3 Precambrian Bedrock – a good environment for a safe disposal of spent nuclear fuel[1]

3.1 Introduction

Since the beginning of the 1980's, the Swedish Precambrian bedrock has been seen as the leading alternative for the permanent disposal of spent fuel from the Swedish nuclear-power industry. An officially approved method for disposal of nuclear waste has not yet been established in Sweden, but the leading method under consideration includes, as it does in most countries, a geological permanent storage. The thought is that a storage facility several hundred meters below the surface in bedrock would offer a stabile environment for storage of the spent-fuel capsules.

In this chapter, we describe the current understanding of the Precambrian bedrock of Sweden. In the debate on safe disposal of nuclear wastes, one quickly ends up in speculative discussions on, for example, the timing of the next ice age, the possibilities of future earthquakes, the climatological conditions for permafrost, etc. In all of these issues, the character of the bedrock is of decisive importance.

The debate has also been intense concerning the siting of the storage facility. The consequences of a future leakage and the effectiveness of the various barriers in a long range perspective have been investigated.

The barriers that are included in the planned disposal facility are, in addition to the fuel itself in its casings, (1) the capsules in

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[1] This chapter has been produced at the Institute of Geoscience, Gothenburg University, by Professor Jimmy Stigh (Member of KASAM) and Professor Sven Åke Larson.

which the fuel is kept, (2) the bentonite-clay layer that surrounds the capsules, and finally (3) the bedrock, which holds the clay and the capsules. These barriers function in different ways. The capsule encloses the radioactive materials, the bentonite-clay layer limits and retards the release of contaminants if the capsule were to begin leaking, and the bedrock provides protection and a final barrier over the long term. The bedrock, thus, is the last link in a series of connected barriers. In case of a potential leakage, the radioactive material could find its way through the bentonite layer and contaminate the groundwater present in the bedrock. Groundwater flow and chemistry are thus a strong control on the spread of these materials. The groundwater chemistry influences both the dissolution of the fuel and the transport of the radioactive materials through the bedrock aquifer. Dissolved ions in the groundwater can give rise to corrosion, even of the fuel capsules. The bedrock is also of importance as a kind of filtering device for the radioactive materials, because different minerals in the bedrock have the ability to bind and sequester many of the radioactive elements not caught by earlier barriers. Because groundwater moves along small cracks and fractures in the bedrock, the radioactive elements can get caught or their transport can be delayed, so that the radiation risk is reduced before the ground surface is reached.

3.2 Time aspects

A decisive factor is the repository stability over a very long time frame – up to 100 000 years. This time frame can seem nearly infinite from a human perspective, but geologically, it is a very short period of time. For example, the geologic history of Sweden is long – the majority of Sweden's bedrock is 1 500 to 2 000 million years old.

How is one able to know that certain portions of our bedrock are of the venerable age of a billion years? It is possible to date a rock sample with the help of naturally occurring radioactive elements. This is done by measuring the radioactive decay in the sample of Uranium to Lead, for example, or Rubidium to Strontium.

In order to achieve some comprehension of the enormous span of time represented, let us translate the age of the Earth (about 4 500 million years) to one 24-hour day. Every hour represents about 200 million years. Most of Sweden's bedrock was made eight to ten hours ago, and the last Ice Age began two seconds ago.

3.3 The bedrock

Our assessment of the importance of the bedrock for the long-term stability of the repository is dependent on the state of our knowledge of the Precambrian bedrock. One proceeds from the assumption that the bedrock will likely remain stabile for over a 100 000-years. There are a large number of factors that can influence a spent-fuel repository. These factors can include characteristics and processes inherent to the facility itself or external factors. These external factors include, for example, future glaciations, active faulting in the bedrock, permafrost, and change in sea level or in the groundwater table, as well as human-caused changes, either in groundwater quality or by a direct human infringement into the facility.

