R-08-19

Geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas

Site descriptive modelling SDM-Site

Björn Söderbäck (editor)
Svensk Kärnbränslehantering AB

June 2008

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 250, SE-101 24 Stockholm
Tel +46 8 459 84 00

ISSN 1402-3091
SKB Rapport R-08-19

Geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas

Site descriptive modelling SDM-Site

Björn Söderbäck (editor)
Svensk Kärnbränslehantering AB

June 2008

A pdf version of this document can be downloaded from www.skb.se.

Preface

The Swedish Nuclear Fuel and Waste Management Company (SKB) is undertaking site characterization at two different locations, the Forsmark and Laxemar-Simpevarp areas, with the objective of siting a geological repository for spent nuclear fuel. The site investigations started in 2002 and were completed in 2007. The analysis and modelling of data from the site investigations, which have taken place during and after these investigations, provide a foundation for the development of an integrated, multidisciplinary site descriptive model (SDM) for each of the two sites. A site descriptive model constitutes a description of the site and its regional setting, covering the current state of the geosphere and the biosphere, as well as those natural processes that affect or have affected their long-term development. Hitherto, a number of reports presenting preliminary site descriptive models for Forsmark and Laxemar-Simpevarp have been published. In these reports, the evolutionary and historical aspects of the site were included in a separate chapter.

The present report comprises a further elaboration of the evolutionary and historical information included in the preliminary SDM reports, but presented here in a separate, supplementary report to the final site description, SDM-Site. The report is common to the two investigated areas, and the overall objective is to describe the long-term geological evolution, the palaeoclimate, and the post-glacial development of ecosystems and of the human population at the two sites. The report largely consists of a synthesis of information derived from the scientific literature and other sources not related to the site investigations. However, considerable information from the site investigations that has contributed to our understanding of the past development at each site is also included. This unique synthesis of both published information in a regional perspective and new site-specific information breaks new ground in our understanding of the evolutionary and historical aspects of the two sites.

The work has been conducted by a project group and the following people have contributed with original texts to the report:
Chapter 1: Björn Söderbäck (SKB)
Chapter 2: Michael Stephens and Carl-Henric Wahlgren (SGU)
Chapter 3: Gustav Sohlenius and Anna Hedenström (SGU)
Chapter 4: Michael Stephens, Gustav Sohlenius and Anna Hedenström (SGU)
Chapter 5: Marcus Laaksoharju (Geopoint), Eva-Lena Tullborg (Terralogica), John Smellie (Conterra), Sven Follin (SF Geologic) and Ingvar Rhen (Sweco)
Chapter 6: Björn Söderbäck (SKB), Anders Löfgren (Ecoanalytica), Anna Hedenström and Gustav Sohlenius (SGU)
Chapter 7: Lotta Rubio-Lind and Björn Söderbäck (SKB), Anders Löfgren (Ecoanalytica)

Stefan Bergman, Jordi Bruno, Reynir Bödvarsson, Lillemor Claesson-Liljedahl, John Cosgrove, Henrik Drake, Robert Lagerbäck, Björn Lund, Roland Roberts, Derek Martin, Raymond Munier, Björn Sandström, Michael C Thorne, Ari Tryggvason and Stefan Wastegård suggested many improvements on earlier versions of the report. Björn Söderbäck edited the text.

Extended summary

Bedrock evolution

Bedrock geological evolution of south-eastern Sweden

The Forsmark and Laxemar-Simpevarp areas are situated in the south-western part of one of the Earth's ancient continental nuclei, referred to as the Fennoscandian Shield. This part of the shield belongs predominantly to the geological unit referred to as the Svecokarelian (or Svecofennian) orogen. The bedrock inside an orogen was affected by major tectonic activity at a particular time interval during the Earth's long geological evolution and the actual geological process is referred to as orogeny. Tectonic activity refers to deformation and metamorphism of the crust in combination with active volcanism and the intrusion of igneous rocks at depth, i.e. major igneous activity. In essence, the branch of geology referred to as "tectonics" addresses the broad architecture of the outer part of the Earth. In order to provide the necessary boundary conditions for an understanding of the bedrock geological evolution of the Forsmark and Laxemar-Simpevarp areas, these two areas are viewed in a broader geological perspective. For this purpose, attention is focused on an area in the Fennoscandian Shield in south-eastern Sweden, which is referred to in this report as the geological reference area.

The bedrock geology at the current level of erosion in the geological reference area can be divided into six major tectonic domains (TD1 to TD6). These domains strike WNW-ESE more or less parallel to an older, Archaean continental nucleus to the north-east. The predominantly igneous bedrock in all these domains had largely formed between 1.91 and 1.75 billion years ago (1.91–1.75 Ga). This bedrock was also affected by a variable degree of deformation in the hot, ductile regime and the various domains had amalgamated together, more or less into their current geometric configuration, during the same time interval. The geodynamic regime involved an accretionary orogenic setting, with approximately northward-directed, oblique subduction of oceanic lithosphere beneath an active continental margin to the north-east. Accretionary tectonics refers to the progressive addition of continental crust along an active boundary between continental and oceanic plates, without major continent-continent collision. Examples of accretionary orogens at the present day occur in the Andes, in the western part of South America, and in the northerly continuation of this Cordilleran mountain belt in the western part of North America.

A conceptual tectonic model for the period 1.91 to 1.75 Ga is presented. This model involves migration of the subduction hinge away from and towards the overriding continental plate to the north-east. This migration gave rise to alternating extensional and compressional deformation, respectively. The latter was transpressive in character. Transpressive deformation involves a combination of strike-slip shear deformation along high-strain zones or broader, high-strain belts in combination with shortening across them. An important component of this transpressive deformation was dextral strike-slip displacement along such zones or belts with WNW-ESE or NW-SE strike. This was accompanied by shortening in a NE-SW direction across them, as well as predominantly constrictional strain with folding and stretching, with variable plunge to the south-east, between them. Crustal behaviour in the form of a "moving concertina" explains the progressively younger igneous activity and ductile deformation in the different tectonic domains, with three separate tectonic cycles, each of which lasted for c 50 million years. The remarkably thick continental crust throughout most of the shield (up to c 60 km) is a heritage from this early, active tectonic history.

Although the bedrock in south-eastern Sweden had already started to stabilise after 1.75 Ga, tectonic activity that involved continued crustal growth and crustal reworking continued during the remainder of the Proterozoic to the west and south (Gothian, Hallandian and Sveconorwegian orogenies). By c 900 Ma, the bedrock in the northern part of Europe had collided with other continental segments to form the supercontinent Rodinia. Break-up of

Rodinia, drift of the newly-formed continent Baltica from cold latitudes in the southern hemisphere over the equator to northerly latitudes, and amalgamation of the new supercontinent Pangaea prevailed between c 600 and 300 Ma. Rifting of the continental crust, and opening and spreading of the North Atlantic Ocean dominated the subsequent geological evolution to the south and west of the geological reference area. This long period of extensional tectonic activity was interrupted during the Late Cretaceous and early Palaeogene by a more compressive tectonic regime, which can be related to the collision of Eurasia and Africa.

An overview of the effects of these different, far-field tectonic events in the near-field realm represented in south-eastern Sweden is described. These effects gave rise to local igneous activity during the Proterozoic, burial and denudation of sedimentary cover rocks during the Proterozoic and Phanerozoic, and predominantly brittle deformation in the bedrock at different times throughout this long time interval. At least two episodes of exhumation of the ancient crystalline bedrock can be inferred, one prior to the Cambrian and the other after the Cretaceous, probably during the Neogene. The relatively thin continental crust (30 km and less) around the margins to the Fennoscandian Shield, for example along the southern coast of Sweden where the Sorgenfrei-Tornquist Zone is situated, is caused by extensional tectonics during the later part of the geological evolution, not least after c 300 Ma.

In conclusion, it appears that two fundamental types of geological process have made a profound impact on the geological evolution of south-eastern Sweden:

- Igneous activity and crustal deformation along an active continental margin at different time intervals mostly during Proterozoic time.
- Loading and unloading cycles in connection with the burial and denudation, respectively, of sedimentary rocks, around and after 1.5 Ga.

As the effects of regional tectonic activity mostly waned in south-eastern Sweden and became prominent solely in the far-field realm, the effects of loading and unloading related to the burial and denudation of sedimentary rocks, respectively, increased in significance. A major difference between the Forsmark and Laxemar-Simpevarp areas concerns the variation in the thickness of the crust in the parts of south-eastern Sweden where these two sites are located. Around Forsmark, the crust is c 46–48 km thick and shows little variation in thickness. By contrast, although the crustal thickness at Laxemar-Simpevarp is similar, there is a sharp gradient in crustal thickness directly south of this area from approximately 48 to 36 km. This thinning appears to be part of the broader regional thinning that prevails in the region close to the Sorgenfrei-Tornquist Zone.

Bedrock geological evolution of the Forsmark and Laxemar-Simpevarp areas

The bedrock geological evolution in the Forsmark and Laxemar-Simpevarp areas has been evaluated with the help of similar surface and borehole observational data at each site as well as similar age determination data. The geochronological work has involved the analysis of different minerals in different isotopic systems with different blocking temperatures. The assembly of these geochronological data has been completed in order to reconstruct the temperature-time history from rock crystallization to the time the rocks were exhumed through the c 70°C geotherm, and to determine the age of certain fracture minerals.

The Forsmark area is situated inside tectonic domain 2 (TD2) in the geological reference area in south-eastern Sweden. An older suite of plutonic, calc-alkaline intrusive rocks formed between 1.89 and 1.87 Ga, and the metagranite inside the tectonic lens, where the target volume is situated, is included within this suite. Amphibolites that intrude the metagranite and a younger suite of calc-alkaline rocks and granites formed between 1.87 Ga and 1.85 Ga. These two suites of intrusive rocks belong to the two Svecokarelian tectonic cycles at 1.91–1.86 Ga and 1.87–1.82 Ga, respectively, that have been recognised in south-eastern Sweden.

Deformation in the Forsmark area initiated between 1.87 and 1.86 Ga with the development of a penetrative grain-shape fabric, with planar and linear components, that formed under amphibolite-facies metamorphic conditions and at mid-crustal depths. The development of broad belts with higher ductile strain that strike WNW-ESE to NW-SE and surround tectonic lenses with generally lower ductile strain also occurred around 1.86 Ga. The amphibolites and other intrusive rocks that belong to the younger suite intruded during the waning stages of and after the development of the penetrative, ductile strain in the area. Regional folding of the variably intense, planar grain-shape fabric also affected the amphibolites. Ductile deformation after 1.85 Ga occurred predominantly inside the belts with higher ductile strain. It successively became more focused along ductile high-strain zones within these belts and cooling ages indicate that ductile strain along these zones probably occurred until at least 1.8 Ga. Dextral transpressive deformation, which is related to bulk crustal shortening in an approximately northward direction during oblique subduction of oceanic lithosphere, is inferred. This subduction occurred beneath an ancient continental margin to the north-east.

The Laxemar-Simpevarp area is situated inside tectonic domain 5 (TD5) in the geological reference area. In strong contrast to Forsmark, the bedrock at Laxemar-Simpevarp formed after the complex geological evolution observed at Forsmark and the intrusive rocks are more or less well-preserved. A c 1.80 Ga suite of intrusive rocks, which belongs to the Transscandinavian Igneous Belt, dominates the area. The rocks in this suite show variable composition (granite to quartz monzodiorite to diorite-gabbro), grain size and texture. They have been affected by magma-mingling and magma-mixing processes, and a close temporal and genetic relationship between the different rocks in this suite is inferred. They formed towards the end of the youngest Svecokarelian tectonic cycle in south-eastern Sweden at 1.83–c 1.79 Ga.

Although there is faint to weak ductile fabric in the intrusive rocks, which developed at a late stage in the magmatic evolution but continued to develop in the solid state after crystallization of the magmas, discrete, low-temperature, brittle-ductile to ductile shear zones form the most prominent ductile structures in the area. This deformation affected the area during the time interval 1.81 to 1.76 Ga, in response to an approximately northward-directed shortening. It is inferred that around and after 1.80 Ga, the tectonic regime in south-eastern Sweden continued to be steered by oblique subduction in an approximately northward direction.

In sharp contrast to Forsmark, the Laxemar-Simpevarp area was affected by significant igneous activity later on during the Proterozoic. Granitic magmatism at 1.45 Ga is inferred to be a far-field effect of Hallandian orogenic activity further to the west and south, and dolerites with an age of c 900 Ma formed as a result of approximately E-W crustal extension during the later part of the Sveconorwegian orogeny. As indicated by especially disturbances of the $^{40}Ar/^{39}Ar$ isotope system in different minerals, both these younger episodes of igneous activity had a significant effect on the thermal evolution of the site. However, the intrusion of the 1.45 Ga granites had only relatively minor effects on its structural evolution.

The brittle deformational history at Forsmark has been evaluated with the help of three lines of approach:

- The use of low-temperature geochronological data that shed light on the exhumation and cooling history.
- The relative time relationships and absolute ages of fracture minerals.
- A comparison of kinematic data from brittle structures along deformation zones, which were evaluated during the geological modelling work at the site, with the tectonic evolution in a regional perspective.

The same approach has been adopted in the Laxemar-Simpevarp area, apart from the use of kinematic data, which, at the present time, are not yet fully evaluated in a regional perspective. In both areas, the sub-Cambrian unconformity forms a key stratigraphic marker horizon. It provides a basis for dividing the brittle deformation and fluid circulation history that took place prior to the late Proterozoic exhumation of this ancient surface, from that which occurred after this exhumation event.

Different generations of fracture minerals have been recognised in both the Forsmark and Laxemar-Simpevarp areas. The more complex pattern at Laxemar-Simpevarp reflects a more complex hydrothermal fluid history relative to that observed at Forsmark. At both sites, an early period of precipitation of a high-temperature mineral assemblage, which includes epidote, was followed by a period of hydrothermal precipitation of different, lower temperature minerals, including adularia (older generation), hematite, prehnite, and calcite. At Forsmark, the fractures that bear epidote formed prior to 1.1 Ga, i.e. are pre-Sveconorwegian in age. In the Laxemar-Simpevarp area, epidote-bearing structures formed prior to 1.45 Ga, and fracture-controlled greisen (quartz, muscovite, fluorite, pyrite and topaz) and intense wall rock alteration developed in connection with the important thermal event at 1.45 Ga. Thermal disturbance around 1.5 Ga is also apparent. The effects of Sveconorwegian tectonothermal activity on the evolution of fracture mineral assemblages are evident at both sites. The integrated evaluation that makes use of the different lines of approach outlined above suggests that the different sets and sub-sets of deformation zones in the Forsmark area had formed and were already reactivated during Proterozoic time, in connection with the late Svecokarelian, Gothian and Sveconorwegian tectonic events.

Several lines of evidence indicate faulting after the establishment of the sub-Cambrian unconformity in both the Forsmark and Laxemar-Simpevarp areas. Furthermore, precipitation of younger low-temperature minerals, including sulphides, clay minerals and calcite, occurred during and probably after Palaeozoic time. At Forsmark, circulation of fluids in the crystalline bedrock, which originated from a sedimentary cover rich in organic material during the Palaeozoic, as well as growth of adularia (younger generation) during the Permian have been established. In the Laxemar-Simpevarp area, adularia (younger generation) formed during the Silurian or Early Devonian, possibly as a far-field effect of the Caledonian tectonic event. The youngest generation of calcite occurs in hydraulically conductive fractures and zones and may have precipitated during a long period including the present.

A conspicuous sedimentary cover was situated on top of the crystalline basement rocks throughout much of the Phanerozoic at both sites. However, in this context there are some differences between the two sites. At Forsmark, the crystalline bedrock close to the contact with the sedimentary overburden exhumed through the 70°C geotherm approximately 100 million years earlier relative to that at Laxemar-Simpevarp. Furthermore, although both sites appear to show a change in exhumation rate during the Phanerozoic, an increase in exhumation rate at Forsmark occurred approximately 50 million years earlier than a decrease in exhumation rate at Laxemar-Simpevarp. These changes in exhumation rate occurred either during the Permian or Jurassic at Forsmark and during the Early Jurassic or the Late Jurassic to Cretaceous at Laxemar-Simpevarp. It is assumed that renewed exhumation of the sub-Cambrian unconformity at both sites, with complete denudation of the sedimentary overburden, did not take place until some time during the Cenozoic.

Migration of fluids downwards from the sedimentary cover into the crystalline bedrock is apparent at both sites. At Forsmark, precipitation of, for example, oily asphaltite derived from Cambrian to Lower Ordovician oil shale occurred along fractures in the upper part of the bed-rock, while infilling of fractures in the sub-Cambrian unconformity with Cambrian sandstone has been recorded in the Laxemar-Simpevarp area. Fluids, which transported glacial sediment, also migrated downwards and filled new or reactivated fractures at Forsmark during the later part of the Quaternary period.

In conclusion, there are both similarities and significant differences in the bedrock evolution at Forsmark and Laxemar-Simpevarp. Late Svecokarelian deformation along at least some of the deformation zones, and the far-field effects of the Sveconorwegian orogeny, in the form of both brittle deformation and thermal disturbance, are apparent in both areas. Evidence for faulting after the establishment of the sub-Cambrian unconformity and for the presence of a sedimentary cover during the Phanerozoic is also present. Furthermore, downward migration of fluids from the sedimentary cover into the crystalline bedrock is also conspicuous at both sites.

By contrast, the two areas are situated in distinctly different tectonic domains in south-eastern Sweden, with different earlier igneous and ductile deformational histories. In particular, an older and more complex early tectonic evolution took place at Forsmark. However, the younger geological history appears to have been more complex at Laxemar-Simpevarp. In particular, later igneous activity, in the form of the intrusion of granites at 1.45 Ga, which formed as a far-field effect of the Hallandian orogeny, and late Sveconorwegian dolerites, is restricted to the Laxemar-Simpevarp area. Furthermore, the history of hydrothermal activity in the Laxemar-Simpevarp area appears to be more complex. Whereas the far-field effects of early Gothian brittle deformation and hydrothermal flushing during the Permian are apparent at Forsmark, the Laxemar-Simpevarp area was affected by thermal disturbances around 1.6 Ga, 1.5 Ga and 1.45 Ga during the far-field Gothian and Hallandian orogenic events, and by brittle reactivation and flushing of hydrothermal fluids during the Caledonian orogenic event. Furthermore, exhumation of the crystalline bedrock through the 70°C geotherm appears to have occurred at a later stage during the Phanerozoic at Laxemar-Simpevarp. Finally, it needs to be emphasized again that there is also a major difference in the variation in the thickness of the crust in the parts of south-eastern Sweden where these two sites are located, with little variation in the Forsmark region and a marked thinning of the crust directly south of the Laxemar-Simpevarp area.

Geological development during the Quaternary period

The Quaternary climate is characterised by large and sometimes rapid changes in global temperature. Ice sheets covered larger areas during the cold periods than at present. The Forsmark and Laxemar-Simpevarp areas have consequently been covered by glacier ice at least three times. However, the total number of glaciations that affected the model areas is not known. The cold glacial periods were much longer than the warmer interglacial periods, which are characterised by a climate similar to the present. However, long ice-free periods have also existed during the glacials. During these ice-free periods the climate was colder than today and tundra conditions probably prevailed in large parts of Sweden. Consequently, it can be assumed that permafrost has prevailed in the model areas for long periods of time. The latest glaciation (Weichselian) started c 115,000 years ago, and there is geological evidence for at least two periods when a large part of Sweden was free of ice. However, the onset of the latest glacial coverage at the two sites and the exact timing and duration of the ice-free periods at the sites are unknown. By contrast, the timing of the latest deglaciation is rather well established along the coast to the Baltic Sea.

The present interglacial, the Holocene, started at the deglaciation of Mid-Sweden when the ice margin had already retreated from Laxemar-Simpevarp but before it had reached Forsmark. The climate during the deglaciation became successively warmer, although some phases with colder climate did occur. In southern Sweden, the warmer climate caused a gradual change from tundra vegetation to forest dominated by decidious trees. The Mid-Holocene climate was characterised by temperatures a few degrees higher than today. The forests in southern Sweden have subsequently been dominated by coniferous forest. The areas covered by forest began to decrease c 3000 BC due to the introduction of agriculture. However, the areas used as arable land are decreasing today and the forested areas are increasing.

The development of the Baltic Sea after the latest deglaciation has been characterised by ongoing shoreline displacement. The interaction between isostatic recovery and eustatic sea level variations has caused varying depth in the straits connecting the Baltic Sea with the Atlantic Ocean in the west, which has, in turn, caused varying salinity throughout the Holocene. At 4500–3000 BC, during the middle of the Littorina Sea stage, the salinity of the Baltic Basin was almost twice as high as it is today in Laxemar-Simpevarp and Forsmark.

It is suggested that all known loose deposits in both of the model areas were deposited during the last phase of the latest glaciation and after the following deglaciation. In Forsmark, a till unit consisting of overconsolidated silty-clayey till was deposited during an earlier phase of the latest glaciation. However, the possibility of the occurrence of older deposits cannot be excluded and there are indications of older deposits in neighbouring areas.

Till and glaciofluvial material was deposited both directly by the ice sheet and by glacial meltwater. Both the Laxemar-Simpevarp and Forsmark regional model areas are completely situated below the highest shoreline and were consequently covered by water after the latest deglaciation, from c 12,000 BC and 8800 BC, respectively. During the deglaciation, glacial clay was deposited in the lowest topographical areas. The following shoreline displacement has had a great impact on the distribution and relocation of fine-grained Quaternary deposits. The most exposed areas have been subjected to wave washing and currents on the bottom. Sand and gravel have consequently been eroded from older deposits, transported and deposited at more sheltered locations. Periods of erosion have occurred also at sheltered locations, which have caused erosion of fine-grained deposits such as glacial clay. Gyttja clay is commonly occurring in the terrestrial valleys and was deposited when these valleys were narrow bays. Shoreline displacement is an ongoing process and new areas are currently exposed to erosion, whereas sheltered bays with conditions favourable for deposition of clay gyttja have formed in other areas.

Lakes and wetlands are gradually being covered by fen peat, which at some locations is being covered by bog peat. In Forsmark, the mires are generally small and too young for raised bogs to develop. In Laxemar, many wetlands have been drained by ditches for agricultural purposes and the peat is consequently being oxidised.

Palaeoseismicity and seismicity during the Quaternary period

An earthquake is the result of a sudden release of energy through movement (faulting) along a deformation zone, resulting in the emission of seismic waves. This movement is normally the result of stresses that have accumulated over a certain time interval in a particular volume. An overview of palaeoseismic activity in Sweden during the latest part of and after the Weichselian glaciation, with special focus on the Forsmark and Laxemar-Simpevarp areas, is presented here. This is accompanied by an assessment of seismic activity in historical time from 1375 up to 2005, over the northern part of Europe. The part of the chapter concerned with activity in historical time is based upon and, with predominantly editorial modifications, is largely extracted from the assessment of earthquake activity in Sweden that has recently been completed and published by SKB.

Palaeoseismic activity has been inferred directly by, for example, distinct displacement of the surface that separates the crystalline bedrock from the Quaternary cover or indirectly by seismically derived deformation of Quaternary sediment. The interpretation of aerial photographs provides a tool to identify morphologically conspicuous lineaments that are candidates for late- or post-glacial faults. A significant number of late- or post-glacial, reverse fault scarps have been identified in the northern part of Sweden and it has been inferred that the accompanying earthquakes reached magnitudes of up to M8 or even larger on the Richter magnitude scale. As yet, conclusive evidence for such fault movements is lacking in the southern part of Sweden.

With the help of a similar methodology to that used in the northern part of Sweden, detailed investigations to evaluate the occurrence of palaeoseismic activity in and around the Forsmark and Laxemar-Simpevarp areas have been carried out in the context of the site investigation work. None of the morphological lineaments that have been recognised have been inferred to represent late- or post-glacial faults. Furthermore, no deformational features in Quaternary sediment have been unambiguously related to seismic activity. On the basis of these results, evidence in the geological record for major earthquakes in these two areas is lacking.

Compared especially with plate boundaries in other parts of the world, there is, in general, a low frequency of earthquakes throughout historical time in the within-plate region of northern Europe, and an absence of earthquakes with a magnitude ≥ M6 on the Richter scale. However, seismic activity in Sweden throughout historical time is not evenly distributed over the country. Areas of relatively high activity are conspicuous along linear alignments in the northern part of Sweden, in a broader region in south-western Sweden and, less conspicuously, in the southernmost part of the country (Skåne). By contrast, much of the geological reference area in south-eastern Sweden, including the Forsmark and Laxemar-Simpevarp areas, shows relatively little seismic activity.

The linear alignments of earthquakes, at least in the northernmost part of Sweden and in adjacent areas in Finland and Norway, have been related to the late- or post-glacial faults that have been recognised with the help of palaeoseismic studies. The linear alignment along the coast of Norrland occurs where both land uplift related to post-glacial isostatic rebound is greatest and where there is also a tendency for a decrease in crustal thickness. A correlation between an increased frequency of seismic events and crustal thinning is apparent in south-western and southernmost Sweden. The crustal thinning occurs in areas where Late Palaeozoic and younger extensional tectonics has taken place. In this context, it is worth recalling the significant decrease in crustal thickness immediately south of the Laxemar-Simpevarp area. The crust in Sweden below c 35 km is seismically quiet and this changeover is most probably related to the more ductile character of the crust beneath this depth. If correct, an average geothermal gradient of approximately 8 to 12°C/km is inferred at the current time.

Although strike-slip movement is the dominant focal mechanism, irrespective of where in Sweden the seismic event occurred, reverse dip-slip or oblique-slip fault plane solutions are also present. Since seismic events predominantly occur along geologically ancient fractures or planes of weakness in the bedrock, the orientation of these structures has an influence on the focal mechanism. It is also important to keep in mind that the solutions discussed above pertain to crustal stress at seismogenic depths. Considerable evidence points to a reverse sense of movement in the uppermost part of the crust (c 1,000 m) in large parts of Sweden, with a vertical or subvertical minimum principal stress.

The maximum principal stress as inferred from the seismic data is oriented WNW-ESE. This direction is in accordance with that expected from plate tectonics with ridge push forces from the mid-Atlantic ridge. These considerations give support to the hypothesis that ongoing plate tectonic processes are important for an understanding of recent seismic activity. Palaeoseismic activity has been explained by the release of stress that accumulated earlier during glacial loading in association with long-term tectonic plate motions. An alternative mechanism that involves the release of high horizontal stresses induced by flexure during loading, in combination with the ambient plate tectonic stresses, has also been discussed. The release of stress and fault instability occurred during unloading and the rapid removal of the ice. Since both Forsmark and Laxemar-Simpevarp share similar loading and unloading cycles and are experiencing, at the present time, the same WNW-ENE ridge push forces from the mid-Atlantic ridge, differences in the measured stress state on a large scale between the two sites and on a local scale within a particular site need to be explained with the help of other factors. As far as large-scale variations between Forsmark and Laxemar-Simpevarp are concerned, differences in the long-term geological evolution and crustal thickness variations at the two sites need to be considered.

An attempt to document local surface deformation with the help of detailed GPS measurements has recently been completed in the Laxemar-Simpevarp area and is presently in progress at Forsmark. Bearing in mind the occurrence of significant bedrock movements close to the ground surface, which are related to release of stress and diminish rapidly at depth, there are intrinsic difficulties in relating ground measurements to deeper seismic or aseismic activity along active faults. This observation also emphasizes the need for extreme care in the use of surface phenomena for the interpretation of palaeoseismic activity.

Groundwater evolution during the Quaternary period

The groundwater evolution in the Forsmark and Laxemar-Simpevarp areas has been strongly affected by climate changes in the past. Investigations have shown that the groundwaters observed today have different origins, including glacial meltwater, meteoric water and marine water, depending on the prevailing conditions. Shoreline displacement plays an important role in understanding the infiltration mechanism for these waters. It is particularly important for the intrusion of the saline Littorina Sea water into the bedrock, as well as for the subsequent flushing processes in the upper, more permeable bedrock horizons. It seems that the most recently recharged water tends to flush older water types, especially in the upper permeable part of the bedrock. However, hydraulic conditions vary over time, and remnants of earlier climatic fluctuations can be preserved in localised areas of low permeability. Thus, palaeohydrogeochemistry thus provides an important framework for understanding the bedrock hydrogeochemical evolution which is crucial for the hydrogeochemical and hydrogeological understanding of the site.

Waters of very different residence times have been documented, ranging in age from recent tritiated meteoric waters (< 50 a), to (late) marine waters (3000–4000 BC), to low $\delta^{18}O$ glacial water (last deglaciation around 8800 BC in Forsmark and 12,000 BC in Laxemar-Simpevarp), to deeper, ancient waters isolated from the atmosphere for more than 1.5 Ma. This means that the changes in hydraulic conditions during at least the Quaternary period have left their imprints in the fracture and pore waters. However, most fracture groundwaters observed today originate from the last glaciation/deglaciation cycle and the subsequent Holocene period, whereas data or imprints from earlier cyclic events, prior to the last Weichselian maximum, are few. The mixing processes and the reactions affect the groundwater composition and may modify the palaeosignatures of the groundwater; these processes have to be understood when interpreting the groundwater data. In contrast, porewaters reflect a much less dynamic system so that palaeosignatures can still be detected, providing important input to site understanding.

