. Samlingsrapport avseende: bergtekniska erfarenheter i regionen, sammanställning av geoinformation vid Forsmarksverket och data från kärnborrhål KF001 vid Forsmark.** SKB PR D-96-025, Svensk Kärnbränslehantering AB.

SKB 1997b. **Förstudie Östhammar. Preliminär slutrapport**. Svensk Kärnbränslehantering AB, September 1997.

Bergman, S., Bergman, T., Johansson, R., Stephens, M., Isaksson, H., 1998a: **Förstudie Östhammar. Delprojekt jordarter, bergarter och deformationszoner. Kompletterande arbeten 1998.** SKB R-98-57, Svensk Kärnbränslehantering AB.

SKB 2000f. **Förstudie Östhammar. Slutrapport.** Svensk Kärnbränslehantering AB, October 2000.

SKB 2001a. **Feasibility Studies – Östhammar, Nyköping, Oskarshamn, Tierp, Hultsfred and Älvkarleby. Summary Report.** SKB TR 01-16, Svensk Kärnbränslehantering AB.

8.3.5 Oskarshamn

The regional geological setting of Oskarshamn municipality is described in the Kalmar Länsstudie (*Antal et al 1998b*) and the regional tectonics in *Milnes et al 1998*. The geoscientific part of the feasibility study consists of reports on bedrock and Quaternary geology, including deformation zones and ore potential (*Bergman et al 1998*), and hydrogeology (*Follin et al 1998*). Special reports consist of a detailed description of conditions in the northeastern part of the municipality, where the Äspö HRL (Section 6.3) is located (*Bergman et al 1999a*), and a review of general rock engineering experience from the municipality (*Larsson & Leijon 1999*). The publication of the preliminary evaluation report (*SKB 1999e*) was followed by field control of geological conditions in the candidate areas (*Bergman et al 2000b*), before the publication of the final evaluation (*SKB 2000g*). In addition to Äspö HRL, or "Aberg" (Section 6.3), the Kråkemåla site, Ävrö island and the Laxemar deep drillholes (Subsection 6.1.7) lie within the municipality. An English summary of the results of the Oskarshamn feasibility study is given in *SKB 2001a*.

Antal, I., Bergman, T., Gierup, J., Rudmark, L., Thunholm, B., Wahlgren, C.-H., Stephens, M., Johansson, R., 1998b. **Översiktsstudie av Kalmar län. Geologiska förutsättningar.** SKB R-98-24, Svensk Kärnbränslehantering AB.

Milnes, A.G., Gee, D.G., Lund, C.-E., 1998. **Crustal structure and regional tectonics of SE Sweden and the Baltic Sea.** SKB TR 98-21, Svensk Kärnbränslehantering AB.

Bergman, T., Johansson, R., Lindén, A.H., Lindgren, J., Rudmark, L., Wahlgren, C.-H., Isaksson, H., Lindroos, H., 1998. **Förstudie Oskarshamn. Jordarter, bergarter och deformationszoner.** SKB R-98-56, Svensk Kärnbränslehantering AB.

Follin, S., Årebäck, M., Axelsson, C.-L., Stigsson, M., Jacks, G., 1998. **Förstudie Oskarshamn. Grundvattnets rörelse, kemi och långsiktiga förändringar.** SKB R-98-55, Svensk Kärnbränslehantering AB.

Bergman, T., Johansson, R., Lindén, A.H., Rudmark, L., Wahlgren, C.-H., Follin, S., Isaksson, H., Lindroos, H., Stanfors, R., 1999a. **Förstudie Oskarshamn. Erfarenheter från geovetenskapliga undersökningar i nordöstra delen av kommunen.** SKB R-99-04, Svensk Kärnbränslehantering AB.

Larsson, H., Leijon, B., 1999. **Förstudie Oskarshamn. Bergtekniska data, erfarenheter och bedömningar.** SKB R-99-05, Svensk Kärnbränslehantering AB.

SKB 1999e. **Förstudie Oskarshamn. Preliminär Slutrapport.** Svensk Kärnbränslehantering AB, June 1999.

Bergman, T., Rudmark, L., Wahlgren, C.-H., Johansson, R., Isaksson, H., Stanfors, R., 2000b. **Förstudie Oskarshamn. Kompletterande geologiska studier.** SKB R-00-45, Svensk Kärnbränslehantering AB.

SKB 2000g. **Förstudie Oskarshamn. Slutrapport.** Svensk Kärnbränslehantering AB, December 2000.

SKB 2001a. **Feasibility Studies – Östhammar, Nyköping, Oskarshamn, Tierp, Hultsfred and Älvkarleby. Summary Report.** SKB TR 01-16, Svensk Kärnbränslehantering AB.

8.3.6 Tierp

The regional geological setting of Tierp municipality is described in the Uppsala Länsstudie (*Antal et al 1998f*). The geoscientific part of the feasibility study consists of reports on bedrock and Quaternary geology, including deformation zones and ore potential (*Bergman T et al 1999b*), and hydrogeology (*Follin et al 1999*). The publication of the preliminary evaluation report (*SKB 2000a*) was followed by field control of geological conditions in the candidate areas (*Bergman T et al 2000c*), before the publication of the final evaluation (*SKB 2000h*). It should be noted that the SKB study site Finnsjön, or "Beberg" (Subsection 6.1.1) lies within the municipality, and that the results of the feasibility study in the adjacent Östhammar (Subsection 8.3.4) provide relevant comparative material. An English summary of the results of the Tierp feasibility study is given in *SKB 2001a*.

Antal, I., Bergman, S., Gierup, J., Persson, C., Thunholm, B., Stephens, M., Johansson, R., 1998f. **Översiktsstudie av Uppsala län. Geologiska förutsättningar.** SKB R-98-32, Svensk Kärnbränslehantering AB.

Bergman, T., Johansson, R., Lindén, A.H., Rudmark, L., Stephens, M., Isaksson, H., Lindroos, H., 1999b. **Förstudie Tierp. Jordarter, bergarter och deformationszoner.** SKB R-99-53, Svensk Kärnbränslehantering AB.

Follin, S., Årebäck, M., Stigsson, M., Isgren, F., Jacks, G., 1999. **Förstudie Tierp. Grundvattnets rörelse, kemi och långsiktiga förandringar**. SKB R-99-57, Svensk Kärnbränslehantering AB.

SKB 2000a. **Förstudie Tierp. Preliminär slutrapport**. Svensk Kärnbränslehantering AB, February 2000.

Bergman, T., Johansson, R., Stephens, M., Wahlroos, J.-E., Isaksson, H., 2000c. **Förstudie Tierp och Älvkarleby. Fältkontroll av berggrunden inom potentiellt gynnsamma områden samt tyngdkrafts-modellering.** SKB R-00-47, Svensk Kärnbränslehantering AB.

SKB 2000h. **Förstudie Tierp. Slutrapport.** Svensk Kärnbränslehantering AB, December 2000.

SKB 2001a. **Feasibility Studies – Östhammar, Nyköping, Oskarshamn, Tierp, Hultsfred and Älvkarleby. Summary Report.** SKB TR 01-16, Svensk Kärnbränslehantering AB.

8.3.7 Älvkarleby

The regional geological setting of Älvkarleby municipality is described in the Uppsala Länsstudie (*Antal et al 1998f*). The geoscientific part of the feasibility study consists of reports on bedrock and Quaternary geology, including deformation zones and ore potential (*Bergman T et al 2000a*), and hydrogeology (*Axelsson et al 2000a*). The publication of the preliminary evaluation report (*SKB 2000b*) was followed by field control of geological conditions in the candidate areas (*Bergman T et al 2000c*), before the publication of the final evaluation (*SKB 2000i*). The results of the feasibility studies in the adjacent Tierp and Östhammar provide relevant comparative material. An English summary of the results of the Älvkarleby feasibility study is given in *SKB 2001a*.

Antal, I., Bergman, S., Gierup, J., Persson, C., Thunholm, B., Stephens, M., Johansson, R., 1998f. **Översiktsstudie av Uppsala län. Geologiska förutsättningar.** SKB R-98-32, Svensk Kärnbränslehantering AB.

Bergman, T., Johansson, R., Lindén, A.H., Rudmark, L., Stephens, M., Isaksson, H., Lindroos, H., 2000a. **Förstudie Älvkarleby. Jordarter, bergarter och deformationszoner.** SKB R-00-04, Svensk Kärnbränslehantering AB.

Axelsson, C.-L., Follin, S., Årebäck, M., Stigsson, M., Isgren, F., Jacks, G., 2000a. **Förstudie Älvkarleby. Grundvattnets rörelse, kemi och långsiktiga förandringar.** SKB R-00-03, Svensk Kärnbränslehantering AB.

SKB 2000b. **Förstudie Älvkarleby. Prelimnär Slutrapport.** Svensk Kärnbränslehantering AB, April 2000.

Bergman, T., Johansson, R., Stephens, M., Wahlroos, J.-E., Isaksson, H., 2000c. **Förstudie Tierp och Älvkarleby. Fältkontroll av berggrunden inom potentiellt gynnsamma områden samt tyngdkrafts-modellering.** SKB R-00-47, Svensk Kärnbränslehantering AB.

SKB 2000i. **Förstudie Älvkarleby. Slutrapport.** Svensk Kärnbränslehantering AB, December 2000.

SKB 2001a. **Feasibility Studies – Östhammar, Nyköping, Oskarshamn, Tierp, Hultsfred and Älvkarleby. Summary Report.** SKB TR 01-16, Svensk Kärnbränslehantering AB.

8.3.8 Hultsfred

The regional geological setting of Hultsfred municipality is described in the Kalmar Länsstudie (*Antal et al 1998b*) and the regional tectonic situation in *Milnes et al 1998*. The geoscientific part of the feasibility study consists of reports on bedrock and Quaternary geology, including deformation zones and ore potential (*Johansson et al 2000*), and hydrogeology (*Axelsson et al 2000b*). The publication of the preliminary evaluation report (*SKB 2000c*) was followed by field control of geological conditions in the candidate areas (*Wahlgren et al 2000*), before the publication of the final evaluation (*SKB 2000j*). The results from the Klipperås study site (Subsection 6.1.5), which lies some 40 km south of the municipality, is used for comparative purposes, as well as the results from the adjacent Oskarshamn (Subsection 8.3.5). An English summary of the results of the Hultsfred feasibility study is given in *SKB 2001a*.

Antal, I., Bergman, T., Gierup, J., Rudmark, L., Thunholm, B., Wahlgren, C.-H., Stephens, M., Johansson, R., 1998b. **Översiktsstudie av Kalmar län. Geologiska förutsättningar.** SKB R-98-24, Svensk Kärnbränslehantering AB.

