Section II Handling the Risks of Nuclear Waste. An Overview of Methods, Problems and Possibilities

3 Some Geological, Geodynamic and Geophysical Investigation Methods Used for the Siting of a Repository in Hard Rock

3.1 Introduction

The purpose of this chapter is to

- Provide an overview of important geoscientific investigation methods,
- Through a critical review, show whether one or more investigation stages or important information is missing in connection with site selection and whether additional investigation methods may have to be developed for the future siting work or in the forthcoming detailed characterisation phase for a repository for spent nuclear fuel.

This review will focus on geological, geodynamic and geophysical investigation methods that are considered to be of particular importance. A systematic review of evaluation methodology and modelling is not included. Furthermore, investigation methods based on Quaternary geology and pure chemical methods are not included in this review.

An important requirement in physical planning today and in the future is that the siting, engineering design and construction of facilities in rock, for example, for the disposal of spent nuclear fuel, should be performed in an environmentally sound and safe manner. This requires comprehensive and accurate information on the properties of the rock. Knowledge is also necessary to ensure an optimum design is achieved and that the construction work can be conducted in a manner that is technically and economically adequate, taking into account the environment and safety. The facility must be able to perform as intended throughout its envisaged "lifetime", namely, for about 100,000 years in the case of a repository for spent nuclear fuel.

The primary task of the rock in a repository for radioactive waste is to ensure stable mechanical, hydraulic and chemical conditions that are favourable to the durability of the canister and clay barrier. Leaching of radionuclides from the spent fuel must be prevented and delayed as far as possible. The siting of a deep repository in suitable bedrock that fulfils these mechanical and chemical conditions is therefore crucial. To be able to evaluate mechanical stability, knowledge must be acquired of the bedrock and of its ancient and most recent geological history. In order to evaluate the chemical stability, knowledge of existing natural conditions and of the substances in the water that affect the stability of the buffer and canister. Furthermore, knowledge is required of the parameters that affect the evolution of water chemistry such as different groundwater types and their origin and of important reactive processes in the bedrock, in the soil cover and in the biosphere. Geological methodology, in the broad sense of the term, is therefore necessary in order to site the repository in a location that meets the safety objectives.

In the report *Site Investigations Investigation Methods and General Execution Programme TR-01-29* (SKB 2001), a system is described for collecting information on geoscientific conditions during different phases of the site selection work. An overview is provided with a flow chart for soils, rock type distribution, structure, hydrology and geochemistry.

The mapping approach involves direct ***geological investigation methods***, such as observations on exposed rock surfaces (outcrops), excavation and drilling. These methods are highly limited in the vertical direction and the investigation depth cannot be greater than the drilling depth. Problems also occur in the horizontal direction when observations from scattered drill holes must be linked. Fracture zones are often associated with movements in the Earth's crust. These displacement zones have been active during different geological periods. It can be assumed that individual zones are also active today. A characteristic of displacement zones is the patterns that can be seen in different types of data and which have arisen from intensive and lengthy shearing between large blocks of the Earth's crust.

The direct or indirect methods used to describe the geology are *static* in the sense that the conditions and properties of the bedrock are characterised in the present time. The dynamic aspect of geology, namely the evolution over time, requires ***geodynamic investigation methods*** in order to observe changes in specific natural reference structures or reference systems that are established for this purpose. This is of particular importance in the Swedish geological environment with very young sedimenttary deposits (soils) that were formed during and after the ice age, directly on top of very old crystalline bedrock types, which were formed over one billion years ago. The geological evolution, as can be seen in the soils, therefore encompasses a very short timescale (a few ten thousands of years at most) while the evolution that can be seen in the crystalline basement occurred an extremely long time ago. In spite of the fact that the soil stratification only contains traces from a short geological timeperiod, it is the only medium in which recent geological evolution can be observed. In order to predict the geological evolution during the lifetime of a planned nuclear waste repository, the geodynamic investigations must cover a timescale that is sufficiently long. For such studies, more tools exist today than were available when the question of nuclear waste disposal in bedrock was first discussed.

Due to erosion, fracture zones are mostly located in soilcovered depressions in the terrain and are therefore difficult to access for direct observations. Furthermore, the displacement indicators that can sometimes be observed are often very old and indicate the characteristics of the zone under completely different conditions than those that currently exist. Therefore, *indirect* mapping must also be made, based on the interpretation of aerial photography and ***geophysical investigation methods***. These methods are sensitive to contrasts in physical properties which characterise the transition from soil to rock or from one rock mass to another, such as in a fracture zone, but are also related to different water contents and water chemistry. Under favourable circumstances, the geophysical methods provide a systematic depth penetration, down to a depth of several kilometres, which is considerably deeper than can usually be achieved by direct observation. Furthermore, they reflect characteristics in conditions that are undisturbed by the investigation. The mapping methods for fracture zones also include the analysis of digital elevation data and aerial photographs. The bedrock in fracture zones is often disintegrated and can therefore be dispersed by weathering or be easily removed (for example by glacial erosion during an ice age) compared with unaffected bedrock. Depressions in the terrain and topographical escarpments can therefore represent the visible traces of fracture zones and they should be investigated by geophysical measurements in order to confirm whether the extent is significant.

However, there is a difference with respect to what geophysics and geology represent. Both approaches are applied to observe the same material in the same state and at the same time. However, each investigation method is limited to what can actually be measured although this is not necessarily what needs to be measured. Measurements require an analysis by which measurement values are transferred to models. These models are characterised by existing concepts, desired results and, above all, by assumptions concerning what it has *not* been possible to measure.

3.2 Geological Methods

3.2.1 Structural and Rock Mechanical Studies

The mechanical stability of the rock types is determined by the different mineral components and by the structural-geological history of the region. Rock structure can be plastic (for example, folding and foliation) or brittle (for example, joints, faults and crushed zones) (Berglund and Stigh 1998). These phenomena are usually included in the concept of *tectonics* and are a result of the geological evolution of the bedrock and of the original composition of the tectonically deformed material. Tectonic impact is therefore important from a repository perspective and the fracture pattern of the bedrock determines the ultimate design of the repository.

Studies of block tectonic patterns in areas of crystalline bedrock show that two types of bedrock blocks are common. *Shear lenses* are delimited by meandering shear zones and are formed in connection with horizontal block movements at depth. *Figures 3.1* and *3.2* show examples of lens-formed bedrock blocks. It is typical to find a meandering sequence of individual zones connected in a network with *shear lenses* located in between. The entire network can be hundreds of kilometres long and several tens of kilometres wide.

In addition more regular block patterns occur in the uppermost part of the Earth's crust due to the proximity to the free ground surface. *Plinths* are bordered by straight lineaments and are formed by fracturing and block movements in the uppermost part of the Earth's crust (an example of such blocks is shown in *Figure 3.4*). The analysis of seismic surface waves shows that the uppermost 1-2 kilometres of the crystalline crust has a lower seismic wave velocity, which can be explained by the occurrence of fractured and crushed zones (Åström & Lund, 1994). These patterns often overprint older deformations (for example, foliation and folding). The overprint can be discordant (cutting through older directions) although in large fracture zones, the new movements preferably follow the older zones of weakness in the crust. This causes a very complicated pattern which is also difficult to observe in the field since these parts of the zones that are most crushed have been eroded.

It is also difficult to drill through these zones and to obtain a sufficient number of drill cores to study the movement patterns in detail since crushed parts of the rock often result in drill core losses. The better-preserved parts of a shear zone are relatively older and the reference structures, which can be used to determine the movement are normally very old.

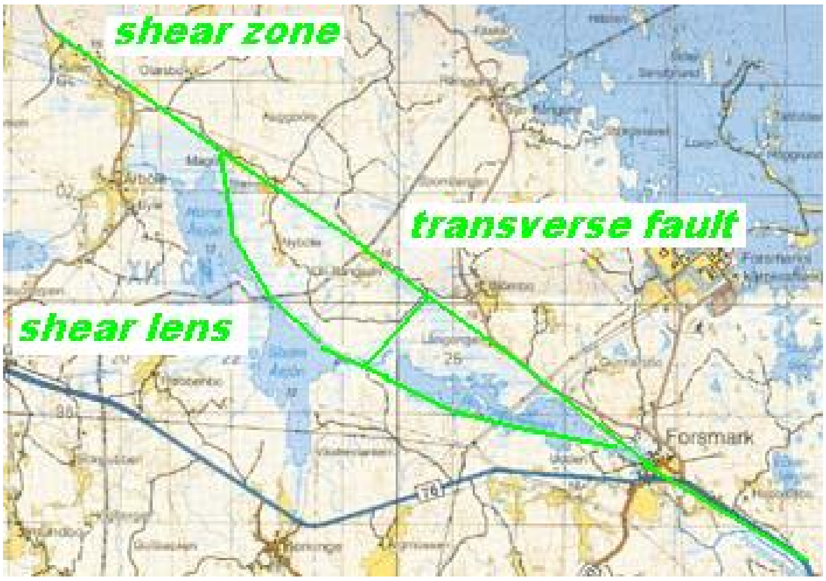


Figure 3.1. *Part of the topographic map of northeastern Uppland. The topographically visible Forsmark lens has been interpreted from elevation data. The lens is down-warped in the terrain and goes diagonally across the map view. The clear transverse step in the terrain in the middle of the lens is supposedly a fault with the southeastern block down-faulted. The Forsmark lens is 10 km long and 2 km wide (from Terrängkartan ©, Lantmäteriet Gävle 2004, permission M 2004/3790).*

The mapping of major fracture zones, shear zones and block shapes is conducted mainly by interpretation of digital elevation data and gravity, aeromagnetic, aero-VLF (Very Low Frequency) data. The mapping can be done, both on a regional scale and on a local scale. For small areas, the resolution is increased by the measurements in grids with a 10 or 20-metre point distance. In good conditions, such data allows the dip of the individual zones and the accumulated displacement with time and the direction of the block movements to be calculated.

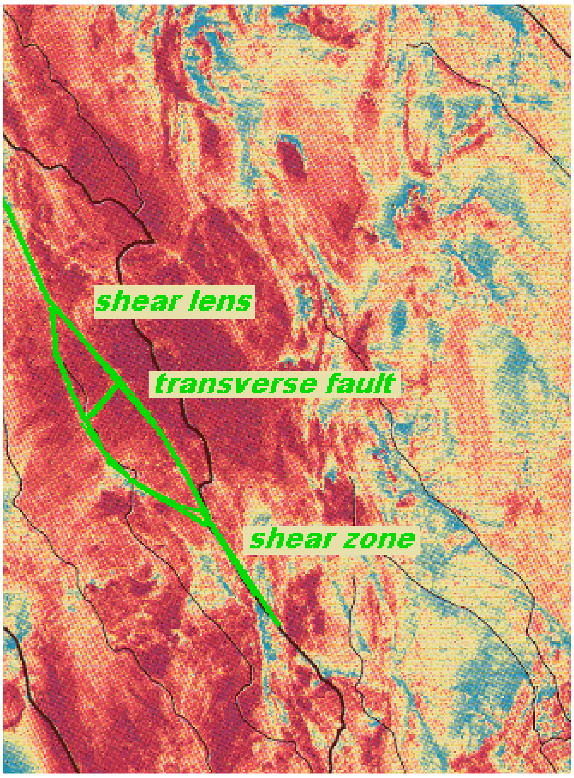


Figure 3.2. *Part of the aeromagnetic map of the inner part of Norrbotten. Shear zones are visible as low magnetic (light red) zones. The Murjek lens in the western part of the map area is interpreted from magnetic data. The transverse low magnetic zone in the middle of the lens is most likely a fault with the southeastern block thrusted over the northwestern block. The Murjek lens is 25 km long and 7 km wide (aeromagnetic measurement, data from Sveriges Geologiska Undersökning, (SGU), permission 30-915/2004).*

Facts

Fracture zone – region (1 m – 10 km) through the bedrock with a large frequency of fractures (0.1 mm – 0.1 m),
Crush zone – region with crushed rock caused by strong deformation,
Shear zone – region in bedrock (1 m – 20 km) with intense deformation caused by shearing,
Movement zone (fault zone) – region in the bedrock where rock blocks have been dislocated,
Shear lens rock block surrounded by shear zones,
Plinth – rock block surrounded by straight lineaments.

Facts

Movement zones in the bedrock described with respect to the *relative* displacement of blocks in the vertical and or in the horizontal direction:
Normal fault – one block is down-faulted,
Reverse fault – one block is pushed over the other,
Thrust – reverse fault at low angle with the horizontal plane,
Horizontal fault (strike-slip fault) – the opposite block has moved to the right (dextral) or to the left (sinistral).

Deformation zones around a rock body (a tectonic lens) can cause the tectonic lens to be less deformed than the surrounding bedrock and future deformation can be taken up in these zones. This requires a major difference in the deformability (competence) of the material in and around the lens. However, in crystalline bedrock, there is usually not a great difference in competence. With further deformation in the surrounding movement zones, the lens can become compressed or pulled apart with a risk of fragmentation. *Figures 3.1* and *3.2* show examples of lenses that have been intersected by fault zones. In certain cases, the lens can be favourable as a repository site if its vertical and horizontal range is adequate. However, rock stresses in such a tectonic lens can be high and this is a disadvantage from the siting perspective. *Rock stress measurements* are performed to investigate these stresses. Geodetic observation networks make it possible to determine the way in which the zones around the lens are active.

The orientation of stress in the bedrock in three dimensions (the *stress field*) can be calculated from registrations of major earthquakes and from measuring the shapes in deep boreholes. There is a considerable difference in depth between earthquakes (usually, deeper than 10 km) and drill hole data (usually less than 2 km deep). The results from such investigations have been compiled in a Neotectonic Map of Norway and Adjacent Areas (Dehls *et al.* 2000). The orientation of the stress field in Norway is different in coastal areas compared with inland areas. Blocks that have a similar stress field have a lateral length of about 250 km. This segmentation follows the coast and the large-scale morphology and the extension towards the northwest of major shear zones with a southeast-northwest orientation. In Sweden, a horizontal principal stress dominates in the southeast-northwest orientation although local deviations occur both horizontally and vertically (Amadei & Stephansson 1997). This orientation is suggested to be related to the pressure from the Mid-Atlantic spreading zone where the North American lithosphere plate separates from the Eurasian plate by about 2 cm per year. There is probably a similar segmentation in large present-day tectonic blocks in Sweden as in Norway. However, data from major earthquakes, which can be used to map this segmentation is lacking. Knowledge of the natural orientation of the stress field is decisive for forecasts of the tectonic evolution in an investigation area. In addition to the natural stress field, rock stresses will occur due to the repository itself and the increase in temperature around the repository that is generated by the radioactive waste. The long-term impact of the natural stress field on the site investigation areas should therefore be modelled together with the induced stress fields that arise as a result of the repository.