Development of ecosystems during the late Quaternary period

Long-term ecosystem development in near-coastal areas of Fennoscandia is driven mainly by two different factors; climate change and shoreline displacement. In addition, human activities have also strongly influenced the development of both terrestrial and aquatic ecosystems, especially during the last few millennia.

Shortly after the latest ice retreat, which started in southernmost Sweden c 15,000 BC, the landscape was free of vegetation and can be characterised as polar desert. Relatively soon after the deglaciation, the ice-free areas were colonised and in southern Sweden the landscape was covered by a sparse Birch forest. Thereafter, the climate has oscillated between colder and warmer periods. During the cold period called the Younger Dryas (c 11,000–9500 BC), large areas of the deglaciated parts of Sweden were again affected by permafrost and much of the previously established flora and fauna disappeared. From the onset of the Holocene (c 9500 BC) and thereafter, southern Sweden has been more or less covered by forests, although the species composition has varied due to climatic changes. Most of the present mammal fauna was established in southern Sweden during the early Holocene. During the last few thousand years, the composition of the vegetation has changed not only to due to climatic changes, but also due to human activities which have decreased the areas covered by forest. In southern Sweden, the introduction of agriculture and the subsequent opening of the landscape started c 3000 BC.

In coastal areas like Forsmark and Laxemar-Simpevarp, shoreline displacement has strongly affected ecosystem development and still causes continuing changes in the abiotic environment. Both areas are situated below the highest coastline, and when the latest deglaciation took place, Forsmark was covered by 150 m and Laxemar-Simpevarp by 50–100 m of water. The first parts of the Laxemar-Simpevarp area emerged from the sea around year 9400 BC, the corresponding time for Forsmark is c 500 BC. Thus, the post-glacial development, especially for Forsmark, is determined mainly by the development of the Baltic basin and by the shoreline displacement.

As a result of an overall regressive shoreline displacement, the sea bottom is uplifted and transformed into new terrestrial areas or to freshwater lakes. The starting conditions for ecosystem succession from the original near-shore sea bottom are strongly dependent on the topographical conditions. Sheltered bays accumulate organic and fine-grained inorganic material, whereas the finer fractions are washed out from more wave-exposed shorelines with a large fetch. During the process of shoreline displacement, a sea bay may either be isolated from the sea at an early stage, and thereafter gradually turn into a lake as the water becomes fresh, or it may develop directly from a bay into a wetland.

After isolation from the sea, the lake ecosystem gradually matures in an ontogenetic process which includes subsequent sedimentation and deposition of substances originating from the surrounding catchment or produced within the lake. Hence, the long-term ultimate fate for all lakes is an inevitable fill-up and conversion to either a wetland or a drier land area, the final result depending on local hydrological and climatic conditions. In Forsmark, all present-day lakes have developed into oligotrophic hardwater lakes, characteristic for the area, whereas most lakes in the Laxemar-Simpevarp area follow another ontogenetic trajectory and show dystrophic (brownwater) conditions.

Mires are formed basically through three different processes; terrestrialisation, paludification and primary mire formation. Terrestrialisation is the filling-in of shallow lakes by sedimentation and establishment of vegetation. Paludification, which is the predominant way of mire formation in Sweden, is an ongoing water logging of more or less water-permeable soils, mainly by expanding mires. Primary mire formation is when peat is developed directly on fresh soils after emergence from water or ice. All three types of processes are likely to occur in the Forsmark and the Laxemar-Simpevarp areas, but peatland filling in lakes (terrestrialisation) is probably the most common type of peatland development in the investigation areas. The richer types of mires which are typical of the Forsmark area will undergo a natural long-term acidification when turning into more bog-like mires. Historically, mires have often been drained for forestry or to gain new agricultural areas, and in Sweden such activities peaked in the 1930s. In the Laxemar-Simpevarp area, a large part of today's agricultural land is characterised by a peat layer which was built up during a previous wetland phase.

Human population and land use

The two studied regions surrounding Forsmark and Laxemar-Simpevarp are both located along the coast to the Baltic Sea. Despite this similarity, they exhibit many differences in the development of human population and land use. This is partly due to their different physical settings, but also to the fact that their societies and economies have developed differently.

Prehistory–1100 AD

The prehistoric period is considerably shorter in the Forsmark region than in Laxemar-Simpevarp, since Forsmark was covered with water for a longer time period. In the Laxemar-Simpevarp region, there is a rich occurrence of prehistoric remains, some of them indicating that the area was highly exploited already during the Older Stone Age. In contrast, the Forsmark region was not permanently settled until the end of the prehistoric period.

Medieval period 1100–1550 AD

The medieval period illustrates the differences between the regions in more detail. One difference is that the Forsmark region during this period was characterised by small villages, whereas single farms dominated the settlement structure in the Laxemar-Simpevarp region. Another difference concerns the phase of expansion in the Forsmark region, whereby new settlements were created in the peripheral areas of the older ones. This expansion cannot be easily observed in the Laxemar-Simpevarp region. The recession during the middle of the medieval period in the Forsmark region, which is often attributed to the plague, has not been confirmed in the Laxemar-Simpevarp region, even though there are indications from the general trend in Småland that it also occurred in the Laxemar-Simpevarp region.

The investigated parishes in the Forsmark region showed a dominance of freeholders at the end of the medieval period and the share of farms belonging to the nobility was small. The Laxemar-Simpevarp region showed instead an unusually large share of farms belonging to the crown, and the share of freeholders was correspondingly very small.

Early modern period 1550–1750 AD

During the early modern period, the establishment of the iron industry in the Forsmark region dramatically affected the surrounding landscape. Production was geared towards the needs of the industry; charcoal production, mining, and the production of fodder for animals used in the industry. The ownership structure also changed abruptly with the establishment of large estates. Similar to many other places in Sweden, there was a strong population expansion in both regions. In the Forsmark region, many crofts were established in the forested areas, inhabited by people involved in charcoal production. The increase in number of crofts was more moderate in the Laxemar-Simpevarp region, even though the settlements in the region increased, partly due to partitioning of farms. The population in both regions doubled or increased at an even faster rate between the 1570s and the 1750s.

Era of modernisation 1750–1950 AD

The number of freehold farmers increased in the Laxemar-Simpevarp region during the 18th century, both due to the partitioning of farms and to the fact that farmers purchased farms previously belonging to the nobility. The trend in the Forsmark region was the opposite; the large estates expanded and, accordingly, the number of freehold farms decreased.

In both regions, the population increased dramatically from the 1780s up to the late 19th century. At the turn of the century the increase ceased and during the latter part of the 20th century the rural population decreased. The number of people involved in agriculture decreased, and instead, the number of people employed in industry and crafts was greater than before.
A common pattern for the two investigated regions during recent centuries was the decrease in the average household size. The Forsmark region had in general larger households than the investigated region in Laxemar-Simpevarp, but from the 1890s and onwards the household sizes were almost the same for both regions.

Contents

1 Introduction

1.1 Background

The Swedish Nuclear Fuel and Waste Management Company (SKB) is undertaking site characterisation at two different locations, the Forsmark and Laxemar-Simpevarp areas, with the objective of siting a geological repository for spent nuclear fuel. The investigations, which started in 2002 and were completed in 2007, have been conducted in campaigns punctuated by data freezes. After each data freeze, the site data have been analysed and modelling work has been carried out with the overall objective of producing a site descriptive model (SDM) for each of the sites.

A site descriptive model is an integrated model for geology, rock mechanics, thermal properties, hydrogeology and hydrogeochemistry, and a description of the surface system. It constitutes a description of the site and its regional setting, covering the current state of the geosphere and the biosphere, as well as those natural processes that affect or have affected their long-term development. The site description is required to serve the needs of both repository engineering and safety assessment with respect to repository layout and construction, and its long-term performance. It is also required to provide a basis for the environmental impact assessment.

Hitherto, a number of reports presenting preliminary site descriptive models for Forsmark and Laxemar-Simpevarp have been published, e.g. SDM Forsmark ver. 1.2 /SKB 2005a/ and SDM Laxemar ver. 1.2 /SKB 2006a/. In these reports, the evolutionary and historical aspects of the site were included in a separate chapter. The present report comprises a further elaboration of the evolutionary and historical information included in the preliminary SDM reports, but presented here in a separate, supplementary report to the final SDM-Site, common to the two investigated areas (see Figure 1-1).

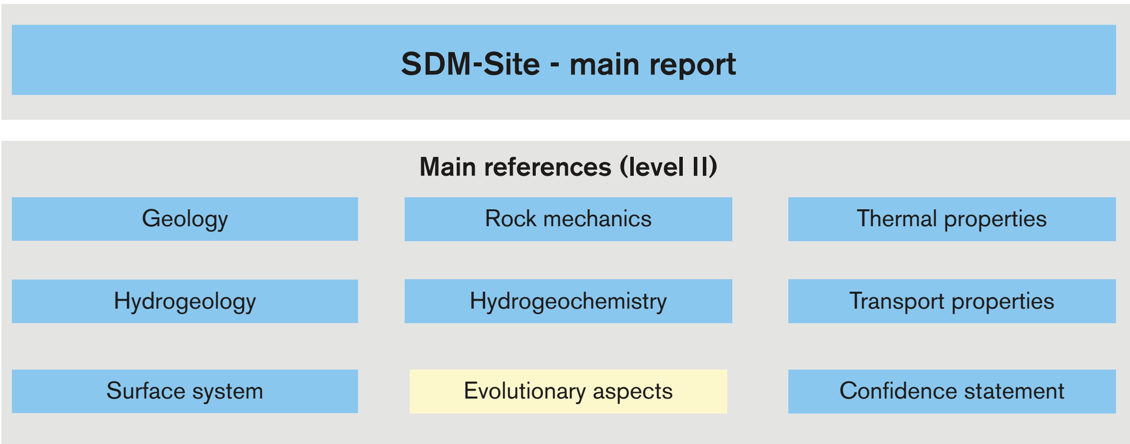


Figure 1-1. *Level I and level II reports planned to be produced during the SDM-Site stage of the analytical and modelling work at Forsmark and Laxemar-Simpevarp. Note that the present report (yellow box) is common to the two sites, whereas the other reports are produced separately for each site. Note also that there are several discipline-specific background reports (level III), supporting each of the main references.*

1.2 Scope and objective

The overall objective of this report is to describe the long-term geological evolution and palaeoclimate of the two sites, as well as the post-glacial development of the ecosystems and of the human population at the sites. The reason for focusing on the developmental aspects of the sites is that knowledge of the processes that have formed the sites is needed for an understanding and description of the present-day conditions. Thus, this information constitutes necessary input to the site descriptive models. Moreover, knowledge of the past is necessary to be able to predict the future development of the sites, although what happens in the future is beyond the scope of the SDM and the present report. The future development of the sites will instead be treated in the safety assessment.

The report largely consists of a synthesis of information derived from the scientific literature and other sources, not related to the site investigations. However, site investigations have also generated much information which contributes to our understanding of the past development of the two sites. No new site data are presented in this report, but relevant data generated at each site are discussed, evaluated and utilized. Although there is no detailed account of input data from the site investigations, reference to the relevant data reports is made wherever site data are used in the descriptions.

1.3 Setting

The Forsmark area is located along the coastline of the Baltic Sea in northern Uppland within the municipality of Östhammar, about 120 km north of Stockholm (Figure 1-2). The candidate area for the repository extends from the Forsmark nuclear power plant in the north-west towards Kallrigafjärden in the south-east. It is approximately 6 km long and 2 km wide and shows a flat topography with a dominance of till in the Quaternary overburden. The bedrock at Forsmark formed between 1.90 and 1.85 billion years ago (1.90 to 1.85 Ga) and is dominated by different types of quartz-rich intrusive rocks (granitoids), The bedrock was affected by metamorphism under high-temperature conditions and by both ductile and brittle deformation. The ductile deformation has resulted in large-scale high-strain belts and more spatially restricted zones oriented WNW-ESE to NW-SE. Tectonic lenses, in which the bedrock is much less affected by ductile deformation, are enclosed between the ductile high-strain belts. The candidate area is located in the north-westernmost part of one of these tectonic lenses that extends from north-west of the nuclear power plant south-eastwards to Öregrund. Subsequent brittle deformation in the candidate area has given rise to fracture zones that vary in size and frequency of occurrence. These zones are predominantly steeply dipping and oriented ENE-WNW and NNE-SSW or are gently dipping.

The Laxemar-Simpevarp area is located along the coastline of the Baltic Sea in Småland within the municipality of Oskarshamn, about 230 km south of Stockholm (Figure 1-3). The area is characterised by a relatively flat topography in a fissure valley landscape. The predominantly thin Quaternary overburden is mainly located in the valleys, whereas the higher-altitude areas are dominated by exposed bedrock or thin layers of till and peat. The bedrock formed approximately 1.80 billion years ago (1.80 Ga) and is dominated by medium-grained intrusive rocks, ranging from greyish red granite to grey quartz monzodiorite. The bedrock is generally well-preserved and only weakly affected by ductile deformation. On a regional scale, steeply or moderately dipping deformation zones oriented NE-SW, N-S and E-W, generally with both low-temperature ductile and brittle deformation, are present.

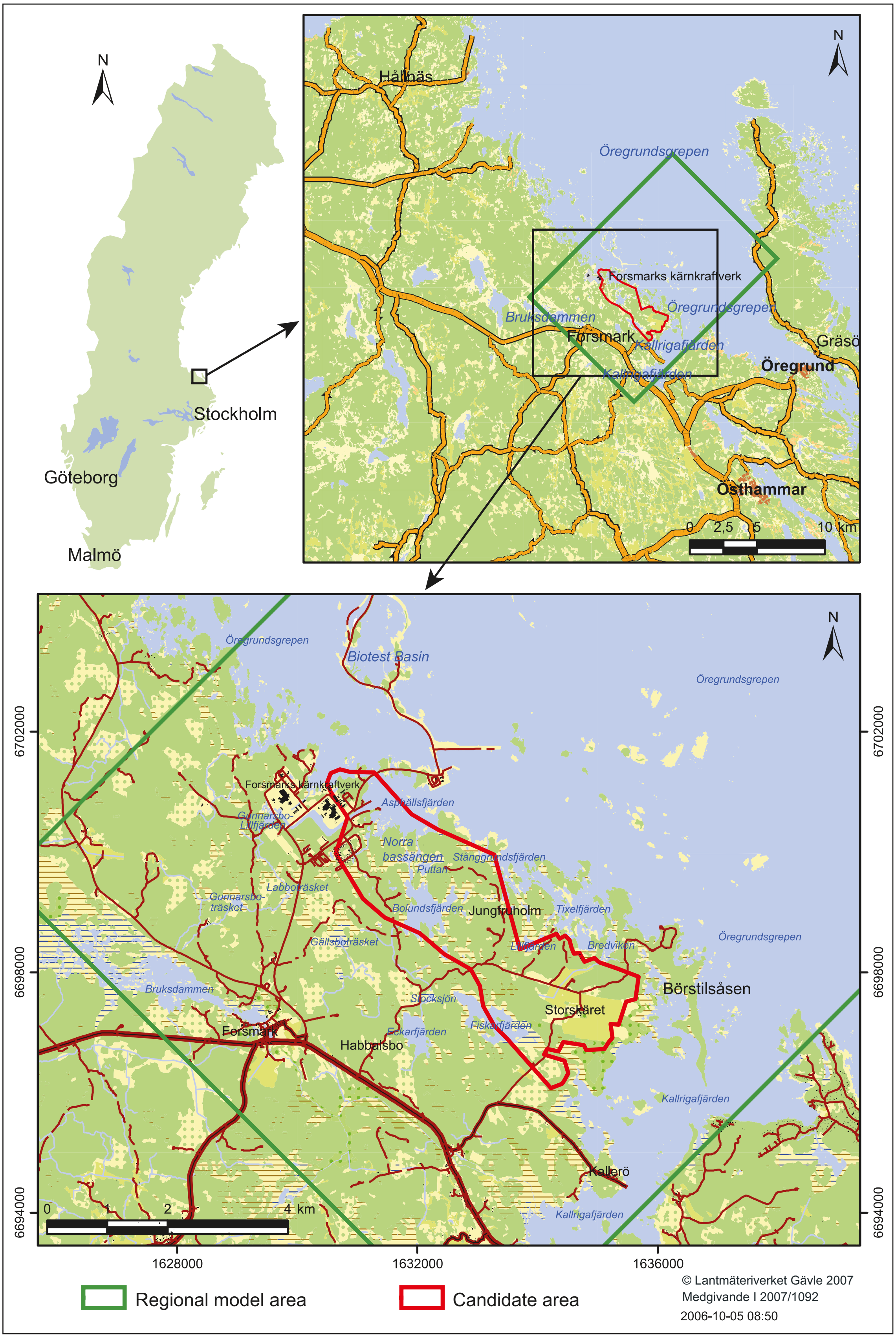


***Figure 1-2.** The location of the Forsmark area. The black rectangles show the spatial extension of the enlarged map.*

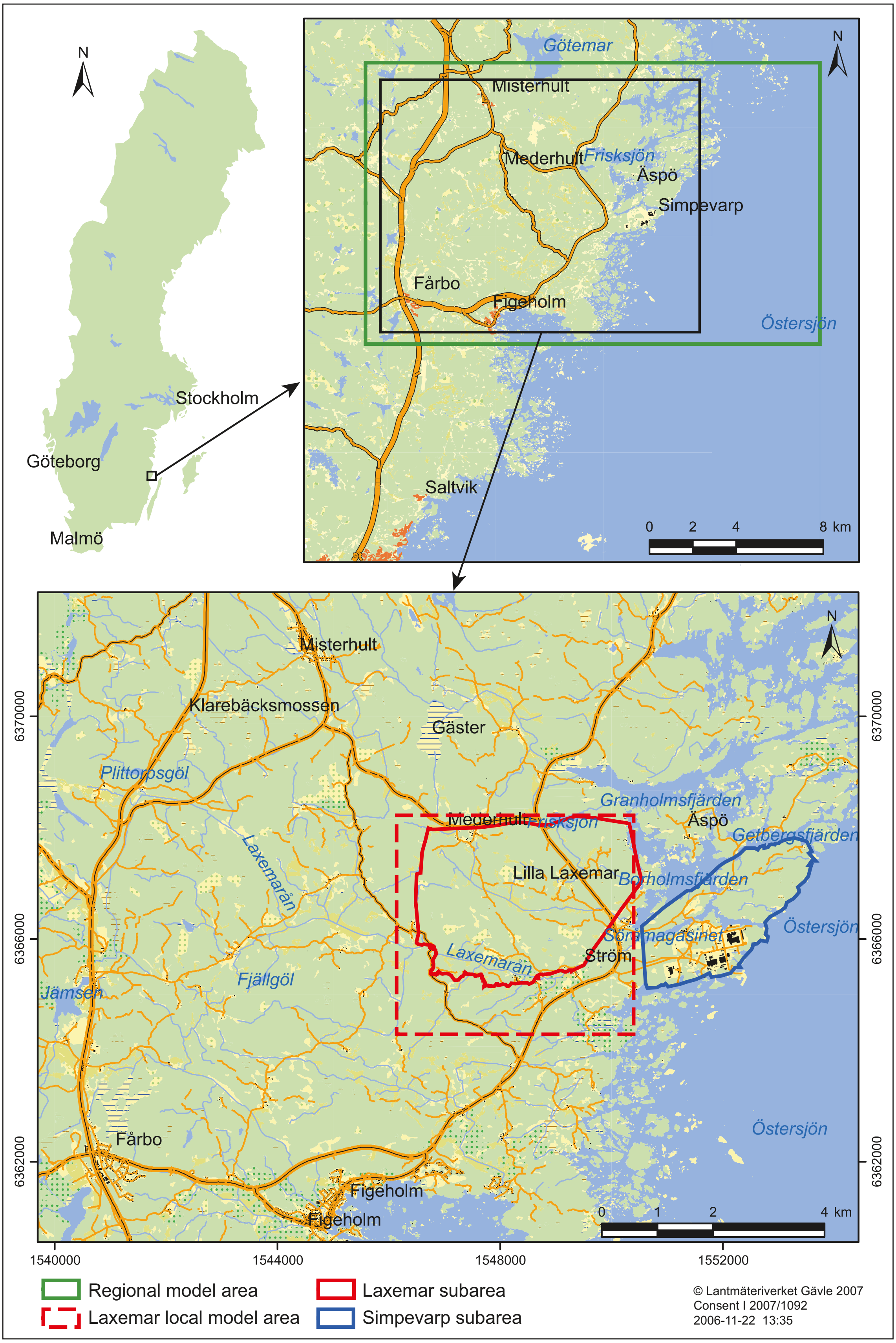


Figure 1-3. *The location of the Laxemar-Simpevarp area. The black rectangles show the spatial extension of the enlarged map.*

1.4 Geographical definitions and terminology

When discussing the two sites in a general sense in a SDM-Site context, and without any consideration of well-defined boundaries, they are called the **Forsmark area** and the **Laxemar-Simpevarp area**, respectively. In the last chapter of this report, the description of the developments in human population and land use over time at the two sites is largely based on a study by /Berg et al. 2006/. This study covers a much larger area that surrounds each site and is defined by the outer borders of a number of parishes at each site that are included in the study (see Figure 7-2 and Figure 7-5). Consequently, in a SDM-Site context, the areas studied by /Berg et al. 2006/ are denoted the **Forsmark region** and the **Laxemar-Simpevarp region**, respectively.

At the start of the site investigations in 2002, regional model areas with clearly defined outer boundaries were specified for each site for the purpose of regional scale modelling (see Figure 1-2 and Figure 1-3). These areas were referred to as the **Forsmark regional model area** and the **Simpevarp regional model area**, respectively. Furthermore, two smaller areas within the Simpevarp regional model area, the Simpevarp subarea and the Laxemar subarea, were defined, and preliminary site descriptions were produced for both of these subareas. Since the two subareas are included in the same regional model area, for the purpose of clarity and to avoid confusion, the former Simpevarp regional area is denoted the **Laxemar-Simpevarp regional model area** in a SDM-Site context. During the complete site investigation stage, work was focused on the southern part of and even south of the Laxemar subarea (cf Laxemar subarea and Laxemar local model area in Figure 1-3).

The present report covers the past development of the sites from a wide range of time perspectives, and the descriptions involve several different disciplines with their own discipline-specific terminology. For example, geologists prefer to use the concept "geological evolution" when describing geological changes over time, whereas ecologists use the word "development" when discussing changes in abiotic conditions, since the word evolution is loaded with biological implications. We have not tried to uniform this terminology throughout the report. The word "evolution" is used in the purely abiotic chapters (Chapter 2 – Bedrock evolution and Chapter 5 – Groundwater evolution), whereas "development" is used in most other parts of the report. The concept "historical time", which is used both in Chapter 4 and in Chapter 7, refers loosely to the period in human history from which written sources exist.

The different chapters in this report are written by specialists from different disciplines, with the overall aim of describing at a professional level and in considerable detail our present-day knowledge. This means that the discipline-specific terminology sometimes may be difficult to understand for non-specialists. In order to help the reader, explanations of some difficult and important terms is included in the text the first time the term is introduced.

1.5 This report

Chapter 1 of the report includes a presentation of the scope and objectives of the work and a short description of the geographical and geological setting. It also addresses some critical questions of nomenclature.

Chapter 2 presents a description of the bedrock geological evolution in the Forsmark and Laxemar-Simpevarp areas. In order to provide the necessary boundary conditions for an understanding of this evolution in the two areas, these are viewed in a broader geological perspective. For this purpose, the first part of the chapter places focus on a larger area in the southern and eastern part of Sweden, whereas the later parts deal specifically, and in separate sections, with the Forsmark and Laxemar-Simpevarp areas. A comparative evaluation of the bedrock geological evolution at Forsmark and Laxemar-Simpevarp completes this chapter.

Chapter 3 provides a description of the geological and climatological development of the Forsmark and Laxemar-Simpevarp areas during the Quaternary period. The chapter is divided into three sections. The first section provides a review of the palaeoclimate and the Quaternary development of Sweden, whereas the second and third sections focus on the Forsmark and the Laxemar-Simpevarp areas, respectively.

Chapter 4 addresses palaeoseismicity and seismicity in the north-western part of Europe during the Quaternary period. The first part of the chapter summarises the causes of seismic activity, i.e. the driving forces, and addresses the palaeoseismological information relevant to inferred late- or post-glacial faulting. A short overview of this phenomenon in Sweden is followed by a summary of the results of detailed studies designed to evaluate the occurrence of such faulting in both the Forsmark and Laxemar-Simpevarp areas. The final part of the chapter addresses macroseismic and seismological instrumental information that has been compiled in historical time for the north-western part of Europe.

Chapter 5 describes the groundwater evolution over time as it is determined by the combined effects of long-term geological evolution, palaeoclimate and geological development during the Quaternary period. The chapter firstly provides a conceptual overview of the driving forces for groundwater evolution. This is followed by descriptions of the groundwater evolution in the Forsmark and Laxemar-Simpevarp areas.

Chapter 6 provides a description of ecosystem development during the late Quaternary period, i.e. since the latest deglaciation. The first part of the section provides a general perspective on long-term ecosystem development in Sweden, whereas the following sections describe ecosystem development at Forsmark and Laxemar-Simpevarp.

Chapter 7 addresses the development of the human population and human land use since the latest deglaciation. The chapter starts with a short description of the human colonization of Scandinavia. This is followed, in separate sections, by a focus on the development of the Forsmark and Laxemar-Simpevarp regions. A comparison between these two regions, in respect of recent changes in land use, completes this chapter.

2 Bedrock evolution

2.1 Introduction

The Forsmark and Laxemar-Simpevarp areas are situated in the south-western part of one of the Earth's ancient continental nuclei, referred to as the Fennoscandian Shield /Koistinen et al. 2001/. This part of the shield belongs predominantly to the geological unit referred to as the Svecokarelian (or Svecofennian) orogen (Figure 2-1). The bedrock inside an orogen was affected by major tectonic activity at a particular time interval during the Earth's long geological evolution and the actual geological process is referred to as orogeny. Tectonic activity refers to regional deformation and metamorphism of the crust in combination with active volcanism and the intrusion of igneous rocks at depth, i.e. major igneous activity. In essence, the branch of geology referred to as "tectonics" addresses the broad architecture of the outer part of the Earth.

The bedrock in the Svecokarelian orogen is dominated by Proterozoic igneous rocks that were affected by complex ductile deformation and metamorphism at predominantly mid-crustal levels, prior to later exhumation to the current level of erosion. It is apparent that different segments of the shield were affected by tectonic activity at different times, and to different extents, during the long period that extends from 1.95 to 1.75 billion years ago (1.95 to 1.75 Ga). The geological time scale that has been used for assessing the bedrock evolution is shown in Figure 2-2. The Proterozoic eon extended from 2.5 Ga to 540 million years ago (540 Ma). This was followed by the Phanerozoic eon which includes the current Quaternary period.

In order to provide the necessary boundary conditions for an understanding of the bedrock geological evolution of the Forsmark and Laxemar-Simpevarp areas, these two areas are viewed in a broader geological perspective. For this purpose, attention is focused here on an area in the southern and eastern part of Sweden that is bounded in the south by the northern tectonic boundary to the Blekinge-Bornholm tectonic belt, to the west by the Sveconorwegian orogen including the so-called Protogine Zone south of lake Vättern, to the north by a major shear zone referred to as the Hassela Shear Zone, and to the east by an arbitrary line on the continental shelf (Figure 2-1). This area is referred to in this report as the geological reference area.

The current level of erosion of the Svecokarelian orogen in the geological reference area can be divided into six major tectonic domains referred to here as TD1 to TD6 (Figure 2-3a). At least partly along their length, the boundaries between these domains consist of belts that are affected by high ductile strain and two of these belts (TD2 and TD4) are sufficiently wide to merit definition as separate tectonic domains. The geological structures within the boundary tectonic belts strike WNW-ESE, more or less parallel to the surface extension of Archaean rocks in the north-eastern part of the shield (Figure 2-1), and the Archaean rocks define the margin of the old continental nucleus. The division into domains has been carried out primarily on the basis of differences in the timing and style of the tectonic activity (ductile deformation, metamorphism and igneous activity) inside each domain.