Milnes, A.G., Gee, D.G., Lund, C.-E., 1998. **Crustal structure and regional tectonics of SE Sweden and the Baltic Sea.** SKB TR 98-21, Svensk Kärnbränslehantering AB.

Johansson, R., Kornfält, K.-A., Lindén, A.H., Svantesson, S.-I., Wahlgren, C.-H., Isaksson, H., Lindroos, H., 2000. **Förstudie Hultsfred. Jordarter, bergarter och deformationszoner.** SKB R-00-11, Svensk Kärnbränslehantering AB.

Axelsson, C.-L., Follin, S., Årebäck, M., Stigsson, M., Isgren, F., Jacks, G., 2000b. **Förstudie Hultsfred. Grundvattnets rörelse, kemi och långsiktiga förändringar.** SKB R-00-12, Svensk Kärnbränslehantering AB.

SKB 2000c. **Förstudie Hultsfred. Preliminär Slutrapport.** Svensk Kärnbränslehantering AB, April 2000.

Wahlgren, C.-H., Kornfält, K.-A., Johansson, R., Isaksson, H., 2000. **Förstudie Hultsfred. Fältkontroll av berggrunden inom potentiellt gynnsamma områden.** SKB R-00-44, Svensk Kärnbränslehantering AB.

SKB 2000j. **Förstudie Hultsfred. Slutrapport.** Svensk Kärnbränslehantering AB, December 2000.

SKB 2001a. **Feasibility Studies – Östhammar, Nyköping, Oskarshamn, Tierp, Hultsfred and Älvkarleby. Summary Report.** SKB TR 01-16, Svensk Kärnbränslehantering AB.

9 Comparable programmes

The geoscientific research programme which has been carried out in Finland and Canada in connection with the search for a deep disposal site for spent nuclear fuel is closely comparable to that in Sweden. The Finnish and Canadian disposal concepts parallel KBS-3 and envisage underground caverns at several hundred metres depth in crystalline rocks, in the Baltic and Canadian Shields, respectively. Hence, a structured overview of the documentation available from these programmes is an important supplement to a guide to the Swedish documentation, particularly with respect to questions of common interests, such as general geoscientific experience in important problem areas (heterogeneity, shear zones, glaciation, seismic risk, fracture hydrology, etc.), methods and techniques of subsurface mapping and site characterisation, and validation of different modelling procedures. However, it must be kept in mind that the siting process in each of these three countries is radically different due to quite different societal and political climates. Hence, each of the Sections in this Chapter – Section 9.1 for Finland, and Section 9.2 for Canada – are preceded by a brief introduction to the development of the siting process in each case. Roughly, one can say that the process in Finland has advanced significantly further than in Sweden (the future deep repository site having already been decided upon), whereas in Canada it has hardly started (the original concept having been judged, in 1998, as lacking acceptance in the population). These developments and an overview of the structuring of the citation lists are outlined at the beginning of each Section.

9.1 Finland

Finland is of particular interest for the Swedish programme because of closely similar geological conditions, and there has been close cooperation between SKB and the Finnish implementing body, Posiva (and its forerunners, TVO/IVO), for many years. At an early stage, Finland chose to base its programme on the KBS-3 concept and to run research and development activities closely coordinated with those of SKB, often as co-operative efforts. However, the siting process diverged considerably from that of Sweden (for a detailed summary of the Finnish siting process, see *McEwen & Äikäs 2000*). Already in 1983, the government established the objectives and timetable for the siting process, with Phase 1 (1983–1985) consisting of a site identification survey, Phase 2 (1986–1992) encompassing preliminary site investigations at a number of sites identified during Phase 1, and a third and final phase, Phase 3 (1993–2000), envisaged as involving the detailed site characterisation of some or all of the sites studied during Phase 2, and culminating in a "Decision in Principle" by the Government as to the future Finnish deep repository site.

During Phase 1, about 85 potential investigation areas were identified on the basis of regional geology, satellite imagery and aerial photo interpretation (rock blocks), together with a consideration of environmental and societal factors. Out of these, after discussions with the communities, five sites were chosen for the preliminary site investigations in Phase 2. These included detailed geological and geophysical surveys, the drilling of numerous deep boreholes with continuous coring, and extensive hydrogeological sampling and testing at each site. After review by the authorities in 1993, three of these sites were retained for more detailed study, including a second series of deep cored drillholes (Olkiluoto, Kivetty and Romuvaara), whereas two of the original sites (Syyry, Veitsivaara) were dropped. Later, a fourth site was added after a positive feasibility study (Hästholmen), and a crash investigation programme was initiated there, to bring investigations up to the same level as the other three sites by year 2000. These efforts culminated in the TILA-99 safety assessment, which was based on the data variations from all four sites, and which was submitted to the Government, supported by a favourable international review, in late 1999, with the request for a positive "Decision in Principle". Already, however, the municipality in which Olkiluoto lies had agreed to allow it to be developed as a potential deep repository site over the next 10 years, if the decision were to be positive, and Posiva had soon published a preliminary RDD plan (research, development, technical design) for excavations leading eventually to the application for a construction licence in 2010 (*Posiva Oy 2000*). The Government made a positive "Decision in Principle" at the end of 2000, and the decision was ratified by the Finnish parliament, almost unanimously, in May 2001.

The documentation listed below is divided into three Subsections as follows:

9.1.1: Methodological and regional aspects
Geoscientific reports of a more general nature, dealing with geoscientific research which was generally not tied to a specific site.

9.1.2: Site investigations
Site characterisation reports for the three sites retained at the end of Phase 2, together with a selection of Phase 3 reports for the Hästholmen site

9.1.3: TILA-99 safety assessment
The TILA-99 safety assessment and its forerunners, TVO-92 and TILA-96, together with the main background reports (site reports and hydrogeological syntheses).

McEwen, T., Äikäs, T., 2000. **The site selection process for a spent fuel repository in Finland – summary report.** Posiva Oy, report POSIVA 2000-15.

Posiva Oy, 2000**. Disposal of spent fuel in Olkiluoto bedrock. Programme for research, development and technical design for the pre-construction phase.** Posiva Oy, report POSIVA 2000-14.

9.1.1 Methodological and regional aspects

Reports dealing with methodology and those concerned with the regional geology of Finland are of particular importance for the Swedish programme for obvious reasons. As earlier in this guide, the citations below have been group in traditional categories dealing with bedrock structure, hydrogeology and "hazards" (glaciation, seismicity, etc.). A separate group deals with a Finnish "speciality", the Palmottu uranium mineralization as a natural analogue of a spent fuel repository. The works cited under bedrock structure focus on fracturing at different scales, starting with the recent definitive compilation of large scale fracture zones in terms of lineament maps at different scales (*Kuivamäki 2000*). At site scale, the definition of "fracture zones" has been a recurring problem in the Finnish programme and this is reflected in the other works collected under this heading: fracture and fracture zone analysis and modelling (*Poteri & Taivassalo 1994, Korkealaakso et al 1994, Front & Okko 1994*) and the identification of fracture zones in boreholes by different methods (*Labbas 1997*). As in Sweden (see Sections 3.3 and 3.4), the number of citations in here in no way reflects the amount of available documentation – this is "hidden" in the site characterisation reports, and particularly in background reports to the site investigations (which, up to recently, are almost all in Finnish).

Also with regard to hydrogeology, most of the material is tied to the individual sites and referenced in the next Subsections, but the documentation contains some important methodological discussions on geohydrological, hydrogeochemical and microbiological themes (*Melamed & Front 1996, Andersson et al 1998, Niemi et al 1999, Smellie et al 1999, Haveman et al 1998*), which are complementary to SKB material in Chapter 5. Under "hazards", a selection of recent works on effects due to the retreat of the last continental ice sheet (*Kuivamäki et al 1998, Eronen et al 1995, Miettinen et al 1999*) are included and, as a "second opinion" on future glaciations in Fennoscandia, the report of *Forsström 1999* (see Section 4.2). The remaining citations under this heading concern seismicity in Fennoscandia and a method of estimating its possible effects on a repository (*Saari 1992, 2000, LaPointe & Cladouhos 1999*), with close parallels in the SKB documentation (see Sections 4.3 and 4.4).

The list ends with key references to the Palmottu natural analogue project, carried out by the Geological Survey of Finland in cooperation with the Finnish regulatory body, STUK. The references refer to the first phase (1988–1991) and second phase (1991–1995) of the project (*Blomqvist et al 1991, Blomqvist et al 1995*). The third phase of the project (1996–1999) was an EU-funded effort coordinated by the Geological Survey of Finland (*GTK 2000*, *p.23, Kaija et al 2000*).

Bedrock structure

Kuivamäki, A., 2000. **Lineament database of the Finnish potential repository sites for the calculation of bedrock movements induced by earthquakes**. Posiva Oy, working report WR 2000-12.

Poteri, A., Taivassalo, V., 1994. **Modelling of fracture geometry in the preliminary site investigations for a nuclear waste repository**. Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-94-08.

Korkealaakso, J., Vaittinen, T., Pitkänen, P., Front, K., 1994. **Fracture zone analysis of borehole data in three crystalline rocks sites in Finland – the principal component analysis approach**. Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-94-11.

Front, K., Okko, O., 1994. **Fractures and fracture zones in conceptual modelling – geological and geophysical considerations**. Posiva Oy, work report PATU-94-27e.

Labbas, K., 1997. **Comparison of 3-D geological and geophysical investigation methods in boreholes KI-KR1 at Äänekoski Kivetty site and RO-KR3 at Kulmo Romuvaara site**. Posiva Oy, report POSIVA 97-03.

Hydrogeology

Melamed, A., Front, K., 1996. **Hydraulically conductive fractures on the basis of correlation between rock-core analysis and borehole-TV study.** Posiva Oy, work report PATU-96-23e.

Andersson, J., Ahokas, H., Koskinen, L., Poteri, A., Niemi, A., Hautojärvi, A., 1998. **A working group's conclusions on site specific flow and transport modelling.** Posiva Oy, report POSIVA 98-02.

Niemi, A., Kontio, K., Kuusela-Lahtinen, A., Vaittinen, T., 1999. **Estimation of block conductivities from hydrologically calibrated fracture networks – description of methodology and application to Romuvaara investigation area.** Posiva Oy, report POSIVA 99-19.

Smellie, J.A.T., Laaksoharju, M., Snellman, M.V., Ruotsalainen, P.H., 1999. **Evaluation of the quality of groundwater sampling: Experience derived from radioactive waste disposal programmes in Sweden and Finland during 1980–1992.** Posiva Oy, report POSIVA 99-29.

Haveman, S.A., Pedersen, K., Ruotsalainen. P., 1998. **Geomicrobial investigations of groundwaters from Olkiluoto, Hästholmen, Kivetty and Romuvaara.** Posiva Oy, report POSIVA 98-09.