3.2.2 Drilling Methods, Borehole Measurements and Drillcore Analysis

The investigation of the properties of the bedrock is made by studying the available outcrops of the rock, with geophysical investigations and drilling. Normal hammer and core drilling is used for investigations in crystalline bedrock. Hammer drilling is carried out using bits with a diameter from 45 to 86 mm. The drilled rock is washed out of the borehole by air or water. The drilling process is logged and a diagram of the sinking of the drill hole is made. The diagram does not provide unambiguous information about the rock quality, especially when the rock is weathered or fragmented. Core drilling is made with rotation drilling and water flushing. The core drilling allows cylindrical drill cores to be recovered from the rock. Mineralogical and petrographical investigations are conducted at the site and on samples and microscope specimens (thin sections prepared by grinding and polishing) in the laboratory. More detailed studies of isotopes, physical properties and mineral composition are made on material from the drill cores. For projects in hard rock at depths greater than a couple of hundred meters, core drilling is the only drilling method used. Results from drill core mapping allow the fracture density of the bedrock to be estimated in several different ways.

The drill hole walls can be examined by TV camera. The camera can be lowered to great depth into water-filled holes. Several methods of measuring different conditions in boreholes are performed with borehole logging methods developed by various prospecting companies.

3.2.3 Rock Mechanics Testing and Rock Materials Testing

It is important to differentiate between rock types at a certain site or in a restricted area and the surrounding bedrock as a whole when the mechanical strength properties of the rock are analysed. The dimension of a rock sample or a small rock volume that is investigated has a considerable impact on the analysis results. The mechanical strength values for a large rock volume may be one-hundredth or less of the corresponding value of a small rock sample. When determining the mechanical strength values, existing stresses and moisture contents as well as the time-dependency that is so vital for deformation must be taken into account (Janelid 1965). Rock engineering leads to changes in stress, which can be of decisive importance for the stability in the short and long term. It is vital to know the state of stress of the undisturbed rock for planning activities. In order to achieve stability in the long term, the changes in stress and deformations that occur in connection with the construction of the repository must also be taken into account. If the factors that from a rock mechanical point of view affect planning are known, the influence of these factors must be determined, by measurements and modelling. The determination of the uni-axial compressive strength of the rock can be tested in the field on drill cores by uni-axial compression tests where the sample is pressed against a blade until a crack occurs (Andersson *et al.* 1984). Laboratories can also test the compressive strength under different load conditions (uni-axial, biaxial and tri-axial), different moisture contents and temperatures. The time factor is of importance since the deformation and creep properties of the rock are of decisive importance for the long-term stability. The stress state of the rock can be determined by analysis of major earthquakes, deformation measurements in large rock volumes or in drill holes. Measurement cells of different designs – from compliant deformation measuring cells (strain gauges) to stiff stress measuring – can be used for this purpose. Modelling can provide invaluable information for planning, for example, by optical stress investigations and load testing on scaled models under known or assumed conditions.

A field method for the determination of the stress state in the bedrock is *hydraulic fracturing* which is based on the measurement of the pressure that is required to create new or reactivate existing fractures. The orientation of the stress field is obtained from an investigation of the orientation of the fractures, which have been activated. In a recently conducted fracturing test in highly fractured crystalline bedrock at the Björkö island in Lake Mälaren, the horizontal stress field was less than previously found in crystalline bedrock areas in Sweden. The largest horizontal principal stress was in the northwestern-southeastern orientation, which is in agreement with other investigations (Ask 2003). Experiments show that the stress field has a local variation, which has also been noted in connection with the classification into tectonic blocks, based on earthquake analysis.

The bedrock characteristics are different in different directions. It is inhomogeneous with discontinuities. The rock varies from hard, massive rock types to rock types that have been weakened by different geological processes and by blasting. The characteristics of some rock material vary from being almost elastic to plastic. In view of this, statistic data must be obtained that is as representative as possible. The mathematical treatment of rock mechanical problems does not only include static stresses and related mechanical strength problems but also dynamic stresses which the rock takes up in connection with different types of deformations (Janelid 1965). If the mechanical strength and stability of the rock is initially inadequate, a certain improvement can be achieved by grouting, rock bolting and concrete injection.

3.2.4 Dating and Evolution Studies

With modern dating, important geological events can be dated. The crystallisation ages of magmatic rock types and the age of metamorphic events can be determined by measurement of isotopes from radioactive decay chains, such as uranium-lead. Zirconium is a suitable mineral for age determination, since it often has a core (which represents the crystallisation age) and an accretion zone around this core (which represents the metamorphic age).

By studying the formation sequence of fracture minerals, a relative age distribution can be obtained (*Figure 3.3*). It is also possible to determine the absolute age of certain fracture minerals with the help of radioactive isotopes and thereby increase the understanding of the tectonic evolution of the area. It is also possible to derive the pressure and temperature conditions under which the fracture minerals have crystallised.

The datable minerals are often considerably older than the intended repository lifetime. Processes that have occurred over the past 100,000 years do not leave any clear measurable traces in the materials that can be investigated. This condition underlines the importance of using geophysical and geodynamic observation networks in connection with site selection and of ensuring that more attention is paid to the youngest geological formations.

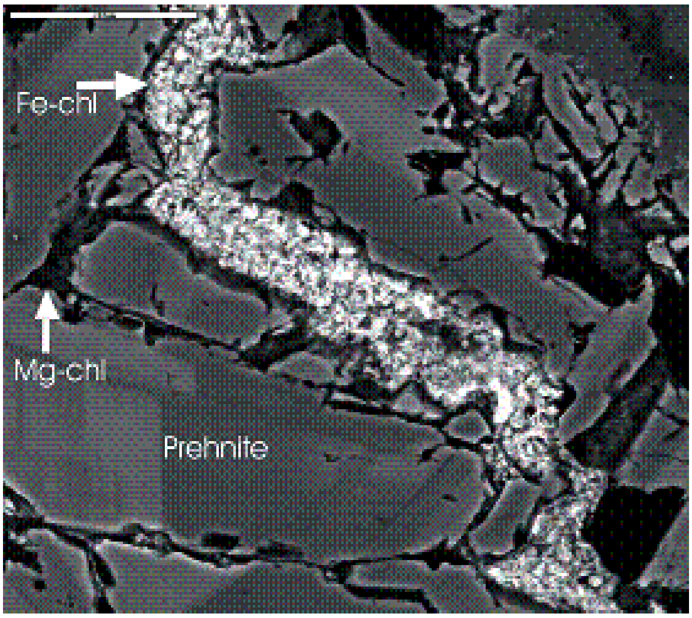


Figure 3.3. *Example of relative ages of healed fractures. (micro photograph). The thin section shows three different fracture minerals. The first generation (prehnite) is broken and the new fractures are filled with the mineral magnesium chlorite (Mg-chl). The youngest generation with iron chlorite (Fe-chl) as fracture fill mineral cuts the older patterns.*

3.3 Geodynamic Methods

Geodynamic processes are reflected in changes in the large-scale topography, the occurrence of land uplift, earthquakes and fault zones. The mapping of the range and intensity of geodynamic processes requires observations of deformations in reference structures or in grids over a longer timescale. However, currently, no measurement data are available which can determine the changes in large-scale topography. In order to achieve these, observations of the land surface and sea bottom changes over long timescales are required, probably for a several decades. Such observations are made in *geodetic* networks which are nationwide and where continuous measurements in comparison with satellites in the Global Positioning System (GPS) are applied. Information about land rise is also nowadays obtained with the same measurement system. Small-scale topography (for example elevated or depressed shear lenses) can indicate geodynamic processes. To study such changes, local geodetic GPS networks must be set up.

The brittle upper part of the Earth's crust is dissected by zones of movement. When adjacent bedrock blocks are displaced, this is referred to as a *fault* (see Berglund & Stigh 1998). Some of these zones were active just after the deglaciation. However, the movement must have displaced a datable geological structure, for example, an esker or a moraine ridge, a measurable distance in order to be able to observe the movement.

The major deformation zones are characterised by deviant topography, deviant land uplift, and the occurrence of earthquakes and systematic displacements of large blocks in the lithosphere. These different characteristics and how they can be studied are treated in greater detail in an ***appendix*** on ***geodynamic processes***.

3.3.1 Measurement of the Change in Gravity

Gravity can be measured with very great accuracy. By repeated measurements at the same sites, slow changes in gravity over time can be studied. The national land surveys in Norway, Sweden and Finland co-operate with measurements that follow the 63rd latitude (Ekman & Mäkinen 1996). The change in gravity is caused by the rising land surface and by the redistribution of masses that occurs at the same time in the lithosphere. This mass flow is controlled by the processes that operate. Measurements of both the land uplift and the change in gravity is an example of how it is possible to acquire better knowledge of geodynamic conditions with several independent methods.

3.3.2 Geodetic Networks

With the Global Positioning System (GPS), positions can accurately be determined in three dimensions. The system is therefore used in networks with GPS stations that register data continuously. If this is conducted over a long period, it is possible to determine how the site with the station has moved (relative to a reference point) due to various geodynamic processes. When the movements of the entire lithosphere plate are excluded from the data set, the differential movements caused by more local displacements can be studied. In Sweden, such a GPS network with 25 stations has been in operation since 1993. Measurement data are compiled at the Onsala Space Observatory. Co-operation is also in progress with nearby Norwegian and Finnish networks. The locations of the stations are determined taking into account land surveying applications. Certain areas may need to be supplemented (for example the Lake Vänern subsidence region and Kvarken) in order to make these data useful for geological applications.

GPS networks can also be designed for local surveys in order to monitor the movement of suspected fault zones or to study how individual tectonic blocks move in three dimensions in, for example, the Oskarshamn region (*Figure 3.4*). The measurement points must then be located on outcropping rock based on a tectonic analysis of the area. Furthermore, the measurement points must be designed so that the antennae can be placed on the point in a unique way (vertically and horizontally) and so that a large part of the horizon is visible. Values are registered for more than about 24 hours. Such local networks exist in Scania (about 50 km between the points), Norrbotten (over a number of shear zones with a distance of a few km between the points) and in the Stockholm area (with 3 points in a number of well-defined tectonic blocks). Personnel from the Royal Institute of Technology (KTH) measure them at intervals of a few years. The results that have been obtained so far are only preliminary. The large data sets mean that special computer codes must be used for the analysis and this is expensive. It is important to maintain the networks and to conduct measurements for as long a time period as possible in order to ensure that clear results are obtained. *Figure 3.5* shows the layout of a local GPS network. *Figure 3.6* shows the national GPS network, SWEPOS, and the change in the Scandinavian land surface.

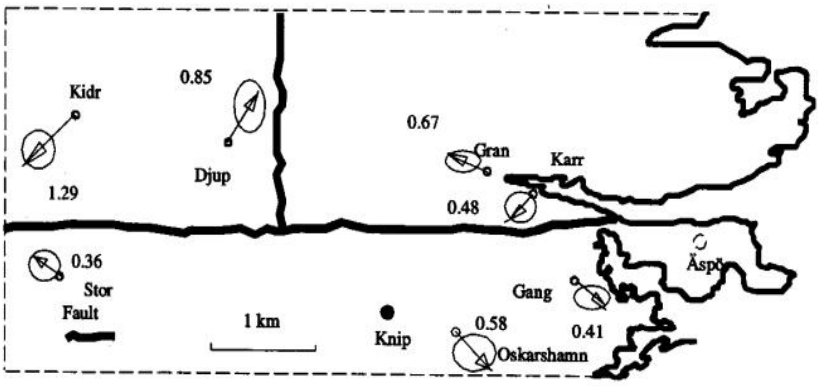


Figure 3.4. The detailed GPS network in the Oskarshamn region for determination of block movements. The observation points have been given shortened place names. Fault zones are marked with a thick line. Arrows mark the displacement velocity in mm per year that have occurred during the observation period (from Sjöberg et al. 2002).

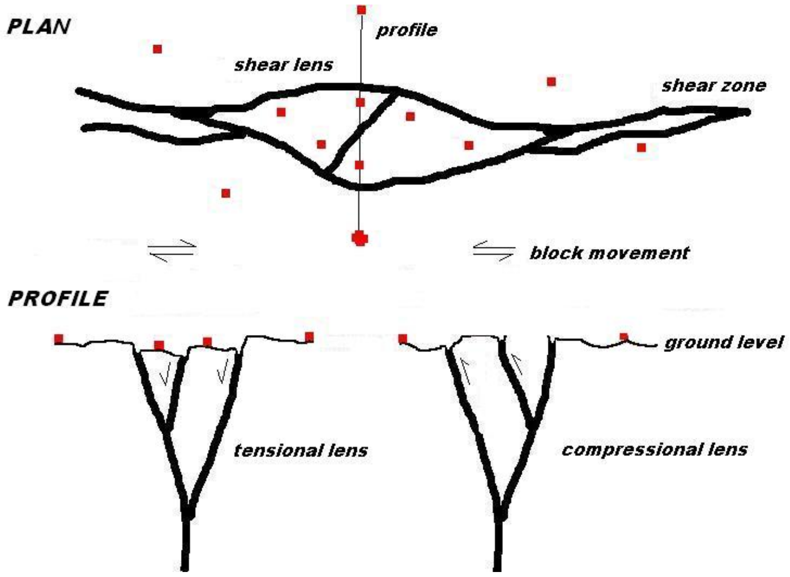


Figure 3.5. Block movements along a shear zone result in the formation of shear lenses. During compression (when the upper block is displaced towards the left), the free ground surface is elevated and during tension (when the upper block is displaced to the left), it is down-warped. The diagonal fracture is a normal fault in tension and a reverse fault in compression. The diagram also shows how a local GPS network can be designed across a shear zone and a shear lens. With three observation points (small squares) in every tectonic unit, the rotation and displacement in three dimensions can be calculated. With one observation point in every unit, only the horizontal movement relative to an external point can be determined.