TD1 and TD3 (Figure 2-3a) are characterised by major folding of rock units and a ductile planar fabric, and, in general, strongly constrictional strain that formed under variable metamorphic conditions. Ductile high-strain zones are also present. TD2 and TD4 (Figure 2-3a) contain broad belts of highly strained rocks, which were deformed under amphibolite-facies metamorphic conditions, and are strongly anisotropic. These high-strain belts also contain a high frequency of retrograde deformation zones that strike WNW-ESE or NW-SE, dip steeply and show transpressive strain with a component of dextral strike-slip deformation /Talbot and Sokoutis 1995, Stephens et al. 1997, Beunk and Page 2001, Persson and Sjöström 2003/. Transpressive strain involves a combination of strike-slip shear deformation along the zones or belts and shortening across them.

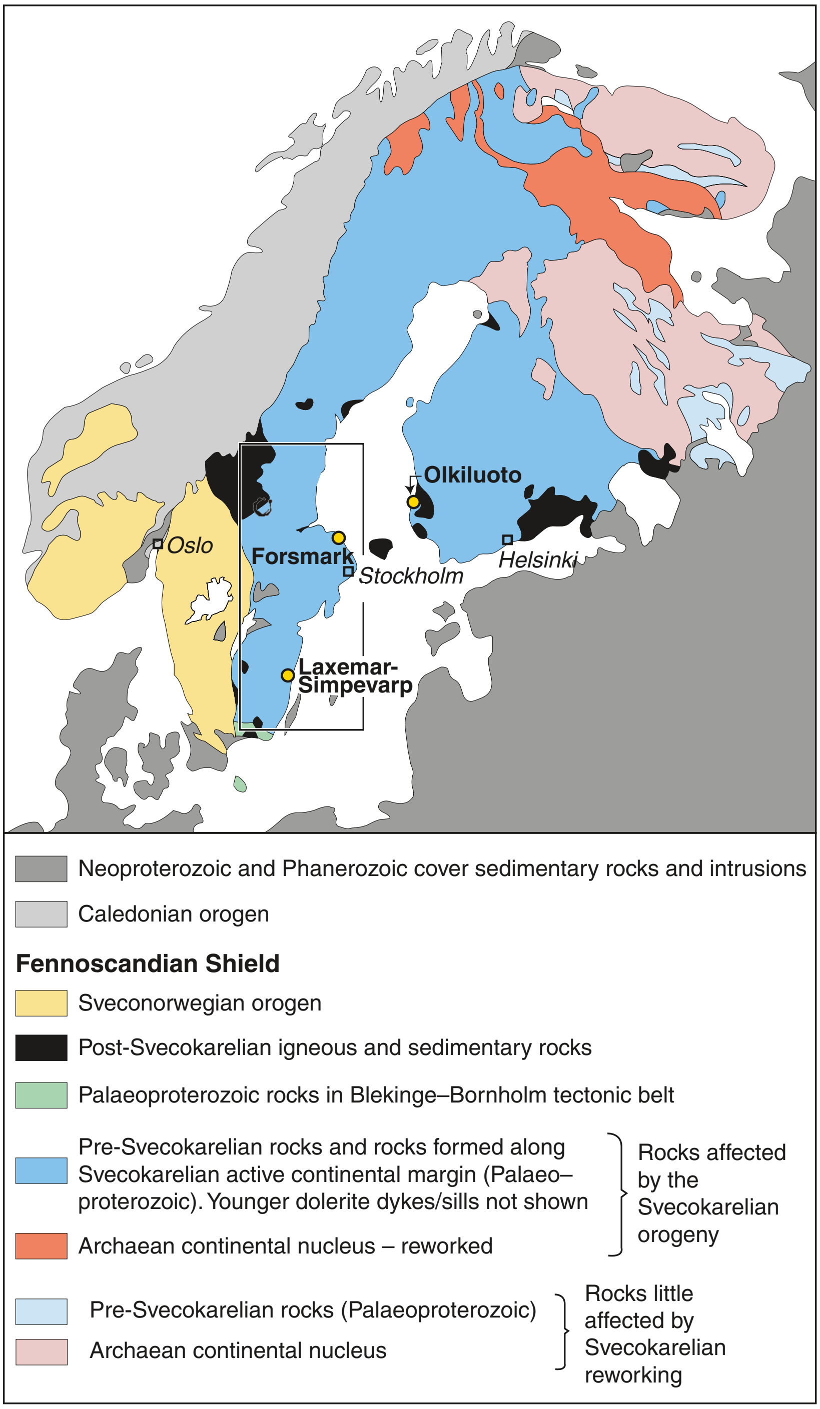


Figure 2-1. *Map showing the major tectonic units in the northern part of Europe at the current level of erosion (modified after /Koistinen et al. 2001/). The area chosen in this report to provide a regional geological perspective is outlined by the rectangle.*

In sharp contrast to the tectonic domains further north, TD5 and TD6 (Figure 2-3a) are dominated by younger igneous bedrock that is, in general, hardly affected by deformation and metamorphism. Nevertheless, areas that show more penetrative ductile deformation as well as low-temperature ductile high-strain zones in the otherwise well-preserved bedrock are present. As with other older Precambrian shields, complex networks of brittle deformation zones (fracture zones) transect the bedrock in all six domains. The Forsmark and Laxemar-Simpevarp areas are situated in the strongly contrasting domains TD2 and TD5, respectively. Similarities and differences between the tectonic domains are addressed in more detail in section 2.2.1.

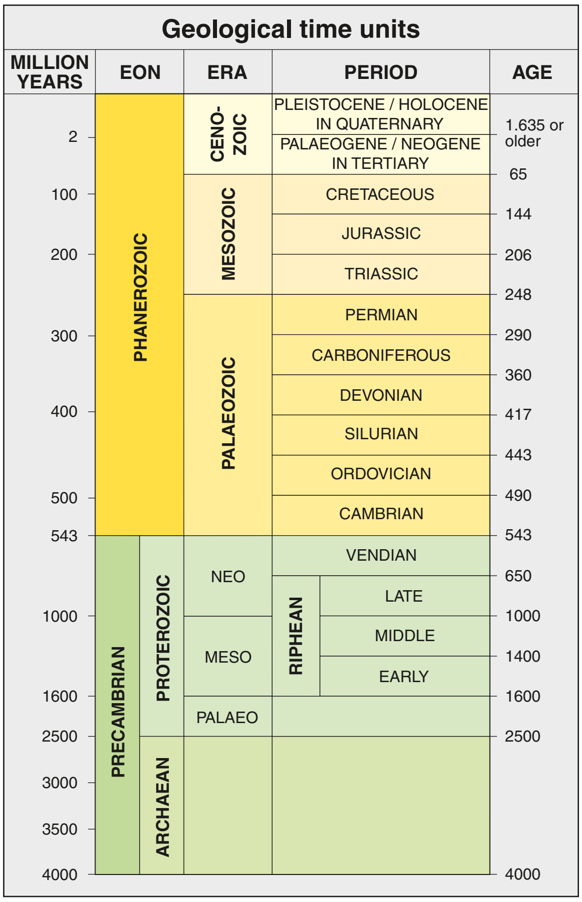


Figure 2-2. *Geological time scale based on the compilation used in /Koistinen et al. 2001/. Note that the boundary between the Quaternary and Tertiary periods is placed at 2.6 Ma in Chapter 3 in this report.*

Only a few remnants of post-Svecokarelian rocks are exposed at the current level of erosion in the geological reference area (Figure 2-3a). Late Palaeoproterozoic (< 1.71 Ga) igneous rocks as well as Mesoproterozoic sedimentary cover rocks and occasional igneous rocks are conspicuous in the northern part of the reference area, while, in the southernmost part, Mesoproterozoic granites (c 1.45 Ga) are present. Some isolated outliers of Neoproterozoic and Lower Palaeozoic sedimentary cover rocks occur in the western part of the geological reference area. By contrast, extensive areas of Mesoproterozoic and especially Palaeozoic sedimentary cover rocks form the bedrock on the continental shelf to the east (Figure 2-3a). The scarcity of exposed post-Svecokarelian rocks seriously limits our understanding of the geological evolution during the long time interval after c 1.75 Ga and up to the Quaternary, i.e. during more than 1,700 million years of Earth history.

The candidate area at Forsmark is situated within a major tectonic lens along a coastal deformation belt in northern Uppland, in the eastern part of TD2 (Figure 2-3b and /Stephens et al. 2007/). The tectonic lens is characterised by a generally low ductile strain relative to that in the bedrock on both sides of the lens. The candidate area is approximately 6 km long and 2 km wide, and the north-western part of this area was selected as the target area for the complete site investigation work /SKB 2005b/. The term "target volume" refers to the extension of this area at depth. The regional model area is approximately 165 km^2 in areal extent.

The Laxemar-Simpevarp area is located in eastern Småland, in the eastern part of TD5 (Figure 2-3c). The area is dominated by well-preserved intrusive igneous rocks, although ductile high-strain zones are also present /Wahlgren et al. 2005/. The regional model area is approximately 275 km^2 in areal extent and the complete site investigation work has been targeted on the southern part of the Laxemar area /SKB 2005c/.

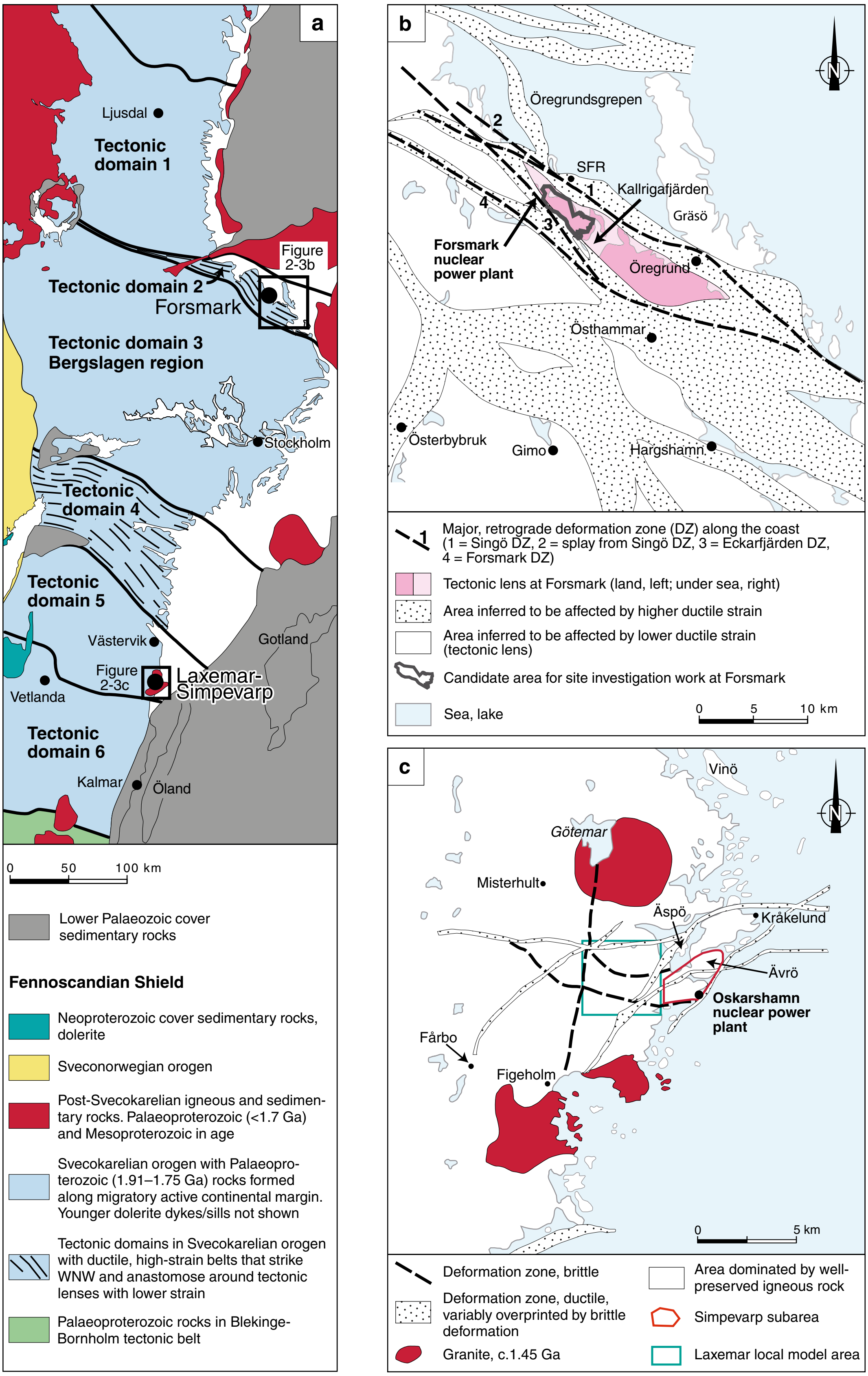


__Figure 2-3.__ a) Svecokarelian tectonic domains and post-Svecokarelian rock units inside the geological reference area in the south-western part of the Fennoscandian Shield, south-eastern Sweden (modified after /Koistinen et al. 2001/). b) Tectonic lens at Forsmark and areas affected by strong ductile deformation in the area close to Forsmark, all situated along the coastal deformation belt in the eastern part of TD2 (after /Stephens et al. 2007/). c) Simplified view of the bedrock geology in the Laxemar-Simpevarp area and surroundings in TD5. The Laxemar subarea occurs inside and corresponds more or less to the Laxemar local model area (see also Chapter 1).

The descriptive model for the evolution of the crystalline bedrock in the geological reference area has made use of the following published information:

- The digital compilation of the bedrock geology of the Fennoscandian Shield including the background database /Koistinen et al. 2001/.
- A review of tectonic regimes in the Fennoscandian Shield from 1,200 Ma up to the present /Larson and Tullborg 1993/.
- A reconstruction of the tectonic history of the Fennoscandian Shield from 100 Ma up to the present, based on data available along its margins to the south and west /Muir Wood 1995/.
- Countrywide descriptions of the bedrock geology of Sweden /Fredén 1994, Stephens et al. 1997/.
- A review of the crustal structure and regional tectonics in the south-easternmost part of Sweden /Milnes et al. 1998/.
- Summaries of the geology of south-eastern Sweden in county reports that were completed by the Geological Survey of Sweden (SGU) on a commission basis for SKB /Antal et al. 1998abcdef, Bergman et al. 1999ab, Gierup et al. 1999abc/.
- A description of the geology of the county of Kalmar /Wik et al. 2005/.
- Peer-reviewed references of more specific relevance, which are cited directly in the text.

Seismic refraction /e.g. Guggisberg 1986/ and seismic reflection /e.g. BABEL Working Group 1990/ data are available in the geological reference area. Although such data provide a critical insight into the broader geometric relationships at depth, at least close to the seismic profiles, they yield only limited or no information on the character and age of the bedrock. Such data are only available from the volume close to or at the current level of erosion. Bearing in mind these considerations, seismic data are not addressed in any detail in this report. Consequently, the development of a broader tectonic evolutionary model, as attempted here for at least the earlier part of the bedrock evolution, has intrinsic uncertainties related to our limited understanding of the character and age of the continental crust at depth.

2.2 Geological evolution of the Fennoscandian Shield in south-eastern Sweden from 1.91 Ga to the Quaternary period

2.2.1 Palaeoproterozoic (1.91 to 1.75 Ga) tectonic activity along a migratory active continental margin

Crustal growth and crustal reworking

Between 1.91 and 1.75 Ga, the geological reference area in south-eastern Sweden as well as the northern part of Sweden and Finland were affected by major igneous activity (Figure 2-4a). Three suites of igneous rock are present, which are referred to, in intrusive rock terms, as the:

- Granitoid–Dioritoid–Gabbroid (GDG) rock suite, with felsic rocks that are variable in composition but consistently rich in quartz (granitoids).
- Granite–Syenitoid–Dioritoid–Gabbroid (GSDG) rock suite, with felsic rocks that are variable in composition including quartz content (granites and syenitoids).
- Granite–Pegmatite (GP) rock suite, with felsic rocks that are limited in range of composition and consistently rich in quartz (granites).

The GSDG rocks that formed in the period 1.86 to 1.65 Ga, both during the later part of and after the Svecokarelian orogenic development, are generally referred to as the Transscandinavian Igneous Belt or TIB /Patchett et al. 1987, Högdahl et al. 2004/.

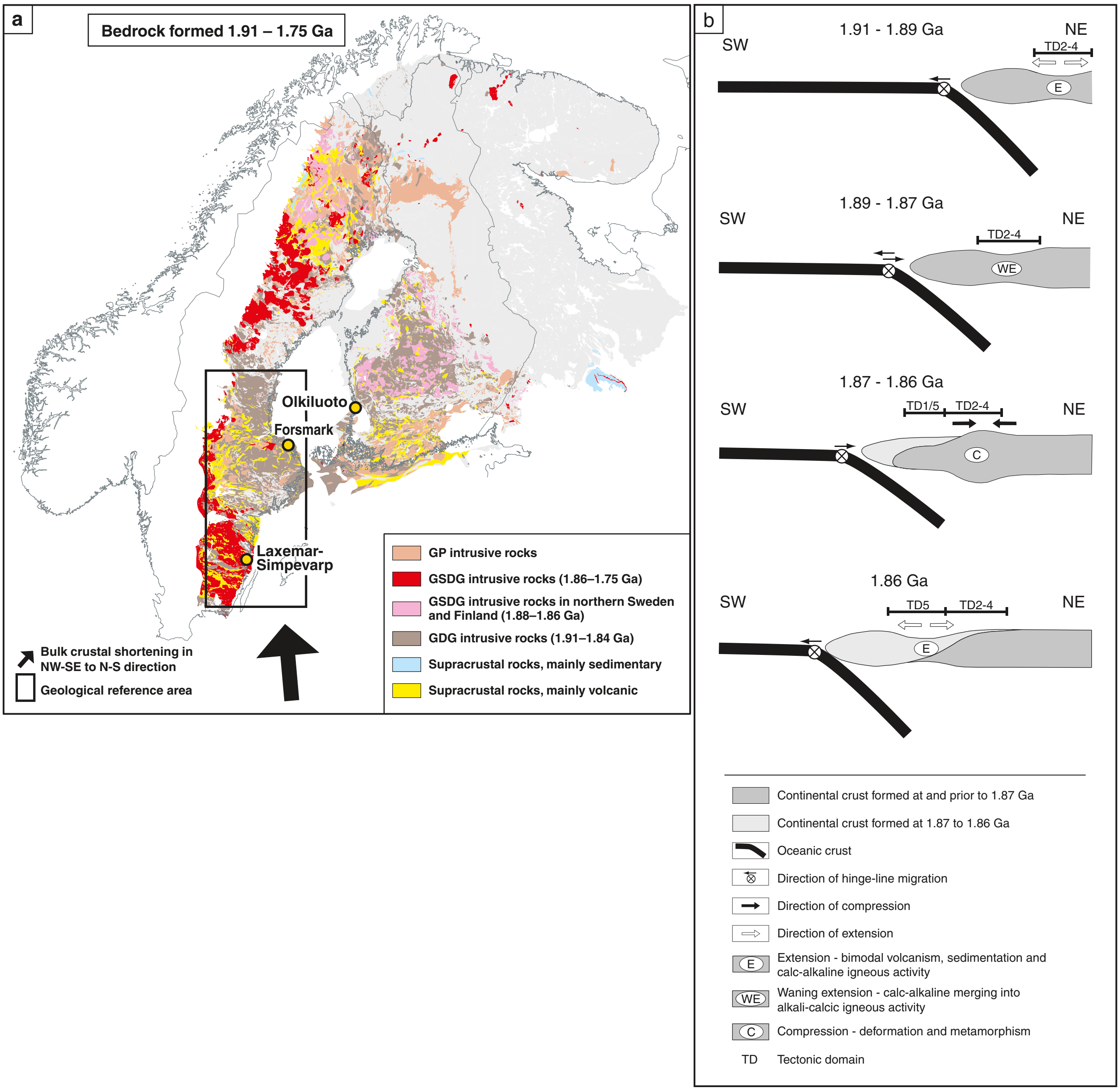


Figure 2-4. *a) Crystalline bedrock formed at 1.91 to 1.75 Ga in the Fennoscandian Shield. All the bedrock shaded with a grey tone had formed prior to 1.91 Ga and represents older continental crust. The figure is based on the database that accompanies the geological map of the Fennoscandian Shield /Koistinen et al. 2001/. b) Conceptual model for the tectonic development of TD1 to TD5 during the time interval 1.91 to 1.86 Ga. The model is directly applicable to the bedrock in the Forsmark area. The bedrock at Laxemar-Simpevarp formed later. The model involves migratory tectonic switching, in which contrasting extensional and compressional regimes are related to migration of a subduction hinge away from and towards the overriding plate, respectively. Note how the continental crust progressively accreted to the south-west, in connection with the tectonic switching. It is inferred that TD1 and TD5 were located along the same tectonic belt prior to 1.86 Ga. On account of dextral strike-slip shear deformation around and after 1.86 Ga, these two tectonic domains are presently separated from each other (see text and Figure 2-6). Figure modified after /Hermansson et al. 2008/.*

In TD3, located in the Bergslagen region in central Sweden, and in the adjacent, generally more strongly deformed domains TD2 and TD4 (Figure 2-3a), much of the continental crust either formed or was strongly reworked during the period from 1.91 to 1.87 Ga. Reworking of slightly older crust at depth in the Bergslagen region has also been inferred /Andersson et al. 2006/. Sedimentary rocks comprise the oldest rocks at the present level of erosion (Figure 2-5). These volcanogenic, distal turbidites pass stratigraphically upwards into volcanic and synvolcanic intrusive rocks that formed during the period 1.91 to 1.89 Ga (Figure 2-5). The volcanic rocks are partly bimodal in character, formed in an extensional back-arc basin setting, and comprise the host rock to abundant Fe oxide and Zn-Pb-Ag-(Cu-Au) sulphide mineral deposits /Allen et al. 1996/. Indeed, the Bergslagen region is historically the most prosperous mining district in Sweden and, during the 18th and 19th centuries, iron ore from over 3,000 workings provided much of Sweden's wealth. Deposition of post-volcanic, sedimentary rocks occurred after 1.89 Ga. Furthermore, significant volumes of predominantly GDG rocks intruded the supracrustal rocks during the period 1.89 to 1.87 Ga (Figure 2-5).

In TD1 and in TD5 around Västervik (Figure 2-3a), renewed crustal growth, which was expressed in the form of widespread igneous activity at the present level of erosion, occurred during the period 1.87 to 1.84 Ga. In TD1, sedimentary rocks and locally bimodal volcanic rocks that formed prior to 1.87 Ga comprise the oldest part of the sequence (Figure 2-5). The sedimentary rocks pass stratigraphically upwards into a younger bimodal volcanic sequence of rhyolites and basalts (Figure 2-5), which formed during the time interval 1.87 to 1.86 Ga, and younger sedimentary rocks /Lundqvist 1968/. Significant volumes of predominantly GDG rocks intruded these supracrustal rocks during the period 1.87 to 1.84 Ga (Figure 2-5).

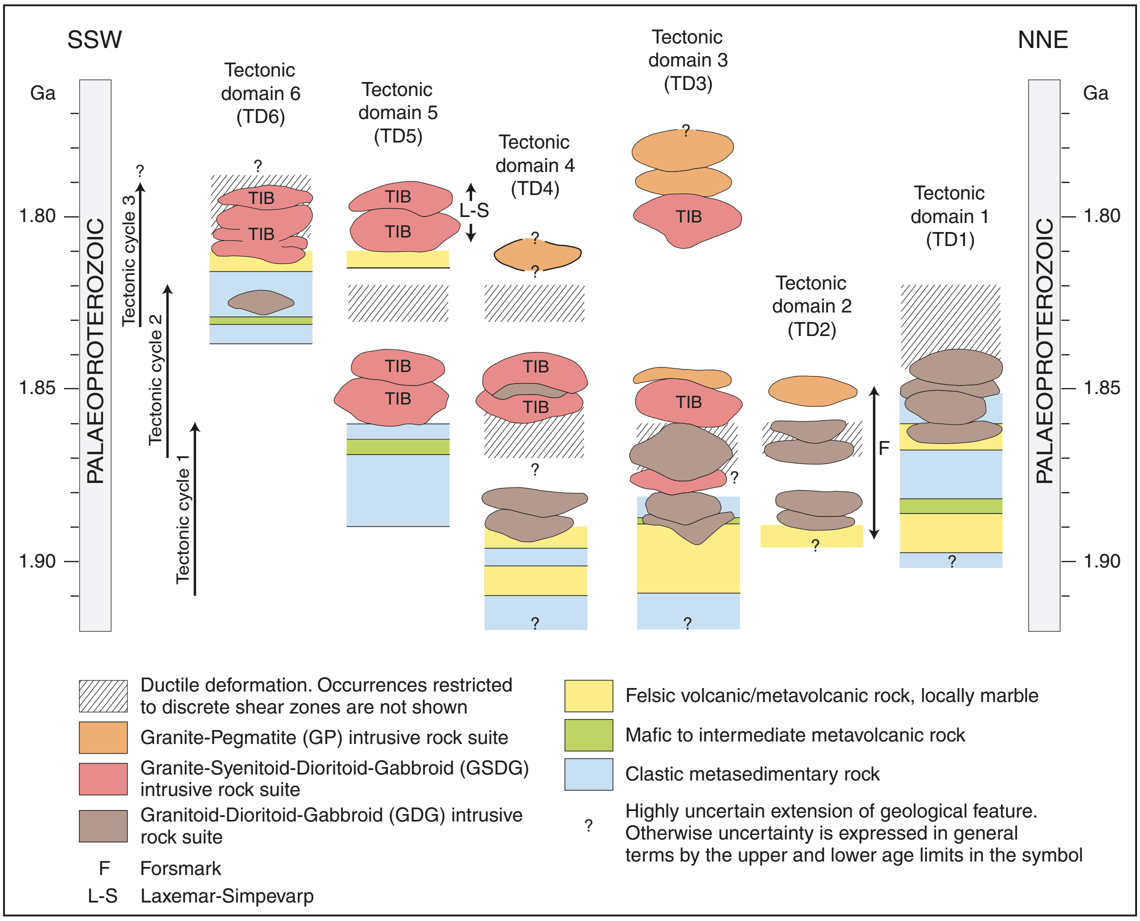


Figure 2-5. *Simplified overview of the time-space relationships of different rock units in the different tectonic domains inside the geological reference area. TIB = Transscandinavian Igneous Belt.*

In TD5, sedimentary rocks comprise the oldest part of the sequence (Figure 2-5). These were deposited during the interval 1.89 to 1.86 Ga and were intruded by GSDG rocks dated to 1.86 Ga that belong to the oldest phase of TIB rocks /Wik et al. 2005/. All these rocks are restricted to the northern part of TD5, against its northern tectonic boundary. Intrusive rocks related to this second major igneous episode, between 1.87 and 1.84 Ga, are also conspicuous inside TD4 and are present, but are volumetrically subordinate in character inside TD2 and TD3 (Figure 2-5).

TD6, in the Kalmar-Vetlanda region (Figure 2-3a), differs from TD5 due to the presence of a third and younger igneous episode /Mansfeld 1996, Åhäll et al. 2002, Mansfeld et al. 2005/. Sedimentary and volcanic rocks, which formed around 1.83 Ga and were intruded by GDG rocks during the period 1.83 to 1.82 Ga (Figure 2-5), occur in the northern part of this domain against its northern tectonic boundary. However, the domain is dominated by major volumes of younger GSDG rocks that formed around 1.81 to 1.79 Ga and that belong to a younger generation of TIB rocks (Figure 2-5). These GSDG rocks are also strongly dominant in TD5. Together with GP rocks, which show ages as young as 1.75 Ga, they are also present in TD3 and TD4 (Figure 2-5).

In summary, rock types that belong to three separate igneous episodes at 1.91 to 1.87 Ga, 1.87 to 1.84 Ga and 1.83 to 1.79 Ga are present inside the geological reference area (Figure 2-5). As each tectonic domain developed, the igneous activity changed from GDG to more GSDG and GP character (Figure 2-5), in accordance with the progressive increase in the maturity of the continental crust at each place with time. It is commonly the occurrence of younger intrusive rocks, in adjacent domains, that provides constraints on the timing of their amalgamation.

Ductile deformation at mid-crustal depths

The rocks around and older than 1.87 Ga in TD2 and TD3, around and older than 1.84 Ga in TD1, TD4 and TD5, and older than c 1.80 Ga in TD6 are affected by penetrative ductile deformation. This deformation took place, in part, under high temperature and, in general, under low pressure metamorphic conditions. The following structural features are present in these rocks in the different domains:

- A planar grain-shape fabric.
- Regional-scale folding which affects an earlier planar fabric and rock contacts.
- A linear grain-shape fabric.
- Focused ductile strain along broader high-strain belts or zones.

The ductile deformation was transpressive in character. Between ductile high-strain belts, deformation was absorbed by folding and the development of a predominantly constrictional grain-shape fabric, i.e linear structures. Inside the high-strain belts or zones, this deformation was taken up by a component of dextral displacement along structures that strike WNW-ESE or NW-SE /Talbot and Sokoutis 1995, Stephens et al. 1997, Beunk and Page 2001, Persson and Sjöström 2003/, combined with shortening in a NE-SW direction across them, i.e. by strain partitioning. Bulk crustal shortening in a NW-SE to N-S direction is envisaged (Figure 2-4).