The decisive factor for this future permanent storage facility within Sweden's borders is the availability of stabile bedrock. A region's stability is determined by its plate-tectonic setting. Plate tectonics is the set of processes that include spreading at the mid-ocean ridges, where new ocean floor is made volcanically and where the Earth's crustal plates diverge at right angles away from each other, as well as subduction along ocean trenches where ocean floor sinks into the inner parts of the Earth's mantle (Fig. 1). The processes are thought to be driven by convection within the mantle beneath a brittle crust. Young ocean floor and old continental crust have a lower density than the underlying mantle material and ’float,’ moving passively within the crustal plates. This means that continental bedrock is more stabile the further one is away from an active plate margin, either a mid-ocean ridge or a subduction zone. The centrally located portions of plates containing old, continental crust are called ’shields.’ An example of this is the Baltic (or Fennoscandinavian) Shield upon which Sweden lies.

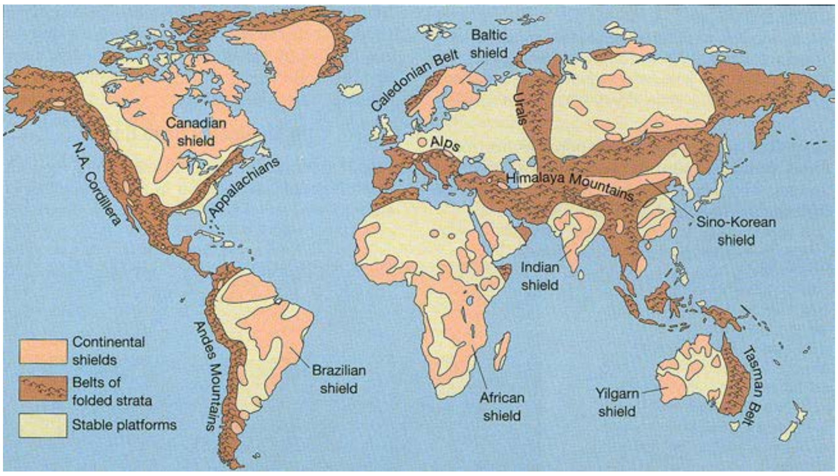

Figure 1. *Shield ares and major mountain belts (From Tarbuck and Lutgens, 1993)*

The plate-tectonic theory was originally developed by Alfred Wegener, who published ”Die Enstehung der Kontinente und Ozeane” in 1915. Wegener suggested that the continents had been assembled into a ’supercontinent’ 200 million years ago, which he called Pangea. This supercontinent split into the separate continents we see today that have subsequently moved into their current positions (Fig. 2). Wegener however had a serious problem, namely to explain the process underlying the horizontal movements of the continents.

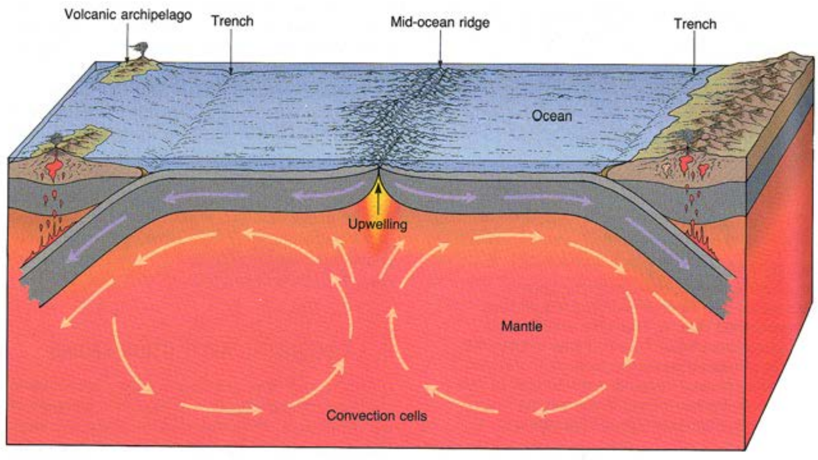

Figure 2. *Sea-floor spreading (From Tarbuck and Lutgens, 1993)*

In the 1960's, geology made giant strides in the understanding of mid-ocean ridges, subduction zones, and mountain-building processes, and the horizontal motion of the continents was explained by mantle convection (Fig. 2).