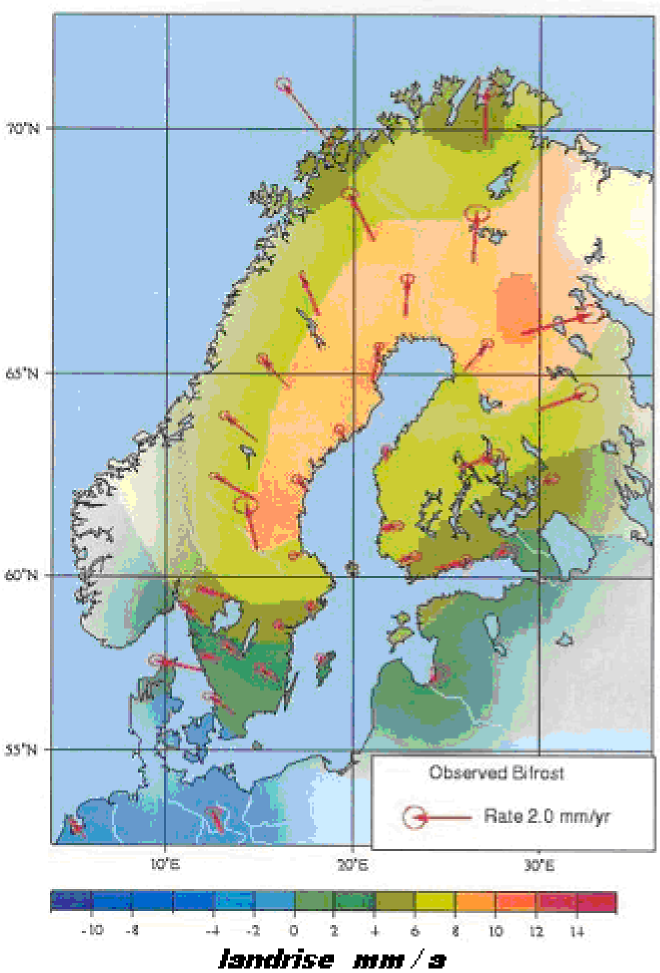


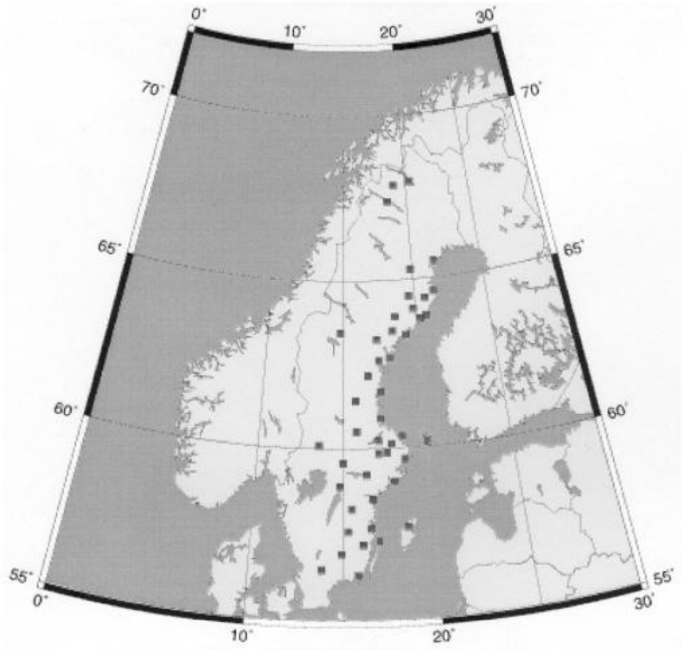
Figure 3.6. *Change of the land surface derived from the GPS network SWEPOS in Sweden and Finland. The map shows the land rise with coloured contour intervals. Arrows indicate the lateral direction and the velocity of movement of the different GPS stations. (The ellipses mark the uncertainty range). With longer observation time a gradually more precise determination of the pattern of movement is obtained. (Scherneck et al. 2002).*

3.3.3 Seismic Networks

Earthquakes occur when the Earth's crust is broken up by the sudden release of stress that has built up for a long period of time. Such stresses accumulate due to differential movement between crustal blocks along shear zones. The earthquakes are registered in national networks with seismograph stations.

In Sweden, a sparse network with seismograph stations has existed for a long time. These stations have mostly been used to register and analyse major earthquakes, which have occurred at remote sites. At the same time, the considerably smaller earthquakes in Scandinavia have also been registered. The long observation period means that there is an extensive catalogue of Swedish earthquakes to analyse. Furthermore, old observations exist which have been compiled from historical sources. This material shows that earthquakes in Sweden occur in two distinct areas: *Lake Vänern depression* and along *the Swedish coast of the Bothnian Sea and Bay* (especially around Luleå). During a few time-periods, seismograph networks have been established in small regions and a network in the coastal area of Norrland is currently being operated. From the registered data from these various sources, important information has been obtained concerning the position of the earthquakes in the crust and, in the case of large earthquakes, the orientation of the movement surface and stress field as well as the size and direction of the displacement. Seismic observation networks can, like GPS networks, be designed on a more local scale to monitor motions in the bedrock. A new seismic network has been established in 2000 focusing on the shore region of the Bothnian Sea and Bay, SNSN (2003), *Figure 3.7*. So far, over 1,000 earthquakes were registered in this network. A seismic observation network was previously located around the seismically active Lake Vänern depression. It is important to make the seismic observation network comprehensive and to ensure that the co-operation between adjacent countries is further developed. Together with

GPS networks, seismic networks are the only tools for monitoring the effects of the ongoing geodynamic processes.



© SNSN - 2003.

Figure 3.7. The Swedish National Seismic Network (SNSN). The squares indicate geophone stations. (SNSN, Uppsala University, Department of Earth Sciences).

3.4 Geophysical Methods

3.4.1 Problems and Objectives

Knowledge of deep conditions, without having to excavate or drill down to the area of interest, is necessary in order to solve a geological investigation problem. This can be achieved by the use of geophysical methods, which can indirectly provide such knowledge. The purpose of geophysical investigation methods is therefore to conduct systematic measurements of the conditions that cannot be directly observed, to present results in an informative manner and, guided by the measurement results, to construct models of the geological situation. Geophysical measurements are very accurate. However, the measurement results do not always have a unique geological cause, which leads to uncertainty in interpretation and modelling. For a calculated model to be able to reflect reality, several independent measurement data most often have to be combined in the same model. For this reason, several geophysical methods should be combined in an investigation to limit the interpretation alternatives. Furthermore, the physical characteristics of the geomaterials should be measured and used as boundary conditions for modelling. Boreholes and borehole investigations should be planned so that they can be used to calibrate and verify the models that have been created. In SKB (2001), the use of geophysical methods for site investigations has been indicated on the different flow diagrams. During the *analysis* stage, different structures are qualitatively and quantitatively determined. A quantitative determination should contain measures of a structure's horizontal and vertical extension.

3.4.2 Processing and Presentation of Geophysical Data

During the last decade, considerable progress has been made in geophysics, primarily with respect to data processing and presentation. Measurement data from the different methods are treated with different forms of modelling techniques. Inverse modelling is often used, which means that the subsurface structure and characteristics are theoretically varied until they agree with the data obtained. A number of computer codes have been developed for these purposes. Ground penetration radar technology uses advanced signal processing. Even if data from several different methods are currently often combined, a method for co-processing is lacking. In certain cases, methods involving *neural networks* have been tested for these purposes.

Geographic Information Technology (GIT) has developed rapidly and is now a standard tool for the analysis of complex geoscientific data. Several Geographical Information Systems (GIS) are available on the market and they can now be run on PCs, as can 3D presentation programs such as CAD programs. The major breakthrough is due to the development of computer capacity, advanced visualisation technology and a multitude of tools for a combination of data, calculations and analyses as well as methods for decision support. Large data sets can be stored on CDs/DVDs. The increased 3D capacity means that data from, for example, borehole investigations, can be illustrated in three dimensions. It is of interest to present repeated or continuous geophysical measurements and take into account the time factor. Such 4D processing and presentation can be used in monitoring programs during the construction and operation stages to study the groundwater conditions and thermal conditions. It can also be used during the pre-investigation stage, for example, to study groundwater changes in heterogeneous environments during hydraulic testing or for the analysis of tracer experiments.

For model calculations, there is a need for knowledge of the physical properties, (i.e. *petrophysics*) of the geological materials (minerals, soils and rock types). The importance of knowledge of petrophysics is described by the following simplified formula for the relationship between measurement (anomaly A), cause (volume and orientation V, O), distance (d) as well as the contrast in the petrophysical property (K):

$$A = (1 / d)\, K\, f\,(V, O)$$

The measurement of A is determined by traditional geophysics and the description of volume and orientation by traditional geology. The relationship also includes a distance-dependent factor (1/d) which shows another typical condition in geophysics, namely the anomaly's or signal's decrease with increasing distance. The relationship shows that if the distance is great and the volume small, the anomaly will rapidly become so small that it can no longer be measured. The petrophysical contrast, K, is included in the relationship as a factor of great importance. The function of f of volume and orientation is not analytical and must therefore be approximated with mathematical methods.

Facts

The connection between geophysical method and characteristic property in crystalline rock:
Gravity – density – varies from 2.5 to 3.3 Mgm^{-3},
Magnetic field – magnetic susceptibility – varies from 10^{-6} to 10 SI,
Seismic – velocity of sound waves – varies from 5 to 8 kms^{-1},
Radar – dielectric property – varies from 1 to 80,
Gamma radiation – radioactive decay of uranium, potassium or thorium,
VES, VLF, slingram, MT, VLF-R – electric resistivity – varies from 10 to 10^5 Ωm,
IP (Induced Polarisation) – *chargeability* – varies from 0 to 20 %.

3.4.3 Measurements of the Physical Properties of Rock and Soil Materials

The physical properties of geological materials must be known in order to make it possible to interpret geophysical measurements. The measurements can be conducted in situ, directly on the soil or rock type, although in many cases, they are based on samples taken from the geological material. Such sampling must be based on statistical principles, which means that the number of samples is in relation to the variance of the property. It is not enough to have a single representative sample. The sampling of the bedrock is best done on rock cuts or drill cores to avoid the effects of weathering which affect the characteristics of the near surface.

The characteristics that are of interest to study relate to the geophysical method that will be used. Furthermore, the selection of a method is dependent on the geological question to be investigated. A short description of some important petrophysical parameters, the units in which they are expressed and how they can be determined, are presented below.

The *density* of geological materials is dependent on the mineral composition and porosity. The density of composite geological material is the sum of the densities of the components in proportion to their quantities. The density is determined by weighing and determining the volume of samples of the material or indirectly, by borehole logging. Knowledge of the density of the geological materials is required in order to calculate geological models based on gravity measurements. The unit for density is Mgm^{-3}.

The *magnetisation* of geological materials is the sum of *induced magnetisation* and the material's permanent magnetisation. It is also dependent on the occurrence of highly magnetic minerals. In Swedish crystalline bedrock, this mineral is usually *magnetite* and, in certain areas, *pyrrhotite*. The induced magnetisation is dependent on the *magnetic susceptibility* of the geomaterial and the *intensity* of the local geomagnetic field. The *magnetic susceptibility* can be measured directly on the geological materials in situ while the determination of permanent magnetisation requires sampling in the field and measurements in the laboratory. The calculation of geological models based on magnetic measurements requires knowledge of the combined magnetisation of the involved materials. *Magnetic susceptibility* is a dimensionless property and can be expressed as μSI.

The *electrical conductivity* (or the inverse – electrical resistivity) of geomaterials depends on the occurrence of electrically conductive minerals (graphite, magnetite and sulphides) and porosity (and the water that fills the pores). The conductivity can be measured in situ using electromagnetic or electrical methods, on drill cores or in boreholes with different types of logging. The interpretation of geophysical models based on electrical or electromagnetic measurements requires knowledge of the electrical conductivity of the materials. The resistivity is expressed in Ωm.

Geological materials can be electrically charged and this ability to be polarised is dependent on the occurrence of the electrically conductive minerals graphite, magnetite and sulphides. The *induced polarisation* can be measured in the field on drill cores or in boreholes with logging. It is an important method for determining the occurrence of electrically conductive minerals in the near field of the measurement and is therefore used in ore prospecting. The polarisation is dimensionless and is expressed as a percentage.

The capacitance per metre of different materials is called the *dielectric constant* (also called permittivity). It is important for the analysis of electromagnetic measurements in radiofrequency ranges and is to a large degree controlled by the water content of different geomaterials. The dielectric constant is often specified as *relative* to the conditions in a vacuum and is therefore dimensionless.

The velocity of propagation of *electromagnetic waves* varies with different geomaterials. Knowledge of this velocity is necessary in order to analyse radar measurements. Above all, it is dependent on the occurrence of water in the geomaterials.

The velocity of propagation of *sound waves* varies with different geomaterials. It can be measured directly in the field or in drill cores. There is a positive correlation between seismic wave velocity and density. The difference in wave velocity between crustal rock types and the upper mantle is so great that it is used as a criterion for the boundary between the crust and the mantle. Knowledge of seismic wave velocity is necessary in order to analyse seismic recordings. The unit used is ms^{-1}.

The *thermal properties* comprise heat production, thermal capacity and thermal conductivity. Crustal *heat production* is considerable due to the decay of naturally radioactive isotopes. This heat production varies from 2 to 20 μWm^{-3}.

Different geomaterials also have different *thermal conductivity*. This, and the crustal heat production and the heat flux from the mantle, determine how the temperature increases with depth in the upper crust. The heat flux from the mantle is about 60 mWm^{-2} and the *temperature gradient* in crystalline rock is 15-20 Kkm^{-1}. Areas with sedimentary rocks have a somewhat higher temperature gradient (the sediments function as insulation) and areas with bedrock rich in quartz have a somewhat lower temperature gradient due to differences in heat conductivity. Knowledge of the heat conductivity of geomaterials is important for forecasting the propagation of the temperature pulse that occurs during the storage of spent, but still radioactive, nuclear fuel.

The thermal capacity indicates how much thermal energy can be stored in a material in order to obtain a certain temperature increase. Water has a high thermal capacity, which is therefore much greater in water-saturated soils than in crystalline rock. This knowledge is important for the modelling of the thermal conditions surrounding the nuclear fuel and for the modelling of the temperature exchange with the biosphere. The thermal capacity is expressed as $WK^{-1}m^{-3}$.

The *gamma radiation* emitted from the ground depends on the content of radioactive minerals, with the components uranium, thorium and potassium. The content of radioactive minerals varies with the formation and age of the rock types. Measurements can be made from the air, on the ground, in boreholes or directly on samples. The radiation is often expressed as the calculated quantity (in ppm for uranium and thorium and as a percentage for potassium) of the different isotopes at the ground surface.

3.4.4 Strategies in Site Selection

Geophysical investigations for site selection start with an analysis of the site in question in relation to regional geological structures. At this stage, literature studies and map information that cover a large part of the country are required. The sites in relation to areas where geodynamic processes (see appendix on geodynamic processes) can be expected to affect the crust are an equally important and early part of site selection. In order to obtain knowledge of these conditions, geodetic and seismic observation networks are established in and around the area. Since it takes a long time to obtain data on changes, the networks should be set up at an early stage.

In the next step, the local conditions of the area are investigated, with the help of geological and geophysical mapping based on the databases (for example, airborne geophysical measurements), which already exist, and by supplementary investigations on the ground and from the air. At this stage, a large enough environment must be taken into account and the petrophysical properties of rock and soil material must be mapped. The extension of the investigation area must be at least 3 times as large as the extent of the area of interest in different directions. This means that an area that is about 10 times greater than a candidate site should be investigated with relevant measurements in order to understand the structural context of the area in relation to its environment.

Important structures are identified and followed up by more detailed ground geophysical measurements in a grid or in profiles. The methods for studying the bedrock are selected from among those that have suitable depth penetration and can cover the supposed investigation depth with a good margin. The methods to study the soil cover and the location of the upper surface of the bedrock beneath the soil cover are selected among those methods that have less depth resolution, see *Table 3.1*.