Hazards (glaciation, earthquakes, etc.)

Kuivamäki, A., Vuorela, P., Paananen, M., 1998. **Indications of postglacial and recent bedrock movements in Finland and Russian Karelia**. Geol. Survey of Finland, report YST-99.

Eronen, M., Glückert, G., van de Plassche, O., van der Plicht, J.,Rantala, P., 1995. **Land uplift in the Olkiluoto-Pyhäjärvi area, southwestern Finland, during the last 8,000 years.** Nuclear Waste Commission of the Finnish Power Companies, report YJT-95-17.

Miettinen, A., Eronen, M., Hyvärinen, H., 1999. **Land uplift and relative sea-level changes in the Loviisa area, southeastern Finland, during the last 8,000 years.** Posiva Oy, report POSIVA 99-28.

Forsström, L., 1999. **Future glaciation in Fennoscandia.** Posiva Oy, report POSIVA 99-30.

Saari, J., 1992. **A review of the seismotectonics of Finland.** Nuclear Waste Commission of the Finnish Power Companies, report YJT-92-29.

Saari, J., 2000. **Seismic activity parameters of the Finnish potential repository sites.** Posiva Oy, report POSIVA 2000-13.

LaPointe, P.R., Cladouhos, T.T., 1999. **An overview of a possible approach to calculate rock movements due to earthquakes at Finnish nuclear waste repository sites.** Posiva Oy, report POSIVA 99-02.

Palmottu

Blomqvist, R., Jaakola, T., Niini, H., Ahonen, L., eds., 1991. **The Palmottu Analogue Project. Progress Report 1990.** Geological Survey of Finland, Nuclear Waste Disposal Research, report YST-73.

Blomqvist, R., Suksi, J., Ruskeeniemi, T., Ahonen, L., Niini, H., Vuorinen, U., Jakobsson, K., 1995. **The Palmottu natural analogue project. The behaviour of natural radionuclides in and around uranium deposits.** Finnish Centre for Radiation and nuclear Safety (STUK), report STUK-YTO-TR 84.

GTK 2000. **Annual Report 1999**. Geological Survey of Finland.

Kaija, J., Blomqvist, R., Suksi, J., Rasilainen, K., 2000. **The Palmottu Natural Analogue Project. Progress Report 1999**. Geological Survey of Finland, Nuclear Waste Disposal Research, Report YST-103.

9.1.2 Site investigations

Descriptions of the 5 sites identified for further study at the end of the stage of preliminary site characterisation (see above) are given in *Teollisuuden Voima Oy 1992* (see also *Öhberg et al 1994*), and a summary of the first stage of detailed site characterisation of the three originally selected sites is to be found in *Posiva Oy 1996b*. In the following, short descriptions of the three sites chosen for detailed characterisation in 1992 are given first, together with the main site characterisation reports which have been published in English. The Hästholmen site, which had a very different investigation history, is treated in more detail at the end.

Kivetty

The Kivetty site is located in the municipality of Äänekoski, an inland area in central Finland. It is in an area of gently undulating topography, mainly 160–180 m a.s.l., and bedrock exposure is very poor (2%). The bedrock of the site, as observed in 13 cored drillholes (total core length ca. 7300 m) and 2 investigation trenches, consists of medium to coarse grained felsic plutonites (granite, granodiorite, porphyritic granodiorite, see Section 2.2), enclosing xenoliths of meta-volcanic rocks and gabbro, cut by occasional ductile shear zones (mylonitic granite). This rock matrix is intersected by aplitic and pegmatitic veins and mafic dykes. The Kivetty granitoids belong to the Svecokarelian orogenic cycle, intruded 1890–1880 Ma ago (see Section 2.5).

The results of Phase 2 investigations are summarised in three related site reports (*Anttila et al 1992a, Heikkinen et al 1992a, Saksa et al 1993a*) and a special report on fracture network modelling (*Kuusela-Lahtinen & Front 1992*), which formed the basis of the earliest safety analysis (TVO-92) and all later studies. These later studies are represented here by two hydrogeology reports (*Taivassalo & Mészáros 1994, Pitkänen et al 1998a*), but are best summarised in the TILA-99 site report and background material (Subsection 9.2.3).

Olkiluoto

The Olkiluoto site is located in the municipality of Eurajoki, on the coast in southwestern Finland. The island of Olkiluoto is extremely flat, mostly only 5–10 m a.s.l., and bedrock exposure is very poor (ca. 4%). The bedrock of the site, as observed in 10 cored drillholes (total core length ca. 5,800 m) and 2,400 m long investigation trenches, consists of migmatitic mica gneisses and veined gneisses of metasedimentary origin, interleaved and folded together with foliated intrusives (tonalitic and granodioritic gneisses, see Section 2.3). These are intruded concordantly and discordantly by granitic and pegmatitic dykes and veins. A subvertical mafic dyke cuts through this rock matrix at one locality. The high grade metamorphism, migmatization and granite/pegmatite intrusion took place during the Svecokarelian orogeny, 1,900–1,800 Ma ago (see Section 2.5), whereas the mafic dyke is considerably younger (1,650–1,250 Ma).

The results of Phase 2 investigations are summarised in three related site reports (*Anttila et al 1992b, Heikkinen et al 1992b, Saksa et al. 1993b*) and a special report on fracture network modelling (*Oudman 1992*), which form the basis for the earliest safety analysis (TVO-92) and all later studies. An important later report discusses methods of characterizing lithological heterogeneity (*Laine 1996*), since the Olkiluoto migmatites are very inhomogeneous and anisotropic. Other structural reports during Phase 3 include descriptions of newer techniques for the acquisition of data on fracturing (*Siddans & Wild 1996, Stråhle 1996, Carlsten 1996*), and a study of the effects of changing structural geometries on geohydrological models (*Koskinen & Laitinen 1995*). The Olkiluoto site has been a continuous testing ground for groundwater flow modelling in fractured rocks (*Löfman 1996, Pöllänen & Rouhiainen 1997*, see also Subsection 9.2.3) and for hydrogeochemical studies (*Pitkänen et al 1994,1998b*, *Vieno 2000*, see also Subsection 9.2.3 and Section 5.2). All later studies are summarised in the TILA-99 site report and background material (Subsection 9.2.3).

It should be noted that Olkiluoto is already the site of one of Finland's repositories for low to intermediate level radioactive wastes (VLJ-repository), constructed in the period 1988–1991 (silos 70–100 m underground, access tunnel ca. 1,000 m) and accompanied by extensive site characterisation studies (all reports in Finnish).

Romuvaara

The Romuvaara site is located in the municipality of Kuhmo, an inland area in northeastern Finland. It is in an area of very low relief at 210–230 m a.s.l., and is very poorly exposed (outcrops ca. 1%). The bedrock of the site, as observed in 11 cored drillholes (total core length ca. 5,500 m) and 2 investigation trenches (150 m, 350 m), consists of migmatitic tonalite gneiss, leuco-tonalite gneiss and mica gneisses (see Section 2.3), cut by felsic and mafic dykes. All these rock types are of Archean age, including the youngest, cross-cutting and undeformed mafic dykes, which are thought to be 2,200–2,100 Ma old. Hence, in contrast to all other sites in Finland and Sweden, Romuvaara lies in an area which has not been affected by the Svecokarelian orogeny (see Section 2.5).

The results of Phase 2 investigations are summarised in three related site reports (*Anttila et al 1990, Saksa et al 1991, Saksa et al 1992*) and a special report on fracture network modelling (*Oudman 1991*). Later studies are represented here by two reports on fracture network modelling of groundwater flow, one of particular methodological interest (*Poteri & Laitinen 1997, Niemi et al 1999*, see Subsection 9.2.1), but are best summarised in the TILA-99 site report and background material (Subsection 9.2.3).

Hästholmen

The Hästholmen site is located in the municipality of Loviisa, on the coast in southeastern Finland. The island of Hästholmen shows a very flat topography, mostly less than 10 m a.s.l., and the bedrock is relatively well exposed, especially on small islands and around the coast line. The bedrock of the site as observed in outcrop, in 5 cored drillholes (total core length ca. 4,100 m) and in the Loviisa VLJ-repository (see below), consists of different varieties of rapakivi granite, generally coarse grained, with or without orbicular structure (see Section 2.2). The granites, which are part of the major

Wiborg batholith (intruded 1,650–1,620 Ma ago), are cut by a few small aplitic and pegmatitic veins, but are otherwise exceptionally homogeneous.

As noted above, investigations on Hästholmen in connection with the siting of a deep spent fuel repository started in 1997, after a feasibility study was carried out in 1996. One of the reasons for the feasibility study was the availability of a large data base from studies in connection with the site characterisation and construction of the Loviisa VLJ-repository (1984–1994, see *Anttila 1997*). In the crash programme which followed (1997–1999), numerous detailed studies were carried out, such as:

– seismic reflection profilling (*Keskinen et al 1998*),
– dipmeter and TV logging of boreholes (*Siddans et al 1997, Siddans et al 1998, Stråhle 1998*),
– difference flow and groundwater flow measurements in boreholes (*Pöllänen & Rouhiainen 1998a, 1998b, 1998c 1999*),
– seismotectonic analysis and rock stress measurement (*Ljunggren 1998, Saari 1998*).

All these studies and other reports (mainly in Finnish) are summarised in *Front et al 1999* and the TILA-99 site report and background material (Subsection 9.2.3).

Teollisuuden Voima Oy, 1992. **Final disposal of spent nuclear fuel in the Finnish bedrock. Preliminary site investigations**. Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-92-32E.

Öhberg, A., Saksa, P., Ahokas, H., Ruotsalainen, P., Snellman, M., 1994. **Summary report of the experiences from TVO's site investigations.** SKB TR 94-17, Svensk Kärnbränslehantering AB.

Posiva Oy, 1996b. **Final disposal of spent fuel in the Finnish bedrock. Detailed site investigations 1993–1996**. Posiva Oy, report POSIVA 96-19.

Kivetty

Antilla, P., Paulamäki, S., Lindberg, A., Paananen, M., Koistinen, T., Front, K., Pitkänen, P., 1992a. **The geology of the Kivetty area. Summary report.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-92-07.

Heikkinen, E., Paananen, M., Ahokas, H., Öhberg, A., Front, K., Okko, O., Pitkänen, P., Cosma, C., Heikkinen, P., Keskinen, J., Korhonen, R., 1992a. **Geophysical investigations in the Kivetty area, Finland. Summary report.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-92-15.

Saksa, P., Paulamäki, S., Paananen, M., Anttila, P., Akohas, H., Front, K., Pitkänen, P., Korkealaakso, J., Okko, O., 1993a. **Bedrock model of the Kivetty area. Summary report.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-93-16.