A compilation of available geochronological data suggests that penetrative ductile deformation and metamorphism occurred between 1.88 and 1.86 Ga in TD3, in the Bergslagen region /Hermansson et al. 2008/. A metamorphic episode around 1.87 Ga was recognised earlier in this domain by /Andersson et al. 2006/. Tighter constraints on the timing of penetrative ductile deformation and metamorphism between 1.87 and 1.86 Ga in TD2, which are based on new geochronological data from the Forsmark area /Hermansson et al. 2008/, are discussed in more detail in section 2.3.4. The field relationships between the intrusion of GSDG rocks and older GDG and supracrustal rocks in TD4 indicate that penetrative deformation and metamorphism in this domain had also initiated prior to 1.86 Ga /Wikström et al. 1997/. In summary, a major tectonic event between 1.87 and 1.86 Ga, which affected the rocks in the oldest igneous episode, is evident in TD2, TD3 and TD4 (Figure 2-5).

Further north, in TD1, penetrative ductile deformation and metamorphism, partly under granulite facies conditions, affected the rocks in the second igneous episode around or after 1.84 Ga. Furthermore, deformation and metamorphism of the GSDG rocks in TD4 at c 1.83 to 1.82 Ga /Andersson et al. 2006/ and between 1.86 and 1.80 Ga in the northern part of TD5 provide further evidence for a second major tectonic event inside these three domains (Figure 2-5). Low-temperature ductile deformation in the northern part of TD6 and along its contact with TD5 affected the rocks in the third igneous episode around or after 1.80 Ga (Figure 2-5).

In summary, at least three events with penetrative ductile deformation and metamorphism can be recognised in the geological reference area:

- The oldest event at 1.87 to 1.86 Ga is prominent in TD2, TD3 and TD4 (Bergslagen).
- The second event, which is inferred to have occurred around 1.84 to 1.82 Ga, is conspicuous in TD1 and TD4, and in the northern part (Västervik) of TD5.
- The youngest event, which is inferred to have occurred around or after 1.80 Ga, is prominent in TD6 close to the boundary with TD5 (Vetlanda).

Each deformational and metamorphic event took place between or after the three igneous episodes recognised above (Figure 2-5). However, as for the igneous episodes, it is envisaged that the effects of the younger events are present in the tectonic domains affected more strongly by older events. These effects take the form of more spatially restricted strain along regionally significant, ductile high-strain zones.

Conceptual tectonic model – migratory tectonic switching

It is inferred that the different phases of igneous activity, ductile deformation and metamorphism, in the geological reference area in south-eastern Sweden, belong to three different tectonic cycles (Figure 2-5). Each of these cycles extended over c 50 Ma in time. However, between the different cycles, the focus of tectonic activity migrated in space from one tectonic domain or groups of domains to another. The presence of a cyclic tectonic evolution in this part of the shield was first proposed by /Allen et al. 1996/, who also suggested an extensional back-arc region, close to an active continental margin, as the setting for the area occupied by TD2, TD3 and TD4 (Bergslagen).

The present conceptual thinking for the tectonic evolution of the Fennoscandian Shield is complex and involves multiple collisions of continental fragments both with the older continental crust in the north-eastern part of the shield and with each other (see, for example, /Nironen 1997, Lahtinen et al. 2005/). These models contrast with earlier and simpler models that emphasised an accretionary tectonic setting with subduction of oceanic crust beneath a single, active continental margin to the north-east /Hietanen 1975, Gaál 1982, Park 1985/. Accretionary tectonics refers to the progressive addition of continental crust along an active boundary between continental and oceanic plates, without major continent-continent collision. Examples of accretionary orogens at the present day occur in the Andes, in the western part of South America, and in the northerly continuation of this Cordilleran mountain belt in the western part of North America.

A conceptual tectonic model for the oldest cycle between 1.91 and 1.86 Ga in TD2, TD3 and TD4 and for the initiation of the second cycle at 1.87 to 1.86 Ga in TD1 and TD5 has recently been presented in /Hermansson et al. 2008/. This model once again highlights the accretionary character rather than the continental collisional character of the Svecokarelian orogen, in the manner envisaged, for example, over 30 years ago by /Hietanen 1975/. Bearing in mind the component of dextral strike-slip displacement along high-strain belts or zones with WNW-ENE and NW-SE strike, approximately northward-directed oblique subduction beneath an active continental margin to the north-east is inferred. Furthermore, prior to 1.86 Ga, TD1 has been restored to a position at an uncertain distance to the north-west relative to TD3. It is envisaged to have formed a lateral continuation of TD4 and the northern part of TD5 at this time in the geological evolution (Figure 2-6).

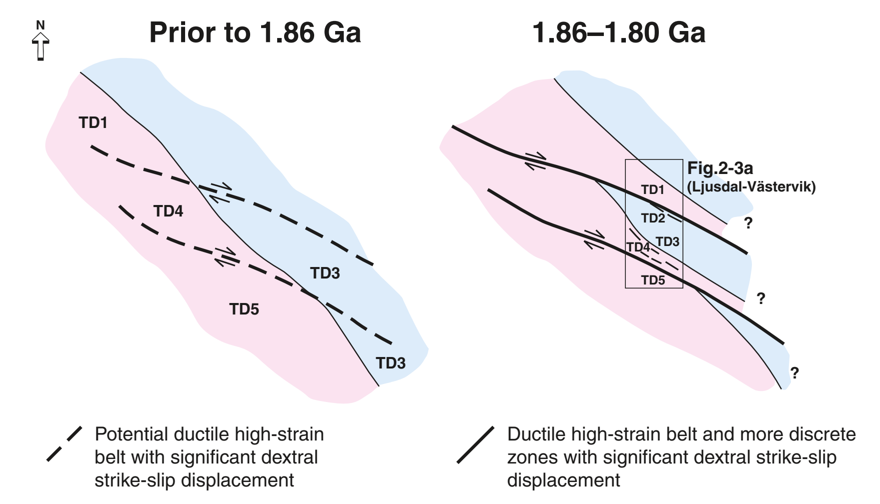


Figure 2-6. *Palaeogeographic cartoon that illustrates the inferred position of TD1 relative to TD3 prior to 1.86 Ga. This cartoon takes notice of the kinematics of WNW-ENE or NW-SE high-strain belts or zones. However, the amount of displacement along these structures is not known. It is envisaged that TD1 formed a lateral continuation of TD4 and the northern part of TD5 prior to 1.86 Ga. Ductile high-strain belts and zones are distinguished solely on the basis of the scale of the structure. Ductile high-strain belts refer to broader crustal segments affected by high ductile strain, the boundaries to which are not well-defined. High-strain zones are more discrete structures, the boundaries to which are better defined.*

In the conceptual tectonic model presented in /Hermansson et al. 2008/, migration of the subduction hinge away from the overriding plate caused continental back-arc extension (Figure 2-4b). This tectonic scenario is expressed, in particular, by the 1.91 to 1.89 Ga bimodal volcanism and clastic sedimentary infill preserved in TD3 (see also /Allen et al. 1996/). Major igneous activity followed at 1.89 to 1.87 Ga (Figure 2-4b). The tectonic setting during this period is uncertain, a waning extensional setting is proposed (Figure 2-4b). As a consequence of a change in the migration of the subduction hinge towards the overriding plate, compressional deformation in the back-arc region followed between 1.87 and 1.86 Ga (Figure 2-4b). During this time, penetrative ductile deformation occurred in TD2, TD3 and TD4 at the same time as new igneous activity started to affect TD1, TD4 and TD5 along the active continental margin, which had now migrated to the south-west (Figure 2-4b). Deformation around and after 1.86 Ga also involved the south-eastward displacement of TD1 relative to TD3. A reversal to migration of the subduction hinge away from the overriding plate caused renewed continental back-arc extension at c 1.86 Ga and the initiation of a new tectonic cycle (Figure 2-4b).

The tectonic model proposed in /Hermansson et al. 2008/ for the oldest tectonic cycle between c 1.91 and 1.86 Ga involved migration of what has been described as tectonic switching, with rapid changes from extensional to compressional tectonics and the reverse, in the younger accretionary orogenic systems of eastern Australia (Lachlan orogen) and New Zealand /Collins 2002/. In south-eastern Sweden, it can equally well be applied to the younger cycle between c 1.87 and 1.82 Ga in TD1, TD4 and the northern part of TD5, and to the youngest cycle between c 1.83 and 1.79 Ga (or younger) in the major part of TD5 and TD6.

2.2.2 Far-field tectonic activity – a potential cause of brittle deformation of the Fennoscandian Shield in south-eastern Sweden after 1.75 Ga

Although the bedrock geological evolution in the geological reference area after 1.75 Ga and up to the Quaternary period is poorly constrained, it can be assumed that various tectonic events in the regions outside the reference area to the west and south potentially controlled geological events inside it during this long time interval. These events include local igneous activity during the Proterozoic eon, deposition of sedimentary cover rocks during both the Proterozoic and Phanerozoic eons, and local ductile but widespread brittle deformation.

In order to provide a necessary background, a short summary of this far-field tectonic activity is presented below. This text is followed, in section 2.2.3, by an assessment of the timing of predominantly brittle deformation in the geological reference area, on the basis of the stratigraphic constraints provided by post-1.75 Ga rocks, both on land and on the continental shelf to the east. The context of these post-Svecokarelian rocks in relation to the far-field tectonic activity is also addressed in section 2.2.3. The reader is referred once again to Figure 2-1, which shows the distribution of the major tectonic units in the Fennoscandian Shield at the current level of erosion.

Late Palaeoproterozoic and Mesoproterozoic tectonic activity (1.7 to 1.55 Ga and 1.5 to 1.4 Ga)

Between 1.75 and 1.275 Ga, i.e. during the latest part of the Palaeoproterozoic and the majority of the Mesoproterozoic eras (Figure 2-2), the focus of tectonic activity in the Fennoscandian Shield had shifted westwards and southwards, outside the geological reference area. The bedrock that formed during this time interval is exposed in south-western and southernmost Sweden, and in southern Norway (Figure 2-7a). Crustal growth and crustal reworking in the Fennoscandian Shield occurred in connection with the Gothian /e.g. Connelly and Åhäll 1996, Åhäll and Gower 1997/ and Hallandian /Hubbard 1975, Christoffel et al. 1999, Söderlund et al. 2002/ orogenies at 1.7 to 1.55 Ga and 1.5 to 1.4 Ga, respectively. Many of the rocks that were affected by these complex tectonic events were also reworked by younger tectonic events (Sveconorwegian and Caledonian, see below).

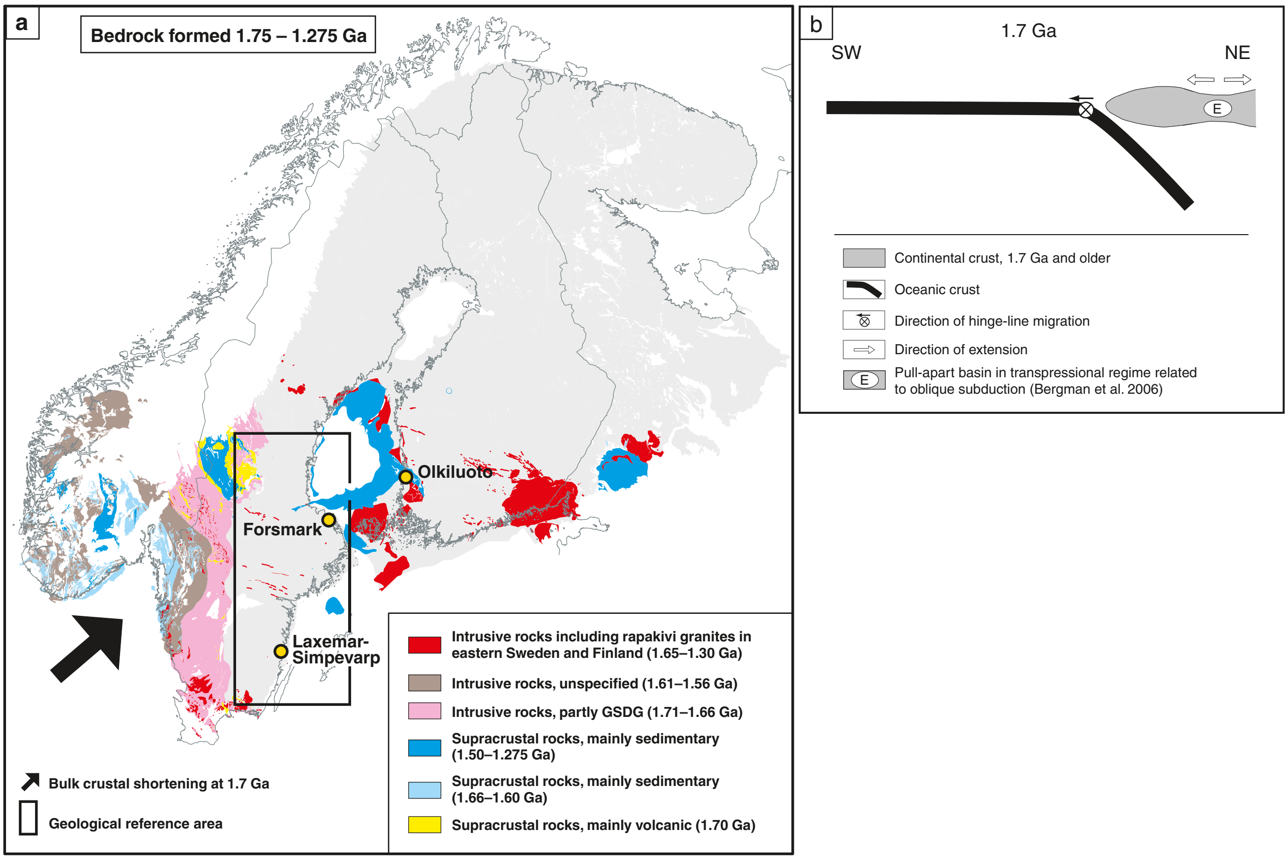


Figure 2-7. *a) Rocks formed during the period 1.75 to 1.275 Ga. All the bedrock shown in grey had formed prior to 1.75 Ga and represent older continental crust. Note the significant increase in area marked in grey relative to that seen in Figure 2-4a. The figure is based on the database that accompanies the geological map of the Fennoscandian Shield /Koistinen et al. 2001/. b) Cartoon showing formation of 1.71 to 1.66 Ga igneous rocks in a pull-apart, back-arc basin. The basin is inferred to have formed during transpressive deformation along an active continental margin. The transpressive deformation was a result of oblique subduction (modified after /Bergman et al. 2006/).*

Late Mesoproterozoic and early Neoproterozoic (1.1 Ga to 900 Ma) tectonic activity – final assembly of the supercontinent Rodinia

The majority of sedimentary and igneous rocks in the Fennoscandian Shield, which formed during the period 1.275 Ga to 900 Ma, are exposed in the westernmost part of southern Sweden and in southern Norway (Figure 2-8). These rocks, as well as older crystalline bedrock further east in south-western Sweden, were affected by complex ductile deformation and metamorphism during the period 1.1 Ga to 900 Ma, during the Sveconorwegian orogeny /Berthelsen 1980, Gorbatschev 1980/.

The series of tectonic events during the Sveconorwegian orogeny culminated in a continent-continent collision. This collision resulted in the development of high-pressure rocks, including granulites and eclogites, in the eastern part of the orogen at 980 to 960 Ma, related to the subduction of older, late Palaeoproterozoic and Mesoproterozoic continental lithosphere /Möller 1998, Hegardt et al. 2005/. Flat-lying thrust sheets are also present in south-western Sweden. The crustal thickening event that gave rise to the high-pressure rocks was followed by partial melting, with formation of migmatites, and major folding with a southerly sense of vergence, related to extensional collapse of the thickened crust and tectonic uplift /Möller et al. 2007/. The swarm of dolerite dykes that strike approximately N-S parallel to the Sveconorwegian orogen (Figure 2-8) are an igneous expression of this later extensional deformation in an approximately E-W direction. At the current level of erosion, these dykes are situated close to the eastern margin of the orogen.

Sveconorwegian deformation along a major, ductile high-strain zone with NW-SE to N-S strike in the north-eastern part of the orogen, part of the Mylonite Zone, is sinistral transpressive in character /Stephens et al. 1996/. Extensional ductile deformation has also been identified along this zone further to the south /Berglund 1997/. In the eastern, frontal part of the orogen, greenschist-facies deformation along ductile high-strain zones with NE-SW strike is dextral transpressive in character /Wahlgren et al. 1994/ and affected the dolerites formed during the earlier extensional deformation. These kinematic studies are consistent with bulk crustal shortening during at least a part of the Sveconorwegian orogeny in an approximately WNW-ENE direction (Figure 2-8). This is apparently in conflict with the southerly vergence direction of the major folding described above. However, it is possible that these folds formed in a hot, ductile part of the crust as a result of the extensional deformation rather than in connection with horizontal shortening in a N-S direction, as proposed by /Möller et al. 2007/.

The Sveconorwegian orogen is one of several major orogenic belts in Precambrian shield areas throughout the world, where the bedrock was affected by ductile deformation and metamorphism during the time interval 1.1 Ga to 900 Ma. At least part of the tectonic activity inside these belts was related to continent-continent collisions. These collisional events resulted in the assembly of the major supercontinent Rodinia around 900 Ma, a development that marks an important milestone in the geological evolution of the planet.

Break-up of Rodinia and opening of the Iapetus Ocean (600 Ma), followed by ocean closure during the Early Palaeozoic (510–400 Ma)

The part of the supercontinent Rodinia that corresponds at the present time to the Fennoscandian Shield in northern Europe was situated at high southerly latitudes during the latest part of Precambrian time, i.e. during the late Neoproterozoic. The following tectonic events dominated during the period 900 to 400 Ma:

- Rift tectonics and ultimate break-up of Rodinia with formation of the Iapetus Ocean and the continent Baltica, at approximately 600 Ma.
- Rotation and drift of Baltica northwards over the globe, so that during the Silurian period, at approximately 430 Ma, this ancient continental plate was situated close to the equator.
- Destruction of Iapetus and ultimate collision of the continent Baltica with the continents Avalonia and Laurentia during the Caledonian orogeny, which took place at approximately 510 to 400 Ma.

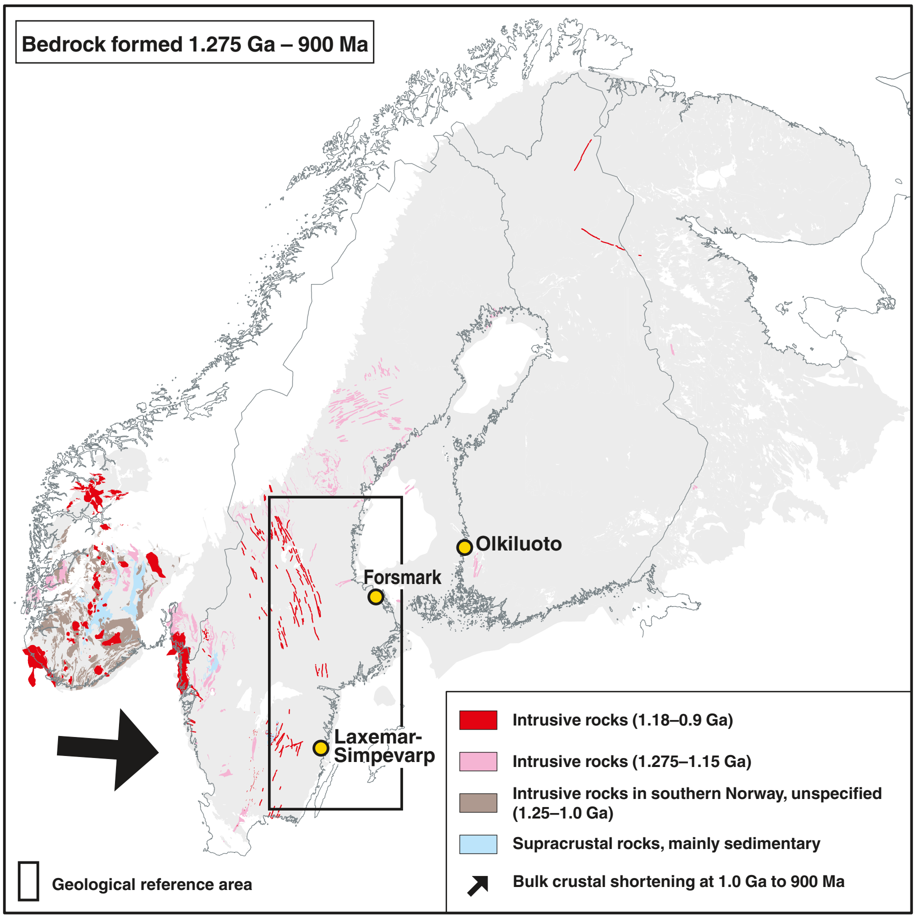


Figure 2-8. *Rocks formed during the period 1.275 Ga to 900 Ma. All the bedrock shown in grey had formed prior to 1.275 Ga and represents older continental crust. The figure is based on the database that accompanies the geological map of the Fennoscandian Shield /Koistinen et al. 2001/.*

Much of the evidence for this geodynamic development is present in the bedrock exposed in the Caledonian orogenic belt (Figure 2-9a). This mobile belt is dominated by major thrust sheets that were transported eastwards over the autochthonous, platformal cover sequence and the underlying Precambrian crystalline rocks of the Fennoscandian Shield (see, for example, /Kulling 1972, Gee 1975, Stephens 1988, Roberts and Stephens 2000/).

Sedimentation and igneous activity that took place in connection with continental rifting are conspicuous in the structurally lower thrust sheets in the Caledonian orogenic belt. Evidence for glaciation at the cold southerly latitudes during the late Neoproterozoic is also present in the rocks in these thrust sheets. Ultimate continental break-up, formation of the Iapetus Ocean and birth of a new continent referred to as Baltica occurred around 600 Ma (Figure 2-9b).

Sedimentation and igneous activity that occurred in connection with destruction of the Iapetus Ocean during the Early Palaeozoic (c 510 to 400 Ma) are preserved in the structurally higher thrust sheets, in north-western Sweden and Norway. These thrust sheets include fragments of old marginal basins with oceanic crust, so-called ophiolites. Complex ductile deformation and metamorphism during the Caledonian orogeny was related to continent-arc collisions and ultimately a major collision between the ancient continents Baltica and Laurentia (Figure 2-9b and c) during the Silurian, with shortening in a WNW-ENE direction (Figure 2-9a). At this stage in its geological evolution, the northern part of Europe had drifted northwards into warm equatorial latitudes. High-pressure rocks, including eclogites, which formed in connection with subduction of one of the margins to the ancient continent Baltica, provide key evidence for the different collisional events that involved this ancient continental margin. During the early part of the Devonian, extensional collapse, sinistral strike-slip deformation and major folding of thinned thrust sheets followed in the western parts of the orogen.

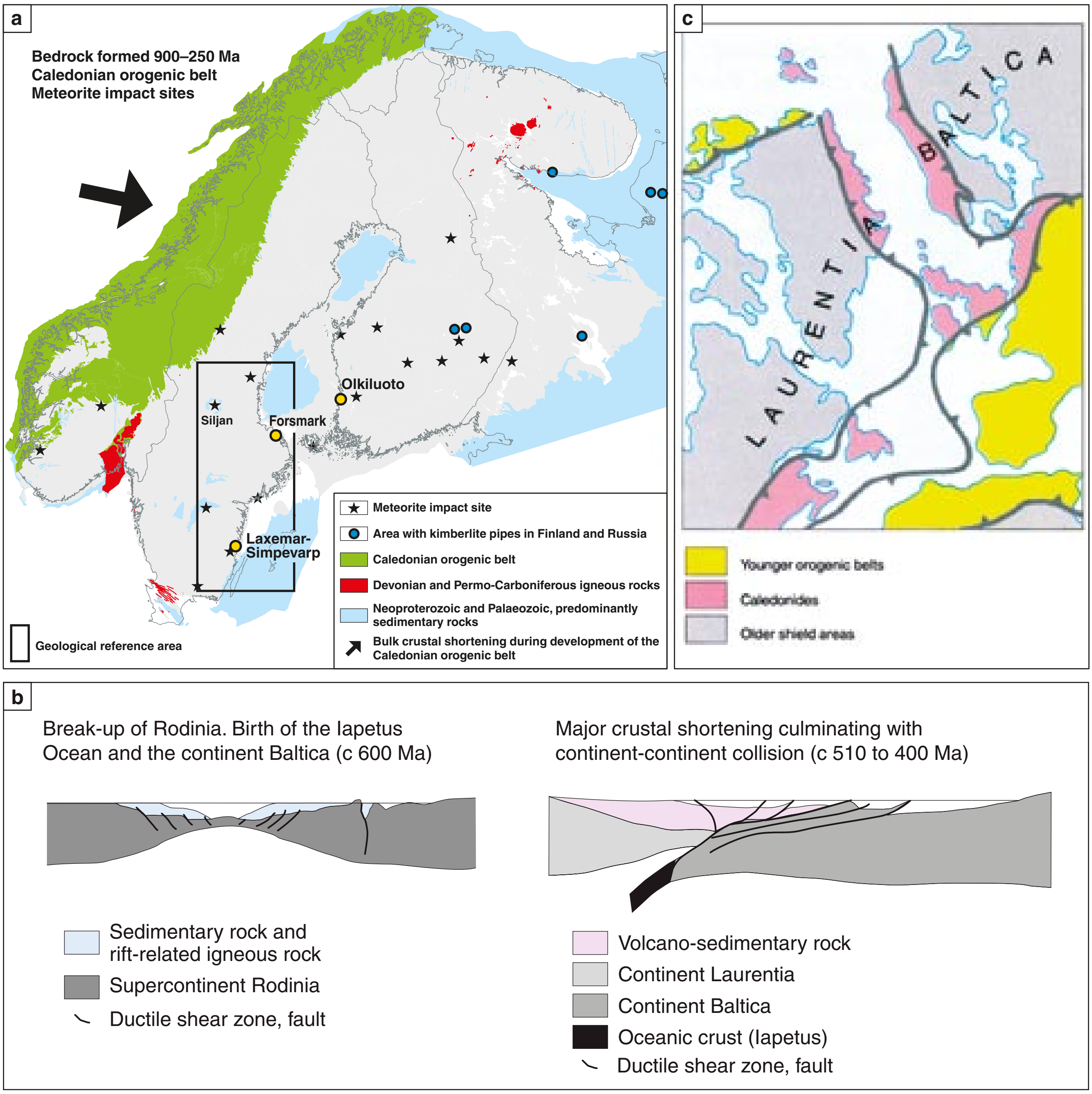


Figure 2-9. *a) Rocks formed during the period 900 to 250 Ma. All the bedrock shown in grey had formed prior to 900 Ma and represents older continental crust. Note the swarm of Permo-Carboniferous dolerite dykes that trend WNW-ENE in the southernmost part of Sweden and the significant igneous activity in the Oslo rift. The figure is based on the database that accompanies the geological map of the Fennoscandian Shield /Koistinen et al. 2001/. b) Cartoon showing rifting of the supercontinent Rodinia and birth of the Iapetus Ocean and the continent Baltica at c 600 Ma and continent-continent collision between Baltica (downgoing plate) and Laurentia during the Silurian. c) Reconstruction of what the North Atlantic region looked like at around 250 Ma /after Stephens et al. 1994/. At this time during the geological evolution, the Pangaea supercontinent had formed, but the present-day North Atlantic Ocean had not yet opened.*

Late Palaeozoic (400–250 Ma) tectonic activity – final assembly of the supercontinent Pangaea

There is poor control on the tectonic developments in most of the old cratonic area of northern Europe during the period 400 to 250 Ma. During the Late Devonian and Carboniferous periods, i.e. at 360 to 295 Ma, the focus of sedimentation, igneous activity and crustal deformation, in connection with tectonic activity, had shifted southwards to the central part of Europe, with the development of the Hercynian-Variscan orogeny. This major orogenic event resulted in the final assembly of the supercontinent Pangaea (Figure 2-9c). During the Carboniferous and Permian, i.e. at 295 to 275 Ma, extensional deformation and associated volcanic and intrusive activity prevailed in the Oslo rift, Norway (Figure 2-9a). During the same period, dextral transtensional deformation and intrusion of mafic dykes and sills occurred along the Sorgenfrei-Tornquist Zone, in the southernmost part of Sweden (Figure 2-9a).