Based on these data, investigation drilling is ultimately required in order to do measurements and sampling in the boreholes. The depth of at least one borehole must extend into the saline groundwater region in order to enable the calibration of the electromagnetic methods used to map the transition to saline groundwater. When structures that are important for the stability of the area have been mapped, calculations are conducted of how displacement zones and the rock in between are affected by continued geodynamics and changes in rock stresses. Knowledge from geodetic and seismic observation networks and the existing rock stresses is necessary for these calculations.

The characterisation of soil types and the shape of the rock surface are important input parameters for the study of groundwater flows and groundwater recharge. Therefore, the methods that are applied for site selection cover a wide spectrum and it is an advantage if several methods are used in order to limit the possible interpretations. The selection of methods is also determined by the petrophysical properties that exist in the rock and soil material in an investigation area and by different types of natural or artificial constraints (for example, power lines).

3.4.5 Geophysical Measurement Systems

The various geophysical measurement methods can be classified in different ways. However, the measurement systems and the design of the measurements are similar within methods where measurements are taken from the *air*, directly on the *ground*, or underground in *boreholes*. For each measurement method, the measurement point distance is related to the size of the object. The measurement point distance should therefore be less than half of the size of the object. Corresponding data collection principles also apply to the selection of measurement data from a large database. Methods with a large-scale range are suitable both for general regional surveys and very detailed characterisations. Methods with limited depth penetration are suitable for investigating the soil cover and rock surface.

In order to establish the existence of a contrast, the object's surroundings must also be included in the measurement to an adequate extent. The surroundings included in a measurement should be as large as the specific area of interest. The measurement point distance and the area that is to be measured are directly related to the cost of the measurements.

Table 3.1 below provides an overview of geophysical methods and their applications, depth penetration and scale range. All of the methods are applicable in connection with site selection for nuclear waste disposal. The methods that are best combined partly depend on the geological conditions and, above all, on the petrophysical properties of the rock. Therefore, the starting point should always be the existing regional and local databases that occur in an investigation area in order to design methods and new investigations. If knowledge of the petrophysical properties is lacking, they should be measured at an early, initial stage of an investigation.

Table 3.1. Various geophysical methods and their fields of application.

METHOD (scale range in parenthesis)	**FIELDS OF APPLICATION**	**DEPTH PENETRATION**
Ground based geophysical measurements (1-100 km):		
Gravity (a)	Rock composition, large block movements	10 m – 10 km
Magnetic field (a)	Large fracture- and movement zones in magnetic rocks, block movements, bedrock mapping	10 m – 1 km
Electromagnetic methods (1 – 10 km):		
Slingram	Occurrence of conductive minerals	1 – 50 m
Radar (GPR)	Depth to bedrock and groundwater level	0.1 – 50 m
IP	Occurrence of conductive minerals	1 – 50 m
MT (a)	Vertical distribution of electric resistivity to large depth, level of salt groundwater	10 m – 10 km
VLF	Occurrence of fracture zones and their approximate dip	10 m – 1 km
VLF-R	Determination of soil and bedrock resistivity	10 m – 600 m
Electric methods (0.1 - 10 km):		
VES (a)	Determination of groundwater level, depth to bedrock, soil layering, level of salt groundwater	1 m – 1 km
Seismic methods (50 m – 1,000 km):		
Refraction (a)	Depth to bedrock and groundwater level, occurrence of steep fracture zones	1 m – 50 km
Reflection (a)	Depth to bedrock and groundwater level, layering in sediments, location of low angle fracture zones	0.1 m – 50 km

METHOD (scale range in parenthesis)	FIELDS OF APPLICATION	DEPTH PENETRATION
Airborne geophysical measurements (1 – 100 km):		
Magnetic field (a)	Orientation of large fracture zones in 3-dimensions, block movements, characterization of bedrock	10 m – 1 km
VLF (*)	Steeply inclined water containing fracture zones	10 – 100 m
Drill hole geophysical loggings (0.1 – 10 m):		
Water flow	Water flow in sections of the bedrock	
Electric resistivity	Porosity and occurrence of fractures	
IP	Occurrence of conductive minerals	
TV camera	Orientation of fractures in 3-dimensions	
Radar	Orientation of fractures in 3-dimensions	
Shape of drill hole	Orientation of the horizontal stress field	
Observation networks (1 – 2,000 km):		
Seismic	Location and orientation of displacements in the bedrock, orientation of the stress field	1 – 30 km
Geodetic (GPS)	Displacement and rotation of bedrock units in 3-dimensions in the uppermost crust, land rise	
Hydrological	Precipitation, run off, changes in groundwater level	

(a) Methods with great depth penetration, > 500 m.
(*) The airborne VLF method is direction selective depending on which transmitter that is used for the measurements.

3.4.6 Limitations Due to Terrain and Artificial Objects

All geophysical measurements are dependent on terrain variations. The more variable the terrain is, the greater the effects will be. This is taken into account when planning the measurements as well as in the analysis. With certain methods, the effect of the terrain can be reduced by applying corrections or by inclusion in the model. It is always suitable to study altitude data in parallel with the analysis of measurement data. This can be accomplished particularly efficiently by using digital data and Geographic Information Technology (GIT). Geophysical measurements can be performed on ice over water-covered areas. However, the increased distance to the soil cover or bedrock under the water reduces the signals to some extent. For certain measurements, constant altitude and the absence of topography over the measurement surface is an advantage. Geophysical measurements over water-covered areas make it possible to obtain more continuous information about rock structures. With methods based on electrical conductivity, water (especially seawater) and electrically conductive parts of the soil cover (such as clay) have a strong shielding effect.

Certain geophysical methods are sensitive to artificial (anthropogenic) objects. This particularly applies to electromagnetic measurements where secondary fields from power lines, telephone lines, large fences, pipes and telephone transmitters predominate the natural variations in the area close to such objects. In the case of large power lines, this can extend over several kilometres. Similarly, the environment around active telephone transmitters is severely disturbed. By using electromagnetic methods with controlled signal formation, these disturbances can be avoided in connection with measurements or they can be filtered out during data processing.

With magnetic measurements, it is large iron structures (such as power line poles and sheet metal roofs) instead that disturb the measurements in their proximity. Furthermore, direct current power lines result in magnetic fields that cause local disturbances. When conducting airborne measurements at low altitudes, large power lines and populated areas are avoided by flying at a higher altitude and the natural signals are thus weakened due to the increase in distance. Broad corridors can therefore occur around anthropogenic objects where the use of electromagnetic measurement methods is rendered difficult or impossible.

3.4.7 Airborne Geophysics

Airborne geophysical measurements are performed from satellites, aeroplanes or helicopters and, on the same measurement occasion, several different types of measurements can be performed simultaneously. The measurements rapidly cover large areas and, today, many countries have comprehensive airborne geophysical databases. Satellite-based measurements are internationally available and have global coverage. In Sweden the Geological Survey of Sweden is responsible for the design, processing and storage of airborne geophysical measurements. The compromise between cost and measurement point distance has so far favoured quite detailed measurements, which can be used for many issues. The measurements are also performed at a low altitude, about 50 metres, *i.e.* at a short distance to the geological structures in the bedrock. The measurement point distance is 20 metres along the flight lines but there are about 200 metres between the flight lines. For the analysis of measurement data, it is therefore important to know where the flight lines are situated, especially since modern interpolation techniques normally cannot reproduce the context of structures at a small angle to the flying direction. The measurement data are presented on maps in the scale 1:50,000, which follow the map sheet division of Sweden. Digital extracts of an optional geographical area can also be obtained from the database.

The measurements performed from airborne surveys in Sweden comprise *magnetic total intensity*, *gamma radiation* (represented as the equivalent content at the ground surface of the natural radioactive isotopes, potassium, uranium and thorium) and *electromagnetic secondary fields* from long-wave (VLF) transmitters. These measurements can be used for many purposes, including mapping of the extent of the rock types under the soil cover and under water, the mapping of large fracture zones in the bedrock, the investigation of radon risk (in soils, the bedrock and groundwater) as well as for prospecting for mineral deposits.

Radar measurements that are conducted from satellites and aircraft can be considered to be geophysical measurements. They are usually very detailed and are conducted in several frequency ranges. The direct geological use is for the mapping of fracture zones as well as the determination of soil water content. In areas with heavy vegetation and intensive forestry, the geological information is hidden by the traces left by the methods of land cultivation (like property boundaries and ploughing grooves) that are clearly visible in the radar measurements. The measurements are not dependent on cloud cover and the effects that occur from cloud and shadow on the ground in connection with aerial photography or satellite scanning in the visible wavelength spectrum can thereby be avoided.

Facts

Measurement direction, measurement spacing, measurement altitude
Airborne measurements – in east-west or north-south direction, 200 m distance between flight lines and about 20 m between measurements, elevation about 50 m above the terrain,
Ground based measurements – selected direction, distance between measurements and measured lines 5 – 20 m,
Regional gravity measurements – irregular net of measurements with 0.8 – 5 km spacing,
Profile measurements – oriented at right angle to the direction of the structure, measurement spacing 1 – 20 m.

3.4.8 Ground Geophysics

Purpose and Access to Data

Geophysical ground surveys have been carried out in connection with the prospecting of ore and industrial minerals and the mapping of gravel deposits as well as for specific investigations within the regular soil and rock type mapping at the Geological Survey of Sweden. From an early stage, ground geophysical surveys have been conducted for groundwater prospecting in Sweden and abroad. In recent decades, ground surveys have had an increased importance within different types of environmental studies.

Geophysical ground surveys, in connection with *underground construction*, such as for a repository for spent nuclear fuel, aim at developing a geological-tectonic model of the studied soil and rock volume. Furthermore, the aim is to increase knowledge of the composition and thickness of the soil cover, the physical properties, fracturing, water content and boundaries between different rock types. The ground surveys are non-destructive, but require considerable interpretation. In general, the resolution decreases with increased depth penetration. To study conditions at a depth of 500 metres, considerable changes in the physical properties (or large structures) are therefore required in order for them to be detected at the ground surface. Also near surface changes in the horizontal direction must be less than those in the vertical direction.

The measurements are performed on the ground, either in an irregular grid over large areas, in a systematic grid over a limited area or as profiles. The measurement point distance is determined by the purpose of the measurement and can vary between 1 metre (detailed profiles) and 5 kilometres (regional nationwide surveys). Measurement data are presented on maps or in profiles. For certain types of measurements, national databases exist that are managed by the Geological Survey of Sweden.

Regional, nationwide surveys currently exist for *gravity*, with point distances that vary between 0.8 and 5 kilometres. The measurements usually follow the road network. On large lakes and near-coastal sea areas, measurements have been conducted on ice.

Seismic surveys are sometimes conducted on a regional scale, especially in sediment-covered areas and for special projects. No complete overview exists of where such measurements have been conducted or of which company or institution that is holding the results.

Measurement Methods

The most important geophysical methods for investigations of structural conditions of the bedrock in the form of fractures and fracture zones are seismic, magnetic, electrical and electromagnetic measurements. Some of these measurement methods also provide information on rock types and rock type boundaries. All methods are sensitive to horizontal near surface variations while changes at depth are much more difficult to detect. It is also easier to detect steeply dipping structures and rock type boundaries than to map horizontal fracture zones and boundaries. In the case of refraction seismic and electrical methods, depth penetration also requires that instruments be arranged over long distances. *Figure 3.8* shows a series of measurements with different methods over a large shear zone in Norrbotten and how the results of the magnetic measurement can be used to determine the dip of the zone (*Figure 3.9*).

Seismic surveys are used to detect structures in the bedrock. The surface structures, for example the occurrence of fractured bedrock, especially steeply dipping fracture zones, can be interpreted from *refraction seismic surveys*, where the refracting part of the sound wave is followed by registering the time until it reaches the geophones that have been set up. The seismic signal velocity is considerably reduced in crushed rock. It is difficult to detect horizontal low velocity zones with refraction seismics. On the other hand, refraction seismics can be used to advantage to determine the depth to the bedrock under the soil cover. This has been carried out in connection with many large construction projects, for example, along the Bolmen tunnel where more than 200 km of refraction seismic profiles were evaluated (Stanfors 1987). With *reflection seismics* the part of the sound wave that is reflected at the interface to a material with a deviating sound velocity is measured. The method requires heavy equipment and more powerful computer processing. Therefore, it is more suitable for local surveys. A major advantage of reflection seismics is that the method is one of the few that can be used to identify rock structures with low angle to the horizontal at great depths, for example, horizontal fracture zones (Andersson 1993, Cosma *et al.* 1994). This is of decisive importance for the siting of a repository since it must be possible to take into account low angle structures when determining the position for the rock volume that can be taken into consideration. Seismic methods have also been used during the construction of underground facilities (Tunnel Seismic Predition, TSP) to predict the conditions and determine the need for reinforcement (Sattel *et al.* 1996).

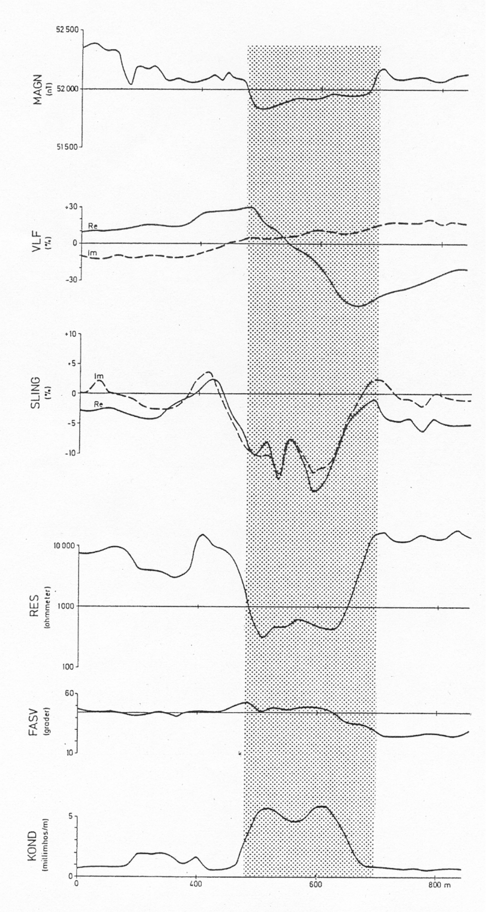


Figure 3.8. *Example of the geophysical response from a large shear zone (marked with grey shading) in Norrbotten. The different methods show a clear response above the zone. From top: Magnetic (MAGN) low anomaly over the zone due to oxidation of magnetite, VLF horizontal component giving a typical anomaly over the zone, Slingram (SLING) gives a negative anomaly, VLF resistivity (RES) shows low resistivity, the phase angle (FASV) varies very little over the zone, and at the bottom a high conductivity (KOND) anomaly is seen. (from Henkel 1988).*

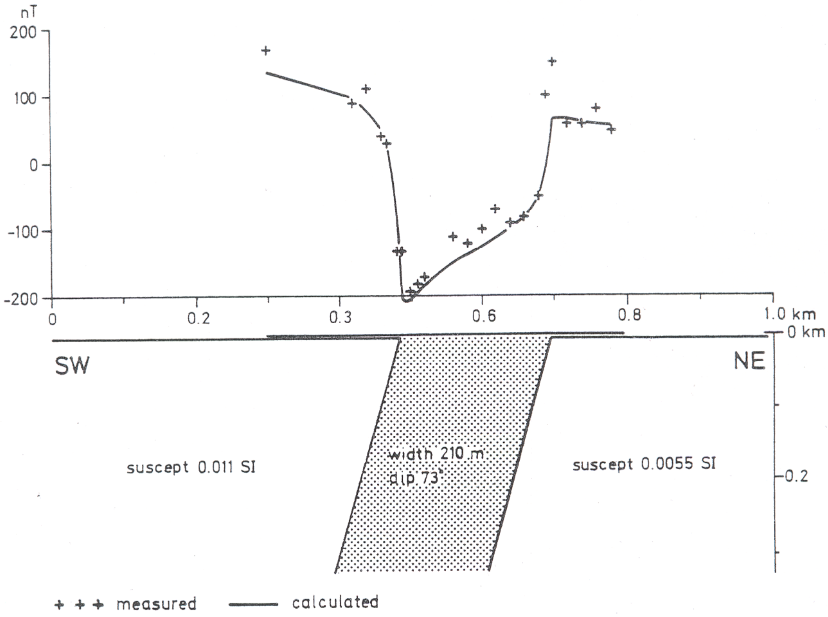


Figure 3.9. The magnetic anomaly seen on top in the previous figure has been used to determine the dip of the zone, which is 73 degrees towards the southwest (from Henkel 1988).