3.3.1 The Baltic Shield

The Baltic Shield (Fig. 3) stretches from the Kola Peninsula in the northeast, through Finland and Sweden, to the southern part of Norway. The term 'shield region' indicates a terrain where Precambrian rock types (rock older than 600 million years) are observed at the surface and where no mountain-building activity has occurred during the last 600 million years. The time period from 600 million years ago to the present is known as the Phanerozoic Eon, and it represents the time during which advanced, multicellular organisms developed on Earth. It is typical that the rocks preserved in the world's shield regions record a long and complicated development during the Precambrian.

Some continental crust must have already existed 4 300 million years ago, but these Archean (the older part of the Precambrian) rocks exist today only in isolated, small outcrops, and because of that, their history is poorly understood. The oldest dated rocks on Earth are found in the Canadian Shield and are 4 000 million years old. Despite the great distance between the world's shield regions (Fig. 1), there are striking similarities among them. For example, the Grenville Province in the eastern parts of the Labrador Peninsula in Canada has great similarities with southern Norway's and southwestern Sweden's bedrock. For that reason, it is reasonable to think that these bedrock complexes were originally part of the same bedrock mass and have since been split and separated by plate-tectonic movement. This observation has been subsequently supported by independent methods used to ascertain the relative positions of these complexes.

The oldest parts of the Baltic Shield (Fig. 3) consist of 3,000 million-year-old rocks that outcrop in northern Norway, eastern Finland, and western Russia. The age of the bedrock in the southwestern part of the shield is considerably younger, ranging from 1,000 to 1,600 million years.

In Skåne, the southernmost part of Sweden, the Precambrian shield rocks are covered by Phanerozoic sedimentary rocks (Fig. 4). Here, there is a tectonic zone that runs northeast southwest from the Black Sea to Skagerak and which is referred to as the Sweden Tornquist Line. This line is an important tectonic zone that was characterized by fault movements during the Phanerozoic Eon.

The mountains of Scandinavia, called the Caledonian Mountains, were formed about 400 million years ago and cover the western part of the Baltic Shield.

The Baltic Shield was subdivided by Lundquist into five provinces depending on age and geologic development. These are the Archean Province, the Svecocarelian Province, the Transscandinavian Igneous Belt, the Southwest Scandinavia Province, and the Blekinge-Bornholm Province (see Fig. 3). A brief discussion of each follows.