Break-up of Pangaea and opening of the North Atlantic Ocean

As for the earlier part of the Phanerozoic, there is poor control on the tectonic developments in most of the old cratonic area of northern Europe during the period from 250 Ma up to the Quaternary, i.e. during the Mesozoic era and during the Palaeogene and Neogene periods in the Cenozoic. Sedimentary and, locally, volcanic rocks, are only preserved in the southernmost part of Sweden, where evidence for the tectonic history can be studied directly, and in offshore areas surrounding the Fennoscandian Shield in Norden and Russia (Figure 2-10). In particular, major thicknesses of sedimentary material accumulated in connection with rifting activity west and south of the Norwegian coast (Figure 2-10). An attempt to reconstruct the tectonic history of the shield area after 100 Ma, i.e. from the Late Cretaceous to the Quaternary, on the basis of the plate tectonic history around its margins was presented in /Muir Wood 1995/.

During the early part of the Mesozoic, differential subsidence controlled by transtensional deformation occurred along the Sorgenfrei-Tornquist Zone in southernmost Sweden /Erlström and Sivhed 2001/. Volcanic activity was also prevalent in this area during the Jurassic and Cretaceous (Figure 2-10). The tectonic environment radically changed during the later part of the Cretaceous and the earliest part of the Palaeogene, i.e. 95 to 60 Ma, when a marine transgression and inversion tectonics with dextral transpressional deformation along the Sorgenfrei-Tornquist Zone took place /Erlström and Sivhed 2001/. The compressional tectonic event during the Late Cretaceous and into the Palaeogene corresponds temporally with the initiation of the Alpine orogeny in southern Europe and the collision between Africa and Eurasia. A maximum principal stress (σ_1) in a NNE-SSW horizontal direction has been inferred during this period (/Muir Wood 1995/ and Figure 2-10).

From 60 Ma and onwards, the North Atlantic Ocean started to open and to spread. During this time, plate motions associated with spreading of the North Atlantic Ocean have dominated the geodynamics of northern Europe. After c 12 Ma, during the Neogene period, a maximum principal stress (σ_1) in a WNW-ESE or NW-SE horizontal direction, steered by ridge push from the mid-Atlantic ridge and, as a consequence, the relative plate motion between the Eurasian and American plates, has prevailed in this region (/Muir Wood 1995/ and Figure 2-10).

Meteorite impact structures

Recent work has suggested the presence of meteorite impact structures in the Fennoscandian Shield and its sedimentary overburden (/Wickman 1988, Henkel and Pesonen 1992/; see Figure 2-9a). A circular topographic, geological or geophysical feature has often triggered such speculations. By far the best-documented structure, with a diameter of c 50 km, occurs in the Siljan area (Figure 2-9a) in the north-western part of the geological reference area. This structure formed at c 360 Ma, during the Late Devonian or Carboniferous periods.

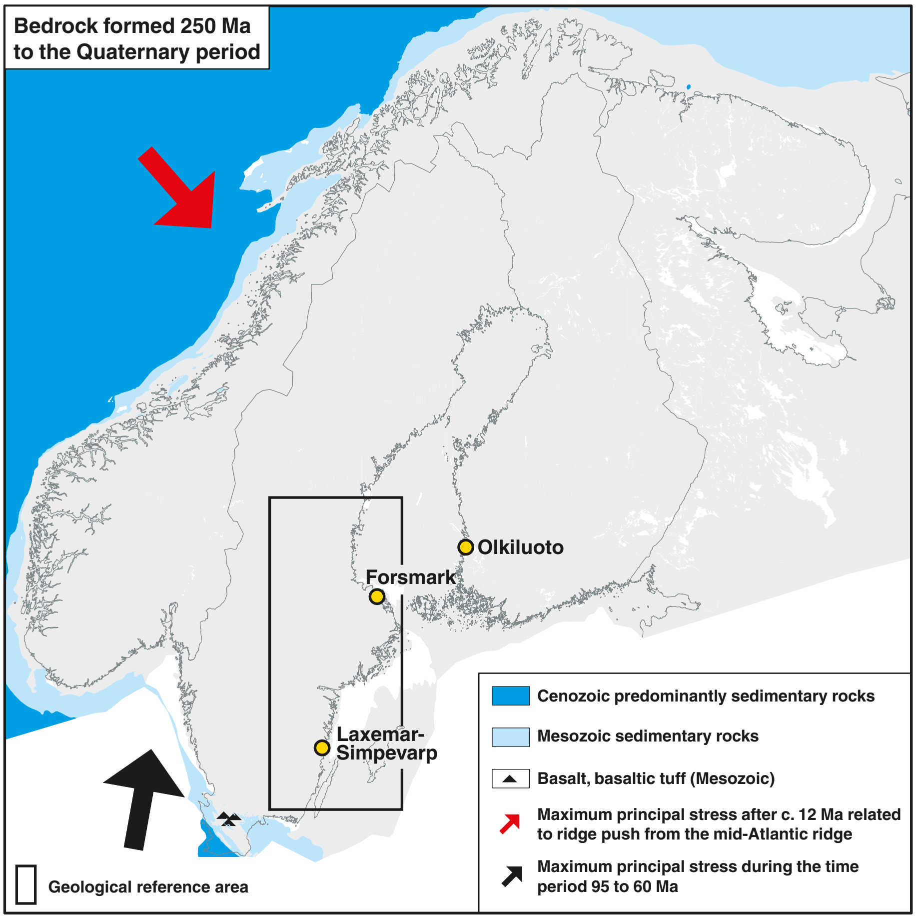


Figure 2-10. *Rocks formed during the period 250 Ma to the Quaternary period. All the bedrock shown in grey had formed prior to 250 Ma and represents older continental crust. Note the occurrence of volcanic activity during the Jurassic and Cretaceous periods in the southernmost part of Sweden. The figure is based on the database that accompanies the geological map of the Fennoscandian Shield /Koistinen et al. 2001/.*

2.2.3 Constraints on the timing of brittle deformation of the Fennoscandian Shield in south-eastern Sweden after 1.75 Ga

The presence of younger (post-1.75 Ga) igneous and sedimentary cover rocks in the geological reference area (Figure 2-3a) provide direct stratigraphic constraints on the timing of predominantly brittle deformation in this part of the Fennoscandian Shield, since deformation in these rocks must have occurred during and/or after their formation. Thus, the maximum age of the deformation is constrained by the age of the deformed rocks. However, deformation zones within or along the boundaries to these rocks may have been established earlier, with the deformation then giving rise to reactivated structures in the older rocks on one side of the boundary and newly formed structures in the younger rocks on the other (Figure 2-11).

Disturbances in the sub-Cambrian unconformity, which marks a conspicuous exhumed denudation surface, also provide constraints on the timing of faulting after the establishment of this major discontinuity /Lidmar-Bergström 1993, 1996/. This surface is actually exposed at the current level of erosion in large parts of southern Sweden, including Forsmark and Laxemar-Simpevarp in the geological reference area /Lidmar-Bergström 1993/. Age determinations of minerals along fractures also provide an insight into the brittle deformational history of the shield in this area. Further details on the character of these stratigraphic and geochronological constraints for the timing of predominantly brittle deformation after 1.75 Ga in the geological reference area are provided in the following text.

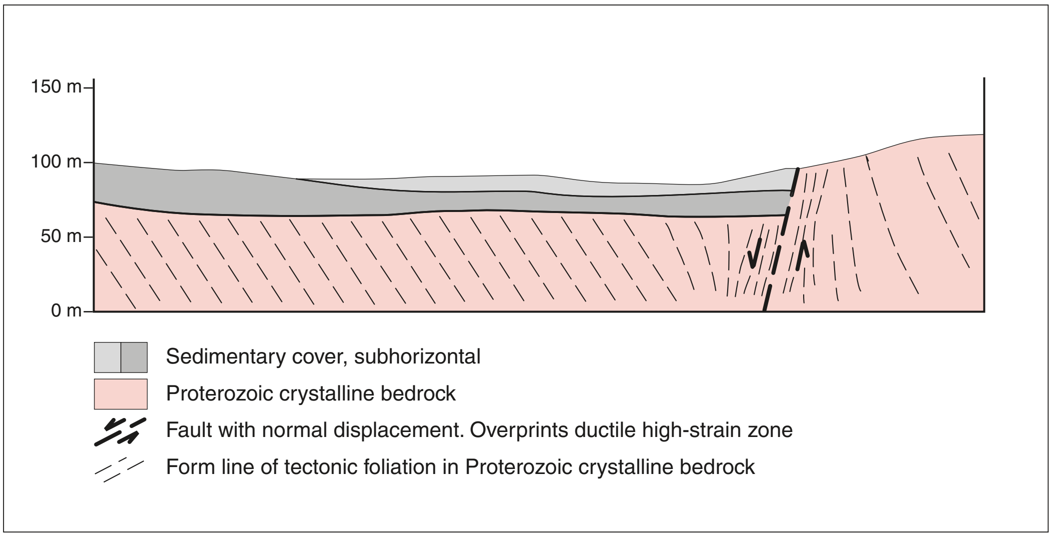


Figure 2-11. *Cartoon that illustrates reactivation of an older ductile deformation zone by brittle faulting with normal sense of movement. The ductile deformation zone is shown by the more intense frequency of form lines. It affected solely the Precambrian crystalline rocks. The brittle reactivation affected both the older crystalline bedrock and the younger sedimentary cover rocks. Complex reactivation in the manner illustrated here is observed along the boundaries to Lower Palaeozoic outliers on land in the geological reference area.*

Igneous response to far-field tectonic activity during the Late Palaeoproterozoic, Mesoproterozoic and Neoproterozoic

/Åhäll et al. 2000/ have proposed a possible causal link between the Gothian tectonic activity in the south-westernmost part of the Fennoscandian Shield and early Mesoproterozoic igneous activity in its eastern, internal parts. Crustal stabilisation, so-called cratonisation, in the eastern parts of the shield had initiated earlier following the Svecokarelian orogeny. An igneous response to the far-field Gothian tectonic activity in the geological reference area is expressed as:

- GSDG igneous rocks in the north-western part of the geological reference area (Figure 2-3a), which are 1.71 to 1.66 Ga in age and form the youngest phase of the Transscandinavian Igneous Belt (TIB),
- Dolerites with an age of 1.60 to 1.59 Ga /Söderlund et al. 2005a/ that strike WNW-ESE parallel to the ductile anisotropy of the bedrock in the central part of the geological reference area, south and west of the Forsmark area (Figure 2-7a).

The GSDG intrusive rocks, and their spatially and temporally associated volcanic rocks (Figure 2-7a), formed in a continental magmatic arc setting /Nyström 2004/. Dextral transpressive deformation occurred along a low-temperature, ductile high-strain zone that strikes NNW-SSE and is situated directly east of and locally affects the GSDG rocks /Bergman et al. 2006/. The transpressive deformation along this zone occurred around 1.67 Ga and was broadly synchronous with the GSDG igneous activity in the area /Bergman et al. 2006/. The ductile deformation is inferred to be related to bulk crustal shortening in an approximately NE-SW direction, in combination with oblique subduction to the north-east (/Bergman et al. 2006/ and Figure 2-7b).

The consistent orientation of the c 1.6 Ga dolerite dykes in the geological reference area indicates crustal extension in an approximately NNE-SSW direction. It is apparent that there was an inversion of the tectonic regime between c 1.7 and c 1.6 Ga from dextral tranpressional to extensional. The dolerites are similar in age to the rapakivi granites that form larger intrusive bodies at the current level of erosion and are exposed on Åland and close to Olkiluoto in south-western Finland (Figure 2-1).

Isolated intrusive bodies of granite, which are approximately 1.45 Ga in age, are prominent in the southern part of the geological reference area, close to Laxemar-Simpevarp. The implications of these rocks for the tectonothermal evolution of the Laxemar-Simpevarp area are discussed in more detail in section 2.4. Further north in the geological reference area, dolerites, felsic porphyry dykes and isolated intrusive bodies of rapakivi granite and quartz syenite have yielded ages that range between 1.50 and 1.46 Ga /Claesson and Kresten 1997, Andersson 1997, Lundström et al. 2002, Söderlund et al. 2005a/. All these igneous rocks are similar in age to the Hallandian tectonic activity in south-west Sweden and it is suggested that they represent an igneous response to this far-field, Mesoproterozoic tectonic activity.

Although mildly alkaline dolerite sills, dated at 1.27 to 1.26 Ga /Söderlund et al. 2005a/, are present in the northern part of the geological reference area, the dolerite dykes with an age of 980 to 950 Ma /Söderlund et al. 2005a/, which strike approximately N-S parallel to and predominantly east of the Sveconorwegian orogen, form the most conspicuous swarm of dykes in the reference area (Figure 2-8). As discussed in section 2.2.2, these dykes indicate crustal extension in an approximately E-W direction during the later part of the Sveconorwegian orogeny. These younger dolerites occur in the western part of the reference area and are present in the Laxemar-Simpevarp area. They are discussed in more detail in section 2.4.

Sedimentary response to far-field tectonic activity during the Mesoproterozoic, Neoproterozoic and Palaeozoic – loading and unloading cycles

Mesoproterozoic, Neoproterozoic and Palaeozoic sedimentary rocks, which formed in response to far-field tectonic activity, are preserved in the geological reference area as isolated outliers on land and in more extensive, tilted successions on the continental shelf beneath the Baltic Sea (Figure 2-3a). A variety of geological and thermochronological data, including fission-track ages, suggest that these rocks covered much broader areas of the Fennoscandian Shield in the geological reference area, compared with that preserved on the ground surface at the present time /e.g. Larson and Tullborg 1993, Larson et al. 1999, 2006, Cederbom et al. 2000/. The burial of the older crystalline bedrock was associated with significant crustal loading and thermal disturbance, not least during the deposition of dense limestones during the Ordovician and Silurian.

Mesoproterozoic clastic sedimentary rocks (Jotnian sandstone and conglomerate), with an age constrained between 1.50 and 1.275 Ga, occur locally in south-eastern Sweden (Figure 2-7a). It is speculated here that these sedimentary rocks formed in response to the late Gothian or Hallandian orogenic events that took place to the south and west. As a result of the major tectonic uplift during the later stages of the Sveconorwegian orogeny (see section 2.2.2), clastic sedimentary rocks, with a thickness of up to 8 km, covered the south-eastern part of Sweden in a foreland basin /Larson et al. 1999/. These Neoproterozoic sedimentary rocks are only preserved at the present time in a small outlier (Almesåkra, north-west of Vetlanda) situated directly east of the Sveconorwegian orogen (Figure 2-3a).

Some time prior to the Cambrian in south-eastern Sweden, i.e. prior to 540 Ma, extensive denudation of the Proterozoic crystalline rocks gave rise to crustal unloading and exhumation of a peneplained landform that, in many areas, including Forsmark and Laxemar-Simpevarp, is more or less identical to that exposed at the ground surface today /Lidmar-Bergström 1996/. This so-called sub-Cambrian peneplain (Figure 2-12) corresponds to the major unconformity between the Proterozoic rocks in the Fennoscandian Shield and the Palaeozoic sedimentary overburden. Opening of the Iapetus Ocean and a major marine transgression during the Cambrian once again started to load the crust with sedimentary material and the peneplain was buried. In the text that follows, the geological rather than the geomorphological significance of this surface is emphasized with the preferential use of the term "sub-Cambrian unconformity".

The sedimentary rocks above the sub-Cambrian unconformity consist of Cambrian to Silurian mature sandstone, oil-shale and limestone. These rocks were deposited in a platformal environment along the passive stable margin of the continent Baltica, as it slowly drifted northwards away from colder latitudes (see section 2.2.2). At the present time, they occur in isolated outliers on land and occupy much broader areas on the sea floor in the eastern part of the geological

Figure 2-12. *View of the sub-Cambrian unconformity in the Laxemar-Simpevarp area and the inspection of fractures that disturb this surface.*

reference area (Figure 2-3a and Figure 2-9a). Devonian clastic sedimentary rocks, which were deposited in a foreland basin that formed in response to Caledonian tectonic activity /Larson et al. 1999, 2006, Cederbom 2001/, are also present beneath the sea floor, in the south-easternmost part of the geological reference area. In this area, the Cambrian to Devonian sedimentary cover is up to c 4 km thick and dips gently to the south-east /e.g. Larson et al. 2006/.

Bearing in mind the absence of Mesozoic deep weathering of the sub-Cambrian unconformity in the geological reference area /Lidmar-Bergström 1991/ and the arguments for Neogene re-exhumation of the sub-Cambrian unconformity in southern Sweden /Lidmar-Bergström 1996, Lidmar-Bergström and Näslund 2002, Japsen et al. 2002/, it is possible that Palaeozoic and younger sedimentary rocks continued to cover the shield in the geological reference area during the Mesozoic and even during the early part of the Tertiary. Furthermore, limestone was deposited in south-eastern Sweden, including the Laxemar-Simpevarp area, during the Late Cretaceous and early Palaeogene marine transgression (see section 2.2.2). It has been estimated that this transgression and burial caused a temperature increase of c 35°C /Cederbom 2002/. However, the extent of these deposits further north is not established. The burial and subsequent denudation and exhumation history of the Forsmark and Laxemar-Simpevarp areas during the Phanerozoic are addressed further in sections 2.3.5 and 2.4.6, respectively, in the context of the new (U-Th)/He ages that have been obtained during the site investigation work.

The various Lower Palaeozoic outliers on land in the western part of the geological reference area (Figure 2-3a) are bounded in part by faults that strike approximately NNE-SSW or E-W. These faults disturb both the sub-Cambrian unconformity and the Lower Palaeozoic rocks, and generally show a dip-slip component of movement. These faults were active either during the Silurian, possibly in connection with the Caledonian orogeny (see section 2.2.2), or after this period (or both). Disturbance of the sub-Cambrian unconformity has been observed at several places in south-eastern Sweden /e.g. Lidmar-Bergström 1994, Bergman et al. 1999c/ and Permian faulting has been proposed, at least in the area around Lake Vättern /Månsson 1996, Milnes et al. 1998/.

Evaluation of seismic reflection data on the continental shelf /Flodén 1977, 1980, 1984/ also provides evidence for faulting after 1.75 Ga. Stratigraphic markers in different parts of the continental shelf that help to constrain a maximum age for the inferred faulting are summarised below.

- In the area around Gävle, c 50 km north-west of Forsmark, both Mesoproterozoic clastic sedimentary rocks and Ordovician limestone (Figure 2-3a) are disturbed by steeply dipping faults with ENE strike that show normal dip-slip kinematics. Graben and small horst structures, which are inferred to have been active both during the Mesoproterozoic and after the Ordovician, are present in this area /Bergman et al. 2002, Bergman et al. 2005/.
- Mesoproterozoic and/or younger faulting has affected the outlier of clastic sedimentary rocks that is present on the floor of the Åland Sea, c 50 km south-east of Forsmark (Figure 2-3a). These faults strike NW-SE and are a south-easterly continuation of the Forsmark and Singö deformation zone system at Forsmark /Stephens et al. 2007/.
- Faults that show a dip-slip component of movement are conspicuous on the continental shelf east of the Laxemar-Simpevarp area and affect even the Devonian rocks in this part of the shelf /Flodén 1984/. Furthermore, structures related to strong brittle deformation of Cambrian sandstone were observed on the island of Furö, immediately south of the Laxemar-Simpevarp area /Bergman et al. 1998/. However, a study of the evidence for post-Ordovician faulting of the sedimentary rocks on the island of Öland (Figure 2-3a) indicated that only very small disturbances could have affected the Ordovician limestone that is exposed on this island /Milnes and Gee 1992, Munier 1995/.

Direct dating of brittle deformational events

In the northern part of Uppland, where Forsmark is situated, U-Pb dating of pitchblende in quartz-, calcite- and chlorite-filled fractures /Welin 1964/ and Rb-Sr dating of epidote-filled fractures /Wickman et al. 1983/ have yielded mineral ages in the time interval 1.59 to 1.45 Ga. Furthermore, Rb-Sr dating of prehnite- and calcite-filled fractures in the same region has yielded younger ages in the time interval 1.25 to 1.1 Ga.

Before any coupling can be made between a mineral age and the actual timing of movement along a brittle structure, it is necessary to know the blocking temperatures for the different minerals within the selected isotope system. If shear or extensional failure along the fracture in combination with fluid flow occurred at temperatures that are lower than the blocking temperature, then the age reflects the time when the fracture mineral crystallised. In such an instance, it is possible to relate the age to the brittle deformational event. If brittle deformation and fluid flow occurred at temperatures above the blocking temperature, then the interpretation of the age is more complicated. An interpretation, which involves a resetting of the isotope system during the brittle event and crystallisation of the dated mineral earlier during the geological history, is also possible. Notwithstanding these uncertainties, the data from the geological reference area described above suggest that brittle deformation occurred in the northern part of Uppland during or prior to the Mesoproterozoic.

In connection with the construction of the Äspö Hard Rock Laboratory, attempts were made to date brittle structures by use of, for example, palaeomagnetic, electron spin resonance (ESR) and both K-Ar and Rb-Sr isotope age dating techniques. This work aimed to constrain the minimum age of the more recent movements /Maddock et al. 1993/. The results of the K-Ar analyses indicate that authigenic growth of illite/smectite took place at least at 250 Ma, while the ESR dating of quartz grains in fault gouge, which was limited by the resolution of the method, yielded minimum ages of movement in the order of several hundred thousand to one million years. Fracture fillings in the Götemar granite, which is also situated close to the Laxemar-Simpevarp area, have been dated by /Sundblad et al. 2004/. The Palaeozoic ages were related in time to the Caledonian orogeny (see section 2.2.2) or possibly also to its migrating foreland basin (see above).

2.2.4 Variation in crustal thickness

On the basis of data obtained from predominantly seismic refraction and seismic reflection surveys along profiles, /Kinck et al. 1993/ compiled the current thickness of the continental crust in the northern part of Europe (Finland, Norway and Sweden). A slightly modified compilation, which also made use of later seismic reflection data, for example for parts of the Baltic Sea /BABEL Working Group 1990/, was presented by /Luosto 1997/. The inferred crustal thicknesses obtained in these compilations are the expression of the accumulative effects of several different tectonic events over an extremely long time interval. In this context, it is important to emphasise that the effects of younger geological processes are considerably less pronounced in the internal parts of the Fennoscandian Shield, compared with those observed in its marginal parts. As indicated in the earlier sections, it is especially extensional tectonics, which gave rise to crustal thinning, that prevailed in the marginal areas during the younger geological history. The crustal thickness of most of Sweden and Norway, based on the compilation presented in /Kinck et al. 1993/, is shown in Figure 2-13.

Two features are conspicuous in this compilation:

- The continental crust in the internal part of the Fennoscandian Shield in Sweden is remarkably thick. The thickest parts of the crust in Sweden (> 50 km) occur close to the coast both north of Forsmark and between Stockholm and Laxemar-Simpevarp (Figure 2-13). In the eastern part of Finland, close to the Archaean crustal nucleus (Figure 2-1), a crustal thickness around 60 km has been inferred /Luosto 1997/.
- The continental crust reduces to a thickness of 30 km and less along the western coast of Norway, along the major rift structure that passes through Oslo and along the southern coast of Sweden where the Sorgenfrei-Tornquist Zone is situated (Figure 2-13).

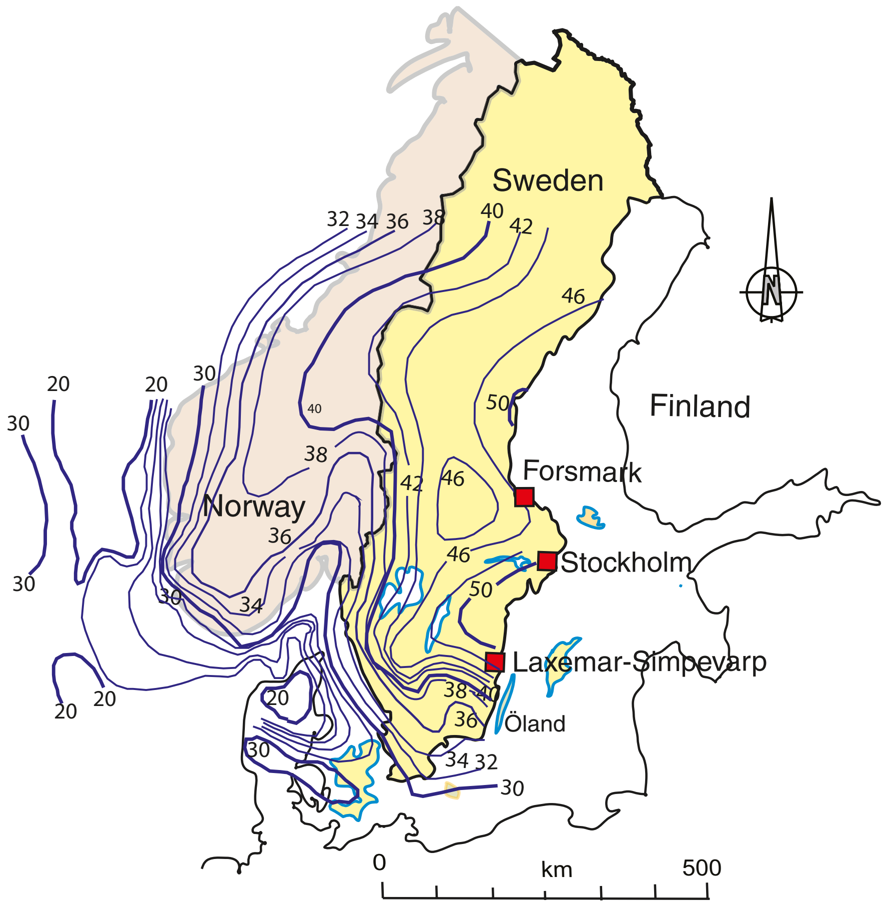


Figure 2-13. Crustal thickness contours in Sweden and Norway based on the compilation in /Kinck et al. 1993/. These contours are in two-kilometre intervals.

In both the areas in Sweden where the crust is thickest, the bedrock at the present level of erosion was affected during the Palaeoproterozoic by high-grade metamorphism at relatively low pressures, under upper amphibolite and locally granulite facies conditions. Such metamorphism can be explained by the input of abundant sheets of high-density, mafic and intermediate igneous material in the crust. By contrast, all areas in Norway and Sweden, where the crust shows "normal" crustal thickness, have been affected by extensional tectonics and crustal thinning during and after Permo-Carboniferous time, i.e. after 300 Ma. These areas include the west coast of Norway, the Oslo rift and the Sorgenfrei-Tornquist Zone in southernmost Sweden (see section 2.2.2). This period in geological time, i.e. after the Permo-Carboniferous, was dominated by the long phase of rifting that occurred prior to the opening of the North Atlantic Ocean during the early part of the Cenozoic era. Furthermore, the extensional collapse that followed crustal thickening during the earlier Sveconorwegian and Caledonian orogenic events also took place in the areas with thinner crust at the current time, i.e. in south-western Sweden and along the west coast of Norway, respectively.

These considerations indicate that the "abnormally" thick crust in the internal parts of the Fennoscandian Shield is a geological heritage from ancient Precambrian time. Low surface relief and isostatic balance characterised the shield, both prior to the adjustments to glacial loading during the Quaternary (see Chapter 3) and prior to the development of the sub-Cambrian unconformity. A thick crust in generally stable isostatic balance over a long period of time can be explained by the inferred significant volume of high-density, Proterozoic igneous material, i.e. mafic and intermediate rocks, at deeper levels in the crust. By contrast, the "normally" thick crust observed along the margin to the shield is caused by geologically much younger processes /Kinck et al. 1993/. These involved crustal thinning in connection with extensional tectonics during at least the later part of the Palaeozoic, the Mesozoic and the Cenozoic, as well as with extensional collapse during the latest parts of the Sveconorwegian and Caledonian orogenic events. The relationship between the occurrence of seismic activity in Finland, Norway and Sweden and the variation in crustal thickness in this part of Europe is addressed in section 4.4.

Although the Forsmark and Laxemar-Simpevarp areas are underlain by approximately the same thickness of continental crust (46 to 48 km), they occur in crustal volumes where the variation in crustal thickness is markedly different. There is little variation in this parameter in the area around Forsmark. By contrast, there is a sharp gradient in crustal thickness directly south of Laxemar-Simpevarp, where the thickness decreases from approximately 48 to 36 km over a horizontal distance that is approximately the length of the island of Öland, i.e. 140 km (Figure 2-13). This thinning appears to be part of the broader regional thinning that prevails in the region close to the Sorgenfrei-Tornquist Zone in southernmost Sweden (see bullet 2 above).

2.2.5 Summary

The Forsmark and Laxemar-Simpevarp areas are situated in the south-western part of one of the Earth's ancient continental nuclei, referred to as the Fennoscandian Shield. This part of the shield belongs predominantly to the geological unit referred to as the Svecokarelian (or Svecofennian) orogen. The bedrock inside an orogen was affected by major tectonic activity at a particular time interval during the Earth's long geological evolution and the actual geological process is referred to as orogeny. Tectonic activity refers to deformation and metamorphism of the crust in combination with active volcanism and the intrusion of igneous rocks at depth, i.e. major igneous activity. In essence, the branch of geology referred to as "tectonics" addresses the broad architecture of the outer part of the Earth. In order to provide the necessary boundary conditions for an understanding of the bedrock geological evolution of the Forsmark and Laxemar-Simpevarp areas, these two areas are viewed in a broader geological perspective. For this purpose, attention is focused on an area in the Fennoscandian Shield in south-eastern Sweden, which is referred to in this report as the geological reference area.