Ground Penetrating Radar (GPR) utilises similar reflection principles as reflection seismics but is based on the propagation of the electromagnetic waves through the ground. A reflection is obtained when the radar wave hits an object with deviant electrical properties. Today, pulse radar systems are often used, whereby electromagnetic pulses are directed by a transmitter antenna into the ground and a receiver antenna registers the reflected signals. The time delay for the reflected signals is measured in nanoseconds, 10^{-9}s. In recent decades, the method has become increasingly important for the mapping of superficial soil and rock layers and has been used for studies of soil layer conditions and geological evolution (Widén 2001, O'Neal & McGeary 2002, Helle 2004). GPR has also been used to study tectonic zones, both active (Rashed *et al.* 2003, Slater & Niemi 2003) and older neotectonic zones (Dehls *et al.* 2000, Tirén *et al.* 2001). Like with reflection seismics, the method can be used to identify low angle tectonic structures and is therefore of importance for studies of the near surface, generally more fractured rock, *Figures 3.10* and *3.11*. In soil-covered areas, the depth to the bedrock and flow-promoting structures in the soil-rock contact zone, that are important for groundwater recharge, can be mapped, *Figure 3.12*. GPR can also be used continuously during the construction phase, directly from the underground facility, to predict fractures, rock boundaries and other rock structures in order to establish reinforcement needs and to map the effectiveness of pre-grouting (Cardarelli *et al.* 2003).

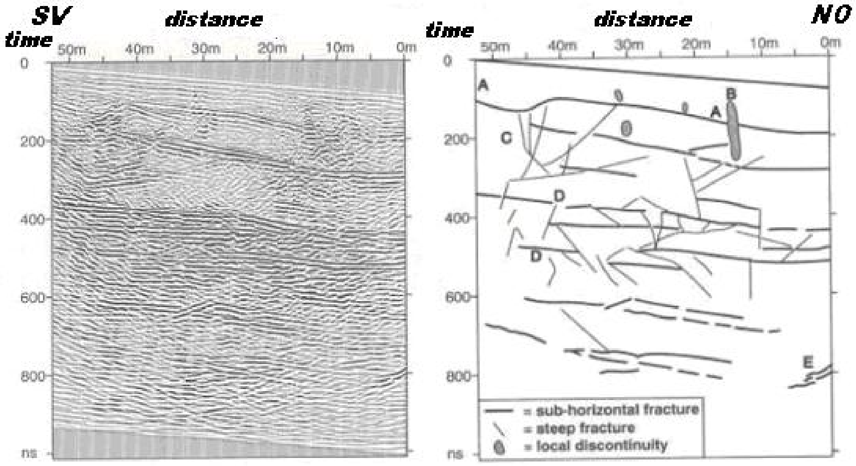


Figure 3.10. *Example of an interpretation of fractures in the near surface bedrock using GPR measurements (Grasmück 1994). From the time scale, the depth to the reflecting structures can be calculated if the velocity of the signal in different geomaterials is known.*

Figure 3.11. *Example of a low angle fracture zone in the Forsmark area. Such fracture zones can be detected in near surface locations with ground penetrating radar and at larger depth with reflection seismic measurements (photograph by Kaj Ahlbom 2003).*

If the crystalline bedrock is magnetic, magnetic measurements from the ground (or from an aeroplane) can be used to map large fracture zones. These zones are always low magnetic due to mineral alterations and can also be mapped beneath the soil cover and in water-covered areas. Through model calculations and with knowledge of the magnetisation of the surrounding bedrock, the dip of the zones can be established.

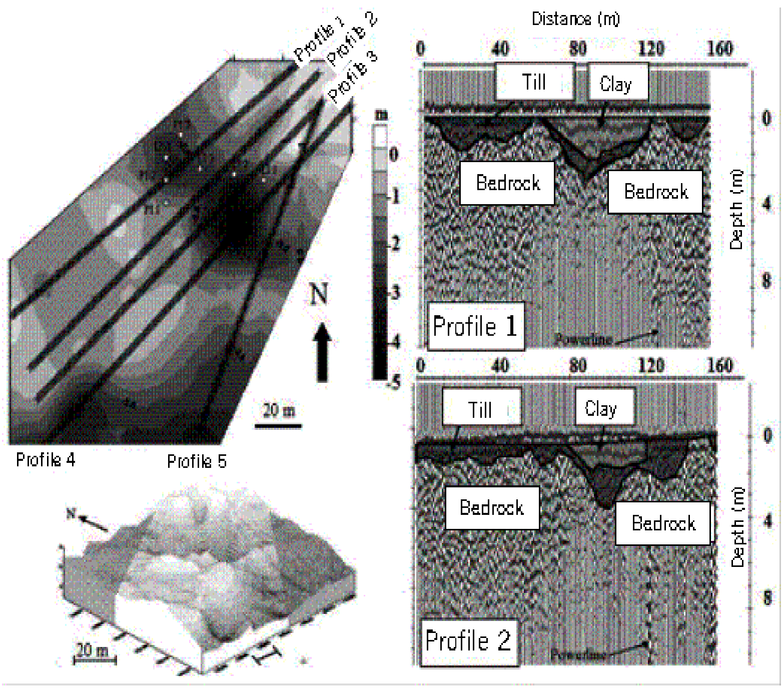


Figure 3.12. Example of interpretation of the depth to the bedrock based on GPR measurements in an area in southeastern Sweden (Olofsson et al. 2004).

Electrical measurements are based on electrical fields created in the subsurface between two current electrodes. The extent of the current field depends on the distance between the electrodes but is also affected by the conductivity of the soil cover. By measuring the voltage with potential electrodes, the *apparent resistivity* can be calculated. The resistivity depends on how the electrodes are arranged as well as on lateral and vertical changes in the electrical properties of the subsurface. Through *inverse modelling*, where the electrical properties of the subsurface and the thickness of the soil cover are varied until an agreement is reached with the measured values, an interpretation of the structure of the subsurface and its electrical properties is obtained. Most often, a multi-electrode system (Continuous Vertical Electrical Sounding, CVES) is used today with a large number of electrodes arranged along lines or in a network together with a computer that determines which electrodes are to be current and which are to be potential electrodes. Through inverse modelling, the resistivity distribution of the ground can then be two- or three-dimensionally calculated. Electrical measurements have become important for the mapping of soil and rock stratification and in determining groundwater surfaces. Other important applications are for environment-related investigations and for environmental control (Bernstone & Dahlin 1998, Aaltonen 2001), *Figure 3.13*. If fixed electrodes are set up in the ground, the method can be used for long-term monitoring, for example, around landfills where pollutants often have a high salinity (Aaltonen & Olofsson 2001) or for the monitoring of climate-related ground moisture conditions and groundwater levels.

Most of the multi-electrode systems occurring on the market only allow sensing to a depth of about one hundred metres. An interesting application of geoelectrical surveys is to map the occurrence of saline water at great depths with a several kilometre-long electrode separation. This is an excellent complement to deep drilling. However, in coastal areas, it may be difficult to avoid the short-circuiting effect of seawater on the measurements.

The *chargeability* of the ground can be measured by *induced polarisation* (IP). The method is based on a current field created over the ground that causes polarisation to occur in the subsurface. When the field is turned off, this polarisation continues for a certain time and can be measured. The method has a considerable potential for studies of polluted soils, like dispersed salt pollutants or oil spills (Dahlin & Leroux 2002, Sjögren 2004). Even without external current fields, a weak polarisation occurs due to the mineral content in the ground and the electrolyte properties of the ground fluid. The measurement of this natural *self potential* (*SP*) with sensitive non-polarising electrodes can, in the same way, be used in connection with ore prospecting and pollutant mapping. The method has also been used in connection with near-surface tracer experiments in rock (Nimmer & Osiensky 2002).

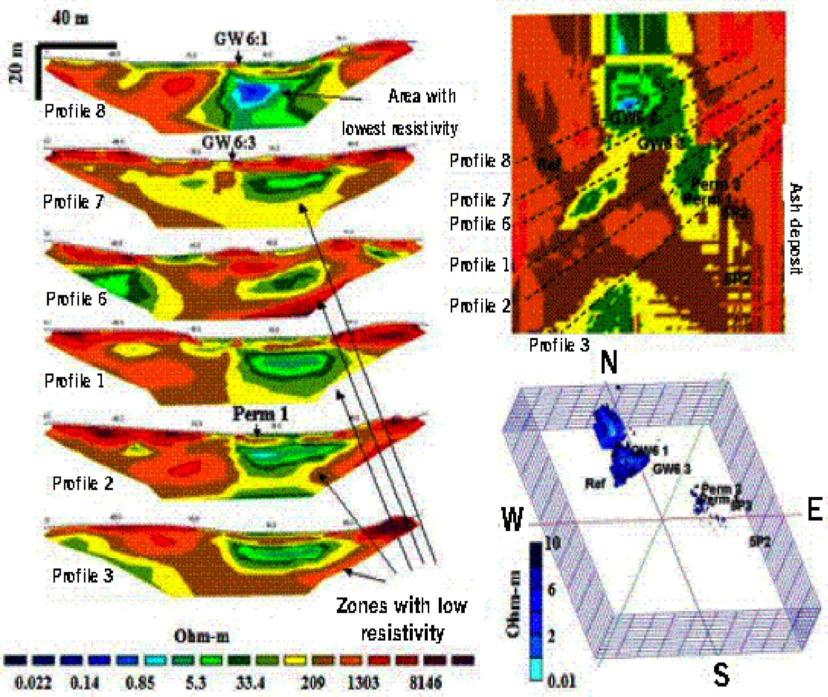


Figure 3.13. *Resistivity measurements for analysis of leacheates spreading from a waste deposit. The measurements are made with CVES technique and are modelled two and three-dimensionally, respectively. The results are presented as profiles (left), horizontal sections in the near surface bedrock about 12 m below the ground (upper right), and as three-dimensional low resistivity zones (lower right) (Olofsson et al. 2004).*

Electromagnetic induction means that a current field is created in electric conductors in the ground with the help of an external electromagnetic field. The secondary electromagnetic field, which occurs, can be measured at the ground surface. There are several frequency-controlled methods that either use natural electrical currents (MT measurements), in the frequency range from 10^{-4} to 1 kHz, or currents induced by radio signals (VLF measurements) in the frequency range from 15 to 25 kHz. Electromagnetic methods are also designed for fields created by a mobile transmitter (slingram) in the frequency range from 5 to 15 kHz. In general, the depth penetration is determined by the frequency of the electromagnetic field and the conductivity of the ground. There is always a high contrast in resistivity between unaffected bedrock and fracture zones in crystalline bedrock. VLF measurements are therefore an effective method of mapping fracture zones on land areas (but not over water-covered areas).

In recent years, electromagnetic measurement methods have been developed to describe the distribution of electrical resistivity down to a depth of several kilometres in the bedrock. A summary of VLF and MT methods is provided in Oskooi & Pederson (2004). With magnetotelluric measurements (MT), natural electrical currents occurring in the bedrock are used, *Figure 3.14*. Penetration depth is up to 10 kilometres and the measurement is conducted so that anisotropic conditions also can be investigated. The observation times are up to 12 hours. Interference from transmitters for mobile telecommunication and power lines can, in most cases, be filtered out. With measurements in a coarse network, three-dimensional electrically conductive structures can be identified. With this method, the depth at which the transition to saline groundwater occurs can be determined.

Electromagnetic measurement methods have been used for ore prospecting, investigations of water-bearing fracture zones in the rock and for studies of pollutant dispersion. The methods are based on complex theory. New instruments are developed for environmental applications, for example, EnviroMT (Bastani 2000).

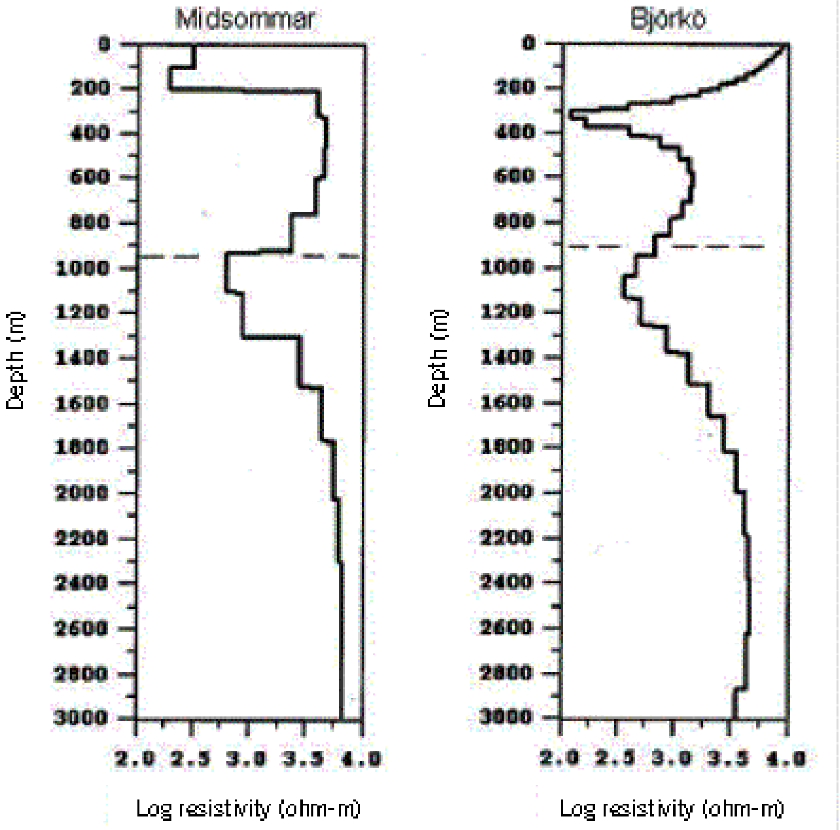


Figure 3.14. *Two models of the resistivity variation with depth based on MT measurements (from the islands Midsommar and Björkö in Lake Mälaren). (From Oskooi and Pedersen 2004).*

3.4.9 Borehole Geophysics

In most deep boreholes in Sweden, measurements have been conducted with different types of geophysical logging in order to determine the variation of the measured characteristic property with depth. Such measurements can be conducted at intervals that vary from 0.1 to tens of metres. Accurate methods have been developed to correlate the depth values obtained in connection with different measurements. However, in Sweden, there are very few boreholes with a depth exceeding 1 kilometre. Consequently, knowledge is lacking of where the transition to saline groundwater occurs in the bedrock and how deep the fracture zones extend into the upper part of the Earth's crust. Boreholes that are deeper than 2 kilometres in crystalline bedrock only exist in the central part of the Siljan structure in Sweden. In borehole measurements, the sensing distance in the horizontal direction is very small, from decimetres for certain methods and, under favourable conditions, up to tens of metres, in the case of borehole radar for example. The measurement of resistivity in boreholes only gives relative values and calibration is required to obtain values that are representative for rock types. This problem is treated in Löfgren & Neretnieks (2002).