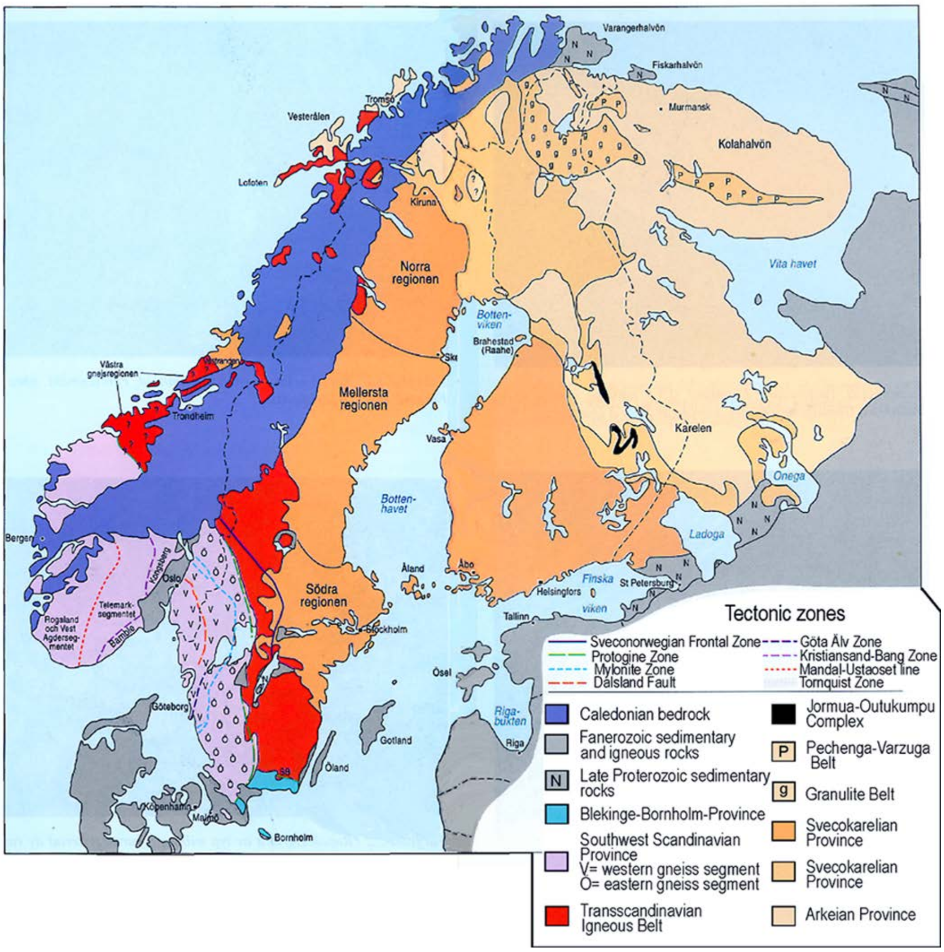

Figure 3. The Baltic Shield (From Lindström et al. 191)

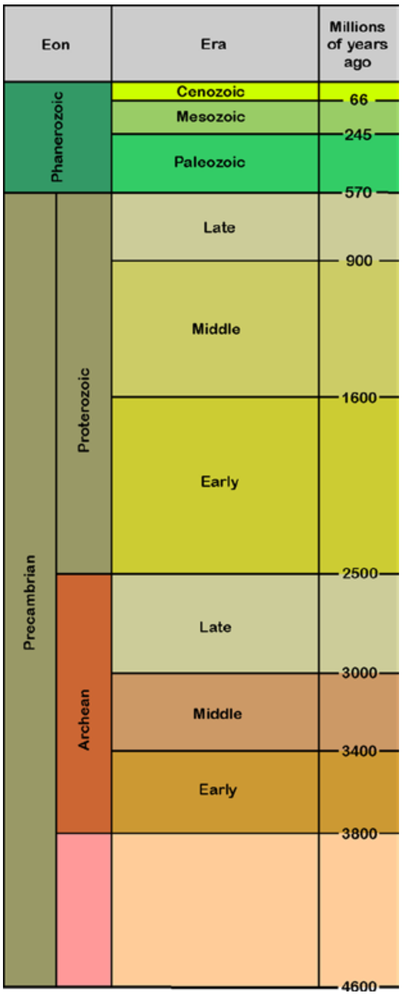

Figure 4. *Geologic time scale (From Tarbuck and Lutgens, 1993)*

3.3.2 The Archean Province

Archean gneiss that is over 2 800 million years old occurs in the northern-most parts of Sweden. These metamorphic rocks (rocks changed by heat and pressure) appear in the Råstojaure complex in northern Lappland among other places. The southern-most outcrops are found near Luleå. These rocks represent preserved fragments of the Archean crust, and they crop out in north-south oriented bands. An interesting question for investigation is whether older Archean rocks underlie the younger bedrock lying to the south. Today, we understand the southwestern margin for the Archean rock to occur in a line from the region between Piteå and Luleå to Jokkmokk. South of this line there is no known occurrence of Archean rock.