The bedrock geology at the current level of erosion in the geological reference area can be divided into six major tectonic domains (TD1 to TD6). These domains strike WNW-ESE more or less parallel to an older, Archaean continental nucleus to the north-east. The predominantly igneous bedrock in all these domains had largely formed between 1.91 and 1.75 billion years ago (1.91–1.75 Ga). This bedrock was also affected by a variable degree of deformation in the hot, ductile regime and the various domains had amalgamated together, more or less into their current geometric configuration, during the same time interval. The geodynamic regime involved an accretionary orogenic setting, with approximately northward-directed, oblique subduction of oceanic lithosphere beneath an active continental margin to the north-east. Accretionary tectonics refers to the progressive addition of continental crust along an active boundary between continental and oceanic plates, without major continent-continent collision. Examples of accretionary orogens at the present day occur in the Andes, in the western part of South America, and in the northerly continuation of this Cordilleran mountain belt in the western part of North America.

A conceptual tectonic model for the period 1.91 to 1.75 Ga is presented. This model involves migration of the subduction hinge away from and towards the overriding continental plate to the north-east. This migration gave rise to alternating extensional and compressional deformation, respectively. The latter was transpressive in character. Transpressive deformation involves a combination of strike-slip shear deformation along high-strain zones or broader, high-strain belts in combination with shortening across them. An important component of this transpressive deformation was dextral strike-slip displacement along such zones or belts with WNW-ESE or NW-SE strike. This was accompanied by shortening in a NE-SW direction across them, as well as predominantly constrictional strain with folding and stretching, with variable plunge to the south-east, between them. Crustal behaviour in the form of a "moving concertina" explains the progressively younger igneous activity and ductile deformation in the different tectonic domains, with three separate tectonic cycles, each of which lasted for c 50 million years. The remarkably thick continental crust throughout most of the shield (up to c 60 km) is a heritage from this early, active tectonic history.

Although the bedrock in south-eastern Sweden had already started to stabilise after 1.75 Ga, tectonic activity that involved continued crustal growth and crustal reworking continued during the remainder of the Proterozoic to the west and south (Gothian, Hallandian and Sveconorwegian orogenies). By c 900 Ma, the bedrock in the northern part of Europe had collided with other continental segments to form the supercontinent Rodinia. Break-up of Rodinia, drift of the newly-formed continent Baltica from cold latitudes in the southern hemisphere over the equator to northerly latitudes, and amalgamation of the new supercontinent Pangaea prevailed between c 600 and 300 Ma. Rifting of the continental crust, and opening and spreading of the North Atlantic Ocean dominated the subsequent geological evolution to the south and west of the geological reference area. This long period of extensional tectonic activity was interrupted during the Late Cretaceous and early Palaeogene by a more compressive tectonic regime, which can be related to the collision of Eurasia and Africa.

An overview of the effects of these different, far-field tectonic events in the near-field realm represented in south-eastern Sweden is described. These effects gave rise to local igneous activity during the Proterozoic, burial and denudation of sedimentary cover rocks during the Proterozoic and Phanerozoic, and predominantly brittle deformation in the bedrock at different times throughout this long time interval. At least two episodes of exhumation of the ancient crystalline bedrock can be inferred, one prior to the Cambrian and the other after the Cretaceous, probably during the Neogene. The relatively thin continental crust (30 km and less) around the margins to the Fennoscandian Shield, for example along the southern coast of Sweden where the Sorgenfrei-Tornquist Zone is situated, is caused by extensional tectonics during the later part of the geological evolution, not least after c 300 Ma.

In conclusion, it appears that two fundamental types of geological process have made a profound impact on the geological evolution of south-eastern Sweden (Figure 2-14):

- Igneous activity and crustal deformation along an active continental margin at different time intervals mostly during Proterozoic time.
- Loading and unloading cycles in connection with the burial and denudation, respectively, of sedimentary rocks, around and after 1.5 Ga.

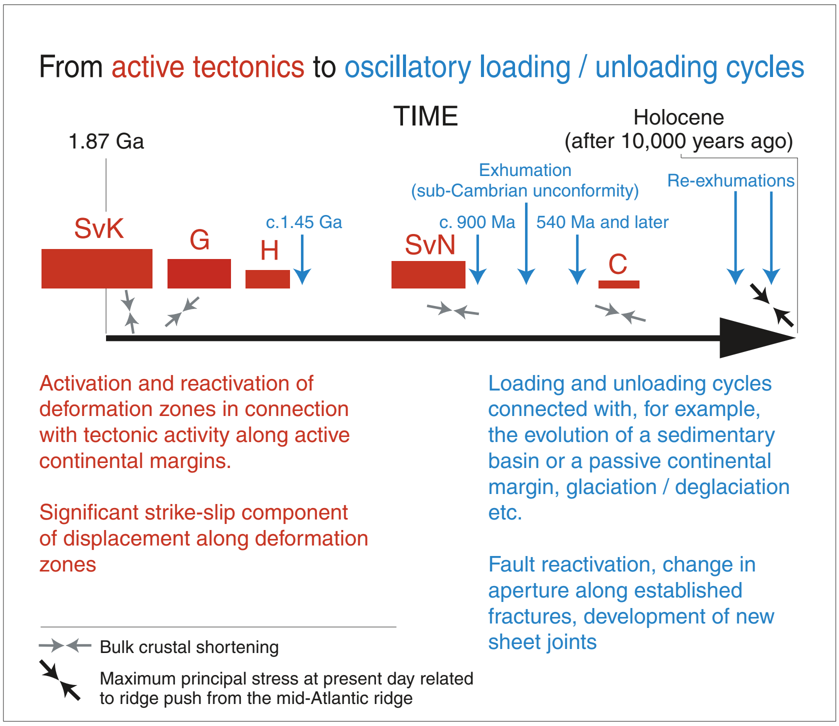


Figure 2-14. *Active tectonics (red) and oscillatory loading and unloading cycles (blue) during geological time in the geological reference area (modified after /Stephens et al. 2007/). The detailed evolution during the Quaternary period with several glaciations (loading) and deglaciations (unloading) is not shown (see Chapter 3). SvK = Svecokarelian orogeny, G = Gothian orogeny, H = Hallandian orogeny, SvN = Sveconorwegian orogeny, C = Caledonian orogeny.*

As the effects of regional tectonic activity mostly waned in south-eastern Sweden and became prominent solely in the far-field realm, the effects of loading and unloading related to the burial and denudation of sedimentary rocks, respectively, increased in significance (Figure 2-14). A major difference between the Forsmark and Laxemar-Simpevarp areas concerns the variation in the thickness of the crust in the parts of south-eastern Sweden where these two sites are located. Around Forsmark, the crust is c 46–48 km thick and shows little variation in thickness. By contrast, although the crustal thickness at Laxemar-Simpevarp is similar, there is a sharp gradient in crustal thickness directly south of this area from approximately 48 to 36 km. This thinning appears to be part of the broader regional thinning that prevails in the region close to the Sorgenfrei-Tornquist Zone.

2.3 Geological evolution of the Forsmark area

2.3.1 Relative and absolute age determinations – overview of primary data

The geological mapping of the bedrock on the ground surface at Forsmark /Stephens et al. 2003a, Bergman et al. 2004/, which was carried out during the initial site investigation stage, provided a wealth of descriptive data that established the relative time relationships between different groups of rock types, and between the different rock types and the ductile deformation in the area. A summary of these relationships was presented in /Stephens et al. 2003b, SKB 2005a/. These data provided the basis for the subsequent geological mapping of rock types in the boreholes. The detailed mapping of fractures and rock types at larger excavated outcrops has also contributed to an understanding of the relative age relationships between these geological entities /Hermanson et al. 2003ab, 2004a, Cronquist et al. 2005, Forssberg et al. 2007a, Petersson et al. 2007/.

In close collaboration with the team who completed the geological mapping of the cored boreholes, the relative time relationships between the growth of different fracture minerals was also established /Sandström et al. 2004, Sandström and Tullborg 2005, 2006, Sandström et al. 2007/. An overview report that integrates all the work on the fracture mineralogy in the area is presented in /Sandström et al. 2008/, and aspects of the fracture mineralogy work as well as a short summary have also been published in scientific, peer-reviewed journals /Sandström et al. 2006a, Sandström and Tullborg 2007/.

In order to provide some tighter, absolute age constraints on the bedrock geological evolution in the Forsmark area, an extensive geochronological programme has been carried out. This programme had two principal objectives and, for this reason, was addressed in two separate studies:

- To provide age data bearing on the timing of crystallisation of the igneous rocks, the timing of ductile deformation, and the exhumation and cooling history.
- To provide age data bearing on the timing of formation of fracture minerals.

The first of the geochronological studies involved the analysis of different minerals in different isotopic systems with different blocking temperatures, with the aim to reconstruct the temperature-time history from rock crystallization to the time the rocks were exhumed through the c 70°C geotherm. In order of decreasing blocking temperature, these systems are U-Pb zircon, U-Pb titanite, $^{40}Ar/^{39}Ar$ hornblende, $^{40}Ar/^{39}Ar$ muscovite, $^{40}Ar/^{39}Ar$ biotite, $^{40}Ar/^{39}Ar$ K-feldspar and (U-Th)/He apatite. U-Pb zircon measurements were carried out using the secondary ion mass spectrometry (SIMS) and thermal ionisation mass spectrometry (TIMS) techniques, whereas U-Pb titanite measurements were completed with the use of the TIMS technique.

Minerals have been separated for analysis from whole-rock samples, both from the surface and from drill cores (Figure 2-15). The analysed samples come from different groups of meta-intrusive rocks in the area, from contrasting ductile structural domains (tectonic lenses and belts affected by high ductile strain around these lenses), and from different bedrock blocks between regionally important deformation zones (Forsmark, Eckarfjärden and Singö). The data are presented in /Page et al. 2004, 2007a/. Furthermore, all these data are discussed in more detail in articles published in scientific, peer-reviewed journals /Hermansson et al. 2007, 2008/, in articles that are now in press in scientific journals /Hermansson et al. in press, Söderlund et al. in press a/ or as an article in a published Ph.D thesis volume /Söderlund et al. 2008/.

Minor modifications to some of the U-Pb ages reported in /Page et al. 2004/ were provided in /Hermansson et al. 2007, 2008/ and these modifications have been accounted for in the discussion below. Furthermore, increasing evidence for a systematic bias between $^{40}Ar/^{39}Ar$ and U-Pb ages suggests that all the $^{40}Ar/^{39}Ar$ ages discussed below need to be revised to approximately 1% older values (see, for example, discussion in /Hermansson et al. in press/). This revision has little effect on the conclusions drawn here and the values presented below have not been corrected for this bias. Uncertainties in age determinations have also been included when, for example, ranges in ages are discussed.

Some new apatite fission track (AFT) data from samples in a drill core (KFM03A) were also presented in /Söderlund et al. 2008/. However, there are significant differences between the ages calculated from these data and the ages obtained from earlier AFT data in the vicinity of Forsmark /Larson et al. 1999, Cederbom et al. 2000/. These serious discrepancies inhibit further geological evaluation of AFT ages at Forsmark.

The second of the geochronological studies primarily made use of the $^{40}Ar/^{39}Ar$ isotope system in K-feldspar with the aim to determine the age of formation of fracture minerals /Sandström et al. 2006b, 2007/. Five adularia samples along fractures and three K-feldspar samples from rock fragments inside fault breccias have been dated with the $^{40}Ar/^{39}Ar$ method. A fracture filling, which includes an assemblage of adularia, prehnite, calcite and altered wall rock, has also been dated by the Rb-Sr method. All samples have been taken from boreholes (KFM04A, KFM05A, KFM07A, KFM08A and KFM09A). The locations of these boreholes are also shown in Figure 2-15.

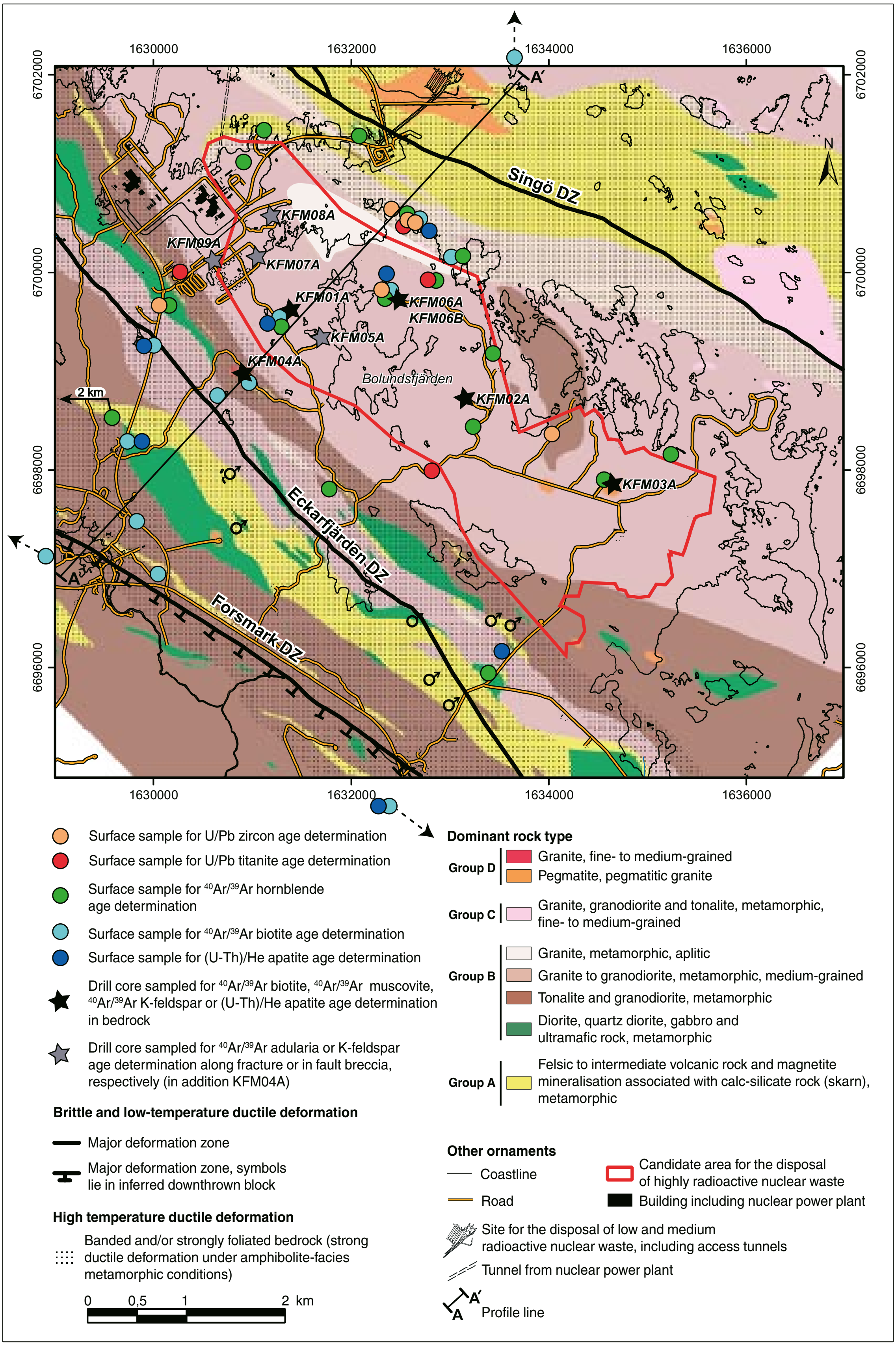


Figure 2-15. *Bedrock geological map of the Forsmark area. The locations of boreholes and surface sites from which samples have been taken for age dating purposes, using different isotope systems, are also shown on the map. Bedrock geological map (model stage 2.2) after /Stephens et al. 2007/.*

2.3.2 Crystallisation of igneous rocks and the regional perspective

Four major groups of rocks (A to D), which are distinguished solely on the basis of their relative age relationships, were identified during the bedrock mapping of the ground surface at Forsmark (Table 2-1 and /Stephens et al. 2003b, SKB 2005a/). Different rock types within each group, with their respective SKB codes, are shown in Table 2-1. The supracrustal rocks and the older suite of plutonic, calc-alkaline igneous rocks in Groups A and B, respectively, were affected by penetrative ductile deformation and amphibolite-facies metamorphism, prior to intrusion of a younger suite of calc-alkaline igneous rocks in Groups C and D, which are largely hypabyssal in character. The rocks in this younger suite intruded during the waning stages of and after this deformational and metamorphic event (Table 2-1 and /Hermansson et al. 2008/).

A summary of the age-dating results that bear on the timing of crystallisation of the metamorphosed igneous bedrock at Forsmark is shown in Table 2-2. These data provide firm age constraints on the various geological events summarised above. Bearing in mind the analytical uncertainties, two samples from the older suite of calc-alkaline, meta-intrusive rocks with tonalitic to granodioritic and gabbroic compositions (Group B) have yielded crystallisation ages in the time range 1.89 to 1.88 Ga. The felsic to intermediate metavolcanic rocks (Group A) are 1.89 Ga or older and the metagranite (Group B) in the target volume (Figure 2-16a) has yielded a younger age of 1.87 Ga. The metavolcanic rocks with their associated magnetite mineralisation and skarn are correlated with the Svecofennian metavolcanic rocks in the Bergslagen region of central Sweden, which have been dated elsewhere in Bergslagen to 1.91–1.89 Ga (see section 2.2.1).

Table 2-1. Major groups of rocks in the Forsmark area, which are distinguished solely on the basis of their relative time relationships in the field. SKB rock codes that distinguish different rock types in each group are shown in brackets. The alteration code 104 for albitization is also included.

Groups of rocks at Forsmark	
All rocks are affected by brittle deformation. The fractures generally cut the boundaries between the different rock types. The boundaries are predominantly not fractured.	
Rocks in Group D are affected only partly by ductile deformation and metamorphism.	
Group D	• Fine- to medium-grained granite and aplite (111058). Pegmatitic granite and pegmatite (101061). Variable age relationships with respect to Group C rocks. Occur as dykes and minor bodies that are commonly discordant and, locally, strongly discordant to ductile deformation in older rocks.
Rocks in Group C are affected by penetrative ductile deformation under lower amphibolite-facies metamorphic conditions.	
Group C	• Fine- to medium-grained granodiorite, tonalite and subordinate granite (101051). Occur as lenses and dykes in Groups A and B. Intruded after some ductile deformation in the rocks belonging to Groups A and B with weakly discordant contacts to ductile deformation in these older rocks.
Rocks in Groups A and B are affected by penetrative ductile deformation under amphibolite-facies metamorphic conditions.	
Group B	• Biotite-bearing granite (to granodiorite) (101057) and aplitic granite (101058), both with amphibolite (102017) as dykes and irregular inclusions. Local albitization (104) of granitic rocks. • Tonalite to granodiorite (101054) with amphibolite (102017) enclaves. Granodiorite (101056). • Ultramafic rock (101004). Gabbro, diorite and quartz diorite (101033).
Group A	• Sulphide mineralisation, possibly epigenetic (109010).
(supracrustal rocks)	• Volcanic rock (103076), calc-silicate rock (108019) and iron oxide mineralisation (109014). Subordinate sedimentary rocks (106001).

Amphibolite dykes and irregular minor intrusions in the metagranite (Group B) inside the target volume (Figure 2-16b) formed between 1.87 and 1.86 Ga (Table 2-2). These minor intrusions are now regarded as the early phase of magmatism in the younger suite of calc-alkaline igneous rocks and granites included in Groups C and D /Hermansson et al. 2008/. A minor intrusion with granodioritic composition (Group C) has yielded an age of 1.86 Ga. Bearing in mind the uncertainties in the age determinations (Table 2-2), this age overlaps with the age of crystallisation of the Group B metagranite in the target volume. However, the field relationships indicate that the Group C rocks are younger, and that they intruded after penetrative ductile deformation and metamorphism had affected the rocks in Groups A and B (Figure 2-16c; see also section 2.3.4). Granite dykes (Group D), which are discordant to the intense tectonic banding in the rocks in the coastal area at Forsmark (Figure 2-16d), have yielded crystallisation ages between 1.86 and 1.85 Ga.

The crystalline rocks at Forsmark, in TD2, formed in connection with the two earlier episodes of igneous activity that occurred at 1.91–1.87 Ga and 1.87–1.84 Ga (see section 2.2.1 and Figure 2-3a). The Forsmark area contains igneous rocks that are prominent in both the adjacent domains TD1 and TD3, and, for this reason, is judged to be transitional in character between them. Bearing in mind earlier comments on the tectonic evolution in the geological reference area (section 2.2.1), it is concluded that between 1.89 (1.91) and 1.85 Ga, this part of the shield was situated along an active continental margin and was affected by the igneous activity in the two earlier tectonic cycles.

Table 2-2. Age of crystallisation of the igneous rocks in the Forsmark area based on /Page et al. 2004, Hermansson et al. 2007, 2008/. TIMS = Thermal Ionisation Mass Spectrometry technique. SIMS = Secondary Ion Mass Spectrometry technique. All samples are from the surface and locations of samples are shown on Figure 2-15.

Geological feature	Dated rock type	Method	Age
Younger dykes and intrusions with granitic composition (Group D intrusive rocks)	Granite	U-Pb zircon (SIMS)	1851±5 Ma 1855±6 Ma Age supported by the U-Pb titanite age of 1844±4 Ma from the same rock type (see section 2.3.4).
Younger dyke-like bodies and minor intrusions with granodioritic to tonalitic composition (Group C intrusive rocks)	Metagranodiorite	U-Pb zircon (SIMS)	1864±4 Ma
Younger dyke-like bodies and irregular minor intrusions with mafic composition (amphibolite) in Group B metagranite	–	–	Age of intrusion inferred to be 1.87–1.86 Ga, based on U-Pb (zircon) age of Group B metagranite and a regression age for the three older U-Pb (titanite) ages in amphibolite (see section 2.3.3).
Older plutons with granitic composition (Group B intrusive rocks)	Metagranite inside the target area	U-Pb zircon (SIMS)	1867±4 Ma
Older plutons with ultramafic to intermediate, tonalitic and granodioritic compositions (Group B intrusive rocks)	Metatonalite to metagranodiorite Metagabbro	U-Pb zircon (SIMS) U-Pb zircon (TIMS)	1883±3 Ma 1886±1 Ma
Supracrustal rocks (Group A)	–	–	Age inferred to be older than 1885 Ma.

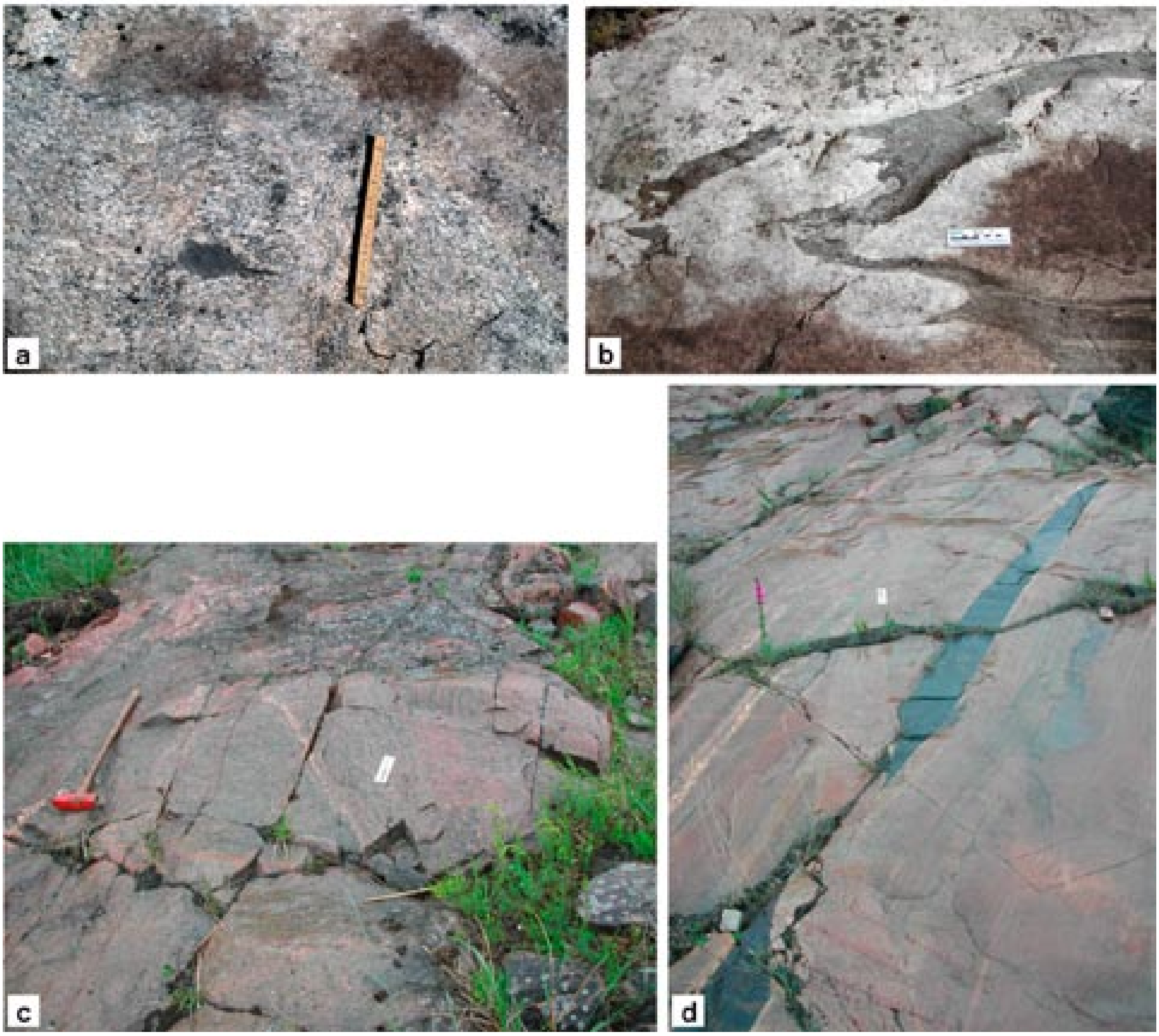


Figure 2-16. Character of rock types in the Forsmark area. a) Group B metagranite with folded tectonic foliation close to drill site 6. The same metagranite has been dated to 1.87 Ga. The tectonic foliation is discordant to a Group D granite dyke in the top right part of the picture. b) Folded amphibolite dyke and tectonic foliation in Group B metagranite south-west of drill site 5. c) Semi-concordant boudin of Group C metagranodiorite with a linear grain-shape fabric (left part of photograph), within strongly foliated Group B metagranite (right part of photograph). Group D pegmatites intrude discordantly both the Group B and Group C rocks. The metagranodiorite at this locality has yielded an age of 1.86 Ga. d) Discordant Group D granite dyke (with scale) that transects the tectonic banding in the Group B host rocks including amphibolite (dark band) at an angle of c 45°. The granite dyke at this locality has yielded an age of 1.85 Ga.

2.3.3 Exhumation and cooling history

The time during the geological evolution when the bedrock at Forsmark ultimately cooled beneath the blocking temperature in isotope systems other than the high-temperature, U-Pb zircon system are shown in Table 2-3. Since the ages have important consequences for the tectonic evolution in the area, the broader implications of the U-Pb titanite and $^{40}Ar/^{39}Ar$ hornblende data for the timing of ductile deformation are addressed in section 2.3.4, and the broader implications of the $^{40}Ar/^{39}Ar$ muscovite, $^{40}Ar/^{39}Ar$ biotite, $^{40}Ar/^{39}Ar$ K-feldspar and (U-Th)/He apatite ages for tectonic developments in the colder, brittle-ductile and brittle regimes are discussed in section 2.3.5.

U-Pb titanite ages

The U-Pb titanite ages (blocking temperature 700–500°C) vary somewhat between 1.86 and 1.83 Ga (Table 2-3). In one of the amphibolite samples (PFM002242A), it was possible to identify two distinct populations of titanite, based on their appearance and age /Hermansson et al. 2008/. Older, olive-brown titanites yielded an age of 1.86 Ga, which was interpreted as the age of regional amphibolite facies metamorphism or the age of cooling after this major metamorphic event. Younger, pale brown or brown titanites showed a spread in ages between 1.84 and 1.83 Ga, and have been interpreted to indicate a mixing of the older 1.86 Ga age group with a second generation of titanite that formed around or after 1.83 Ga.

Table 2-3. Cooling ages in the Forsmark area based on /Page et al. 2004, 2007a, Hermansson et al. 2007, 2008, in press, Söderlund et al. 2008, in press a/. The locations of boreholes that have been sampled and surface samples are shown on Figure 2-15.