The following types of borehole measurements are common and can be used in connection with site selection:

Methods that characterise rock types and rock type boundaries

Gravity measurements
Measurements of magnetisation
Induced polarisation (IP)
Gamma radiation (several different methods)

Methods that identify fracture zones and the occurrence of water

Measurement of electrical resistivity (several different methods)
Radar measurements
Water flow measurements
Measurement of borehole shape (calliper)
Temperature measurements
Video photography

Methods that identify stress and temperature conditions

Response to pressure changes
Measurement of borehole shape
Temperature measurements
Gamma radiation measurements (several different methods)

The methods are often used in combination and several sophisticated measurement probes have been developed for the electrical methods including a choice of different electrode configurations, *Figure 3.15*. Measurements involving radar, borehole shape and photography also provide information on the *orientation* of structures that have been detected. Water flow measurements are performed in limited sections, in response to pressure changes. The response in the bedrock displacement is measured and identified during the test period with the help of local seismograph networks. The connection between borehole data, which is very detailed (dm-scale) and continuous, with surface data that are dispersed (1 metre to 10 metre scale) and incomplete, is a difficult problem. The difficulty is related to how local phenomena can be distinguished from those that cover a large area. The distance dependence of the measurement method implies that the spatial resolution rapidly decreases with distance from the borehole and with depth in ground based surveys. The problem cannot be resolved with more frequent or more sensitive measurements – instead, more boreholes are needed – which however change the properties of the bedrock in an unfavourable manner.

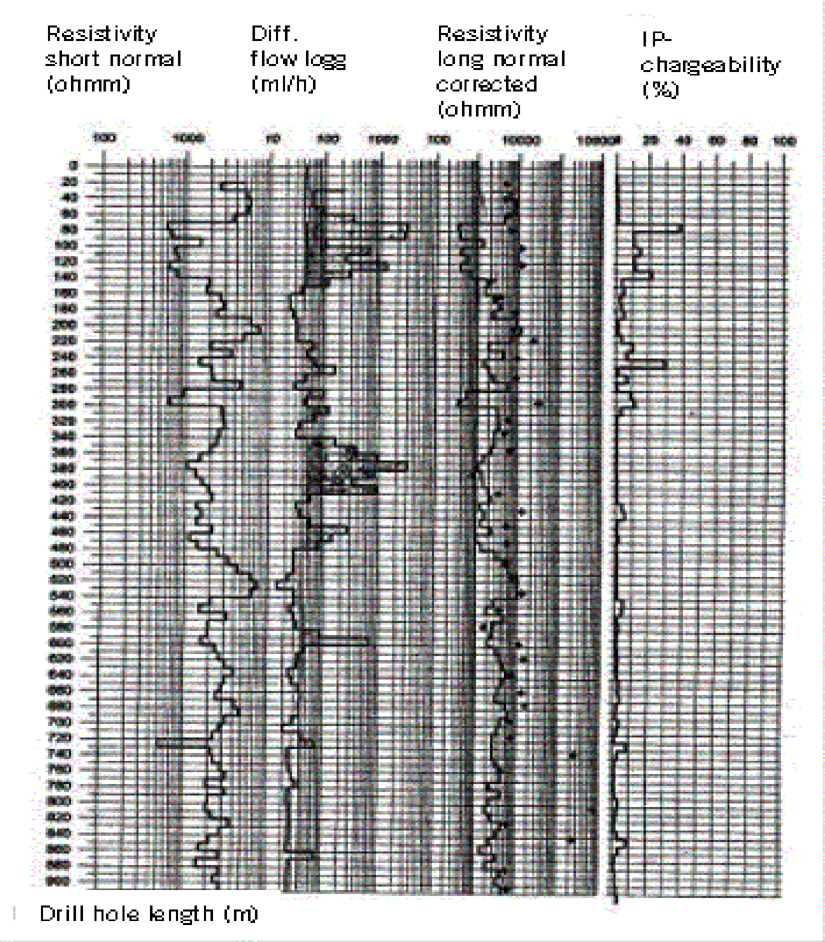


Figure 3.15. *Example of logging data from a 900 m deep drill hole (on Björkö in Lake Mälaren) with electric resistivity (two methods, short normal and long normal), water flow, and induced polarization (IP) generalised over 10 m intervals. (Sträng 2003). The variation in resistivity reflects the fracture frequency. Higher water flow indicates open fractures and increased IP effect indicates sections where electrically conductive minerals occur.*

3.4.10 Databases at SGU and the Swedish Maritime Administration

The Geological Survey of Sweden (SGU) holds a large number of databases with *digital* and *analogue* geoscientific information. They are available for research, prospecting, geotechnical and environmental investigations. A licence is required and fee must be paid to use the data. Digital data can be obtained for an optional geographical area and they are often directly suitable for analysis with Geographical Information Technology (GIT). Furthermore, geoscientific maps with different degree of detail occur all over the country.

Regional surveys are conducted systematically by SGU while detailed surveys are conducted by geological consulting companies, prospecting companies and geoscientific departments.

Queries about seismic measurements should be primarily directed to SGU. Several international projects, with the aim of determining the structure and thickness of the Earth's crust, have been based on seismic investigations covering many 100 kilometres.

In connection with prospecting for ore, large areas in Västerbotten and Norrbotten have been mapped in great detail with several types of ground geophysical measurements. These are documented at SGU.

The Swedish Maritime Administration handles bathymetric data, often with a high degree of detail, over coastal areas and inland lakes where shipping occurs. These bathymetric data can be used in the same way and in combination with altitude data to study the occurrence of fracture zones in water areas (or their extension from land to water areas). Such a combined study has, for example, been conducted for the Lake Vänern basin (Isaac 1992) and southern Björkfjärden (Chuang 2003).

3.5 Conclusions

Geological Methods

Swedish crystalline bedrock is a complex heterogeneous medium, formed by geological processes during more than 2,000 million years. Many of these processes are ancient but affect the stability and safety of a repository for radioactive waste. Other processes are active and gradually change the geological conditions. The geological situation in the shield with a very young soil cover over a considerably older crystalline bedrock means that the time-period during which ongoing geological changes can be studied is much less than the planned lifetime of the repository. Therefore, it is important to conduct systematic studies in the young geological deposits with respect to the effects from land uplift, earthquakes and fault movements. Many of these dynamic processes will probably continue for a foreseeable time in the future.

Geodynamic Methods

Much research has been conducted on the induced geodynamic changes that will occur locally through the construction of a repository for spent nuclear fuel, also coupled to the heat exchange that will occur between the repository and the environment. However, natural geodynamics has not attracted the same interest. Nevertheless, several indicators show that systematic movements between crustal blocks occur continuously. Such movements have been quantified in some cases with geological methods, with measurements in the Global Positioning System (GPS) and by analysing major earthquakes. The movements are located in limited areas or zones. These zones can be mapped geographically and in terms of depth using geological and geophysical methods. The movements along the zones are relatively small and, therefore, long observation periods are required in order to determine them with certainty.

The displacement zones function as part of a larger regional context and, at present, there is insufficient information on the way in which they function locally. Consequently, local systems must be built up and measured for a long time. The ongoing deformation is one of the key problems in making forecasts of the bedrock stability. Therefore, knowledge of the position and extent of the zones (horizontal and vertical), the velocity and direction of the motion, the function of the zones in time and their function in the regional and plate tectonic deformation is necessary. How plinths and shear lenses react to changes in the stress field should therefore be modelled. Such modelling can be made for observed structures in the investigation areas and their regional context.

The methods that must be further developed to provide such knowledge are both direct and indirect, for example measurement techniques with GPS and seismograph networks, age determinations of minerals and geological observations, in order to provide increased knowledge of the structure and performance of the lithosphere. The existing geodetic and seismic networks should be nationwide and co-operation over national boundaries should be developed to create databases that can be used for several geoscientific purposes. The GPS networks which were previously set up should also be measured in the future in order to obtain time series that are as long as possible. This also applies to measurements of the change in gravity.

Geophysical Methods

A large number of geophysical surveys have been conducted so far or are planned in connection with site investigations prior to the construction of a repository for spent nuclear fuel. The measurements have had different purposes and scales, from general airborne surveys to detailed characterisations in boreholes. In many cases, the aim has been to build up a geological/tectonic model over the area or to predict geological and tectonic changes during the construction phase, such as during the construction of the Äspö tunnel. A limited amount of research work has been conducted on the possibilities of transforming measurements to input variables for chemical dispersion models. Certain development efforts have been made, for example, resistivity measurements for determination of diffusion in massive rock (Löfgren & Neretnieks 2002).

Geophysical surveys are a very valuable tool since, in principle, they are the only methods that provide non-destructive measurements of the rock volume where the repository will be constructed. Therefore, it is of great importance that surface-based geophysical surveys should be conducted at an early stage. A combination of several methods with high data point density and determination of the physical properties of the geomaterials and control drilling is necessary in order to reduce uncertainty when interpreting the measurements.

A combination of magnetotelluric (MT) measurements, which have great depth penetration capabilities, and reflection seismic measurements are tools to determine the depth to saline groundwater and the occurrence of deep fracture zones. Such measurements must be made systematically and with sufficient coverage of the investigation area and its surroundings. Ground geophysical surveys are of particular importance, such as surface-covering measurements with ground penetrating radar in order to map the soil stratigraphy, the soil thickness, the contact zone between soil and rock and the fracture conditions of the near surface rock, as a basis for calculating groundwater recharge in the bedrock.

In the case of geological and geophysical investigations, the extent of the measurements must be large enough to include an adequate environment outside the actual area of interest is included. This also applies to water-covered areas. The extent should be about 3 times greater than the area of interest in all directions. The total investigation area should thereby be about

10 times greater than the area of interest. Reflection seismic and radar investigations should be conducted in a systematic manner in the entire investigation area in order to map the occurrence of low angle fracture zones since these can not normally be observed in outcrops or with other geophysical methods.

3.6 Appendix: Geodynamic Processes

The mapping of the extent and intensity of geodynamic processes requires observations of deformations in reference structures or in observation networks over a long time-period. The deformation of the crust over the past million years and the ongoing deformation of the crust are referred to as *neotectonics*. In Sweden, this particularly refers to the deformation that occurred after the last glaciation. The deformation that is currently in progress is almost unnoticeable over short time-scales (decades). However, it can accumulate to a considerable size during geological time periods (millions of years). Due to the constant movement of the global lithosphere plates, all parts of the crust are affected all over the Earth. Along the plate boundaries, the deformation is very great and causes severe earthquakes and volcano eruptions. Inside a lithosphere plate, the deformation is considerably less, hardly noticeable and does not cause catastrophes. The boundaries of our lithosphere plate (the Eurasian plate) are located in the middle of the North Atlantic (*Figure 3.16*), in the Arctic Ocean, along the Japanese island chain, Indonesia, the Himalayas, Anatolia, the Alps and the Atlas mountains. The Eurasian plate largely comprises continents and moves due to the growth of the Atlantic ocean crust by about 1 centimetre per year (i.e. the same order of magnitude horizontally as the land uplift). Several active deformation zones are located in this plate, for example, the graben system that stretches from the North Sea via the Rhine valley to the Rhone valley. Areas also exist in our vicinity that can be suspected, on good grounds, to be active deformation zones, such as the mountain belt, Lake Vänern and the Bothnian Sea and Bothnian Bay. The deformation zones are characterised by anomalous topography, anomalous *land uplift*, the occurrence of *earthquakes* and the systematic displacements of large crustal blocks. These characteristics, as well as how they can be studied, are treated briefly below.

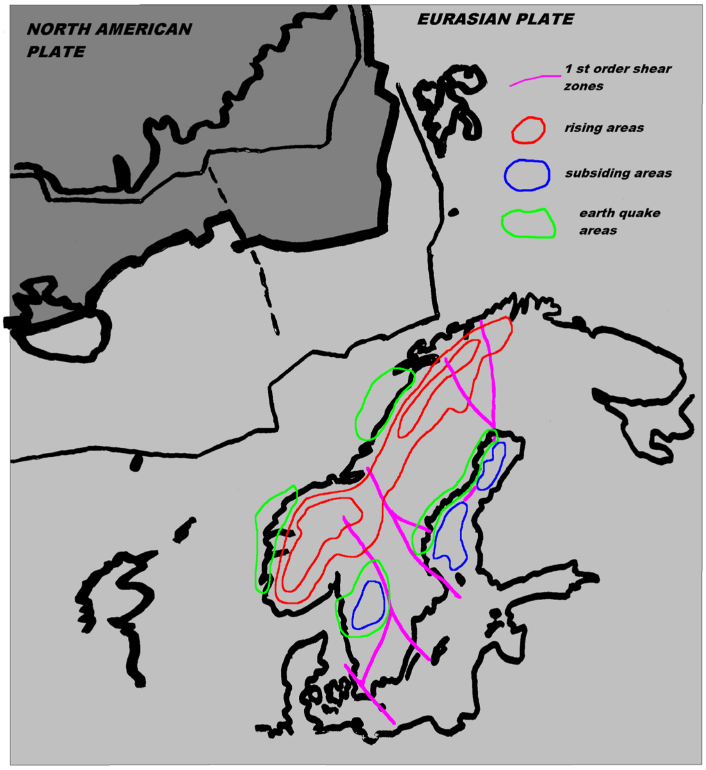


Figure 3.16. *The plate tectonic situation of Sweden. The Mid-Atlantic ridge is our nearest plate boundary between the North American (dark grey) and the Eurasian (light grey) lithosphere plate. The large-scale geomorphic regions are the rising area in the Scandian mountain belt (red lines) and the parallel, about 400 km to the east located, areas of down warping (blue lines) around Lake Vänern and the Bothnian Sea and Bay. Generalised areas with earthquakes are outlined green. The first order shear zones are marked with purple lines (Henkel & Roslund 1994).*

On a more detailed scale, neotectonics manifests itself by the occurrence of fault escarpments with varying height (from less than 1 metre to over 20 metres), landslides, slumping and liquefaction structures in soil layers, boulder fields and caves, and as displacements of glacially shaped outcrops. Some of these phenomena can also occur due to other geological processes and the connection between occurrence and cause requires extensive mapping over large areas. The terrain shapes that are associated with young fault zones were first discovered by studies of aerial photography in areas located over the highest shoreline and which, therefore, have not been exposed to seashore erosion. Landslides can be detected in the same way (and run the risk of erosion if they have been exposed to shore erosion). Therefore, these neotectonic indicators have so far mostly been found in northwestern Norrbotten and it is still unclear whether they indicate an anomalous neotectonic active area or whether they have also occurred in areas below the highest shoreline. Considerable new road construction work has created road cuts with sections that are suitable for detailed studies of disturbances in the soil stratification. These are common phenomena in mobile sedimentary environments and a determination of the boundaries of tectonically caused structures requires regional mapping and dating of the sediment stratification. Boulder fields and caves can be related to earthquakes but also occur through frost heaving and frost erosion. Minor displacements of glacially shaped rock outcrops across fractures are a clear indication of block movements that have occurred after the formation of the surface. An interruption in such surfaces, where one block is missing, occurs when the missing part is transported away by ice. In Mörner (2003), a thorough neotectonic interpretation of a large number of observations is made, which is connected to paleoseismic activity. Many of the observed phenomena are located in time to the deglaciation phase, which was a period of relatively major changes in the stress field.

