by Alan Geoffrey Milnes¹, Michael B. Stephens², Carl-Henric Wahlgren², and Liisa Wikström³

Geoscience and high-level nuclear waste disposal: the Nordic scene

1 GEA Consulting, Grand-Rue 7C, 2035 Corcelles (NE), Switzerland. E-mail: agmilnes@compuserve.com

2 Geological Survey of Sweden, Box 670, 75128 Uppsala, Sweden. E-mail: michael.stephens@sgu.se and carl-henric.wahlgren@sgu.se

3 Posiva Oy, 27160 Olkiluoto, Finland. E-mail: Liisa.Wikstrom@posiva.fi

In Norden, two countries, Sweden and Finland, are actively engaged in site investigations for the location of deep repositories for spent nuclear fuel from power-producing nuclear reactors. These investigations are being carried out in crystalline rocks of the Fennoscandian Shield. In Sweden, a long history of site selection has led to the identification and investigation of two sites, Forsmark and Laxemar/Simpevarp, based on a strategy of combining favourable bedrock with consent by the local population. Surface-based geoscientific investigations of the two candidates, with extensive deep drilling, are now drawing to a close. A proposal as to which of the sites would be most suitable for the development of a deep repository will be submitted to the governmental regulatory authorities in 2009. In Finland, the site selection process was shorter and less politically controversial, and led to a "Decision in Principle" by the Finnish parliament, in May 2001, to develop a deep repository at the Olkiluoto site. The access tunnel to an underground rock characterisation facility at 400–500 m depth is at present under construction, accompanied by extensive geoscientific investigations in the subsurface. An application for a construction licence for a deep repository will be submitted in 2012. Although all sites are located in Precambrian crystalline rocks, the Swedish sites both lie in relatively homogeneous granitic rocks, whilst the Finnish site is located in an heterogeneous migmatite complex. The Nordic approach to high-level nuclear waste disposal in crystalline rock will be the theme of a Topical Symposium at the 33rd International Geological Congress at Oslo, in August 2008, and the three sites mentioned above will be the focus of Congress Excursion no. 14.

Introduction

Nuclear wastes from nuclear power production occur in solid, liquid and gaseous forms and in a variety of isotopic compositions and radiation intensities, depending on reactor type, production strategy and processing method. They can be roughly subdivided into two main categories (Milnes, 1985): low-level waste (LLW) and high-level waste (HLW). This subdivision is based on an estimation of the long-term health hazard posed by the waste, which is roughly related to its content of long-lived radioisotopes, such as plutonium, which

emit α -particles and are thus highly radiotoxic if inhaled or ingested. For the purposes of this brief overview, HLW will encompass various radioactive waste categories, including spent nuclear fuel, vitrified reprocessing waste, and intermediate-level waste (ILW, see Miller et al., 2000), which all contain long-lived radioisotopes. Waste has to be solidified and packaged prior to disposal in a repository. Emphasis is on the *geological aspects* of nuclear waste disposal, and these are similar for all the different categories of HLW.

To a first approximation, LLW can be regarded as material that is not initially heat-producing and which must be isolated from the biosphere for 100 to 1,000 years, after which it becomes innocuous from the point of view of its radioactivity. HLW, by contrast, must be isolated for much longer times, because of its content of long-lived radioisotopes. The period generally used as a guideline for developing appropriate disposal concepts for HLW is 100,000 to 1,000,000 years, which brings geology into the forefront of nuclear waste research. Based on our knowledge of human history, LLW management could include some degree of social commitment, i.e., disposal concepts depending on monitoring, surveillance, and, if necessary, remedial action. However, HLW remains potentially hazardous for times much longer than the life span of the most stable of human societies and must be managed accordingly, i.e., disposal must depend largely on engineered barriers and the behaviour of natural systems, although some degree of supervision is usually envisaged in the initial stages.