Geological feature	Dated rock type	Method	Age
Cooling below c 70°C	Group B metagranite to metagranodiorite. Surface samples and samples from KFM01A, KFM02A and KFM03A	(U-Th)/He apatite	Surface samples: F_T-corrected ages are predominantly c 750 to 500 Ma. Uncorrected ages are predominantly c 500 to 300 Ma.
			Drill core samples: F_T-corrected ages are predominantly c 700 to 200 Ma. Uncorrected ages are predominantly c 550 to 100 Ma. Decreasing age with depth in KFM01A and KFM03A. Poorly reproducible ages in especially KFM02A.
Minimum age for cooling below c 225–200°C	Group B metagranite in KFM06B (near top) and KFM06A (near base)	$^{40}Ar/^{39}Ar$ K-feldspar	1.55–1.49 Ga
Cooling below c 300°C	Various Group B and Group C felsic meta-intrusive rocks, amphibolite. Surface and drill core samples	$^{40}Ar/^{39}Ar$ biotite	Surface samples: Range from 1.73–1.66 Ga.
			Drill core samples: Ages in the upper parts of boreholes range from 1.71–1.68 Ga. Ages in the lower parts of boreholes at c 1,000 m depth range from 1.68–1.63 Ga.
Cooling below c 350°C	Muscovite-bearing rock affected by strong ductile deformation in KFM04A	$^{40}Ar/^{39}Ar$ muscovite	1.76–1.71 Ga
Cooling below c 500°C	Amphibolite and metagabbro (surface samples)	$^{40}Ar/^{39}Ar$ hornblende	Ages between 1.86 and 1.80 Ga occur in the rock affected by a lower degree of ductile deformation inside the tectonic lenses. Only ages between 1.81 and 1.79 Ga occur in the rock affected by a higher degree of ductile deformation.
Cooling below 700–500°C	Group D granite (surface sample)	U-Pb titanite (TIMS)	909±200 Ma (lower intercept age)
			1844±4 Ma (upper intercept age)
	Amphibolite (surface samples)	U-Pb titanite (TIMS)	1840±2 Ma to 1832±3 Ma ($^{207}Pb/^{206}Pb$ ages, pale brown or brown titanites)
			1854±3 Ma (upper intercept age)
			1858±2 Ma (upper intercept age)
			1858±3 Ma ($^{207}Pb/^{206}Pb$ age, olive-brown titanite)
			1860±2 Ma ($^{207}Pb/^{206}Pb$ age, olive-brown titanite)

Titanite in one sample (PFM001183B) yielded an age of 1854±3 Ma. It has been suggested that this age possibly reflects growth of a third generation of titanite, in response to heat and/or fluid movement during the intrusion of the Group D granites /Hermansson et al. 2008/. However, bearing in mind the uncertainty in the age, it is not unequivocally distinguishable from the ages obtained from the olive-brown titanites. The Group D granites cooled beneath the U-Pb titanite blocking temperature between 1.85 and 1.84 Ga, i.e. soon after their crystallisation (Table 2-2). A titanite lower intercept age of 909±200 Ma from such a granite indicates disturbance of this isotope system during the time interval when intense tectonic activity prevailed in south-western Sweden during the Sveconorwegian orogeny (/Hermansson et al. 2007/ and see section 2.2.2).

$^{40}Ar/^{39}Ar$ hornblende ages and the onset of greenschist facies metamorphic conditions

$^{40}Ar/^{39}Ar$ hornblende ages (blocking temperature c 500°C) vary considerably between 1.86 Ga and 1.79 Ga (Table 2-3). A wide range of ages from 1.86 to 1.80 Ga (nine samples) occurs inside two tectonic lenses at Forsmark (SD 1 in Figure 2-17). By contrast, only younger ages in the range 1.81 to 1.79 Ga (seven samples) are present along the high-strain belts, which are either situated around the tectonic lenses or occur as a folded structural unit within one of them (SD 2 in Figure 2-17).

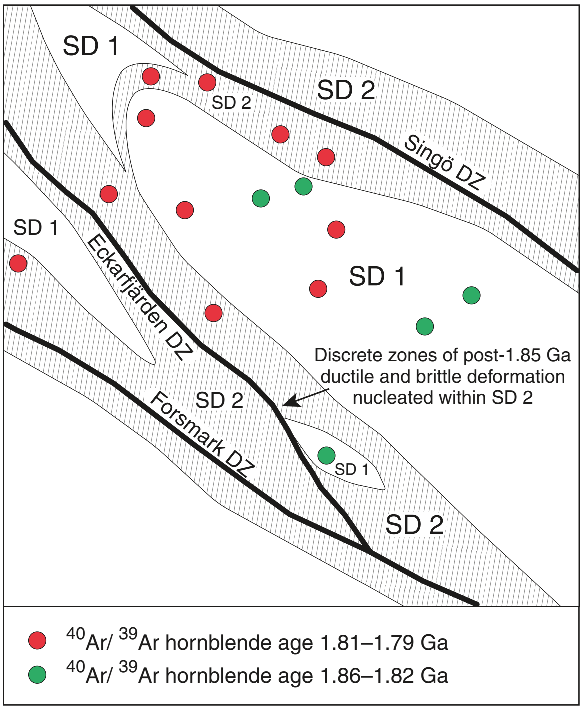


Figure 2-17. *Location of amphibolite and metagabbro samples for $^{40}Ar/^{39}Ar$ hornblende age determinations /Hermansson et al. in press/, in relation to the different ductile structural domains in the Forsmark area /SKB 2005a, Stephens et al. 2007/. Structural domain 1 (SD 1) in the map sketch (not to scale) refers to areas with an inferred lower degree of ductile deformation with LS-tectonites and folding of a tectonic foliation. By contrast, structural domain 2 (SD 2) refers to areas with an inferred higher degree of ductile deformation characterised by both planar and linear grain-shape fabrics and commonly a tectonic banding. The SD 2 high-strain belts formed and were folded, prior to 1.85 Ga /Hermansson et al. 2007/. Post-1.85 Ga ductile deformation was concentrated in discrete zones that nucleated in the pre-existing SD 2 high-strain belts. These zones have been active several times both under ductile and later under brittle conditions (modified after /Hermansson et al. in press/).*

The geological significance of the $^{40}Ar/^{39}Ar$ hornblende ages is addressed in /Hermansson et al. in press/. The oldest age (1854±7 Ma) has been attributed to cooling of hornblende with a higher closing temperature compared with the majority of samples in the Forsmark area. The remaining ages may reflect separate events, with regional cooling beneath c 500°C at 1.83 to 1.82 Ga and subsequent local resetting of the argon isotopic system. The resetting occurred in response to retrogressive, lower amphibolite to upper greenschist facies deformation along discrete high-strain zones within the broader high-strain belts at 1.81 to 1.79 Ga. Alternatively, a period of slow cooling of hornblendes with slightly different closure temperatures, from 1.83 to 1.80 Ga, may have caused the age variation observed within the tectonic lenses, whereas locally maintained higher temperatures, due to activity along the discrete high-strain zones, can explain the consistently young ages in the enveloping high-strain belts. An increase in cooling rate, in response to regional uplift, finally closed the argon isotopic system in hornblende at 1.81 to 1.79 Ga. If the ages are revised to 1% older values, as discussed earlier (see section 2.3.1 and /Hermansson et al. in press/), then all ages will be 0.02 Ga older. Resetting or final closure of the argon isotopic system in hornblende in the alternative interpretations would have occurred earlier at 1.83 to 1.81 Ga, i.e. at the end of the second tectonic cycle in the region (see Figure 2-5 and section 2.2.1).

$^{40}Ar/^{39}Ar$ muscovite, biotite and K-feldspar ages, and the onset of sub-greenschist facies metamorphic conditions

$^{40}Ar/^{39}Ar$ muscovite ages (blocking temperature c 350°C), which have been obtained from two samples close to a depth of c 350 m in borehole KFM04A (Figure 2-15 and Figure 2-18), lie in the range 1.76 to 1.71 Ga (Table 2-3). $^{40}Ar/^{39}Ar$ biotite ages (blocking temperature c 300°C) from surface samples range between 1.73 to 1.66 Ga (Table 2-3). The majority of these samples were taken along a SW-NE profile in the north-western part of the Forsmark area across the steeply dipping WNW or NW regional deformation zones, Forsmark, Eckarfjärden and Singö (Figure 2-15). These ages indicate that the bedrock at the surface in the Forsmark area had started to cool beneath c 300°C at 1.73 Ga and had entered the realm of sub-greenschist facies metamorphic conditions prior to 1.73 Ga. They are consistent with the range in $^{40}Ar/^{39}Ar$ biotite ages in the upper parts of boreholes from 1.71 to 1.68 Ga (Table 2-3). As expected, the ages in the lower parts of boreholes are younger and fall in the range from 1.68 to 1.63 Ga at c 1,000 m depth (Table 2-3). The locations of the boreholes are shown in Figure 2-15 and the sample locations in each borehole are shown in Figure 2-18.

By making use of the different $^{40}Ar/^{39}Ar$ biotite ages at different depths, an uplift rate of 22 m/Ma can be estimated at Forsmark between 1.70 and 1.64 Ga /Söderlund et al. in press a/. Furthermore, by combining the $^{40}Ar/^{39}Ar$ hornblende, muscovite and biotite data, with their different blocking temperatures, a slow cooling rate of c 0.6 to 4°C/Ma can be estimated for the time interval 1.80 to 1.67 Ga /Söderlund et al. in press a/. These authors have speculated that cooling may have been associated with relaxation of the geothermal gradient or with isostatic uplift and exhumation after the Svecokarelian orogeny. However, it has also been suggested /Söderlund et al. in press a/ that uplift and cooling may have occurred in response to the far-field effects of c 1.70 Ga orogenic activity further to the west (see section 2.2.2). The more specific implications of the $^{40}Ar/^{39}Ar$ biotite ages for the character and timing of faulting in the area are addressed below (section 2.3.5).

$^{40}Ar/^{39}Ar$ K-feldspar ages from two samples close to the surface near the top of KFM06B and at c 825 m depth close to the base of KFM06A (Figure 2-15 and Figure 2-18) yield step-heating spectra typical of slowly cooled K-feldspar. The ages attain maximum values at 1.49 Ga and 1.55 to 1.50 Ga, respectively (Table 2-3). These ages have been interpreted as the minimum age for cooling through approximately 225 to 200°C /Page et al. 2007a/.

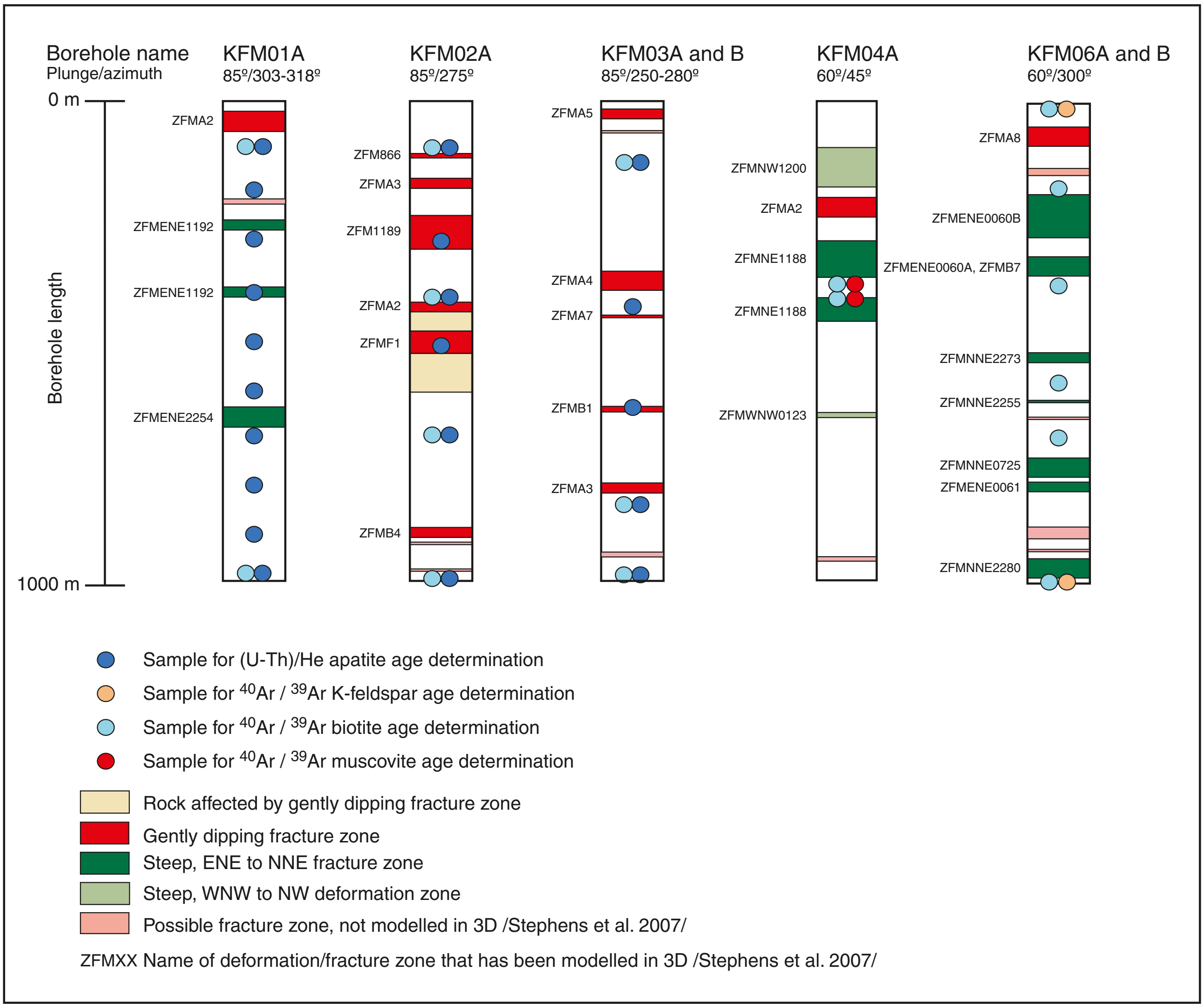


Figure 2-18. *Location of samples for $^{40}Ar/^{39}Ar$ muscovite, biotite and K-feldspar and (U-Th)/He age determinations in boreholes KFM01A, KFM02A, KFM03A, KFM03B, KFM04A, KFM06A and KFM06B, in relation to deformation zones (deterministically modelled and possible) in the Forsmark area, stage 2.2 /Stephens et al. 2007/. Figure modified after /Söderlund et al. in press a/.*

(U-Th)/He apatite ages

Apatite from different structural blocks at the surface and at different depths along the boreholes KFM01A, KFM02A and KFM03A (Figure 2-15 and Figure 2-18) have been analysed for (U-Th)/He age determination. In order to test for data reproducibility, several analyses were carried out on each sample, both at each surface site and at each depth in a borehole. Following correction for loss of He due to ejection of α-particles (F_T-correction), such analyses are perceived to provide an estimate of when the bedrock cooled below c 70°C /Farley 2000/. Application of the F_T-correction factor assumes, amongst other factors, an homogeneous distribution of U in the apatite grains and an homogeneous grain morphology /Fitzgerald et al. 2006/. The uncertainties in all the data cited are reported with ±1σ.

After the exclusion of some highly anomalous old ages that are probably caused by inclusions in the apatite grains /Page et al. 2007a/, the majority of the F_T-corrected (U-Th)/He ages from the surface at Forsmark lie in the range 751±71 to 513±81 Ma, i.e. they are Neoproterozoic to Cambrian in age (Figure 2-2). Younger ages in one sample (PFM002213A) are Devonian to Carboniferous (361±30 to 342±45 Ma). The corresponding range in the uncorrected ages is 484±33 to 316±22 Ma, i.e. Ordovician to Carboniferous, with uncorrected ages in one sample as young as Triassic (246±17 to 213±15 Ma).

The (U-Th)/He ages in borehole KFM01A generally decrease with depth (Figure 2-19). However, at each depth along the borehole, the ages are variable and the older or oldest ages obtained are highly variable (Figure 2-19). There is also some tendency for an increase in slope in the age-depth diagrams below c 600 m (Figure 2-19). This corresponds to an age of c 250 Ma (Permian), if the F_T-corrected ages are used, or between 200 and 150 Ma (Jurassic), if the uncorrected ages are adopted (/Page et al. 2004/ and Figure 2-19). This possible break in slope occurs close to the intersection of a steeply dipping fracture zone (ENE2254).

The youngest, F_T-corrected (U-Th)/He ages at each depth lie in the range 421±29 Ma (100 m depth) to 185±13 Ma (500 m depth) in the upper part of the borehole, above the change in slope, and in the range 239±17 (600 m depth) to 186±13 Ma (1,000 m depth) in the lower part of the borehole. These ages correspond to the Silurian to Early Jurassic and to the Triassic to Early Jurassic periods, respectively, in the geological time scale (Figure 2-2). The ranges in corresponding uncorrected ages are 241±17 to 89±6 Ma and 197±14 to 97±7 Ma in the upper and lower parts of KFM01A, respectively, i.e. they are entirely Mesozoic.

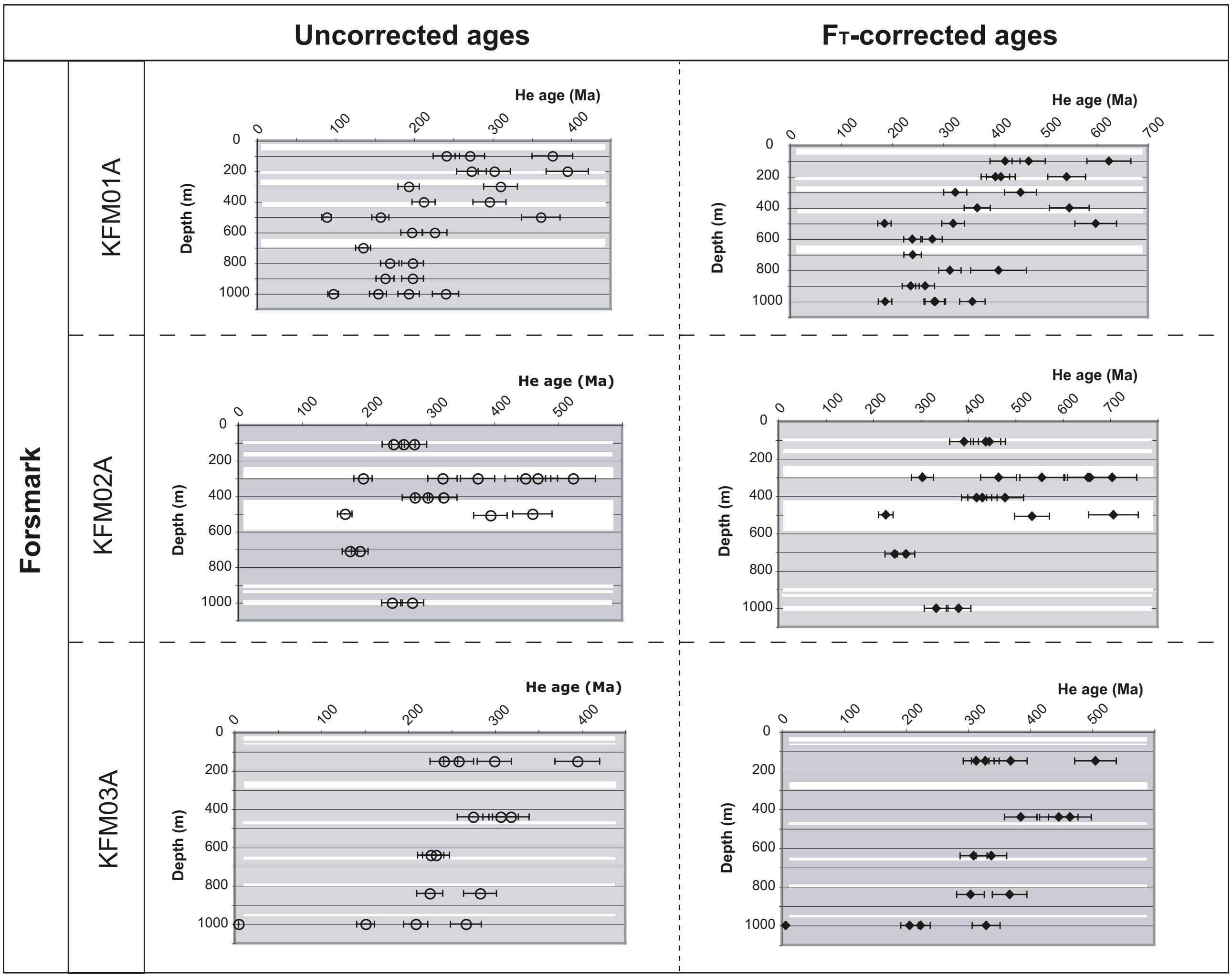


Figure 2-19. *Apatite (U-Th)/He age results from boreholes KFM01A, KFM02A and KFM03A at Forsmark. The left-hand column shows uncorrected ages whereas the right-hand column shows F_T-corrected ages. Uncertainties are reported with ±1σ. White bars indicate the locations of fracture zones that are intersected in the respective boreholes. In KFM01A, these zones are predominantly steeply dipping and, in KFM02A and KFM03A, they are gently dipping (modified slightly after /Söderlund et al. 2008/).*

The (U-Th)/He ages in boreholes KFM02A and KFM03A are more difficult to interpret since several samples have been taken within or close to gently dipping fracture zones and, especially in borehole KFM02A, the ages at a given depth are highly variable (Figure 2-19). Nevertheless, the youngest, F_T-corrected ages at each depth are Silurian to Triassic, and the corresponding uncorrected ages vary from Permian to Jurassic. These results are similar to those observed in borehole KFM01A.

The predominantly Neoproterozoic to Cambrian, F_T-corrected (U-Th)/He ages at the surface are not consistent with the inferred exhumation of Proterozoic crystalline rocks and the establishment of the sub-Cambrian unconformity in the Forsmark area (see section 2.2.3). Only the younger surface ages at PFM002213A are consistent with these geological constraints. Furthermore, the fission track work in borehole KFM03A indicates that U is distributed in a highly variable and complex manner inside the apatite grains and that the morphology of these grains is also highly variable /Söderlund et al. 2008/. Both these observations inhibit a confident interpretation of the (U-Th)/He ages at Forsmark /Söderlund et al. 2008/. In particular, it is possible that the F_T-correction factor for loss of He yields too old ages. Some tentative conclusions bearing on the sedimentary cover at Forsmark during Palaeozoic and Mesozoic time are addressed below in section 2.3.5. Alternative lines of approach, using either the youngest F_T-corrected or the uncorrected (U-Th)/He ages, are adopted in this evaluation of the geological significance of the (U-Th)/He data.

2.3.4 Ductile deformation and the regional perspective

Progressive ductile deformation at Forsmark involved planar and linear, grain-shape fabric development throughout the area, the development of high-strain belts in some parts with a dextral strike slip component of movement, and folding of the planar structures /Stephens et al. 2007/. The age of crystallisation of the igneous rocks, in combination with the critical field relationships between different suites of igneous rocks (see section 2.3.2 and Figure 2-16), constrain the timing of penetrative, ductile grain-shape fabric development under amphibolite facies metamorphic conditions to the time interval 1.87 to 1.86 Ga /Hermansson et al. 2007, 2008/. This phase in the deformational history had reached a waning stage at the time of intrusion of the Group C rocks and had more or less ceased prior to intrusion of the Group D granite dykes at 1.85 Ga /Hermansson et al. 2008/.

Ductile deformation after 1.85 Ga occurred predominantly inside the high-strain belts around the tectonic lenses. This strain progressed further with the development of steep WNW and NW ductile deformation zones along the high-strain belts, including, for example, the Forsmark, Eckarfjärden and Singö zones. Shear displacement, with a dextral strike-slip component of movement, and mylonites that formed under greenschist or lower amphibolite facies metamorphic conditions are present along these zones (see property tables in /Stephens et al. 2007/). The U-Pb titanite ages indicate that the area was indeed affected by one or more tectonothermal events during or after 1.83 Ga, following the penetrative deformation and metamorphism. Furthermore, the consistently younger $^{40}Ar/^{39}Ar$ hornblende ages along the high-strain belts support the concept that younger ductile strain was focused inside this structural domain.

The timing of penetrative ductile deformation at Forsmark is consistent with the main phase of ductile deformation that has been recognised in TD3 inside the geological reference area, as well as the pre-1.86 Ga deformational event that has been identified in TD4 (see section 2.2.1). Furthermore, the occurrence and character of younger deformation at Forsmark after 1.85 Ga are consistent with the later tectonic evolution in TD1, TD4, TD5 and TD6. Bearing in mind the regional perspective in the geological reference area, including the tectonic model for the time interval 1.91 to 1.86 Ga, it is inferred that the Forsmark area was affected during the early part of its geological evolution by transpressive deformation related to approximately northward-directed, oblique subduction of oceanic crust beneath an active continental margin to the north-east.

2.3.5 Brittle deformation and the regional perspective

Fracture minerals – relative time relationships and absolute ages

Establishment of the relative time relationship between different mineral parageneses primarily makes use of the cross-cutting relations between fractures and the growth of different fracture minerals as observed in samples from drill cores. Stable isotope analyses on calcite and pyrite as well as geochemical analyses have further contributed to the subdivision into different fracture mineral generations. These generations include relatively high temperature minerals such as epidote (greenschist facies), lower temperature minerals such as prehnite (pumpelleyite-prehnite facies) and laumontite (laumontite-prehnite or zeolite facies) and low temperature minerals such as clay minerals. Examples of the fracture minerals in the four different generations are shown in Figure 2-20. The different fracture mineral generations are summarized below in decreasing relative age of formation.

- Generation 1 (oldest) consists mainly of epidote, quartz and Fe-rich chlorite. Furthermore, the wall-rock to the fractures that contain this generation of minerals is altered and shows a red staining with fine-grained hematite dissemination. The deformation associated with this generation of minerals varies from brittle-ductile to brittle, in contrast with the deformation during the younger phases (see below) that is entirely brittle in character.
- Generation 2 is a sequence of hydrothermal minerals that probably formed over an extended time interval. The absolute time span is not known. The sequence consists of a first phase of hematite-stained adularia (low temperature K-feldspar) and albite, followed by prehnite and calcite, and a later phase of hematite-stained laumontite and calcite. Once again, the wall-rock to the fractures that contain this generation of minerals is altered and shows a red staining with fine-grained hematite dissemination.
- Generation 3 is dominated by euhedral quartz, calcite and pyrite, together with subordinate albite, euhedral adularia that lacks hematite staining, corrensite and analcime. Asphaltite is also present, predominantly in the upper parts of the boreholes (see section 3.6.5 in /Stephens et al. 2007/).
- Generation 4 (youngest) represents the latest fracture minerals and consists of clay minerals and calcite that precipitated as an outermost layer in open fractures. The youngest calcites are found in fractures and fracture zones that are hydraulically conductive at the present time /Sandström and Tullborg 2007/.

Five adularia samples from both the generation 2 and generation 3 mineral assemblages have been dated with the $^{40}Ar/^{39}Ar$ method and one fracture filling, which includes an assemblage of generation 2 adularia, prehnite, calcite and altered wall rock, has been dated by the Rb-Sr method (Table 2-4). All sampled fractures dip steeply, strike ENE-WSW or NNE-SSW, and are situated along fracture zones or within bedrock that is affected by such zones. These zones dip steeply and have been referred to as ENE or NE in the geological modelling work (Table 2-4 and /Stephens et al. 2007/). The $^{40}Ar/^{39}Ar$ method has also been used to date K-feldspar in rock fragments that are encased in fault breccias (Figure 2-21 and Table 2-4). The breccias are present along deformation zones that dip steeply and have been referred to as NE, ENE and NW in the modelling work (Table 2-4 and /Stephens et al. 2007/).

$^{40}Ar/^{39}Ar$ dating of generation 2, hematite-stained adularia has yielded ages of 1093±3 Ma, 1072±3 and 1034±3 Ma (Table 2-4). These ages are similar to a Rb-Sr errorchron, defined by generation 2 minerals and altered wall rock, that yielded an age of 1096±100 Ma (Table 2-4). All these ages indicate the importance of Sveconorwegian tectonothermal activity in the Forsmark area. On account of the inclusion of different minerals and even a whole-rock sample in the Rb-Sr dating work, the age inferred from the Rb-Sr data should be handled with caution.