3.3.3 The Svecocarelian Province

The Svecocarelian Province, in comparison with the older Archean gneiss, has a much larger geographic distribution (Fig. 3). The province can be divided geologically into two subprovinces, the Carelian-Lapponian subprovince and the Svecofennian subprovince.

The Carelian-Lapponian subprovince stretches from western Carelia to Finnish Lappland and northernmost Sweden. This subprovince is composed of sedimentary and volcanic rock that was deposited long ago on the continental platform that would later become the northern part of the Baltic Shield. This subprovince also includes large intrusions of predominantly granitic rocks with some gabbroic rocks.

The upper-crustal rocks in the Svecofennian subprovince have an age between 1 880 and 1 950 million years and are penetrated by granitic rocks of about the same age. In two large regions, the Bergslagen region and the Skelleftefältet-Kiruna region, the upper-crustal rocks of this subprovince are dominated by volcanic rocks with lesser amounts of sedimentary rocks that include limestone, shale, and sandstone. In between these two regions lies the Bothnian basin of central Sweden, which continues into Finland on the other side of the Gulf of Bothnia. Here, thick deposits of greywacke (a 'dirty' sandstone with immature mineralogy and even some clay) and shale occur.

The sedimentary and volcanic rocks of this province have been intruded by large amounts of plutonic rocks (igneous rocks that crystallized deep below the earth's surface). These plutonic rocks are further differentiated based on their age relationship with the Svecocarelian Orogeny, which occurred 1 900 to 1 800 million years ago. The rocks that formed in the early phases are referred to as early-orogenic rocks, others are late-orogenic or post-orogenic rocks. Additionally there are anorogenic rocks, which are intrusive rocks that formed unrelated to the orogeny due to tensional movements (rift building).

Large regions are covered with granites that can be classified as S-type, I-type, and A-type granites. The S-type granites are derived from the melting of sedimentary rocks. These granites are commonly pegmatitic, meaning they contain many dykes of very-coarse-grained, granite-like igneous rock. I-type granites are derived from the melting of older igneous rocks, and A-type granites are related to the anorogenic phase. Anorogenic granites in Sweden are most commonly represented by the so-called Rapakivi granites, which are red and equigranular and also the youngest of these granites (between 1 650 and 1 740 million years old). These anorogenic granites are thought to have formed in the lower part of the crust by the melting of older, granite-like rocks, and they have intruded along zones of movement that reach all the way down to the boundary between the crust and the Earth's mantle. These granites occur alongside rocks of more basic composition occurring as plutonic rocks (gabbro) or in dikes (diabase).

Rocks that have developed on top of the already-deformed crustal rock have been found in several parts of the Svecocarelian Province, and these are known as upper-crustal rocks. These upper-crustal rocks include the characteristically red Jotnian sandstones, conglomerates, and shales. These sedimentary rocks have a significantly larger occurrence in the Gulf of Bothnia, the north part of the Baltic Sea, western Finland, and in Dalarna, Härjedalen, Nordingrå, Gävle, and Mälaren in Sweden.

3.3.4 The transcandinavian igneous belt

To the west of the Svecocarelian Province lies a large north-south trending belt of granites and volcanic porphyries called the Transcandinavian Igneous Belt (TIB). The belt's southernmost portion is composed of a large body of Smålands-Värmlands granite. This granite, which can be traced into Norway, has ages between 1 650 and 1 850 million years, with most dates around 1 800 million years. The younger portions of the Smålands-Värmland granite are found in the western part of its occurrence. Where it is connected to the north-south zone of deformation called the Protogene Zone, the granite is schistose. The Smålands-Värmlands granite has a large variation in grain size and is usually red. It is also, for the most part, equigranular and massive but in places can have a foliation.

Large regions within the TIB are dominated by volcanic rocks that are associated with the different granitic regions. Magmas of more basic composition, such as gabbro, mixed in most places with more granitic magmas and formed intermediate magma. The igneous rocks resulting from this mixture are generally more magnetic than the associated granites and volcanic porphyries. For this reason, these more basic rock types appear clearly on aerial magnetic surveys.