Geoscience, therefore, has been heavily involved in the problem of HLW disposal since the development of nuclear energy for peaceful purposes started in the 1950s. In Norden, Norway and Denmark decided not to develop nuclear power for electrical energy production and hence have not been directly involved in disposal-related geoscientific research. In contrast, Sweden built a total of 12 nuclear power stations during the 1970s and 1980s (now reduced to 10, but with retained capacity), and, since 1975, has played a leading role internationally in geoscientific research related to HLW disposal in deep repositories in fractured crystalline rock. During the same period, 4 nuclear power stations were built in Finland and a fifth facility is at present under construction. Since the 1980s, the problem of disposal within Finland has been the subject of intensive geoscientific research, in close cooperation with Swedish scientists due to the similarity of the disposal concepts in the two countries. Both Sweden and Finland have followed the "once-through" option for dealing with the HLW disposal problem, i.e., the spent nuclear fuel is considered as "waste", to be disposed of directly within the country boundaries and not to be transported abroad for reprocessing. In the following text, we concentrate on the present status of disposal-related geoscientific research for spent nuclear fuel in these two Nordic countries, after a short historical sketch of the site selection process in each case.

Historical sketch, Sweden and Finland

A large part of Sweden and all of Finland are underlain by the thick cratonic crust of the Fennoscandian Shield (Figure 1), which predominantly formed towards the end of the Paleoproterozoic and has been relatively stable ever since. However, the edges of the craton were affected by younger orogenic activity (e.g., Gothian, Hallandian, Sveconorwegian, Caledonian) and the craton itself was segmented by faulting in different periods (late Paleoproterozoic, Mesoproterozoic, Neoproterozoic, Paleozoic), as well as having been flexured by the growth and decay of continental ice sheets several times (Neoproterozoic, Pleistocene, and expected in the geologically near future). The fracturing and faulting related to this segmentation and flexuring are the focus of most of the geological, hydrogeological and rock mechanics investigations in the two countries, which both favour a deep repository (500 m below the surface), in combination with a multi-barrier disposal system. The aim of the necessary safety analyses is to show that the proposed systems guarantee isolation from the biosphere without supervision for 10^5 to 10^6 years. The repository concept also allows access, if necessary, by future generations. The locations of the Swedish sites and the Finnish site at present under investigation, which are described below, are shown in Figure 1. A more detailed summary of the geoscientific work carried out during the site selection process in both Sweden and Finland is to be found in Milnes (2002).

Figure 1 Overview geological map of the Fennoscandian Shield, showing the location of the three main sites which are being studied as potential repository sites for spent nuclear fuel in Sweden (Forsmark and Laxemar/Simpevarp) and in Finland (Olkiluoto).

In Sweden, nuclear power and its future became one of the main political themes during 1976 and 1977, culminating in a change of government in the April 1977 elections. The new government immediately passed the "Stipulation Law" 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 then nuclear waste company initiated the so-called KBS project, which aimed, among other things, at synthesizing geoscientific data on a national scale as a prerequisite to screening the country for suitable repository sites. However, 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 continued, and studies in varying degrees of detail were carried out at several sites by various bodies. However, this work often provoked the local nuclear opposition and helped to create the polarized atmosphere which culminated in the 1980 referendum on the future of nuclear power in Sweden. Nevertheless, the geoscientific work carried out in this period contributed to an important report, the KBS-3 report, which was completed in May 1983 and laid the basis for the present HLW disposal research programme. In 1985, radioactive waste management in Sweden was reorganised, resulting in the founding of the Swedish Nuclear Fuel and Waste Management Company (SKB). From that point on, all disposal-related work 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.