Kuusela-Lahtinen, A., Front, K., 1992. **Analysis of the fracture data from the Kivetty area for the use in fracture network model.** Teollisuuden Voima Oy, TVO/Site investigations, work report 92-47.

Taivassalo, V., Mészáros, F., 1994. **Simulation of the groundwater flow of the Kivetty area.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-94-03.

Pitkänen, P., Luukkonen, A., Ruotsalainen, P., Leino-Forsman, H., Vuorinen, U., 1998a. **Geochemical modelling of groundwater evolution and residence time at the Kivetty site.** Posiva Oy, report POSIVA 98-07.

Olkiluoto

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

Heikkinen, E., Paananen, M., Kurimo, M., Öhberg, A., Akohas, H., Okko, O., Front, K., Hassinen, P., Pitkänen, P., Cosma, C., Heikkinen, P., Keskinen, J., Honkanen, S., Korhonen, R., 1992b. **Geophysical investigations in the Olkiluoto area, Finland. Summary report.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-92-34.

Saksa, P., Paulamäki, S., Paananen, M., Antilla, P., Ahokas, H., Front, K., Pitkänen, P., Korkealaakso, J., Okko, O., 1993b. **Bedrock model of the Olkiluoto area. Summary report.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-92-15.

Oudman, A., 1992. **Analysis of the fracture data from the Olkiluoto area for the use in fracture network model.** Teollisuuden Voima Oy, TVO/Site investigations, work report 92-03.

Laine, E., 1996. **Geostatistical methods applied to characterisation of the heterogeneity of the migmatite formation at Olkiluoto, Finland.** Posiva Oy, work report WR 96-05e.

Siddans, A., Wild, P., 1996. **Acoustic borehole televiewer survey, processing and interpretation, borehole OL-KR10 at the Olkiluoto site, Finland 1996.** Posiva Oy, work report WR 96-66e.

Stråhle, A., 1996. **Borehole-TV measurements at the Olkiluoto site, Finland 1996. Report and appendices for OL-KR1, OL-KR2 and OL-KR4.** Posiva Oy, work report WR 96-59e.

Carlsten, S., 1996. **Detailed borehole radar measurements at the Olkiluoto site, Finland 1995.** Posiva Oy, work report WR 96-03e.

Koskinen, L., Laitinen, M., 1995. **Numerical study of the effects of alternative structure geometries on the groundwater flow at the Olkiluoto site.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-95-15.

Löfman, J., 1996. **Groundwater flow modelling at the Olkiluoto site. Flow under natural conditions.** Posiva Oy, working report PATU-96-76e.

Pöllänen. J., Rouhiainen, P., 1997. **Groundwater flow measurements at the Olkiluoto site in Eurajoki, boreholes KR1-KR4 and KR7-KR-9.** Posiva Oy, working report WR 97-27e.

Pitkänen, P., Snellman, M., Leino-Forsman, H., Vuorinen, U., 1994. **Geochemical modelling of the groundwater at the Olkiluoto site.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-94-10.

Pitkänen, P., Luukkonen, A., Ruotsalainen, P., Leino-Forsman, H., Vuorinen, U., 1998b. **Geochemical modelling of groundwater evolution and residence time at the Olkiluoto site.** Posiva Oy, report POSIVA 98-10.

Vieno, T., 2000. **Groundwater salinity at Olkiluoto and its effects on a spent fuel repository.** Posiva Oy, report POSIVA 2000-11.

Romuvaara

Antilla, P., Paulamäki, S., Lindberg, A., Paananen, M., Pitkänen, P., Front, K., Kärki, A., 1990. **The geology of the Romuvaara area. Summary report.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-90-21.
Saksa, P., Paananen, M., Ahokas, H., Öhberg, A., Pitkänen, P., Front, K., Okko, O., Vaittinen, T., Cosma, C., Heikkinen, P., Keskinen, J., Korhonen, R., 1991. **Geophysical investigations in the Romuvaara area, Finland. Summary report.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-91-15.

Saksa, P., Paananen, M., Paulamäki, S., Antilla, P., Ahokas, H., Pitkänen, P., Front, K., Vaittinen, T., 1992. **Bedrock model of the Romuvaara area. Summary report.** Nuclear Waste Commission of Finnish Power Companies (YJT), report YJT-92-06.

Poteri, A., Laitinen, M., 1997. **Fracture network model of the groundwater flow in the Romuvaara site.** Posiva Oy, report POSIVA 96-26.

Niemi, A., Kontio, K., Kuusela-Lahtinen, A., Vaittinen, T., 1999. **Estimation of block conductivities from hydrologically calibrated fracture networks – description of methodology and application to Romuvaara investigation area.** Posiva Oy, report POSIVA 99-19.

Oudman, A., 1991. **Analysis of the fracture data from the Romuvaara area for the use in fracture network model.** Teollisuuden Voima Oy, TVO/Site investigations, work report 91-61.

Hästholmen

Anttila, P., 1997. **Geological studies during the first construction phase of the VLJ-repository in Loviisa, Finland, summary report.** Imatran Voima Oy, VLJ working report 97-03.

Keskinen, J., Cosma, C., Heikkinen, P., Enescu, N., 1998. **HSP survey at Hästholmen in Loviisa, 1997 – Survey lines HSP1-HSP7.** Posiva Oy, working report 98-27e.

Siddans, A., Wild, P., Adams, R., 1997. **Dipmeter survey, processing and interpretation, Hästholmen site, Finland 1997.** Posiva Oy, working report WR 97-60e.

Siddans, A., Simpson, G., Wild, P., 1998. **Dipmeter survey, processing and interpretation, Hästholmen site, Finland 1997.** Posiva Oy, working report WR 98-67.

Stråhle, A., 1998. **Borehole-TV measurements at the Hästholmen site, Finland 1997.** Posiva Oy, working report WR 98-19e.

Pöllänen, J., Rouhiainen, P., 1998a. **Difference flow measurements at the Hästholmen site in Loviisa, boreholes KR1-KR3.** Posiva Oy, working report WR 97-41e.

Pöllänen, J., Rouhiainen, P., 1998b. **Difference flow measurements at the Hästholmen site in Loviisa, boreholes KR4-KR6.** Posiva Oy, working report WR 97-28e.

Pöllänen, J., Rouhiainen, P., 1998c. **Groundwater flow measurements at the Hästholmen site in Loviisa, boreholes KR1-KR4.** Posiva Oy, working report WR 98-69.

Pöllänen, J., Rouhiainen, P., 1999. **Groundwater flow measurements at the Hästholmen site in Loviisa, boreholes KR5-KR6.** Posiva Oy, working report WR 99-38.

Ljunggren, C., 1998. **Overcoring rock stress measurements in borehole KR6 at Hästholmen, Finland.** Posiva Oy, working report WR 98-70.

Saari, J., 1998. **Regional and local seismotectonic characteristics of the area surrounding the Loviisa nuclear power plant in SE Finland.** University of Helsinki, Institute of Seismology, report S-36.

Front, K., Paulamäki, S., Ahokas, H., Anttila, P., 1999. **Lithological and structural bedrock model of the Hästholmen study site, Loviisa, SE Finland**. Posiva Oy, report POSIVA 99-31.

9.1.3 TILA-99 safety assessment

This Subsection collects documents directly related to the TILA-99 safety assessment. TILA-99 (*Vieno & Nordman 1999*) represents a further development of earlier preliminary safety assessments TVO-92 and TILA-96 (*Vieno 1992, Vieno & Nordman 1996*), and related reports (*Posiva Oy 1996a, Vieno & Nordman 1997, Crawford & Wilmot 1998*). The geoscientific background material to TILA-99 is summarised in site characterisation reports, one for each site (*Anttila et al 1999a, 1999b, 1999c, 1999d*), which take into account the data collected since 1997. In the case of Hästholmen, where site investigations started in 1997, this report (*Anttila et al 1999a*) is the first and only detailed synthesis. Rock mechanical aspects of the four sites are summarised in *Johansson & Rautakorpi 2000,* and some detailed reports on special rock mechanical problems (*Hakala 2000, Autio et al 2000*) and on the suggested engineering rock mass classification (*Äikäs et al 2000*) have appeared in English. The latter, for the Olkiluoto site, contains a thorough reworking of all the data in the Olkiluoto site characterisation report (*Antilla et al 1999c*).

Of particular importance for TILA-99 is the geohydrological data acquisition, data processing and modelling, as summarised in a series of separate reports dealing with both near-field and far-field conditions at each site (*Ahokas 1999, Löfmann 1999a, 1999b, 2000, Kattilakoski & Mészáros 1999, Kattilakoski & Koskinen 1999, Poteri & Laitinen 1999*). Hydrogeochemical conditions are discussed in considerable detail in the site reports and in a series of separate documents (*Pitkänen et al 1996, 1998a, 1998b, Luukkonen et al 1999*), and the results of geomicrobial investigations at the four sites are reported by *Haveman et al 2000*. The main conclusions of the TILA-99 safety assessment for the siting process are: (1) from the point of view of long-term safety, all the sites would be suitable for hosting a KBS-3-type repository for spent nuclear fuel, and (2) the release and transport analyses do not provide firm grounds for ranking one site above the others.

Safety assessment

Vieno, T., Nordman, H., 1999. **TILA-99. Safety assessment of spent fuel disposal in Hästholmen, Kivetty, Olkiluoto and Romuvaara.** Posiva Oy, report POSIVA 99-07.

Vieno, T., 1992. **Safety analysis of disposal of spent nuclear fuel (TVO-92)**. Technical Research Centre of Finland (VTT), Publication 177.

Vieno, T., Nordman, H., 1996. **Interim report on safety assessment of spent fuel disposal TILA-96**. Posiva Oy, report POSIVA 96-17.

Posiva Oy, 1996a. **Final disposal of spent fuel in the Finnish bedrock. Scope and requirements for site-specific safety analysis**. Posiva Oy, report POSIVA 96-16.

Vieno, T., Nordman, H., 1997. **FEPs and scenarios. Auditing of TVO-92 and TILA-96 against International FEP database**. Posiva Oy, report POSIVA 97-11.

Crawford, M.B., Wilmot, R.D., 1998. **Normal evolution of a spent fuel repository at the candidate sites in Finland.** Posiva Oy, report POSIVA 98-15.

Site reports

Anttila, P., Ahokas, H., Front, K., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M.V., Wikström, L., Öhberg, A., 1999a. **Final disposal of spent nuclear fuel in Finnish bedrock – Hästholmen site**. Posiva Oy, report POSIVA 99-08.

Anttila, P., Ahokas, H., Front, K., Heikkinen, E., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M.V., Wikström, L., Öhberg, A., 1999b. **Final disposal of spent nuclear fuel in Finnish bedrock – Kivetty site report.** Posiva Oy, report POSIVA 99-09.