Knowledge of the ongoing geodynamic processes is important for judging the long-term stability of a nuclear waste repository. Without actual measurements of geodynamic changes and knowledge of the underlying processes, predictions of future changes are based on assumptions.

3.6.1 Topography

Tectonic processes and erosion primarily cause the variation in the large-scale topography in Scandinavia. Elevated areas cannot last for long geological time-periods due to continuous erosion. In the same way, sinks cannot last for long periods of time due to continuous *sedimentation*. On the other hand, areas without significant topographical variation are relatively stable (for example, the Småland highlands and Finland). By studying elevation data (in the form of topographical maps or digital elevation data), older erosion surfaces can be reconstructed (Lidmar-Bergström 1988). However, only exceptionally can the age of these be determined. The large-scale topography in Scandinavia is young. Studies of sedimentation in the sea areas off the coast of Norway indicate increased sedimentation starting about 5 to 10 million years ago and distinct uplift areas have been identified in the mountain belt (Riis & Fjedskaar 1992). In Lake Vänern and the southern and northern parts of the Bothnian Sea and Bay, there is still no occurrence of thick young sediments despite ongoing mountain belt erosion and the fact that materials are being transported to these sinks by rivers. The cause of the young topography is not yet known. However, due to the large dimensions, it is likely to be related to plate tectonic processes. The natural evolution of the young oceanic lithosphere in the North Atlantic is gradually leading to the formation of a subduction zone at the edge of the continental lithosphere where the oceanic lithosphere is being submerged below the continental lithosphere. At a distance and in parallel with the subduction zone, a subsiding region would develop, as the lithosphere is dragged apart by an opposing current in the upper mantle. However, at present, no measurement data are available for determining changes in the large-scale topography.

In order to obtain such data, observations of the land surface and sea bottom changes are required over long periods of time, probably decades. Such observations are conducted in nationwide geodetic networks where continuous measurements are used against the satellites in the GPS system. Small-scale topography (such as elevated or depressed shear lenses) can also indicate geodynamic processes. *Figure 3.17* shows a cross-section of the Earth's crust from northwest Lofoten to central Finland (Henkel & Lund 2004). *Figure 3.18* shows a profile over a major shear zone in Värmland.

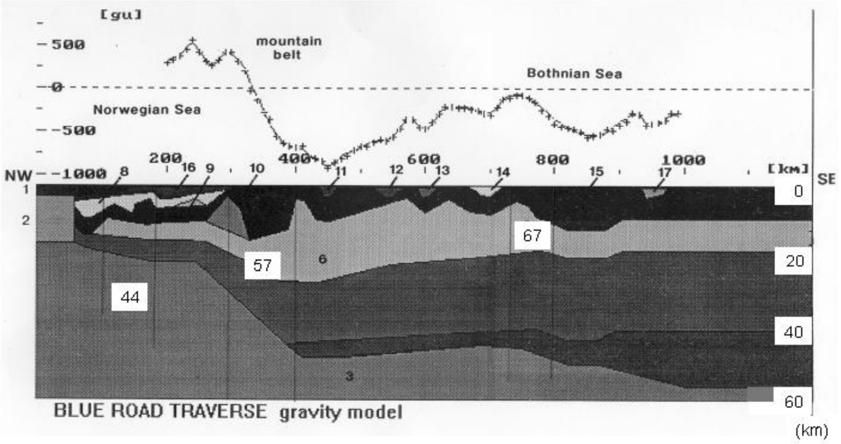


Figure 3.17. Section through the Earth's crust from northwest of Lofoten to central Finland. The model is based on a combination of refraction seismic and gravity data. To the northwest, the change from the oceanic crust to the continental shelf is seen. The thickness of the crust is larger under the mountain belt and increases to its largest value in Finland. The number of earthquakes, which occur in three distinct zones (delineated by vertical lines), is presented with numbers in their approximate depth location. (The gravity anomaly is in gu (= 0.1 mgal). The small numbers mark areas of different density.

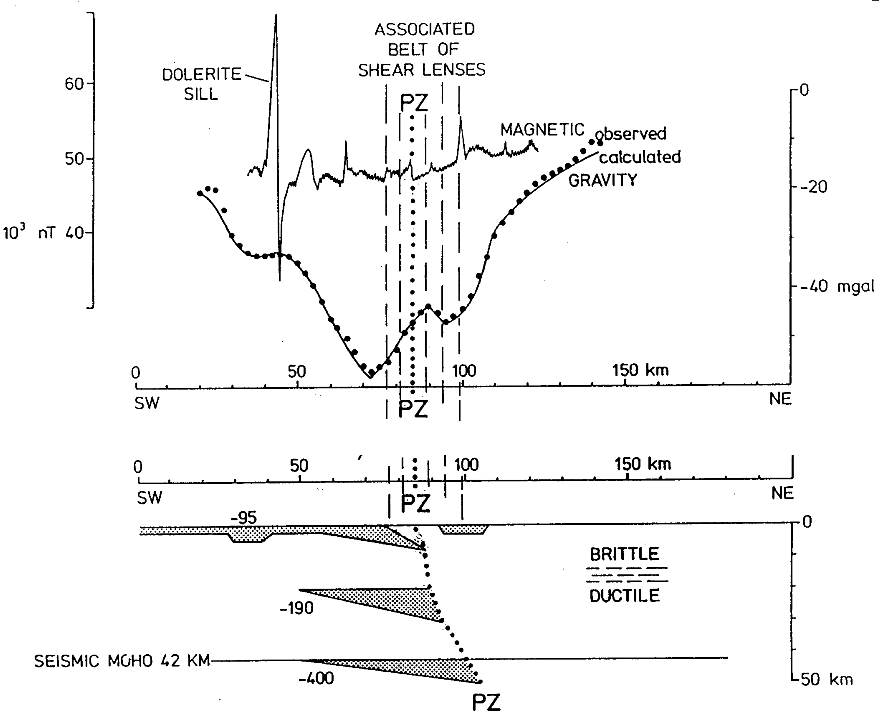


Figure 3.18. Profile across one of the first order shear zones in Värmland (marked as PZ), which cuts through the entire crust (here about 40 km thick) (Henkel 1992). In the upper part of the diagram magnetic measurements are shown which are the basis for calculations of the near surface dip of the zone. In the lower part of the diagram gravity measurements are shown which are the basis for calculations of the extent of the zone through the Earth's crust. It also shows down warping of different layers in the crust from west towards the zone, which dips steeply towards the east.

Facts

Plate tectonics – the deformation of the lithosphere due to heat convection from the Earth's mantle,
Lithosphere – the uppermost shell of the Earth, which is displaced as a unit in plate tectonic processes. Its thickness is about 250 km in central Scandinavia,
Mantle – the region between the lithosphere and the Earth's core, about 3,000 km thick,
Earths crust – the uppermost part of the lithosphere outside the mantle, the thickness in central Scandinavia is about 50 km,
The boundary between the crust and the mantle is the Moho (the Mohorovicic discontinuity).

3.6.2 Land Uplift

In Scandinavia, land uplift is well-known, has been measured for centuries and can be seen in the young geological deposits that are reshaped in shore zones and which have gradually ended up at increasingly higher levels above the present sea surface. Land uplift is currently the greatest, about 9 mm per year, in the vicinity of Umeå. It is zero close to the boundary of the crystalline shield against the surrounding sediment covered areas. In the area just south and east of the shield (i.e. in northern Germany, Denmark, the southernmost part of Scania, the Gulf of Riga and around Lake Ladoga) a slight land subsidence occurs. The cause of the land uplift is attributed to the deglaciation that occurred over 10,000 years ago. However, there are several indications that other forces are active. The extent of the land uplift is not compatible with the extent of the ice. Local deviations in the land uplift also exist (known as *differential* land rise) and there is a considerable difference in the land uplift gradient between the western and eastern part of the land uplift area. Areas with a significant deviation from the general land uplift (which can be connected to the deglaciation) show relative *rising areas* by more than 1.5 mm/year in the mountain belt and relative *subsiding areas* with corresponding deviations in the southern part of the Bothnian Bay and Sea (see *Figure 3.16*, areas within the red and blue lines respectively). The subsiding area extends further towards the northeast beyond the northern part of the Bay of Bothnia. It also includes northern Uppland (Fjeldskaar *et al.* 2000). Investigations of shoreline displacements in northeastern Uppland (Hedenström & Risberg 2003) show that the exponentially decreasing land uplift has turned into a linear trend about 5 500 years ago. This is a strong indication that other processes besides isostatic compensation after deglaciation are active.

The land uplift can be measured by recurring levelling of fixed points and such measurements provide the basis for knowledge of the present land uplift. However, since 1993, traditional levelling measurements have been replaced by data obtained from 25 permanent GPS reference stations placed all over Sweden, known as the SWEPOS network. After a long observation period, the relative movement of the observation points, horizontally and vertically, can be calculated from the measurement data.

3.6.3 Earthquakes

Earthquakes occur when the Earth's crust breaks apart due to the sudden release of stresses that have built up over a long period of time. Such stresses accumulate due to differential movements between crustal blocks along shear zones. In Scandinavia, only mild earthquakes occur and earthquakes with a magnitude of 5 or larger (on the Richter scale) are rare. The earthquakes occur in the brittle part of the crust at an average depth of about 18 kilometres along certain zones and in a few limited areas. The present-day seismic active areas in Sweden are especially the Lake Vänern depression and the Swedish coast along the Bothnian Sea and Bay (see map in *Figure 3.19*). The earthquakes are registered in a network of seismograph stations, which operate over a long period of time. The more dense the network, the better it is to locate and characterise also minor earthquakes. Registered data from average and large earthquakes can be evaluated with regard to the orientation of the stress field and the movement surface, its area and the displacement that has occurred. Such evaluations are conducted by the seismology division (Department of Earth Sciences) at the University of Uppsala, which also since the year of 2000 operates the new seismograph network, SNSN. So far, over 1,000 earthquakes have been registered in this network, *Figures 3.19* and *3.20*.

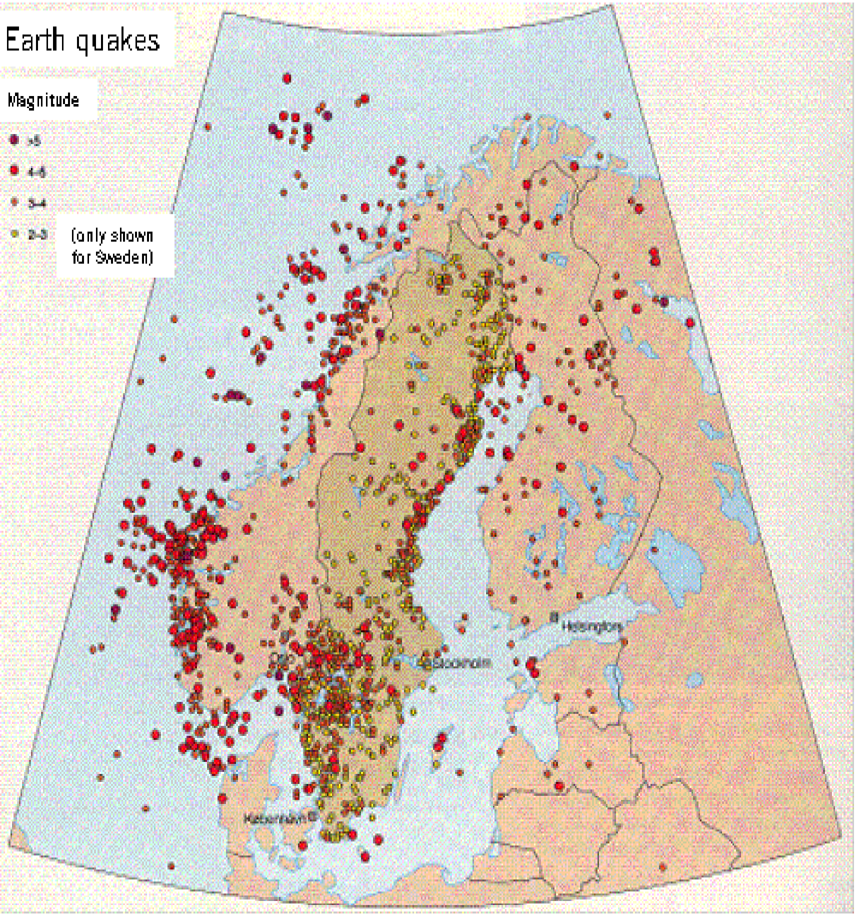


Figure 3.19. The occurrence of earthquakes in Scandinavia. The increased number of earthquakes in the four regions marked green in Fig. 3.16 is clearly visible (from Sveriges Nationalatlas ©, Lantmäteriet Gävle 2004, permission M 2004/3790).