The siting concept which had evolved up to 1985, and which was embedded in the KBS-3 report, was that Sweden could be subdivided into geological provinces, which are more or less favourable for a deep KBS-3-type repository. The province which was considered most favourable was the Precambrian basement complex in the Fennoscandian Shield, a vast area of crystalline, plutonic and metamorphic rocks. From 1985 to 1992, detailed investigations of individual study sites at different locations within this basement complex were carried out and final reports on all investigations, which had been carried out at six of the sites, were published in 1991–1992. In addition, a large amount of problem-oriented information from SKB-financed operations at several other localities became available. 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 metres below the surface. The main objective with the study sites was to obtain geoscientific information at depth in different geological settings, as well as to test and develop techniques, equipment, concepts, assessment methods, etc. This work was supported and complemented by results from the International Stripa Project, which was managed by SKB and located in the abandoned Stripa iron mine (SKB, 1993), and by pre-investigations for the construction of the Äspö Hard Rock Laboratory. In 1992, the Swedish government requested SKB to present a supplementary study to the current research and development programme, specifying in detail the planned scope and content of the siting programme, including the technical and other requirements on which site selection would be based (SKB, 1994). This strategy was later accepted by the Government and has since been the basis of the siting process in Sweden.

The starting point of the strategy is that no areas within the Swedish part of the Fennoscandian Shield can be excluded from consideration as a potential site for a HLW repository on general grounds, and that there is no way of distinguishing more favourable and less favourable areas without carrying out project-oriented 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. Furthermore, the identification of an homogeneous bedrock was favoured. Overview studies were subsequently carried out over the whole country on a county-by-county basis, and feasibility studies in more detail, with field checks, in several municipalities. Local acceptance and local cooperation were taken as a prerequisite for carrying out a

feasibility study at the municipality level ("strategy of consent"). In all, feasibility studies were carried out in eight municipalities between 1993 and 2000. These feasibility studies identified many favourable areas, both at county and municipality level. Following a control by the regulatory authorities and a "strategy of consent" from the respective municipalities, specific site investigations, including deep drilling, were started during 2002 at two identified favourable areas, Forsmark and Laxemar/Simpevarp, as outlined below.

In Finland, there has been close cooperation between the Swedish implementing body, SKB, and the corresponding 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 cooperative efforts. However, the siting process diverged considerably from that of Sweden (see McEwen and Äikäs, 2000). Already in 1983, the Finnish 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 photograph interpretation (rock blocks), together with a consideration of environmental and societal factors. After discussions with the relevant municipalities, five sites inside these areas 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 (Olkiluoto, Kivetty, Romuvaara), including a second series of deep cored drillholes. Later, a fourth site was added after a positive feasibility study (Hästhölm), and a crash investigation programme was initiated there, to bring investigations up to the same level as the other three sites by the 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". However, the municipality in which the Olkiluoto site lies had already agreed to allow it to be developed as a potential deep repository site over the next 10 years, if the decision was positive. Hence, Posiva had published a preliminary RDD plan (research, development, technical design) for underground investigations at Olkiluoto, which would lead to the application for a construction licence around 2012. 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. Afterwards, Posiva concentrated its efforts on Olkiluoto and underground investigations started in 2004, with the start of excavation of the access tunnel to the planned underground research and characterisation facility, ONKALO, as outlined below.

Present status and future outlook, Sweden

The prime objective of the site characterisation at Forsmark and Laxemar/Simpevarp (Figure 1) is to locate a repository for spent nuclear fuel at c. 500 m depth in crystalline rock, which fulfils the safety requirements established by the governmental regulatory authorities. Both sites are composed of Paleoproterozoic rocks and are situated in the western part of the Fennoscandian Shield (Koistinen et al., 2001 and Figure 1).

As far as geological aspects are concerned, the following tasks have been completed during the period 2002–2007:

- Geological mapping of the crystalline bedrock and Quaternary cover at the surface.
- Acquisition of airborne (helicopter) and higher-resolution surface geophysical data.
- Acquisition of high-resolution reflection and refraction seismic data at the surface.
- Extensive cored drilling down to c. 1000 m depth, and percussion drilling down to c. 200 m depth with associated geological and geophysical logging work.
- Vertical seismic profiling along selected cored boreholes.
- Acquisition of mineralogical, geochemical, petrophysical, structural geological and geochronological analytical data, both at the surface and along boreholes.

The acquisition and evaluation of fracture mineralogical and geochronological data have been completed in the framework of four Ph.D studies at the Universities of Göteborg and Lund.