Anttila, P., Ahokas, H., Front, K., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M.V., Wikström, L., Öhberg, A., 1999c. **Final disposal of spent nuclear fuel in Finnish bedrock – Olkiluoto site report**. Posiva Oy, report POSIVA 99-10.

Anttila, P., Ahokas, H., Front, K., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M.V., Wikström, L., Öhberg, A., 1999d. **Final disposal of spent nuclear fuel in Finnish bedrock – Romuvaara site report**. Posiva Oy, report POSIVA 99-11.

Geomechanics, engineering geology

Johansson, E., Rautakorpi, J., 2000. **Rock mechanics stability at Olkiluoto, Hästholmen, Kivetty and Romuvaara**. Posiva Oy, report POSIVA 2000-02.

Hakala, M., 2000**. Interpretation of the Hästholmen *in situ* state of stress based on core damage observations**. Posiva Oy, report POSIVA 2000-01.

Autio, J., Johansson, E., Kirkkomäki, T., Hakala, M., Heikkilä, E., 2000**. In-situ failure test in the Research Tunnel at Olkiluoto.** Posiva, Oy, report POSIVA 2000-05.

Äikäs, K., Hagros, A., Johansson, E., Malmlund, H., Sievänen, U., Tolppanen, P., Ahokas, H., Heikkinen, E., Jääskeläinen, P., Ruotsalainen, P., Saksa, P., 2000. **Engineering rock mass classification of the Olkiluoto investigation site.** Posiva Oy, report POSIVA 2000-08.

Geohydrology

Ahokas, H., 1999. **Summary of certain input data for groundwater flow modelling in Hästholmen, Kivetty, Olkiluoto and Romuvaara.** Posiva Oy, working report WR 99-11.

Löfman, J., 1999a. **Site scale groundwater flow in Olkiluoto**. Posiva Oy, report POSIVA 99-03.

Löfman, J., 1999b. **Site scale groundwater flow in Hästholmen**. Posiva Oy, report POSIVA 99-12.

Kattilakoski, E., Mészáros. F., 1999. **Regional-to-site groundwater flow in Kivetty**. Posiva Oy, report POSIVA 99-13.

Kattilakoski, E., Koskinen, L., 1999. **Regional-to-site groundwater flow in Romuvaara**. Posiva Oy, report POSIVA 99-14.

Poteri, A., Laitinen, M., 1999. **Site-to-canister scale flow and transport in Hästholmen, Kivetty, Olkiluoto and Romuvaara**. Posiva Oy, report POSIVA 99-15.

Löfman, J., 2000. **Site scale groundwater flow in Olkiluoto – complementary simulations.** Posiva Oy, report POSIVA 2000-07.

Hydrogeochemistry

Pitkänen, P., Snellman, M., Vuorinen, U., Leino-Forsman, H., 1996. **Geochemical modelling study on the age and evolution of groundwater at the Romuvaara site.** Posiva Oy, report POSIVA 96-06.

Pitkänen, P., Luukkonen, A., Ruotsalainen, P., Leino-Forsman, H., Vuorinen, U., 1998a. **Geochemical modelling of groundwater evolution and residence time at the Kivetty site.** Posiva Oy, report POSIVA 98-07.

Pitkänen, P., Luukkonen, A., Ruotsalainen, P., Leino-Forsman, H., Vuorinen, U., 1998b. **Geochemical modelling of groundwater evolution and residence time at the Olkiluoto site.** Posiva Oy, report POSIVA 98-10.

Luukkonen, A., Pitkänen, P., Ruotsalainen, P., Leino-Forsman, H., Snellman, M., 1999. **Hydrogeochemical conditions at the Hästholmen site.** Posiva Oy, report POSIVA 99-26.

Haveman, S.A., Nilsson, E.L., Pedersen, K., 2000. **Regional distribution of microbes in groundwater from Hästholmen, Kivetty, Olkiluoto and Romuvaara, Finland.** Posiva Oy, report POSIVA 2000-06.

9.2 Canada

The governments of Canada and the province of Ontario established the Nuclear Fuel Waste Management Program in 1978 and made Atomic Energy of Canada Ltd. (AECL) responsible for research and development on disposal. In 1981, the governments decreed that no decision on site selection would be made until the disposal concept was accepted. The acceptability of the disposal concept, which is in many ways similar to KBS-3, was subject to review by a special panel, appointed by the Canadian government (Federal Environmental Assessment Review Panel), from 1989 onwards. This review culminated in a series of public hearings in 1996–1997, to examine the disposal concept and associated Environmental Impact Assessment. After the hearings, the Review panel arrived at the following conclusions (from the news release of 14.4.1998):

- While the safety of the AECL concept has been adequately demonstrated from a technical perspective, from a social perspective it has not.
- The AECL concept for deep geologic disposal in its current form does not have broad public support, and does not have the required level of acceptability to be adopted as Canada’s approach for managing nuclear fuel wastes.

The panel put forward recommendations for a thorough-going institutional reform, which resulted in responsibility for nuclear fuel waste management being transferred to a new body (Nuclear Fuel Waste Management Agency), “at arm’s length” from the nuclear power companies and AECL, and with a board of directors appointed by the Government. The Review panel was also critical of the role played by the Canadian regulator, Atomic Energy Control Board, which already in 1997 was reconstituted as the Canadian Nuclear Safety Commission. With regard to siting, no real site selection process has been carried out, in the first place due to the early government decree (see above), and recently also because of the Review panel's conclusion that, until their recommendations have been implemented and until "broad public acceptance of a nuclear fuel waste management approach has been achieved, the search for a specific site should not proceed".

Against this background, AECL geoscientific research and development has concentrated on a number of research areas in plutonic rocks of the Canadian Shield, in different geological environments. The aim was to develop adequate site characterisation techniques for the prediction of underground conditions (at 500–1,000 m depth) from surface-based activities. As for Finland (Section 9.1), the approach has been similar to that of SKB, concentrating on the regional setting of the research areas, on surface geological and geophysical surveying in the areas, and on core drilling, borehole logging and hydrogeological sampling, testing and modelling of sites within the areas – and, eventually, on the construction of an Underground Research Laboratory (URL) for detailed validation of surface-based models, for testing and demonstrating disposal technology, and for carrying out of flow and transport experiments (see Section 6.3). Consequently, the documentation below follows a similar structure to Section 9.1:

9.2.1: Methodological and regional aspects,

9.2.2: Research areas and their characterisation, including investigations in the URL,

9.2.3: General documents on the Canadian programme, including performance assessment exercises).

9.2.1 Methodological and regional aspects

The AECL concept envisages the canistered spent CANDU nuclear fuel being deposited in underground vaults, or in boreholes drilled from underground vaults, at 500–1,000 m below the surface in crystalline rocks of the Canadian Shield, surrounded by buffer and backfill, and ultimately sealed, as in KBS-3. The geoscience research concentrated on understanding the mode of formation, later fracturing and long-term stability of potential host rocks and on the hydrogeological conditions at specific sites, together with a series of more general studies. In this Subsection, we collect reports with are not overtly site-specific, either dealing with the development or testing of methods and techniques for subsurface mapping or with regional aspects of importance for the understanding of specific sites or for long-term safety.

The first heading gathers reports dealing with bedrock geology and fracturing, starting with two reports on the "big picture" – the processes of formation of the Precambrian Shield in Canada and their petrological signatures (*Brown et al 1997, Ejeckam & Brown 1997*). The following citations deal with methodology of data acquisition and processing, particularly of fracture systems (*Barton & Bakhtar 1987, Read 1990*) and the geophysical identification of fracture zones and the dating of their formation and movement (*Davison et al 1984, Hillary & Hayles 1985, Gascoyne et al 1997*). The final group contains two important works on experience gained from the characterisation of fracture systems at the research areas (*Sikorsky 1996, Everitt 1999*) and, more generally, from the multitude of mines and other underground excavations in Canada (*Raven & Gale 1986, Raven & Clark 1993*).

The second heading contains, first, citations on more general aspects of hydrogeology, particularly concerning the brines and redox conditions in the Canadian Shield and the significance of the microbial content of deep groundwater for radioactive waste disposal (*Pearson 1987, Gascoyne 1996, Brown 1996, King & Stroes-Gascoyne 1996*, cf. Sections 5.2 and 5.3). Geological events likely to have adverse effects on the integrity of an underground repository –"hazards"– are discussed in the next set of reports (cf. Sections 4.4 and 5.4): the evidence for post-glacial faulting and the potential impact of future glaciations (*Adams 1981, Ates et al 1997, Chan et al 1998*); the probability and potential effects of seismic events (*Atkinson & McGuire 1993, Ates et al 1995, Martin &Chandler 1996*); and the long-term risk of a meteorite impact (*Wuschke et al 1995*). Finally, some Canadian reports on natural analogues, including the Cigar Lake uranium deposit, are added (*Griffault et al 1992, Cramer 1994, 1995, 1999*) – cf. Section 7.1.

Bedrock geology, fracturing

Brown, A., Ejeckam, R.B., Everitt, R.A., 1997. **Plutonic rock, crustal deformation and tectonism in the Canadian Precambrian shield: concepts affecting the siting of a nuclear fuel waste disposal vault.** Atomic Energy of Canada Ltd., report AECL TR-738.

Ejeckam, R.B., Brown, A., 1997. **Use of petrochemistry to infer tectonic origin of granitoid rocks: A test case using AECL`s chemical samples from the Atikokan and Whiteshell Research Areas.** Atomic Energy of Canada Ltd., report AECL TR-763.

Barton, N., Bakhtar, K., 1987. **Description and modeling of rock joints for the hydrothermomechanical design of nuclear waste vaults, Volume I and Volume II.** Atomic Energy of Canada Ltd., report AECL TR-418.

Read, R.S., 1990. **Methodology for the acquisition, analysis and presentation of geological data from the Underground Research Laboratory subsurface drilling program. Volume I and Volume II.** Atomic Energy of Canada Ltd., report AECL TR-484.

Davison, C.C., Keys, W.S., Paillet, F.L., 1984. **The use of borehole geophysical logs and hydrologic tests to characterize plutonic rock for nuclear fuel waste disposal.** Atomic Energy of Canada Ltd., report AECL-7810.

Hillary, E.M., Hayles, J.G., 1985. **Correlation of lithology and fracture zones with geophysical borehole logs in plutonic rocks.** Atomic Energy of Canada Ltd., report AECL TR-343.

Gascoyne, M., Brown, A., Ejeckam, R.B., Everitt, R.A., 1997. **Dating fractures and fracture movement in the Lac du Bonnet Batholith.** Atomic Energy of Canada Ltd., report AECL-11725.