Granites belonging to the TIB reveal a joint system with two prominent trends that lie approximately perpendicular to each other. These joints produce a blocky pattern and in several places, the rock is quarried along these lines and used as a decorative stone.

3.3.5 The Southwest Scandinavia Province

To the west of the TIB lies the Southwest Scandinavia Province, which is dominated by gneisses. This province includes bedrock that was deformed and metamorphosed during the Sveconorwegian Orogeny, which occurred 1 150 to 900 million years ago. The eastern margin of this province coincides for the most part with the east side of the Protogene Zone, a broad zone of shear with schistose rocks. The bedrock has experienced several phases of deformation in connection with the orogeny and consequently displays a pronounced metamorphic character. Because of this, the Southwest Scandinavia Province is characterized by very complex bedrock.

The bedrock is characterized by veined, red and gray gneisses with ages between 1 600 and 1 700 million years. The gneisses are, to a large degree, derived from granite magmas, but possibly also from sedimentary rock types. In earlier usage, these gneisses were referred to as ”iron gneisses.” This distinction comes from the small amount of the ore mineral magnetite that characterizes some of these gneisses, particularly the red portions. The structure of the rock is banded to schistose (parallel structures in the rock developed because of recrystallization and mineral growth in the direction of least pressure). The rocks are easily split along these parallel planes of weakness. Mineralogically, they are dominated by plagioclase feldspar, orthoclase feldspar, quartz and mica. (Plagioclase, a calcium- and sodium-rich feldspar, is a group of feldspars, commonly white to gray in color, that are composed of a mixture of calcium aluminosilicate and sodium aluminosilicate.)

These granitic gneisses that characterize the Southwest Scandinavia Province also have a significant component of uppercrustal rocks in the form of sedimentary rocks (predominantly graywackes) and interbedded basalt. These rocks are about 1 600 million years old. The so-called Stor Le-Marstrand Group predominates in the west and grades to the east into the slightly older Åmål Group of uppercrustal rocks. Additionally, younger sedimentary and volcanic rocks (at least 1 030 million years old) are present in Dalsland in the Dal Formation.

3.3.6 The Blekinge-Bornholm Province

The bedrock in Blekinge is composed of rock between 1 400 and 1 800 million years old. To the north, these rocks are replaced by the Småland granites, which are part of the TIB. It is likely that significant crustal movements took place along the east-west boundary between Blekinge's bedrock in the south and Småland's in the north. To the west, the Protogene Zone separates the Blekinge Province from the Southwest Scandinavian Province.

Uppercrustal rocks and granite present in Blekinge lack the overprinting of the Sveconorwegian Orogeny seen in the Southwest Scandinavian Province, and is therefore less deformed and metamorphosed. The most common rock types are sedimentary and volcanic rocks that belong to the Västanå Group, dominated by gray, medium-grained granitic gneiss, commonly clearly lineated (the Blekinge Coast Gneiss). Present also is a fairly undeformed granite belonging to the Karlshamn-Spinkamåla-Vånga Group. Finally, diabase dikes, referred to as the Blekinge-Dala dikes, intrude into a north-south joint system that continues north of Blekinge to Dalarna.

3.4 The bedrock as a permanent disposal site

The Precambrian of Sweden offers an environment that should provide favorable conditions for the geologic, permanent disposal of spent nuclear fuel. It is thought that a mechanically, hydrologically, and geochemically safe environment would be provided by burying the waste around 500 meters below the land surface into the bedrock. At this depth

- the disposal site is protected from possible disturbances from the surface, such as well drilling, shaft work, road building and the like as well as from the permafrost and erosion that would be experienced during a future glaciation;
- the physical and chemical environment is stabile;
- the groundwater is reducing;
- the groundwater flow is very slow in the joints in the bedrock blocks; and
- the groundwater's path to the surface is long, and in that distance there is a chance of chemical exchange between the water and the bedrock.