Following the acquisition of data at each data freeze, analytical and modelling work has been completed. These tasks comprise the iterative steps of identification, control and evaluation of primary data, descriptive and quantitative modelling in 3-D space and an assessment of uncertainties. A site descriptive model (SDM) is an integrated model for geology, rock mechanics, thermal properties, hydrogeology and hydrogeochemistry, and a description of the surface system.

The geological models at both sites address rock domains and deformation zones in a deterministic manner. Aspects of penetrative ductile deformation at the Forsmark site are included in the rock domain model. By contrast, the fractures inside the bedrock between deformation zones are addressed in a stochastic manner. At Forsmark, the strongly anisotropic character of the bedrock has provoked the need for its division into fracture domains, prior to the execution of the stochastic modelling procedure (Olofsson et al., 2007). In order to address the problems encountered with variable data resolution in different volumes, models at different scales have been constructed at both sites. The site descriptive models for Forsmark and Laxemar, version 1.2 (SKB, 2005, 2006a) formed the basis for a preliminary repository layout at each site (SKB, 2006b,c). Furthermore, both these site descriptive models and the respective preliminary layouts provided a basis for the first evaluation of the long-term safety for potential KBS-3 repositories at Forsmark and Laxemar (SKB, 2006d).

In essence, two contrasting types of geological process have affected the bedrock at the two sites. Tectonic activity occurred at different time intervals, predominantly during the Proterozoic, and produced the compressional structures with a conspicuous component of strike-slip deformation as described below. As the effects of tectonic activity, for the most part, waned, the effects of loading and unloading in connection with the deposition and uplift/erosion, respectively, of sedimentary material during, for example, the Phanerozoic increased in significance.

Forsmark

The Forsmark site is located along the eastern coast of Sweden, approximately 120 km north of Stockholm (Figure 1). It lies within a major deformation belt which extends several tens of kilometres across the WNW to NW strike of the rocks. In this belt, rocks show high ductile strain anastomosing around tectonic lenses, within which the bedrock is folded and generally affected by lower ductile strain. The ductile deformation, which formed under amphibolite-facies metamorphic conditions at mid-crustal levels, has contributed to the development of a strong bedrock anisotropy (Figure 2).

The potential repository is situated inside one of these tectonic lenses, directly to the southeast of the nuclear power station at Forsmark (Figure 2). Regionally important, discrete deformation zones occur solely within the broader, high-strain rocks around the tectonic lenses at the site (Figure 2). They dip steeply and are retrograde in character with both ductile and polyphase brittle strain. The bedrock is dominated by granitoids with subordinate ultramafic, mafic and

Figure 2 3-D regional model (stage 2.2) for selected rock domains and steeply dipping, regional deformation zones at Forsmark. View from the south. The focussed volume for the potential location of a repository is situated in rock domain 29 (RFM029R). R indicates regional model, directly to the southeast of the nuclear power station and in the hinge of a major synform that plunges moderately to steeply to the southeast.

intermediate rocks (Figure 2). An older plutonic suite of meta-intrusive rocks, dated to 1.89–1.87 Ga, was affected by penetrative ductile deformation under amphibolite-facies metamorphic conditions prior to the intrusion of a younger granitoid suite, dated to 1.86–1.85 Ga (Hermansson et al., 2007, in press). The latter intruded during the waning stages of and after this major compressional tectonic event. Younger ductile strain at lower metamorphic grade was concentrated along the regional deformation zones and culminated with a regional uplift at c. 1.80 Ga. The bedrock was able to respond to deformation in a brittle manner prior to 1.70 Ga.

Metagranite with a high content of quartz (24–46%), which is partly altered to a finer-grained, quartz-plagioclase rock, dominates the focussed volume inside the tectonic lens that has been selected for the potential location of a repository. Steeply dipping fracture zones strike ENE to NNE across the potential repository at c. 500 m depth (Figure 3a). The damaged and core parts of these predominantly strike-slip zones are up to a few tens of metres thick and contain a high frequency of sealed fractures. Only two of these zones (ENE60A and ENE62A in Figure 3a) show a trace length at the

ground surface that is greater than 3 km. Some gently, south- and SE-dipping, hydrogeologically conductive fracture zones (e.g., A2 in Figure 3) occur in the rock volume above 500 m depth, but such zones are far more conspicuous to the southeast of and outside the potential repository volume (Juhlin and Stephens, 2006 and Figure 3a). The gently dipping zones show evidence for reverse dip-slip and strike-slip displacement.