Sikorsky, R.I., 1996. **The distributions of subsurface fractures in the rocks at AECL`s research areas on the Canadian shield.** Atomic Energy of Canada Ltd., report AECL TR-750

Everitt, R.A., 1999. **Experience gained from the geological characterisation of the Lac du Bonnet batholith, and comparison with other sparsely fractured granite batholiths in the Ontario portion of the Canadian Shield.** Ontario Power Generation Report No: 06819-REP-01200-**0069**-R00.

Raven, K.G., Gale, J.E., 1986. **A study of the surface and subsurface structural and groundwater conditions at selected underground mines and excavations.** Atomic Energy of Canada Ltd., report AECL TR-177.

Raven, K.G., Clark, I.D., 1993. **Survey of geoscientific data on deep underground mines in the Canadian Shield.** Atomic Energy Control Board (Canada), report AECB 92-012.

Hydrogeology

Pearson, F.J. Jr., 1987. **Geochemical and isotopic evidence on the origin of brines in the Canadian shield.** Atomic Energy of Canada Ltd., report AECL TR-429.

Gascoyne, M., 1996. **The evolution of redox conditions and groundwater geochemistry in recharge-discharge environments on the Canadian Shield.** Atomic Energy of Canada Ltd., report AECL-11682.

Brown, D.A., 1996. **Introduction to microbiology relevant to the Canadian Nuclear Fuel Waste Management Program – a literature review.** Atomic Energy of Canada Ltd., report AECL TR-581.

King, F., Stroes-Gascoyne, S., 1996. **Predicting the effects of microbial activity on the corrosion of copper nuclear fuel waste disposal containers.** Atomic Energy of Canada Ltd., report AECL TR-429.

Hazards (glaciation, earthquakes, etc.)

Adams, J., 1981. **Postglacial faulting: A literature survey of occurrences in Eastern Canada and comparable glaciated areas.** Atomic Energy of Canada Ltd., report AECL TR-142.

Ates, Y., Bruneau, D., Ridgway, W.R., 1997. **Continental glaciation and its potential impact on a used-fuel disposal vault in the Canadian shield.** Atomic Energy of Canada Ltd., report AECL-10140.

Chan, T., O'Connor, P.A., Stanchell, F.W., 1998. **Finite-element modelling of effects of past and future glaciation on the host rock of a used nuclear fuel waste vault.** Ontario Hydro, report 06819-REP-01200-**0020**-R00.

Atkinson, G.M., McGuire, R.K., 1993. **Probability of damaging earthquakes in Northwestern Ontario (draft).** Atomic Energy of Canada Ltd., report AECL TR-M-0023.

Ates, Y., Bruneau, D., Ridgway, W.R., 1995. **An evaluation of potential effects of seismic events on a used-fuel disposal vault.** Atomic Energy of Canada Ltd., report AECL TR-623.

Martin, C.D., Chandler, N.A., 1996. **The potential for vault-induced seismicity in nuclear fuel waste disposal: Experience from Canadian mines.** Atomic Energy of Canada Ltd., report AECL-11599.

Wuschke, D.M., Whitaker, S.H., Goodwin, B.W., Rasmussen, L.R., 1995. **Assessment of the long-term risk of a meteorite impact on a hypothetical Canadian nuclear fuel waste disposal vault deep in plutonic rock.** Atomic Energy of Canada Ltd., report AECL-11014.

Natural analogues

Griffault, L.Y., Gascoyne, M., Kamineni, D.C., Vandergraaf, T.T., 1992. **A study of the migration of radionuclides, major, trace and rare-earth elements along deep fractures in the Lac du Bonnet batholith, Manitoba.** Atomic Energy of Canada Ltd., report AECL TR-545.

Cramer, J.J., 1994. **Natural analogs in support of the Canadian concept for nuclear fuel waste disposal.** Atomic Energy of Canada Ltd., report AECL-10291.

Cramer, J.J., 1995. **The Cigar Lake uranium deposit: Analog information for Canada`s nuclear fuel waste disposal concept.** Atomic Energy of Canada Ltd., report AECL-11204.

Cramer, J.J., 1999. **Status of natural analogue research and recommendations for future work.** Ontario Power Generation, report 06819-REP-01200-**0074**-R00.

9.2.2 Characterisation of research areas

Site characterisation studies in Canada have been concentrated in a number of research areas (up to 400 km^2), and each containing a number of small study areas ("grid areas" of 1–2 km^2) in which detailed work was carried out, including in most cases, the drilling of deep boreholes (*Whitaker et al 1994*). The five research areas were White Lake, Chalk River, Algoma, Atikokan and Whiteshell. The White Lake research area was only used in 1975–1976 and then abandoned, and work at Chalk River was discontinued in 1983. Both these areas lay in gneissic metamorphic terrains (cf. Section 23) of the Grenville province of the Canadian Shield (= Sveconorwegian in Scandinavia, cf. Section 2.5).

In the other three areas, work continued, with varying degrees of intensity, into the mid-1990s. The lists below contain a selection of reports from these three areas, which have in common that they each lie within major plutons of the Superior province, the ancient Archean-early Proterozoic core of the Canadian Shield. The Algoma research area lies within an early Proterozoic layered gabbro-anorthosite complex. (cf. Section 2.4) in southeastern Ontario. Investigations began in 1980 (*Brown & Kamineni 1989*) and in the early 1980s, four deep cored drillholes were sunk in the area (*Ejeckam et al 1987, 1988a, 1988b, 1990*). Hydrogeological investigations (e.g. *Bottomley et al 1986*) and monitoring continued at the site until 1992. The results from this site are of interest for comparison with the only site in mafic rock studied in Sweden, Taavinunnanen (Section 2.4). The Atikokan research area lies in a large pluton of coarse grained biotite-hornblende granite (Eye-Dashwa Lakes pluton, cf. Swedish and Finnish localities in Section 2.2) in southwestern Ontario. Investigations began in 1979, continued with surface site characterisation studies and the sinking of five cored drillholes in the early 1980s (for an overview and a list of basic data reports, see *Stone 1984*), followed by a long period of routine hydrogeological monitoring. A selection of results from the drilling campaign and from surface geophysical studies are included in the list below (*Hillary 1982, Kerrich 1984, Kerrich et al 1985, Soonawala et al 1987, Gibb et al 1988*). The Whiteshell research area lies in a large granite pluton (Lac du Bonnet batholith, cf. Swedish and Finnish localities in Section 2.2) in southern Manitoba, and includes the area of the AECL Whiteshell Laboratories. Investigations started in 1977 and site characterisation studies were carried out at several grid areas throughout the 1980s, mainly aimed at testing and comparing methodologies, and, in the early stages, at siting the proposed Underground Research Laboratory (e.g. *Stone et al 1984, INTERA 1985, Ejeckam et al 1988c*). The Whiteshell area was also used as a testing ground for regional hydrogeological and geophysical modelling (e.g. *Ophori et al 1995, Stevenson et al 1996a, 1996b, Tomsons et al 1995*).

The Canadian Underground Research Laboratory (URL) was constructed beneath a 5 km^2 site in the Whiteshell research area. Reconnaissance site investigations began in 1980 (geological mapping, airborne and ground geophysical surveys, shallow boreholes, etc.), followed by detailed investigations with the drilling of five deep cored boreholes (core logging, downhole geophysics, hydrogeological sampling and testing, etc.). Later, an additional 8 cored boreholes and 30 percussion holes (depths 150 to 1,100 m) were drilled, before construction of the URL shaft began in May 1984. A new methodology had to be developed for the handling of the large amount of raw data which these and later URL activities produced (*Read 1990*). These investigations correspond to the “pre-investigation phase” at Äspö (Section 6.3) and, as in Äspö, were used as a preliminary for a major experiment to evaluate structural and groundwater flow models (URL Shaft Drawdown Experiment, e.g. *Guvanasen et al 1985, Stone & Kamineni 1988, Frost 1997*). Later, with the completion of underground construction, the URL was used for the study and modelling of a whole spectrum of site characteristics (e.g. *Everitt et al 1995, Gascoyne et al 1996, Young & Collins 1997, Martino et al 1997, Martino 2000, Haveman et al 1995, Stroes-Gascoyne 1997*), in addition to its use for migration experiments, and technology development and demonstration (*Ohta & Chandler 1997*).

Whitaker, S.H., Brown, A., Davison, C.C., Gascoyne, M., Lodha, G.S., Stevenson, D.R., Thorne, G.A., Tomsons, D., 1994. **AECL strategy for surface-based investigations of potential disposal sites and the development of a geosphere model of a site.** SKB TR 94-18, Svensk Kärnbränslehantering AB.

Algoma (East Bull Lake layered gabbro)

Brown, A., Kamineni, D.C., 1989. **A reconnaissance study of structures at the East Bull Lake pluton, Ontario.** Atomic Energy of Canada Ltd., report AECL TR-417.

Ejeckam, R.B., Sikorsky, R.I., Kamineni, D.C., McCrank, G.F.D., 1987. **Geology and summary of results from borehole EBL-2 in the East Bull Lake research area (RA-7), Algoma district, North-eastern Ontario.** Atomic Energy of Canada Ltd., report AECL TR-409-2.

Ejeckam, R.B., Sikorsky, R.I., Kamineni, D.C., McCrank, G.F.D., McGregor, R.G., 1988a. **Geology and summary of geological information obtained from borehole EBL-3 in the East Bull Lake research area (RA-7), Algoma district, Ontario.** Atomic Energy of Canada Ltd., report AECL TR-409-3.

Ejeckam, R.B., Sikorsky, R.I., Kamineni, D.C., McCrank, G.F.D., 1988b. **Geology and summary of results from borehole EBL-4 in the East Bull Lake research area (RA-7), Algoma district, North-eastern Ontario.** Atomic Energy of Canada Ltd., report AECL TR-409-4.

Ejeckam, R.B., Sikorsky, R.I., Kamineni, D.C., McCrank, G.F.D., 1990. **Geology and summary of results from borehole EBL-1 in the East Bull Lake Research Area (RA-7), Algoma District, North-eastern Ontario.** Atomic Energy of Canada Ltd., report AECL TR-409-1.

Bottomley, D.J., Gascoyne, M., Ross, J.D., Ruttan, J.T., 1986. **Hydrogeochemistry of the East Bull Lake pluton, Massey, Ontario.** Atomic Energy of Canada Ltd., report AECL TR-382.

Atikokan (Eye-Dashwa Lakes granite)

Stone, D., 1984. **Summary of geoscience work at the AECL research site near Atikokan, Ontario.** Atomic Energy of Canada Ltd., report AECL-7815.

Hillary, E.M., 1982. **Geometric representation of subsurface fracturing in boreholes ATK-1, ATK-2, ATK-3, ATK-4 and ATK-5, Atikokan, northwestern Ontario (RA 4).** Atomic Energy of Canada Ltd., report AECL TR-182.