The dissolved oxygen found in precipitation, and which infiltrates into the bedrock from the surface, is used by the bacteria found in the uppermost part of the bedrock. Further below the surface, the groundwater has no free oxygen. This is important because the fuel is relatively insoluble and copper is chemically stabile in oxygen-free water.

Slow groundwater-flow velocity and a large contact area between groundwater and the bedrock helps to stabilize groundwater chemistry and also hinder and delay radionuclide transport in groundwater.

Apart from these central characteristics, it is important to avoid future intrusion by situating the repository in a rather common type of bedrock with no economically significant ore or mineral deposits that could potentially be of interest for future mining.

The geological aspects primarily affect the repository's function and security, but the geology is also of importance for the construction of the repository in the sense that there is a relationship between the repository's design and its placement in the bedrock. The long-term function and security of a deep geological repository must be determined for each site in question and in a scale that has relevance. The repository is considered to need an area of about 1 km^2.

The bedrock character and quality – a product of geologic history

The bedrock's physical and mechanical stability is based on its mineralogical composition and texture as well as its geologic structure, which includes surfaces that have arisen through preferred orientation of mineralization (schistosity), surfaces that have formed because of tectonic movements (fault surfaces), and surfaces along joints and fractures. The contacts among the different rock types in the bedrock are also important. An inhomogeneous bedrock with several different lithologies provides, in general, a less-secure repository site. Favorable characteristics in regard to the mechanical stability for the repository rock are normally the rock stresses, thermal conductivity, and its uniform compositional and textural qualities. Unfavorable characteristics are anomalous stresses and a low tensile and compressive strength, which weakens the rocks physical stability. A pronounced heterogeneity, for example local variations of diverse bedrock types, can reduce rock strength and make large parts of the bedrock unusable for a repository. Such variation at depth can be difficult to determine using only limited drilling, and in that case, the wrong conclusions can be reached in judging a site's suitability as a waste repository.

The distribution of rock types at potential sites can be mapped and presented in varying scales from small (regional maps) to large (detailed, site-specific maps). Regional geologic maps at a scale of 1:250,000 provide only a general picture of the variation in rock types and show only the prominent faults and deformation zones. Knowledge about site-specific characteristics such as rock genesis, composition, grain size, textures, and structure requires more detailed investigation and mapping. Seismic activity from a regional perspective can be determined from existing databases and can reveal the occurrence and frequency of near-surface earthquakes. Likewise, the possibility of future glaciations and periods of permafrost can be determined in a general way using existing glaciologic and climatic models.

Large earthquakes with devastating consequences occur predominantly along plate boundaries (spreading boundaries and subduction zones) where stresses in the crust can be great and suddenly released (see Fig. 1). For about 100 years, seismographs have recorded numerous earthquakes in the Baltic Shield, but these have been relatively small. This is not merely a coincidence. Bedrock stresses have built up very slowly, generated predominantly in our time from the mid-ocean ridge in the North Atlantic and from post-glacial, isostatic uplift. Sweden's Precambrian bedrock contains many fractures of varying ages, size and orientation, and most bedrock movements occur along such fractures. If bedrock stress grows slowly and if there are many fractures present, bedrock stresses are relieved through small movements along these existing fractures generating low-magnitude earthquakes.

The situation is different when, at the end of a glacial episode, thick, glacier ice melts in a geologically short period of time. The normal stress from the glacier ice closes many bedrock fractures, and atypically large stresses can build up. At the close of the most recent Ice Age, ice cover remained over the mountainous parts of Sweden. East of the mountains, land that had experienced the greatest isostatic depression during the Ice Age was now ice-free. The buoyant forces generated in the depressed bedrock became so great that they caused fault movement along old fractures in the bedrock. Such fault movements and their associated earthquakes also occurred in some areas of northern Sweden during the end of the last Ice Age.