The bedrock above the potential repository, down to a maximum depth of c. 200 m (see base of fracture domain FFM02 in Figure 3b), shows a relatively high frequency of sub-horizontal and gently dipping fractures with apertures, and is hydrogeologically conductive. It is suggested that unloading of younger sedimentary material resulted in the reactivation of especially sub-horizontal and gently dipping fractures in the form of extensional failure and the development of joints (Juhlin and Stephens, 2006). Newly formed fractures in the form of sheet joints may also have formed in connection with unloading.

Figure 3 2-D cross-sections in the crystalline bedrock at Forsmark, based on regional model stage 2.2. The lines of section and the local model volume stage 2.2, where the potential repository is situated, are shown in the lower part of the figure. Yellow = felsic metavolcanic rock, dark green = metagabbro (1.89 Ga), dark brown = metatonalite (1.88 Ga), dark brown with black dots = strongly foliated metagranodiorite and metatonalite (1.88 Ga), pale brown = metagranite (1.87 Ga), pale brown with black dots = strongly foliated metagranite (1.87 Ga), beige with black dots = strongly foliated metagranite partly altered to quartz-plagioclase rock. Continuous black line = fracture zone, dashed black line in section (a) = fracture zone situated outside section line and included only in local model, dashed black line in section (b) = base of the more strongly fractured domain FFM02, continuous blue line = borehole. The c. 500 m elevation level inside the focussed volume is shown by a red line.

This phenomenon is coupled with a release of stress in the bedrock and is most conspicuous close to the surface interface and in the vicinity of the geologically ancient, gently dipping zones. For this reason, the bedrock above c. 200 m depth in the modelled repository volume forms a separate fracture domain from the bedrock at repository depth.

Laxemar/Simpevarp

The Laxemar/Simpevarp site is located along the southeastern coast of Sweden, approximately 230 km south of Stockholm (Figure 1). The bedrock is dominated by a 1.80 Ga suite of granitic, granodioritic, monzodioritic and gabbroic rocks belonging to the 1.86–1.65 Ga Transscandinavian Igneous Belt (Figure 4). Furthermore, two 1.45 Ga old granites occur, both north and south of the focussed volume (Figure 4). In contrast to the Forsmark site, the bedrock is mainly composed of well preserved igneous rocks, with little sign of ductile deformation, except for some low-grade ductile high-strain zones of mesoscopic to regional nature. These deformation zones are interpreted to have formed shortly after the emplacement and crystallization of the parent magmas, i.e., shortly after 1.80 Ga.

The focussed area for the potential location of a repository is situated in the southern part of the Laxemar subarea, west of the nuclear power station along the Simpevarp peninsula. The dominant rock types comprise equigranular quartz monzodiorite and finely porphyritic quartz monzodiorite to granodiorite (“Ävrö granite”). They show a conspicuously lower content of quartz (10–25 %) relative to the dominant rock types at Forsmark. Important subordinate rock types are smaller bodies of diorite to gabbro, and dykes, lenses and irregular small bodies of fine-grained granite, pegmatite and fine-grained mafic rock. The latter commonly occur as composite intrusions together with fine-grained granite.

Deformation zones strike NE, NW and NS, and dip steeply or are vertical (Figure 5). They include both ductile structures reactivated in a polyphase manner in the brittle regime and zones that are essentially brittle in character. By contrast, zones with EW strike are inclined (40–60°) with both northerly and southerly dips (Figure 5). The most prominent ductile deformation zones with NS to NE strike and sub-vertical dips show sinistral, strike-slip kinematics. One of the NE-striking zones, the so-called Äspö shear zone, separates the Laxemar and Simpevarp sub-areas. Ductile deformation zones with E-W strike are compressional and, if inclined, show reverse displacements. The kinematics of the brittle deformation along the zones has so far not been resolved.