Kerrich, R., 1984. **Chronology and ambient temperature/pressure conditions of fluid flow through the Eye-Dashwa Lakes pluton based on the 18 O/16 O ratio and fluid inclusions.** Atomic Energy of Canada Ltd., report AECL TR-267.

Kerrich, R., Kamineni, D.C., 1985. **Oxygen and hydrogen isotope study of fracture-related fluid flow in the Eye-Dashwa lakes pluton, Atikokan, northwestern, Ontario.** Atomic Energy of Canada Ltd., report AECL TR-361.

Soonawala, N.M., Huang, C.-F., Fogarasi, S., Hayles, J.G., 1987. **Geophysical structural discontinuity mapping and overburden depth determinations at the Atikokan research area: 1985.** Atomic Energy of Canada Ltd., report AECL TR-399.

Gibb, R.A., Nagy, D., Coderre, J., Fogarasi, A., Thomas, M.D., 1988. **Gravity surveys and interpretation, Eye-Dashwa Lakes pluton, Atikokan (RA-4), Ontario.** Atomic Energy of Canada Ltd., report AECL TR-438.

Whiteshell (Lac du Bonnet granite)

Stone, D., Kamineni, D. C., Brown, A., 1984. **Geology and fracture characteristics of the underground research laboratory lease near Lac du Bonnet, Manitoba.** Atomic Energy of Canada Ltd., report AECL TR-243.

INTERA Ltd, 1985. **Hydrogeological modelling of the underground research laboratory site: characterisation and prediction.** Atomic Energy of Canada Ltd., report AECL TR-345.

Ejeckam, R.B., Kamineni, D.C., Stone, D., Thivierge, R.H., 1988c. **Surface and subsurface geology of permit area G in Lac du Bonnet batholith, Manitoba.** Atomic Energy of Canada Ltd., report AECL TR-462.

Ophori, D.U., Stevenson, D.R., Gascoyne, M., Brown, A., Davison, C.C., Chan, T., Stanchell, F.W., 1995. **Revised model of regional groundwater flow of the Whiteshell Research Area: Summary.** Atomic Energy of Canada Ltd., report AECL-11286.

Stevenson, D.R., Brown, A., Davison, C.C., Gascoyne, M., McGregor, R.G.,Ophori, D.U., Scheier, N.W., Stanchell, F., Thorne, G.A., Tomsons, D.K., 1996a. **A revised conceptual hydrogeologic model of a crystalline rock environment, Whiteshell Research Area, Southeastern Manitoba, Canada.** Atomic Energy of Canada Ltd., report AECL-11331.

Stevenson, D.R., Kozak, E.T., Davison, C.C., Gascoyne, M., Broadfoot, R.A., 1996b. **Hydrogeologic characteristics of domains of sparsely fractured rock in the granitic Lac du Bonnet Batholith, Southeastern Manitoba, Canada.** Atomic Energy of Canada Ltd., report AECL-11558.

Tomsons, D.K., Lodha, G.S., Street, P.J., Auger, J.L.F., 1995. **A Bouger gravity anomaly map and geophysical interpretation of the geometry of the Lac du Bonnet batholith, Whiteshell Research Area, Southeastern Manitoba.** Atomic Energy of Canada Ltd., report AECL TR-633

Underground Research Laboratory (URL)

Read, R.S., 1990. **Methodology for the acquisition, analysis and presentation of geological data from the Underground Research Laboratory subsurface drilling program. Volume I and Volume II.** Atomic Energy of Canada Ltd., report AECL TR-484.

Guvanasen, V., Reid, J.A.K., Nakka, B.W., 1985. **Predictions of hydrogeological perturbations due to the construction of the Underground Research Laboratory.** Atomic Energy of Canada Ltd., report AECL TR-344.

Stone, D., Kamineni, D.C., 1988. **Structural analysis of the thrust fault at a depth of 271 to 275 meters in the underground research laboratory shaft.** Atomic Energy of Canada Ltd., report AECL TR-461.

Frost, L.H., 1997. **Underground Research Laboratory Shaft Excavation Drawdown Experiment: Estimate of hydraulic parameter values for moderately fractured rock.** Atomic Energy of Canada Ltd., report AECL TR-751.

Everitt, R.A., Chernis, P.J., Woodcock, D.R., 1995. **Compilation of fracture zones, lithostructural domains and alteration haloes from surface and subsurface geological information for the Underground Research Laboratory.** Atomic Energy of Canada Ltd., report AECL TR-534.

Gascoyne, M., Stroes-Gascoyne, S., Porth, R.J., Watson, R.L., 1996. **Investigation of the development of a salt-halo around excavations at the Underground Research Laboratory, Manitoba.** Atomic Energy of Canada Ltd., report AECL TR-733.

Young, R.P., Collins, D.S., 1997. **Acoustic emission/microseismic research at the Underground Research Laboratory, Canada (1987–1997).** Ontario Hydro Report No.: 06819-REP-01200-**0045**-R00.

Martino, J.B., Thompson, P.M., Chandler, N.A., Read, R.S., 1997. **The In Situ Stress Program at AECL`s Underground Research Laboratory, 15 years of research (1982–1997).** Ontario Hydro Report 06819-REP-01200-**0053**-R00.

Martino, J.B., 2000. **A review of excavation damage studies at the Underground Research Laboratory and the results of the excavation damage zone study in the tunnel sealing experiment.** Ontario Power Generation Report 06819-REP-01200-**10018**-R00.

Haveman, S.A., Stroes-Gascoyne, S., Hamon, A., Delaney, T.L., 1995. **Microbial analysis of groundwaters from seven boreholes at AECL`s Underground Research Laboratory.** Atomic Energy of Canada Ltd., report AECL TR-534.

Stroes-Gascoyne, S., 1997. **Microbial aspects of the Canadian used fuel disposal concept – Status of current knowledge from applied experiments**. Ontario Hydro, Report No.: 06819-REP-01200-**0026**-R00.

Ohta, M.M., Chandler, N.A., 1997. **AECL`s Underground Research Laboratory: Technical achievement and lessons learned.** Atomic Energy of Canada Ltd., report AECL-11760.

9.2.3 General, performance assessment

Although there are many parallels between the Canadian and Finnish programmes, it is clear that the Canadian programme is not as immediately relevant to the Swedish siting process as the Finnish one. For this reason, the lists above are less systematic and the texts less detailed. The Canadian research areas and the URL are far away, in a similar, but clearly significantly different geological environment, and the Canadian programme has not evolved beyond the research and development of site characterisation and modelling techniques, because of a completely different political climate. Nevertheless, the efforts of Canadian workers to develop the conceptual framework for site evaluation and performance assessment (e.g. *Whitaker et al 1994, Davison et al 1994a, 1994b, Goodwin et al 1994, Russell et al 1997*) and a preliminary safety assessment (summarised in *Wikjord et al 1996*) are of considerable interest for Swedish and Finnish authorities. For an overview of research reports from the whole of Canada's radioactive waste management programme up to 1990, see *AECL 1990*.

Whitaker, S.H., Brown, A., Davison, C.C., Gascoyne, M., Lodha, G.S., Stevenson, D.R., Thorne, G.A., Tomsons, D., 1994. **AECL strategy for surface-based investigations of potential disposal sites and the development of a geosphere model of a site.** SKB TR 94-18, Svensk Kärnbränslehantering AB.

Davison, C.C., Brown, A., Everitt, R.A., Gascoyne, M., Kozak, E.T., Lodha, G.S., Martin, C.D., Soonawala, N.M., Stevenson, D.R., Thorne, G.A., Whitaker, S.H., 1994a. **The disposal of Canada`s nuclear fuel waste: Site screening and site evaluation technology.** Atomic Energy of Canada Ltd., report AECL-10713.

Davison, C.C., Chan, T., Brown, A., Gascoyne, M., Kamineni, D.C., Lodha, G.S., Melnyk, T.W., Nakka, B.W., O'Connor, P.A., Ophori, D.U., Scheier, N.W., Soonawala, N.M., Stanchell, F.W., Stevenson, D.R., Thorne, G.A., Vandergraaf, T.T., Vilks, P., Whitaker, S.H., 1994b. **The disposal of Canada`s nuclear fuel waste: The geosphere model for postclosure assessment.** Atomic Energy of Canada Ltd., report AECL-10719.

Goodwin, B.W., Stephens, M.E., Davison, C.C., Johnson, L.H., Zach, R., 1994. **Scenario analysis for the postclosure assessment of the Canadian concept for nuclear fuel waste disposal.** Atomic Energy of Canada Ltd., report AECL-10969.

Russell, S.B., Goodwin, B.W., Villagran, J.E., Jensen, M.R., Kempe, T.K., 1997. **Performance assessment plan for the used fuel disposal project.** Ontario Hydro Report No:06819-REP-01200-**0018**-R00.

Wikjord, A.G., Baumgartner, P., Johnson, L.H., Stanchell, F.W., Zach, R., Goodwin, B.W., 1996. **The disposal of Canada`s nuclear fuel waste: A study of postclosure safety of in-room emplacement of used CANDU fuel in copper containers in permeable plutonic rock. Vol. 1: Summary.** Atomic Energy of Canada Ltd., report AECL-11494-1.

AECL 1990. **Radioactive waste management in Canada: AECL research publications and other literature 1953–1990.** Atomic Energy of Canada Ltd., report AECL-6186 (Rev. 5).

10 Broader context

The references in this Chapter outline the broader context of SKB's geoscientific research programme, especially as regards the siting process. They do not contain complete presentations of scientific methods and results, as the citations in earlier Chapters, except as examples or outlines of research published in technical reports. Since the titles are self-explanatory as regards aim and scope, they will not be commented here. They are arranged in Sections and Subsections according to the themes designated in the headings. Included are reports arising out of SKI's project SITE-94, and reviews of SKB's results by SKI and others.

10.1 SKB conceptual studies and planning

10.1.1 KBS-3 concept, siting process, evaluation criteria

KBS 1983. **Final Storage of Spent Nuclear Fuel – KBS-3.** Swedish Nuclear Fuel Supply Co./Division KBS.

SKB 1992b. **FUD-Program 92. Kärnkraftavfallets behandling och sluförvaring.** Svensk Kärnbränslehantering AB.

SKB 1994. **FUD-Program 92. Kompletterande Redovisning.** Svensk Kärnbränslehantering AB.

SKB 1998a. **FUD-program 98. Kärnkraftavfallets behandling och slutförvaring.** Svensk Kärnbränslehantering AB.

SKB 1998b. **Underlagsrapport till FUD-program 98. Detaljert program för forskning och utveckling 1999–2004.** Svensk Kärnbränslehantering AB.

Siting process

Scherman, S., 1978. **Förarbeten till platsval, berggrundsundersökningar.** KBS TR 60, Svensk Kärnbränslehantering AB.