Our present geologic period, the Quaternary Period, began about 2,5 million years ago. Investigation of sediment from the bottom of the North Sea reveals that the climate in Scandinavia during the Quaternary was much colder than present. Glacier ice has completely covered the Scandinavian peninsula on several occasions, each time followed by ice recession. Therefore, the bedrock has experienced similar stress conditions at repeated times during the Quaternary. However, if the waste repository is placed at depth in bedrock that shows only minor traces of movements during the Quaternary, then it is arguable that such a site will not be strongly effected during a future Ice Age.

3.5 Siting

It is SKB's intention to provide the knowledge needed to make a sound decision about the location of a final repository for Sweden's spent nuclear fuel. In order to produce the necessary foundation for further site investigation and selection, SKB has carried out preliminary reconnaissance studies over large parts of the country to give a broad, geologic overview and to describe the general geologic character of potential repository sites. These reconnaissance studies also illuminate the conflicts of interest in the way one judges what are suitable vs. unsuitable characteristics for the placement of the repository. A collection of reports from several reconnaissance studies has been assembled by SKB.

Preliminary studies from a number of interested municipalities show where suitable sites are present, based on geologic and sociopolitical factors. These studies describe how a repository can be constructed and how waste transportation would be arranged. These studies also investigate the consequences that could be expected from the establishing of a repository site in respect to environmental, economic, industrial and lifestyle issues within the county and the neighboring region. Altogether, SKB has completed such studies for six different counties; Östhammar, Tierp, Älvkarleby, Nyköping, Hultsfred, and Oskarshamn. In an earlier phase, studies were also conducted in the counties of Storuman and Malå, but further studies in these counties were abandoned because of loss of local public support.

Continued site investigations will involve further geologic investigations and determination of the requirements for site-specific safety analysis, an environmental impact statement, and the actual blueprint for the layout of the repository. A certain degree of uncertainty is present concerning the deeply buried bedrock because drilling has not been a part of the preliminary studies. Therefore, further studies must begin with an introductory phase to demonstrate that the site actually meets the potential indicated by the preliminary study. This introductory phase includes geologic mapping and geophysical measurements together with a number of drill holes and associated bore-hole analyses down to the depth of the intended repository. If the results show that the site is not suitable, the investigations will be moved to another site within the municipality or to another municipality entirely. On the other hand, if the site meets the required criteria, the investigation is broadened to a complete site investigation.

For site investigations, SKB has chosen the following bedrock/geologic environments:

- Östhammar municipality – A so-called tectonic lineament has been identified adjacent to the Forsmark region in Östhammars county. By this it is meant that a granite-gneiss province of typical character is surrounded by zones of deformed rock. It is thought that any future tectonic movements would be taken up in the existing zones of weakness, which would in all probability provide a stabile environment in the center for the repository;
- Älvkarleby and Tierp municipalities – Coarse-grained granite intruding older Svecofennian bedrock occurs in the Älvkarleby-Tierps region. This granite is commonly porphyritic and is around 1 780 million years old. SKB has judged this region to be worthy of further investigation;
- Oskarshamn municipality – Large bodies of homogeneous Smålands granite have been identified during preliminary investigations in Oskarshamn county immediately to the west of the Simpevarp peninsula. A series of fracture zones has produced large blocks of granite that are considered favorable from a waste perspective in that any future tectonic activity can be taken up along the sides of the blocks. This large

expanse of granite is judged to provide good conditions for a safe site.

These three regions are composed of some of the most common bedrock types in Sweden. The common characteristic drawing these three areas together is that they are composed of crystalline Precambrian bedrock belonging to a shield region – the Baltic Shield.

This report is not the appropriate place to judge the relative merits of these three chosen sites. KASAM will conduct the appropriate analysis in connection with investigation of SKB's supplement to RD&D Programme 98.