Figure 4 3-D regional model (version Laxemar 1.2) for rock domains at Laxemar/Simpevarp. Apart from some granite dated to 1.45 Ga, all rocks are 1.80 Ga in age. Red = granite (1.45 Ga), pink = quartz monzodiorite, purple = fine-grained granite, yellowish green = diorite to gabbro, dark green = “Ävrö granite” mixed with frequent diorite to gabbro, light green = fine-grained dioritoid, grey = high frequency of ductile shear zones. The transparent domain (black) is composed of “Ävrö granite”. The inset map provides a top view. FV = focussed volume.

Figure 5 Deformation zones in the local model volume in the Laxemar sub-area. Red = zones with a high confidence of existence, green = zones with a medium confidence of existence, grey = zones with a low confidence of existence. FV = focussed volume.

Future outlook

At the time of writing of this paper, multidisciplinary work, in connection with model stages 2.2 and 2.3, are in progress at both sites. The models produced during this work will form the basis for the final repository layout. The final site descriptive models for the two sites, as well as the final assessment of their long-term safety, will be completed during 2008–2009. The selection of a repository site will be decided and the motivation documents submitted to the governmental regulatory authorities during 2009.

Present status and future outlook, Finland

As described above, the nuclear waste disposal organization in Finland, Posiva, was granted a “Decision in Principle” in May 2001 by the Finnish parliament. Even though the work continued following submittal of the application, this democratic support provided a major impetus for drawing up detailed plans for the underground activities at the Olkiluoto site. A report on baseline conditions (Posiva, 2003a) and a detailed plan of the proposed underground investigations (Posiva, 2003b), based on the earlier site report (Anttila et al., 1999), were finalised before the construction of the access tunnel to the planned underground research and characterisation facility, ONKALO, was started in August 2004. The ONKALO access tunnel is located in the central part of Olkiluoto island and in the central part of the well-investigated area (Figure 6).

ONKALO

The ONKALO access tunnel is constructed for investigation purposes, but it is anticipated that it will probably be included in a licence application as a part of the repository access tunnel. It is constructed with the traditional drill and blast method. However, for better control of the excavation disturbed zone (EDZ), emulsion charging was adopted in 2006. The tunnel advances approximately 30 m per week, and the blasting takes place in about 5 m rounds. The construction work is scheduled for tunnelling to reach the main investigation level at about 420 m by the end of 2009. The first lesson learnt was that it always takes time, in this case, about half a year, before the parallel construction work and systematic geoscientific investigations can proceed smoothly.

Figure 6 Upper: Olkiluoto island with existing drill holes, the ONKALO access tunnel and the cube defining the nominal volume of the Olkiluoto site area, which also represents the well-investigated area. Lower: Proposed layout of ONKALO facility and the access tunnel. View from the southwest.

In constructing the access tunnel, pilot holes are drilled within the tunnel perimeter to check the existence and the exact location of predicted deformation zones and other features, and to assess the rock quality. These pilot holes are subsequently excavated away. The length of the drillholes varies between 100–200 m. These cored boreholes are used for design, construction and investigation purposes, e.g., the layout design can be adjusted if a really significant feature is encountered. Furthermore, pre-grouting planning is based on pilot hole information and the investigations along, as well as the information from, these boreholes are used especially for prediction-outcome studies and for updating the ONKALO area model.

The mapping of walls and roof along the tunnel proceeds together with the construction work. The tunnel is mapped for construction and work safety purposes, i.e., reinforcement and grouting needs, after each round. However, systematic geological mapping is carried out approximately 100 m behind the face, due to time limitations and working safety. The grouting of the tunnel is a very important part of the construction work. The tunnel needs to be as dry as possible to avoid the up-coning of saline water from deeper levels. At the moment, the limiting value for the water leakage into the tunnel is set at 2 l/100 m tunnel, and, so far, this has not been exceeded. Furthermore, Posiva is developing low-pH cement for the grouting purposes deeper down in the repository level to avoid the high-pH plumes caused by usual grouting material, which could affect the isolation capacity of the bentonite buffer.