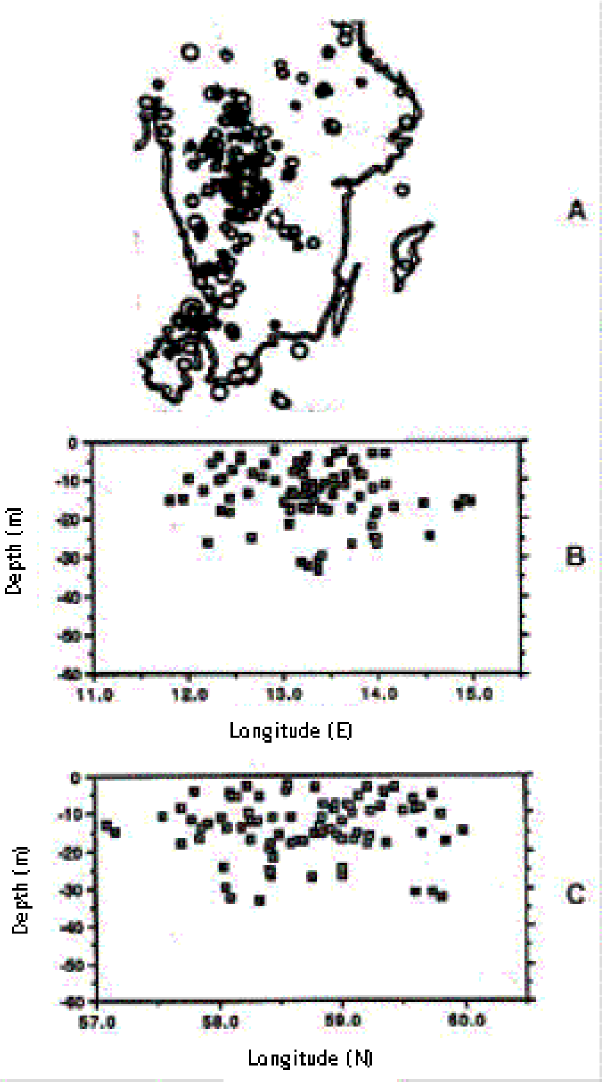


Figure 3.20. The distribution of earthquakes in the Vänern region shows an accumulation of earthquakes (map view A) and their distribution projected onto a west-east (section B) and a south-north section (profile C). (from Isaac 1992).

Traces of earthquakes can also be found in sediment stratification and in the bedrock. In the former case, the time of the earthquake can often be identified, while the age of the traces in the bedrock can seldom be determined. In the sediment stratification, the occurrence of *landslides* and *liquefaction* indicate earthquakes. In the bedrock, the occurrence of *friction melting* indicates the position and extent of fossil earthquakes. It has also been suggested that *bedrock caves* are caused by earthquakes.

3.6.4 Fault Movements

The brittle uppermost part of the Earth's crust is dissected by movement zones. When adjacent bedrock blocks are displaced, this is called a *fault* (see Berglund & Stigh 1998). Some of these zones have been active just after the deglaciation (*Figures 3.21* and *3.22*). However, the movement must displace a geological structure that can be dated, for example an esker or a moraine ridge, a measurable distance in order for the movement to be observable. If the movement has occurred in a completely homogeneous environment or is only very small, the movement cannot be determined. The geological environment must also be so stable that the displacements can be preserved. In recent years, methods have been developed that allow all systematic bedrock movements to be measured, for example, with repeated GPS measurements of fixed points positioned strategically with respect to the zones that are to be investigated (see *Figures 3.4* and *3.5*). The measurement series must be conducted over a period of at least 6 years in order to obtain interpretable results. Investigations so far conducted with GPS measurements show that lateral movements that are a few mm per year occur along the Tornquist zone in Scania (one of the first order shear zones – see *Figure 3.16*) (Pan *et al.* 2001). In the network in Norrbotten, where the observation time is only 5 years, it has not been possible to prove any movements with certainty

(Ågren 2001) and in that region, the measurements should be repeated several times. Information on deformations that have occurred very long ago has been compiled in Milnes (1998). However, their present function is still unclear. It is not well understood where, how and why present-day movements occur since this requires both detailed local investigations and a good knowledge of the movement pattern in the plate tectonic unit to which Sweden belongs. Furthermore, the problem would require a three-dimensional approach, which is difficult to achieve since the distribution of horizontal fractures are often unknown.

Figure 3.21. *Post-glacial faults in northern Scandinavia (red dashed lines), (from Lagerbäck (1988).*

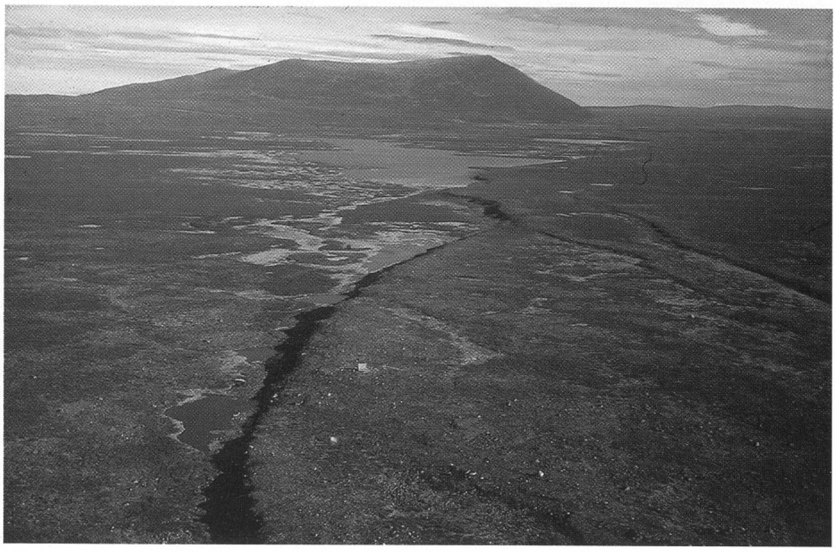


Figure 3.22. The Pärve fault – one of the large post-glacial fault zones in Scandinavia, view towards north (from Lindström et al. 2000), (photograph by J. Lundquist 1975).

When the position and movements of fracture zones have been established, questions arise concerning the future function of the zones. For example, which changes in the strength and orientation of the stress field can activate a certain fracture direction as well as how the stress field will change due to the plate tectonic evolution or due to future glaciations. In LaPointe et al. (2000), model calculations describe how earthquakes that occur in the vicinity of a repository affect the repository through the activation of existing fracture zones. With the same technology, it is possible to model the size of the change in the stress field that is needed to activate the fracture and shear zones mapped in the investigation area.

References (some references are in Swedish)

Aaltonen, J., 2001: Ground monitoring using resistivity measurements in glaciated terrains. Doktorsavhandling, KTH, Institutionen för Mark- och Vattenteknik, TRITA-AMI PHD 1042.

Aaltonen, J. & Olofsson, B., 2001: Direct current (DC) resistivity measurements in long-term groundwater monitoring programmes. Environmental Geology 41:662–671.

Amadei, B., & Stephansson, O., 1997: Rock stress and its measurements. Chapman and Hall, London.

Andersson, O., Bergdahl, U., Nemeth, T., Nyberg, I., Stille, H., Svesson, P.L., Tenne, M. & Viberg, L.,1984: Fältundersökningsmetoder – Kapitel G08. Handboken bygg. Liber - Förlag.

Ask, D., 2003: Hydraulic rock stress measurements in borehole BJO01, Björkö Island, Lake Mälaren, Sweden. KTH, Department of Land and Water Resources Engineering. TRITA-LWR. Report 3003.

Bastani, M., 2001: EnviroMT – a new controlled source/radio magnetotelluric system. Acta Universitatis Upsaliensis. Uppsala Dissertations from the Faculty of Science and Technology 32.

Berglund, J. & Stigh, J., 1998: Sprickor i berg. Kunskapsläget på kärnavfallsområdet. SOU 1998:68.

Bernstone, C. & Dahlin, T., 1998: DC resistivity mapping of old landfills: Two case studies. European Journal of Environmental and Engineering Geophysics 2:121–136.

Cardarelli, E., Marrone, C. & Orlando, L., 2003: Evaluation of tunnel stability using integrated geophysical methods. Journal of Applied Geophysics 52:93–102.

Dehls, J.F., *et al.* 2000: Neotectonic map of Norway and adjacent areas. In Olesen *et al.*, NGU Report 2000.002.

Dehls, J.F., Olesen, O., Olsen, L. & Blikra, L.H., 2000: Neotectonic faulting in northern Norway; the Stuoragurra and Nordmannvikdalen postglacial faults. Quaternary Science Reviews 19:1447–1460.

Fjeldskaard, W., Lindholm, C. & Fjeldskaard I., 2000: Geodynamic modeling regional and local. *In* Olesen *et al.* 2000: Neotectonics in Norway. NGU Report 2000.002:74–82.

Grasmück, M., (1994): Application of seismic processing techniques to discontinuity mapping with ground-penetrating radar in crystalline rock of the Gotthard Massif, Switzerland. Proc. of the fifth international conference on ground penetrating radar, June 12–16, 1994, Ontario, Canada, pp. 1135–1150.

Hedenström, A. & Risberg, J., 2003: Shore line displacement in northern Uppland during the last 6500 calendar years. SKB TR 03-17.

Helle, S.K., 2004: Sequence stratigraphy in a marine moraine at the head of Hardangerfjorden, western Norway: evidence for a high-frequency relative sea-level cycle. Sedimentary Geology (in press).

Henkel, H., 1988: Tectonic studies in the Lansjärv region. SKB TR 88-07.

Henkel, H., 1992: Geophysical aspects of the Protogine Zone in three traverses. GFF 114:344–349.

Henkel, H. & Lund, C-E., 2004: Integrated gravity and refraction seismic model along the Blue Road traverse and its extensions. The 26th Nordic Geological Winter Meeting, GFF 126:90.

Henkel, H. & Roslund, M., 1994: Första ordningens branta skjuvzoner i Sverige. SKB AR 94-56.

Isaac, E, 1992: An integrated study of the Vänern lens with a GIS. MSc thesis, Univ. of Washington, Seattle USA.

Janelid, I., 1965: Bergmekaniken och dess betydelse vid planering av gruvor och bergrum. Bergmekanik. Ingeniörsvetenskapsakademiens (IVA) meddelande 142:7–12.

Lagerbäck, R., 1988: Postglacial faulting and peleoseismicity in the Lansjärv area, northern Sweden. SKB TR 88-25.

LaPointe, P.R., Outters, N. & Folin, S., 2000: Evaluation of the conservativeness of the methodology for estimating earthquake-induced movements of fractures intersecting canisters. SKB Tr 00-08.

Lidmar-Bergström, K., 1988: Denudation surfaces of a shield area in south Sweden. Geogr. Ann. 70 A:337–350.

Lindström, M., Lundqvist, J. & Lundquist, T., 2000: Sveriges geologi från urtid till nutid. Studentlitteratur ISBN 91-44-090875-9.

Löfgren, M. & Neretnieks, I., 2002: Formation factor logging in-situ by electrical methods. Background and methodology. SKB Tr 02-27.

Milnes, G., 1998: Crustal structure and regional tectonics of SE Sweden and the Baltic Sea. SKB TR 98-21.

Nimmer, R. & Osiensky, J., 2002: Direct current and self-potential monitoring of an evolving plume in partially saturated fractured rock. Journal of Hydrology 267:258–272.

Olofsson, B., Jernberg, H., & Rosenqvist, A., 2004: Tracing leachates at waste sites using geophysical and geochemical modelling (manuscript).

O´Neal, M. & McGeary, S., 2002: Late Quaternary stratigraphy and sea-level history of the northern Delaware Bay margin, southern New Jersey, USA – a ground penetrating radar analysis of composite Quaternary coastal terraces. Quaternary Science Reviews 21:929–946.

Oskooi, B., & Pedersen, L.B., 2004: Magnetotelluric studies on Björkö impact structure, west of Stockholm. Report, Department of Earth Sciences, Geophysics, Uppsala University.

Pan, M., Sjöberg, L.E. & Talbot, C., 2001: Crustal movements in Scania, between 1992 and 1998 as observed by GPS. J. of Geodynamics 31:311–322.

Rashed, M., Kawamura, D., Nemoto, H., Miyata, T. &

Nakagawa, K., 2003: Ground penetrating radar investigations across the Uemachi fault, Osaka, Japan. Journal of Applied Geophysics vol. 53, pp. 63–75.

Sattel, G, Sander, B.K., Amberg, F. & Kashiwa, T, 1996: Tunnel Seismic Prediction, TSP – some case studies. Technical article, Amberg Measuring Technique Ltd, Regensdorf-Watt, Switzerland.

Scherneck, H.-G. *et al.,:* Observing the Three-Dimensional Deformation of Fennoscandia. *In:* /Glacial Isostatic Adjustment and the Earth System, /edited by J.X. Mitrovica and B.L.A. Vermeersen, pp. 69–93, Geodynamics Series, Volyme 29, American Geophysical Union, Washington, D.C., 2002.

Sjöberg, L.E., Pan, M., & Asenjo, E., 2002: An analysis of the Äspö crustal motion monitoring network observed by GPS in 2000, 2001, and 2002. SKB R 02-33.

SKB 2001: First TRUE Stage – Transport of solutes in an interpreted single fracture. Proceedings from the 4th International Seminar Äspö, September 9–11, 2000, SKB Technical Report TR-01.24.

Slater, L., & Niemi, T.M., 2003: Ground-penetrating radar investigation of active faults along the Dead Sea Transform and implications for seismic hazards within the city of Aqaba, Jordan. Tectonophysics, vol. 368, pp. 33–50.

SNA 1994: Sveriges Nationalatlas, Berg och Jord. ISBN 91-87760-27-4.

Sträng, T., 2003: Geofysisk borrhålsloggning i borrhål BJO 01 på Björkö och MID 01 på Midsommar. Geosigma AB. 15.

SWEPOS 2003: Displacement rates. http.//www.oso.chalmers.se.

Tirén, S., Wänstedt, S. & Sträng, T., 2001: Moredalen – a canyon in the Fennoscandian Shield and its implication on site selection for radioactive waste disposal in south-eastern Sweden. Engineering Geology 61:99–118.

Widén, E., 2001: Groundwater flow into and out of two lakes partly surrounded by peatland. MSc thesis, KTH, Institutionen för Mark- och Vattenteknik.

Ågren, J., 2001: Processing the 1992, 1994 and 1997 campaign on the northern GPS deformation traverse. Licentiate thesis, KTH, Department of Geodesy.

Åström, K., & Lund, C-E., 1994: Thin superficial layer and lateral heterogeneities in southern Sweden using short-period Rayleigh-wave dispersion. Geoph. J. Int. 118:231–244).

Recommended reading

Lindsröm, M., Lundqvist, J. & Lundquist, T., 2000: Sveriges geologi från urtid till nutid. Studentlitteratur ISBN 91-44-090875-9.

Lundqvist, J., 2001: Geologi. Processer – utveckling – tillämpning. Studentlitteratur.

Mazor, E., 2004: Chemical and isotopic groundwater hydrology. Third Edition. Marcel Dekker, New York. Basel.

Milsom, J., 2003: Field Geophysics. Third Edition. John Wiley & Sons, Chichester.

SNA 1994: Berg och jord. Sveriges Nationalatlas.

Stanfors, R., Triumf, C-A., & Emmelin, A., 2001: Geofysik för bergbyggare. SveBeFo K 15.