Tunbrandt, S., 1992. **Sammanställning och analys av tillämpliga lagar vid lokalisering av ett djupförvar för använt kärnbränsle.** SKB PR 44-923-008. (tidigare nr LOK 92-08), Svensk Kärnbränslehantering AB.

McEwen, T., Balch, C., 1993. **Review of the status of siting radioactive waste repositories.** SKB PR 44-93-001, Svensk Kärnbränslehantering AB.

SKB 1995b. **General Siting Study 95 – Siting of a deep repository for spent nuclear fuel.** SKB TR 95-34, Svensk Kärnbränslehantering AB.

Leijon, B., 1998. **Nord-syd/Kust/inland. Generella skillnader i förutsättningar för lokalisering av djupförvar mellan olika delar av Sverige.** SKB R-98-16, Svensk Kärnbränslehantering AB.

Evaluation criteria

Andersson, J., Almén, K.-E., Ericsson, L.O., Frederiksson, A., Karlsson, F., Stanfors, R., Ström, A., 1997. **Parametrar att bestämma vid geovetenskaplig platsundersökning.** SKB R-97-03, Svensk Kärnbränslehantering AB.

Ström, A., Almén, K.-E., Andersson, J., Ericsson, L.O., Svemar, C., 1998. **Geovetenskapliga värderingsfaktorer och kriterier för lokalisering och platsutvärdering. Lägesredovisning.** SKB R-98-20, Svensk Kärnbränslehantering AB.

Ström, A., Almén, K.-E., Ericsson, L.O., Svemar, C., 1999. **Geoscientific evaluation factors and criteria for siting and site evaluation.** SKB R-99-07, Svensk Kärnbränslehantering AB.

Andersson, J., Ström, A., Svemar, C., Almén, K.-E., Ericsson, L.O., 2000a. **Vilka krav ställer djup-förvaret på berget? Geovetenskapliga lämplighetsindikatorer och kriterier för lokalisering och platsvärdering.** SKB R-00-15, Svensk Kärnbränslehantering AB.

Andersson, J., Ström, A., Svemar, C., Almén, K.-E., Ericsson, L.O., 2000b. **What requirements does a KBS-3 repository make on the host rock? Geoscientific suitability indicators and criteria for siting and site evaluation.** SKB TR 00-12, Svensk Kärnbränslehantering AB.

SKB 2000k. **Geovetenskapligt inriktat program för undersökning och utvärdering av platser för djupförvaret.** SKB R-00-30, Svensk Kärnbränslehantering AB.

SKB 2000l. **Geoscientific programme for investigation and evaluation of sites for the deep repository.** SKB TR 00-20, Svensk Kärnbränslehantering AB.

10.1.2 Performance, safety, risk

Scenario development, performance and safety assessment

Andersson, J., Carlsson, T., Eng, T., Kautsky, F., Söderman, E., Wingefors, S., 1989. **The joint SKI/SKB scenario development project.** SKB TR 89-35, Svensk Kärnbränslehantering AB. Statens kärnkraftinspektion, report SKI 89:14.

Eng, T., Hudson, J., Stephansson, O., Skagius, K., Wiborgh, M., 1994. **Scenario development methodologies.** SKB TR 94-28, Svensk Kärnbränslehantering AB.

Moreno, L., Gylling, B., Neretnieks, I., 1995. **Solute transport in fractured media – The important mechanisms for performance assessment.** SKB TR 95-11, Svensk Kärnbränslehantering AB.

Rosén, L., 1995. **Estimation of hydrogeological properties in vulnerability and risk assessments**. Doctoral thesis, Chalmers University of Technology, Göteborg.

Selroos, J.-O., 1996. **Contaminant transport by groundwater: Stochastic travel time analysis and probabilistic safety assessment**. Doctoral thesis, Royal Institute of Technology (RTH), Stockholm.

Smellie, J.A.T., Karlsson, F., 1996. **A reappraisal of some Cigar Lake issues of importance to performance assessment.** SKB TR 96-08, Svensk Kärnbränslehantering AB.

Elert, M., 1997. **Retention mechanisms and the flow wetted surface – implications for safety analysis.** SKB TR 97-01, Svensk Kärnbränslehantering AB.

SKB 1992c. **SKB-91. Final disposal of spent nuclear fuel. Importance of bedrock for safety.** SKB TR 92-20, Svensk Kärnbränslehantering AB.

Wiborgh, M. (ed.), 1995. **Prestudy of final disposal of long-lived low and intermediate level waste.** SKB TR 95-03, Svensk Kärnbränslehantering AB.

Final reports of the safety analysis project SR-97

SKB 1999a. **Deep repository for spent nuclear fuel. SR-97-post-closure safety. Summary. Volume I. Volume II.** SKB TR 99-06, Svensk Kärnbränslehantering AB.

SKB 1999b. **SR-97. Processes in the repository evolution.** SKB TR 99-07, Svensk Kärnbränslehantering AB.

SKB 1999c. **SR-97. Waste, repository design and sites.** SKB TR 99-08, Svensk Kärnbränslehantering AB.

Andersson, J., 1999. **SR-97. Data and data uncertainties. Compilation of data and data uncertainties for radionuclide transport calculations.** SKB TR 99-09, Svensk Kärnbränslehantering AB.

Pers, K., Skagius, K., Södergren, S., Wiborgh, M., Hedin, A., Morén, L., Sellin, P., Ström, A., Pusch, R., Bruno, J., 1999. **SR97 – Identification and structuring of process.** SKB TR 99-20, Svensk Kärnbränslehantering AB.

SKB 1999d. **Deep repository for long-lived low- and intermediate-level waste. Preliminary safety assessment.** SKB TR 99-28, Svensk Kärnbränslehantering AB.

Report series "Beskrivning av risk"

Hedin, A., 1997. **Använt kärnbränsle – hur farligt är det?** SKB R-97-02, Svensk Kärnbränslehantering AB.

Ahlström, P.-E., 1997. **Plutonium – data, egenskaper m m.** SKB R-97-10, Svensk Kärnbränslehantering AB.

Wallroth, T., 1997. **Vad betyder en istid för djupförvaret?** SKB R-97-11, Svensk Kärnbränslehantering AB.

Sellan. P., 1997. **Använt kärnbränsle – barriärernas säkerhetsmässiga betydelse.** SKB R-97-20, Svensk Kärnbränslehantering AB.

Morén. L., 1997. **Använt kärnbränsle – djupförvarets funktion och utveckling.** SKB R-97-21, Svensk Kärnbränslehantering AB.

Pettersen, L., Ringi, M., 1997. **Använt kärnbränsle – transporter.** SKB R-97-22, Svensk Kärnbränslehantering AB.

Jones, C., 1997. **Farliga ämnen i människans omgivning.** SKB R-97-23, Svensk Kärnbränslehantering AB.

10.1.3 Alternatives to KBS-3 as disposal concept

Ekendahl, A.-M., Papp, T. (eds.), 1998. **Alternativer metoder. Långsiktigt omhänderlagande av kärnbränsleavfall**. SKB R-98-11, Svensk Kärnbränslehantering AB.

PASS – Project on Alternative Systems

Pusch, R., Börgesson, L., 1992. **PASS – Project on Alternative Systems Study. Performance assessment of bentonite clay barrier in three repository concepts: VDH, KBS-3 and VLH.** SKB TR 92-40, Svensk Kärnbränslehantering AB.

Olsson, L., Sandstedt, H., 1992. **Project on Alternative Systems Study – PASS. Comparison of technology of KBS-3, MLH VLH and VDH concepts by using an expert group.** SKB TR 92-42, Svensk Kärnbränslehantering AB.

Birgersson, L., Skagius, K., Wiborgh, M., Widén, H., 1992a. **Project Alternative Systems Study – PASS. Analysis of performance and long-term safety of repository concepts.** SKB TR 92-43, Svensk Kärnbränslehantering AB.

Ageskog, L., Högbom, T., 1992. **Project on Alternative Systems Study – PASS. Cost comparison of repository systems.** SKB TR 92-44, Svensk Kärnbränslehantering AB.

SKB 1993b. **Project on Alternative Systems Study (PASS). Final report.** SKB TR 93-04, Svensk Kärnbränslehantering AB.

Werme, L., Eriksson, J., 1995. **Copper canister with cast inner component. Amendment to project on Alternative Systems Study (PASS), SKB TR 93-04.** SKB TR 95-02, Svensk Kärnbränslehantering AB.

WP-cave

Lindgren, M., Skagius, K., 1989. **SKB WP-Cave project. Radionuclide release from the near-field in a WP-Cave repository.** SKB TR 89-04, Svensk Kärnbränslehantering AB.

Moreno, L., Arve, S., Neretnieks, I., 1989. **SKB WP-Cave project. Transport of escaping radionuclides from the WP-Cave repository to the biosphere.** SKB TR 89-05, Svensk Kärnbränslehantering AB.

Bergström, U., Nordlinder, S., 1989. **Individual radiation doses from nuclides contained in a WP-Cave repository for spent fuel.** SKB TR 89-06, Svensk Kärnbränslehantering AB.

Björklund, S., Josefson, L., Moreno, L., Neretnieks, I., 1989. **SKB WP-Cave project. Some notes on technical issues. Part 1: Temperature distribution in WP-Cave: when shafts are filled with sand/water mixtures. Part 2: Gas and water transport from the WP-Cave repository. Part 3: Transport of escaping nuclides from the WP-Cave repository to the biosphere. Influence of the hydraulic cage.** SKB TR 89-07, Svensk Kärnbränslehantering AB.

Hopkirk, R.J., 1989. **SKB WP-Cave project. Thermally induced convective motion in groundwater in the near field of the WP-Cave after filling and closure.** SKB TR 89-08, Svensk Kärnbränslehantering AB.

SKB 1989. **WP-Cave – assessment of feasibility, safety and development potential.** SKB TR 89-20, Svensk Kärnbränslehantering AB.

Very deep boreholes and other concepts

Juhlin, C., Sandstedt, H., 1989. **Storage of nuclear waste in very deep boreholes: feasibility study and assessment of economic potential. Part I Geological considerations; Part II Overall facility plan and cost analysis.** SKB TR 89-39, Svensk Kärnbränslehantering AB.

Sandstedt, H., Wichmann, C., Pusch, R., Börgesson, L., Lönnerberg, B., 1991. **Storage of nuclear waste in long boreholes.** SKB TR 91-35, Svensk Kärnbränslehantering AB.

Juhlin, C., Wallroth, T., Smellie, J.A.T., Eliasson, T., Ljunggren, C., Leijon, B., Beswick, J., 1998. **The Very Deep Hole Concept: Geoscientific appraisal of conditions at great depth**. SKB TR 98-05, Svensk Kärnbränslehantering AB.

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