Investigations both on the surface and underground proceed at the same time as the construction work along the tunnel. The number of drillholes is optimised in order to provide enough information, but to avoid too many holes from the surface to the repository level. At the present time, no deep investigation holes (length 500–1000 m) are now drilled in the central part of the investigation area. Surface

investigations are focussed on an extension of the investigation area towards the east. In the ONKALO area, the surface investigations are complemented by characterisation holes drilled from underground locations along the ONKALO tunnel.

Olkiluoto

The latest interpretation of the geology of the Olkiluoto site is presented in Andersson et al. (2007). The bedrock at Olkiluoto mostly comprises supracrustal rocks, metamorphosed under upper amphibolite-facies conditions, the source materials of which are epiclastic and pyroclastic sediments. These rocks are variably migmatitic and contain abundant veins and irregular masses of pegmatitic granite. The whole complex has undergone multiple deformation (several phases of folding, some coeval with migmatisation), and is cut by a few, narrow, post-tectonic, mafic dykes. In terms of their mineral composition, texture and migmatite structure, the rocks of Olkiluoto can be divided into four major classes: 1) migmatitic gneiss, 2) TGG gneiss, 3) gneiss and 4) pegmatitic granite. The migmatitic rocks can further be subdivided into stromatic gneiss, veined gneiss and diatexitic gneiss on the basis of their migmatite structures. Radiometric age dating indicates that the migmatisation took place between 1.89 and 1.87 Ga., i.e., coeval with the formation of the older meta-intrusive rocks at Forsmark (see the Forsmark section). Comprehensive petrographic and geochemical description of the lithologies is presented in Kärki and Paulamäki (2006) and the methodology of treating the anisotropy and heterogeneity of these rocks is described in Milnes et al. (2006).

Based on the 2006 site description (Andersson et al., 2007), the Olkiluoto bedrock has a more fractured and, hydrogeologically, more conductive part, containing meteoric (depth of 0–30 m) and brackish water ($\text{TDS} < 10 \text{ g/l}$), in the upper 100 to 150 m. These features are also present in the ONKALO tunnel. Below this depth, down to the –300 m level, the rock is clearly less fractured. At the –300 m level, a group of sub-horizontal deformation zones, with clearly increased hydraulic conductivity and fracturing, are inferred to be present. At the repository level, between 400 and 500 m, the rock is expected to be clearly less fractured and less conductive than in the zone above, but to contain saline groundwater ($\text{TDS} > 10 \text{ g/l}$). The repository block is expected to be limited by the large, hydraulically conductive, sub-horizontal to gently SE-dipping deformation zone at a depth of approximately 600 m in the ONKALO area. The highest salinity met in Olkiluoto of 84 g/l is encountered close to 1000 m depth.

With regard to the modelling of deterministic structures, the latest published version is the Geological Site Model, version 0 (Paulamäki et al., 2006). The model consists of four sub-models, the ductile deformation model, the lithological model, the alteration model and the brittle deformation model, which, although closely interdependent, are distinguished for practical reasons. A new version of the model, version 1.0, is already constructed and the main advances are the integration of the different sub-models, the inclusion of conceptual models and the increased understanding of the geological history of the site. As an example of the integration of the sub-models, the site-scale sub-horizontal deformation zone underneath the repository block is associated with large bodies of illite alteration (Figure 7), indicating that the faults have acted as pathways for the circulation of hydrothermal fluids. In addition, major improvements in the sub-models for alteration, ductile deformation and brittle deformation have been included, compared to the 2006 model. An extensive amount of detailed kinematic data from fractures in all the drill cores was collected between 2004 and 2005. These data have now been applied to reconstruct the kinematic history of the main fault zones.

One of the main developments during the modelling work has been the application of prediction-outcome studies. Before the construction of each tunnel segment, different characteristics of the bedrock, i.e., geological features, rock mechanical behaviour and hydrological characteristics, are predicted based on existing models, and available data and pilot holes. After the excavation of the tunnel

Figure 7 Illitisation in relation to the main faults of the Olkiluoto site area. Illitisation is shown as green volumes and faults as brown surfaces. View from the east.

segment, the actual observed relationships (“outcome”, mainly based on tunnel mapping) are compared to the predictions. With this method, the predictive capacity of the models as well as the degree of site understanding is continuously tested. The method is planned to be developed further, to be used in future at the repository level to define suitable areas for the deposition tunnels and canister holes.

Future outlook

In the future, Posiva is heading towards the licencing process, to demonstrate the long-term safety capability of the whole repository system, together with an application for a construction licence for the repository around 2012. The operation of the repository is planned to be started at 2020.

Concluding remarks

The title of this short paper, geoscience and high-level nuclear waste disposal, has two sides. Here we have concentrated on one of these: the significance of geoscientific research for providing insights and solutions relevant to one of the most burning current environmental problems—one for which, because of the long time intervals involved, geoscientists are particularly qualified to address. However, the other side of the coin should not be forgotten, and may be equally important. Nuclear waste disposal and the history and politics of nuclear energy have provided a background against which a vast amount of human and material resources have been invested in geoscientific investigations, which would otherwise not have been carried out. The detailed knowledge of the petrology, structural geology including brittle deformation, hydrogeology and geophysics of selected areas and sites, both surface and subsurface, of the Fennoscandian Shield, together with the techniques and methodologies, which have been developed and subject to continuous scientific scrutiny, will provide a permanent contribution to geoscience of enormous value in the future. Both SKB and Posiva follow a policy of transparency with regard to geoscientific data: all recent technical, progress and working reports can be downloaded free of charge from the company web sites: www.skb.se and www.posiva.fi, which also instruct how to order free hard copies of earlier reports.

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Alan Geoffrey Milnes is currently working as a geoscientific consultant. He was formerly Titular Professor at the Swiss Federal Institute of Technology (ETH) in Zürich and Professor of Geology at Bergen University with speciality in structural geology and tectonics. Since the mid-1970s he has been involved in the problem of radioactive waste disposal, mainly in Switzerland, Sweden, Finland and Lithuania, and has worked for both the nuclear safety authorities and the nuclear waste disposal institutions. His particular area of expertise is site characterisation and geological modelling for deep repositories in structurally complex crystalline rocks, and more generally in continental geodynamics.

Carl-Henric Wahlgren is currently employed as a senior geologist at the Geological Survey of Sweden. He completed a Ph.D study at the University of Lund, prior to employment at the geological survey, where he has carried out structural geological and tectonic studies in the Fennoscandian Shield in southern Sweden. Since 1996, he has been working on a commission basis for SKB, and, since 2002, he has been working with geological investigations and modelling at the Laxemar/Simpevarp site.

Michael Bernard Stephens is currently employed as a senior geologist at the Geological Survey of Sweden. Following education at the University of Cambridge and a Ph.D study at the University of Leicester, he was employed at the universities of Melbourne, Stockholm and Oslo, and subsequently the geological survey. He has carried out structural geological and tectonic studies in the Scandinavian Caledonides, southeastern Australia and the Fennoscandian Shield. Since 1996, he has been working on a commission basis for SKB, and, since 2002, his work has involved geological investigations and modelling at the Forsmark site.

Lüsa Wikström is currently Research Manager of the Geology and Geophysics section of Posiva Oy, the nuclear waste management company in Finland. She received her M.Sc in geology from Åbo Akademi university in 1996. She joined Posiva Oy in 1997 as a geologist and has subsequently worked with site investigations. She became Chief Geologist at Posiva Oy in 2003 and, since then, has been responsible for the geological modelling work. She has served on the Boards of the Geological Society of Finland and the Geological Section of the Finnish Association of the Mining and Metallurgical Engineers.