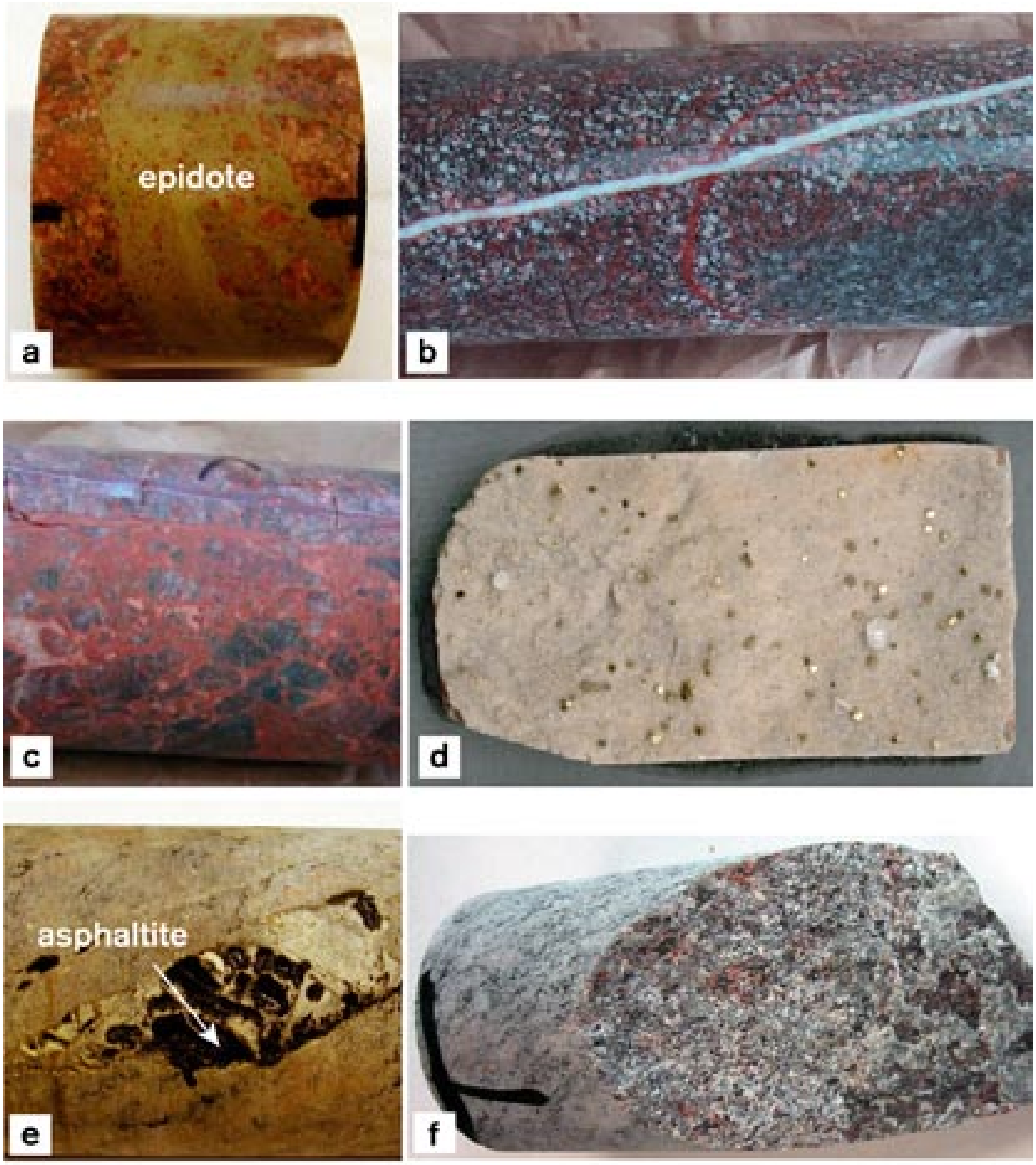


Figure 2-20. *Drill core photographs showing fracture minerals in the four different generations of fracture minerals in the Forsmark area. a) Generation 1. Epidote-bearing cataclasite (KFM06A, 268.77–268.82 m, /Sandström and Tullborg 2005/). b) Generation 2. Fracture filled by brick-red, hematite-stained adularia cut by fracture filled with prehnite (KFM05A, 689.33–689.61 m, /Sandström and Tullborg 2005/). c) Generation 2. Laumontite-sealed breccia (KFM04A, 244.46–244.58 m, /Sandström and Tullborg 2005/). d) Generation 3. Calcite and pyrite crystals on top of a fracture surface coated with quartz (KFM01A, 267.0 m, /Sandström et al. 2004/). e) Generation 3. Asphaltite in voids in older, partly dissolved calcite along a steeply dipping fracture (KFM06A, 106.94–107.14 m, /Sandström and Tullborg 2005/). f) Generation 4. Open fracture with a thin coating of calcite. This generation of calcite often occurs together with clay minerals (KFM08B, 97.37–97.43 m, /Sandström and Tullborg 2006/).*

Table 2-4. $^{40}Ar/^{39}Ar$ adularia (fracture), $^{40}Ar/^{39}Ar$ K-feldspar (rock fragment in breccia) and Rb-Sr errorchron (fracture minerals and wall rock) ages at Forsmark (based on /Sandström et al. 2006b, 2007/). The orientation of the fracture studied, presented as strike and dip using the right-hand-rule method, is also shown. The locations of boreholes that have been sampled are shown on Figure 2-15. An errorchron refers to an isochron along which data are scattered, not only because of analytical uncertainty, but also because of departures of the geological system investigated from an ideal model. The prefix letters "ZFM" used for deformation zones in the Forsmark area have been removed.

Borehole	Borehole length	Mineral	Fracture orientation and DZ (model stage 2.2)	Method	Age
KFM08A	245.47 m	Generation 3 adularia	039°/84° along zone ENE1061A	$^{40}Ar/^{39}Ar$	277±1 Ma
KFM07A	882.95 m	Generation 3 adularia	236°/67° along zone ENE1208A	$^{40}Ar/^{39}Ar$	Problem with excess argon. Age less than 456±2 Ma
KFM05A	692.00 m	Generation 2 adularia	032°/86° along zone ENE0401A	$^{40}Ar/^{39}Ar$	1034±3 Ma
KFM05A	395.75 m	Generation 2 adularia	057°/68° along zone NE2282	$^{40}Ar/^{39}Ar$	1072±3 Ma
KFM08A	183.77–183.88 m	Generation 2 adularia	026°/75° along interval affected by zone ENE1061A	$^{40}Ar/^{39}Ar$	1093±3 Ma
KFM05A	395.75 m	Generation 2 adularia, prehnite and calcite (individual minerals and combination), altered wall rock	057°/68° along zone NE2282	Rb-Sr (errorchron)	1096±100 Ma
KFM09A	732.90–733.10 m	K-feldspar in rock fragment inside fault breccia sealed with laumontite and calcite (generation 2 minerals)	Fault breccia along zone NW1200	$^{40}Ar/^{39}Ar$	1107±7 Ma
KFM09A	230.34–230.46 m	K-feldspar in rock fragment inside fault breccia sealed with laumontite and calcite (generation 2 minerals)	Fault breccia along zone ENE0159A oriented 207°/68°	$^{40}Ar/^{39}Ar$	No plateau defined in the step-heating spectrum. No age defined
KFM04A	347.32–347.50 m	K-feldspar in rock fragment inside fault breccia sealed with laumontite and calcite (generation 2 minerals)	Fault breccia along zone NE1188. Calcite-sealed fracture that cuts the breccia is oriented 230°/74°	$^{40}Ar/^{39}Ar$	1354±6 Ma

Figure 2-21. *Laumontite- and calcite-sealed fault breccia in KFM04A (347.32–347.50 m) at Forsmark, within which a rock fragment has been dated using the $^{40}Ar/^{39}Ar$ K-feldspar technique.*

K-feldspars in the fault breccias from boreholes KFM04A and KFM09A yield variable ages that are younger than the background K-feldspar ages in the bedrock outside deformation zones (see section 2.3.3), but older than the dated generation 2 adularia along fractures. These ages indicate a partial resetting of the $^{40}Ar/^{39}Ar$ isotope system in the host rock, probably in response to the influence of hot hydrothermal fluids during the Sveconorwegian tectonothermal event. The sensitivity of this isotope system to resetting in the prehnite-pumpelleyite to laumontite-prehnite temperature realm raises the question whether the $^{40}Ar/^{39}Ar$ dates for generation 2 adularia around 1.1 to 1.0 Ga represent the crystallization age of this mineral /Sandström et al. 2006b, Sandström and Tullborg 2007/ or a thermal resetting of the $^{40}Ar/^{39}Ar$ isotope system. Such a resetting could have occurred in connection with a later flushing of hot fluids along the deformation zones during the Sveconorwegian tectonothermal event (see also discussion earlier in section 2.2.3). If the second of these hypotheses is correct, then at least hematite-stained adularia in the generation 2 mineral paragenesis is older than Sveconorwegian.

$^{40}Ar/^{39}Ar$ dating of generation 3 adularia has yielded ages of 456±2 and 277±1 Ma (Table 2-4). The sample that yielded the older age is inferred to contain excess argon and no reliable plateau age was obtained. The Ordovician age obtained from this sample can only be inferred as the maximum age. The younger Permian age is based on a well-defined plateau and is considered to be a more reliable age determination. The Permian adularia has grown on generation 3 pyrite and represents a late phase of the generation 3 mineral precipitation. A Palaeozoic age for the generation 3 minerals is supported by the isotopic compositions of the associated minerals calcite, pyrite and asphaltite, which all indicate an organic influence in the fluid from which these minerals precipitated /Sandström et al. 2006a, Sandström and Tullborg 2007/. Further discussion of this point in the context of burial by a sedimentary cover and loading of the crust during the Palaeozoic is provided below.

Brittle deformation and hydrothermal fluid activity prior to establishment of the sub-Cambrian unconformity

The $^{40}Ar/^{39}Ar$ hornblende and biotite ages (section 2.3.3) indicate that the bedrock at the current level of erosion at Forsmark had entered the realm of sub-greenschist facies metamorphic conditions between 1.8 and 1.7 Ga. On the basis of these data, it is apparent that this crustal level would have responded to deformation in a brittle-ductile or brittle manner during the latest part of the Svecokarelian orogeny and, in a brittle manner, during the subsequent, far-field tectonic events outlined in section 2.2.2. Alteration of, for example, feldspar in the bedrock, with growth of the secondary minerals prehnite and pumpelleyite, would also have been possible at this stage in the geological history.

The $^{40}Ar/^{39}Ar$ ages for the generation 2 adularia indicate that the older fracture minerals with epidote (generation 1) formed prior to 1.1 Ga, i.e. prior to the Sveconorwegian orogeny. The occurrence of similar fracture minerals and wall-rock alteration along different fracture sets inside the distinctive sets and sub-sets of deformation zones at Forsmark /Stephens et al. 2007/, including the generation 1 mineral epidote, suggest that all zones had formed prior to the Sveconorwegian tectonothermal event. However, the occurrence of different generations of minerals along the fractures in these zones and the kinematic data both indicate a complex tectonic evolution with activity at several times during geological history /Stephens et al. 2007/. Since the bedrock started to behave in a brittle manner some time between 1.8 and 1.7 Ga and at least one of these sets, the WNW to NW set, was affected by ductile deformation /Stephens et al. 2007/, it is apparent that at least this set of zones formed during the waning stages of the Svecokarelian orogeny. Furthermore, the kinematic data suggest phases of brittle deformation during which bulk shortening occurred in NW-SE, N-S or NE-SW directions. These are reminiscent of those proposed for the late Svecokarelian and early Gothian tectonothermal events (see sections 2.2.1 and 2.2.2, respectively).

Independent evidence for a geological response at Forsmark to the far-field, Sveconorwegian tectonic activity in south-western Sweden is provided by:

- The $^{40}Ar/^{39}Ar$ generation 2 adularia ages.
- The Rb-Sr errorchron for the generation 2 minerals (see description to Table 2-4 for a definition of the term "errorchron").
- The disturbance of both the U-Pb isotope system in titanite (see section 2.3.3) and the $^{40}Ar/^{39}Ar$ isotope system in K-feldspar.

Since all the $^{40}Ar/^{39}Ar$ generation 2 adularia ages are from fillings of fractures along brittle deformation zones, these data also indicate that even these zones were, in some manner, active during the Sveconorwegian orogeny. Bearing in mind the evidence for reactivation of deformation zones at Forsmark (see sections 3.6.5 and 5.3.2 in /Stephens et al. 2007/) and the previous discussion concerning the interpretation of $^{40}Ar/^{39}Ar$ generation 2 adularia ages, it remains uncertain to what extent the Sveconorwegian event is related to formation of new brittle structures in the bedrock or to a major reactivation of brittle structures that had formed earlier during the Proterozoic. Kinematic data along the different sets and sub-sets of zones at Forsmark (see synthesis in /Stephens et al. 2007/) suggest a phase of brittle deformation that involved bulk shortening in a WNW-ESE direction. This is reminiscent of that proposed for the later part of the Sveconorwegian orogeny (see section 2.2.2).

Faulting and fluid movement after establishment of the sub-Cambrian unconformity

$^{40}Ar/^{39}Ar$ biotite ages at the current level of erosion vary inside the different bedrock blocks between the regionally important Forsmark, Eckarfjärden and Singö deformation zones (Figure 2-22). It has been inferred that fault reactivation, which involved north-side-up, dip-slip movement along at least the Forsmark deformation zone and tilting of the intervening bedrock block between the Forsmark and Eckarfjärden zones to the north, occurred after 1.67 Ga, i.e. after the Svecokarelian orogenic activity /Söderlund et al. in press a/. These authors also suggested that the potential age trend between the Eckarfjärden and Singö deformation zones (Figure 2-22) was disturbed by the common occurrence of ENE and NNE fracture zones in the north-western part of this block /Stephens et al. 2007/. If correct, this implies that faulting with a conspicuous dip-slip sense of movement also occurred after 1.67 Ga along the steeply dipping ENE and NNE fracture zones inside the target volume /Söderlund et al. in press a/.

On the basis of geomorphological data, dip-slip disturbance and eastward or northward tilting of the sub-Cambrian unconformity are apparent along faults that strike NNE-SSW, NNW-SSE or WNW-ESE in northern Uppland, where Forsmark is located (/Lidmar-Bergström 1994, Bergman et al. 1999c/ and Figure 2-15). In particular, dip-slip displacement of the sub-Cambrian unconformity along the Forsmark deformation zone, with uplift and northward tilting of the bedrock block to the north of this zone, has been inferred. The consistent sense of kinematics and sense of block tilt inferred from both the $^{40}Ar/^{39}Ar$ biotite and the geomorphological data across the Forsmark zone suggest that at least some dip-slip displacement along this zone occurred after the establishment of the sub-Cambrian unconformity during the latest part of the Proterozoic and/or the Phanerozoic /Söderlund et al. in press a/. Dip-slip disturbances have also been documented in the kinematic data from the Forsmark area (see synthesis in /Stephens et al. 2007/). However, the timing of this dip-slip displacement is not constrained.

Independent evidence for Palaeozoic reactivation along deformation zones at Forsmark is provided by the $^{40}Ar/^{39}Ar$ ages for generation 3 adularia. In particular, Permian fluid movement and precipitation of adularia has been documented along one of the steeply dipping ENE deformation zones (ENE1061A). Furthermore, a change in exhumation rate at Forsmark during the Permian is also indicated from the corrected (U-Th)/He apatite data. These observations are consistent with the evidence for Silurian or younger faulting in the geological reference area (see section 2.2.3). Faulting may also have played a role in the renewed exhumation of the sub-Cambrian unconformity after Palaeozoic time and prior to the Quaternary (see below).

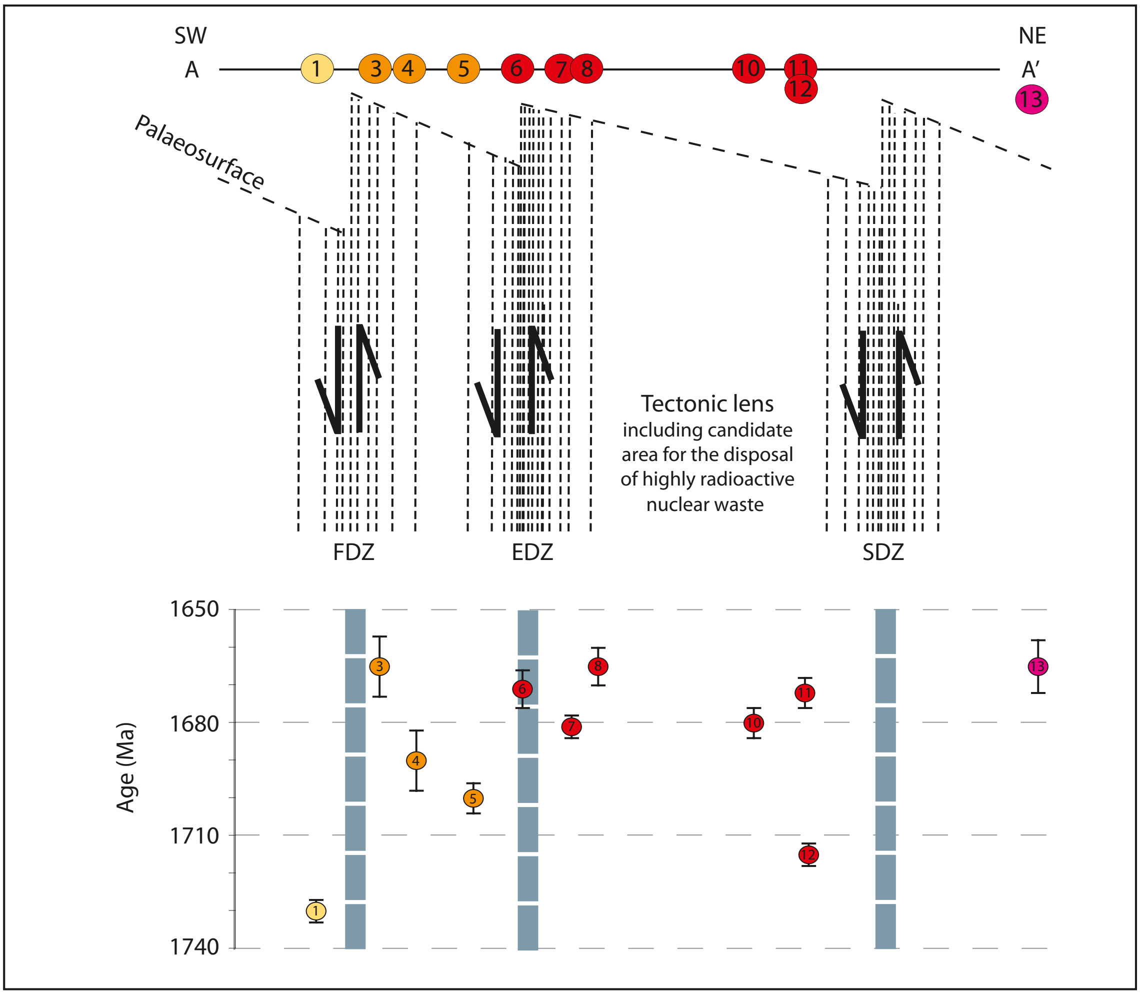


***Figure 2-22.** Variation in $^{40}Ar/^{39}Ar$ biotite ages from surface samples along the SW-NE profile A-A' across the regional Forsmark (FDZ), Eckarfjärden (EDZ) and Singö (SDZ) deformation zones (see Figure 2-15) in the Forsmark area. The samples (encircled numbers) have been projected onto profile A-A' and the $^{40}Ar/^{39}Ar$ biotite ages are shown in the lower part of the figure. The inferred dip-slip offsets and block tilting occurred after the establishment of the $^{40}Ar/^{39}Ar$ biotite cooling ages. They are based on the age variation across especially the Forsmark zone /after Söderlund et al. in press a/.*

Sedimentary loading and exhumation after establishment of the sub-Cambrian unconformity

The youngest, F_T-corrected (U-Th)/He apatite ages close to the surface in boreholes KFM01A, KFM02A and KFM03A at Forsmark indicate that a conspicuous sedimentary cover was situated on top of the crystalline basement rocks throughout Late Palaeozoic and Mesozoic time, at least as young as the Jurassic. Alternatively, if the youngest, uncorrected (U-Th)/He apatite ages at different depths are used, then it is apparent that a conspicuous sedimentary overburden existed even later, from the Permian and throughout much of Mesozoic time, at least into the Cretaceous. Notwithstanding the difficulties with the interpretation of the (U-Th)/He apatite ages, it is apparent that both these alternatives indicate the presence of a substantial sedimentary cover at the Forsmark site during the Phanerozoic.

Assuming a geothermal gradient of 25°C/km in the sedimentary rocks and a closing temperature for the isotope system at 70°C, a sedimentary overburden of approximately 3 km can be inferred at each elevation and inferred age. The surface and near-surface ages indicate a predominantly sedimentary cover that has now been removed by erosion, while the ages at depth indicate a combination of crystalline bedrock and eroded sedimentary cover. If the youngest, F_T-corrected (U-Th)/He apatite ages are used, then it can be inferred that a sedimentary overburden with a thickness of c 3 km existed during the Silurian at, for example, drill site 1, in the structural block between the Eckarfjärden and Singö deformation zones. Furthermore, this cover had reduced in thickness but was probably still greater than 2 km by the Early Jurassic. These estimates are consistent with earlier results in the geological reference area (see section 2.2.3) that suggested there was a relatively thick sedimentary overburden on top of the crystalline basement rocks during the Late Palaeozoic /Larson et al. 1999, 2006, Cederbom 2001/ and that Mesozoic deep weathering of the sub-Cambrian unconformity is absent /Lidmar-Bergström 1995/. Bearing in mind the results from southern Sweden /Lidmar-Bergström and Näslund 2002, Japsen et al. 2002/, it is assumed that renewed exhumation of the sub-Cambrian unconformity did not take place until some time during the Cenozoic.

A comparison of, for example, the youngest, F_T-corrected age at the top of borehole KFM01A with the equivalent age at c 600 m depth, as well as between the youngest, F_T-corrected ages at the top and bottom of borehole KFM03A suggest a slow exhumation rate in the order of 3 to 10 m/Ma during the Late Palaeozoic and Mesozoic. The exhumation rate calculated in KFM03A is somewhat higher than that calculated for the upper part of borehole KFM01A and this accounts for the variation. These estimates can be compared with the significantly faster rate of 22 m/Ma between 1.70 and 1.64 Ga (see section 2.3.3). As pointed out in section 2.3.3, there is also some tendency for an increase in the exhumation rate during the Permian, if the F_T-corrected ages are assumed to be correct /Page et al. 2004/, or during the Jurassic if the uncorrected ages are adopted.

The interplay between sediment loading or unloading and the effects of these processes on the local stress field were addressed in the conceptual structural model for the Forsmark area (see section 5.2 in /Stephens et al. 2007/). Naturally, these effects are most prominent in connection with the Quaternary evolution, when the bedrock was covered by ice and subsequently exhumed at a rapid rate several times.

Downward fluid migration along fractures

The organic influence on the generation 3 fracture minerals is inferred to originate from downward migration of fluids from the overlying, Palaeozoic sedimentary cover sequence that was rich in organic material /Sandström and Tullborg 2007/. In particular, the Cambrian to Lower Ordovician oil shale has been proposed as a source rock for, at least, the oily mineral asphaltite /SKB 2005a, Sandström et al. 2006a/. The depth dependence of the occurrence of asphaltite (see section 3.6.5 in /Stephens et al. 2007/) is reminiscent of the occurrence of clastic sedimentary dykes immediately beneath the sub-Cambrian unconformity in south-eastern Sweden and south-western Finland (see, for example, /Bergman 1982, Röshoff and Cosgrove 2002/ and section 2.4.6). In this case, the source of material is the overlying Cambrian sandstone. In both cases, fluids appear to have moved downwards through the pile of Lower Palaeozoic sedimentary cover rocks into either newly formed or reactivated older fractures in the underlying crystalline bedrock. Movement of fluids took place after the Cambrian period, in connection with either loading or unloading of the Phanerozoic sedimentary cover.

During the later part of the Quaternary period, fluids that transported glacial sediment also migrated downwards and filled, to variable extent, new or reactivated fractures at Forsmark (/Carlsson 1979, Leijon 2005/ and Figure 2-23). A more detailed discussion of the fractures at Forsmark that are filled by Quaternary sediment is provided in section 3.4.2.

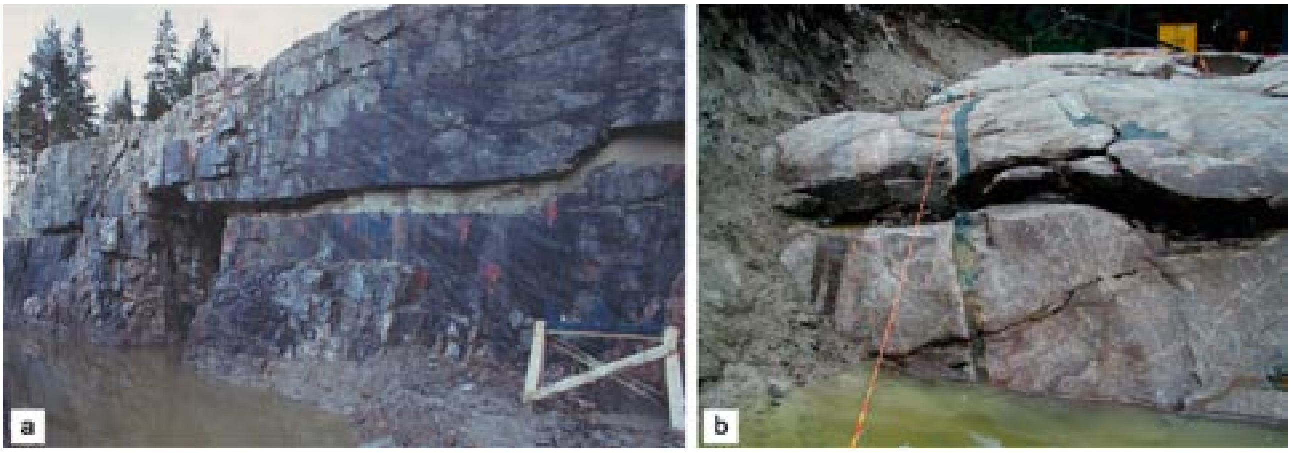


Figure 2-23. *Subhorizontal and gently dipping fractures close to the current ground surface at Forsmark. a) Subhorizontal fracture filled with glacial sediment inferred to be a sheet joint formed in connection with release of stress close to the ground surface. Excavation for unit 3 at the nuclear power plant /after Carlsson 1979/. b) Gently dipping fracture with wide aperture at drill site 5. The impressive aperture along this fracture is also inferred to have formed in connection with the release of stress close to the ground surface. Several fractures with this orientation at drill site 5 are filled with glacial sediment. See also section 3.4.2.*

2.4 Geological evolution of the Laxemar-Simpevarp area

2.4.1 Relative and absolute age determinations – overview of primary data

The bedrock geological mapping of the ground surface in the Laxemar-Simpevarp area /Wahlgren et al. 2004, 2005, Persson Nilsson et al. 2004/, which was carried out during the initial site investigation, forms the basis for the general understanding of the evolution of the bedrock in the area. It provided important descriptive data bearing on the field and relative age relationships between the different rock types, and an important basis for the subsequent geological mapping of rock types in the boreholes. As at Forsmark, detailed mapping of larger excavated outcrops, including mapping of fractures and rock types, has also contributed to the general understanding of the bedrock geological relationships /Cronquist et al. 2004, 2006, Hermanson et al. 2004b, Forssberg et al. 2005, 2007b/. A summary description of the bedrock geological data has been presented in /SKB 2004, 2005d, 2006a/. In close collaboration with the team who carried out the mapping of the drill cores from the cored boreholes, the relative time relationships between the growth of different fracture minerals and wall rock alteration was also established /Drake and Tullborg 2004, 2005, 2006abcd, 2007/.

Absolute age constraints are a necessity to better understand the bedrock geological evolution in the Laxemar-Simpevarp area. For this reason and using the same methodology as at Forsmark, geochronological studies relating to different isotopic systems have been carried out. The different isotope systems, in order of decreasing blocking temperature, include: U-Pb zircon and titanite with measurements by the TIMS technique, $^{40}Ar/^{39}Ar$ whole-rock, $^{40}Ar/^{39}Ar$ hornblende, $^{40}Ar/^{39}Ar$ muscovite, $^{40}Ar/^{39}Ar$ biotite, $^{40}Ar/^{39}Ar$ adularia, $^{40}Ar/^{39}Ar$ illite and (U-Th)/He apatite.

Minerals have been separated for analysis from whole-rock samples, both from the surface and in drill cores (Figure 2-24), and from fracture fillings in drill cores. The analysed samples come from different rock types and from different bedrock blocks on both sides of a regionally important deformation zone (Äspö shear zone). The data are presented in /Wahlgren et al. 2004, Söderlund et al. 2005b, 2008, in press b, Drake et al. 2007, Page et al. 2007b/. As at Forsmark, all the $^{40}Ar/^{39}Ar$ ages discussed below need to be revised to approximately 1% older values (see, for example, discussion in /Hermansson et al. in press/). However, this revision has little effect on the conclusions drawn here and the $^{40}Ar/^{39}Ar$ ages have not been corrected for this bias.

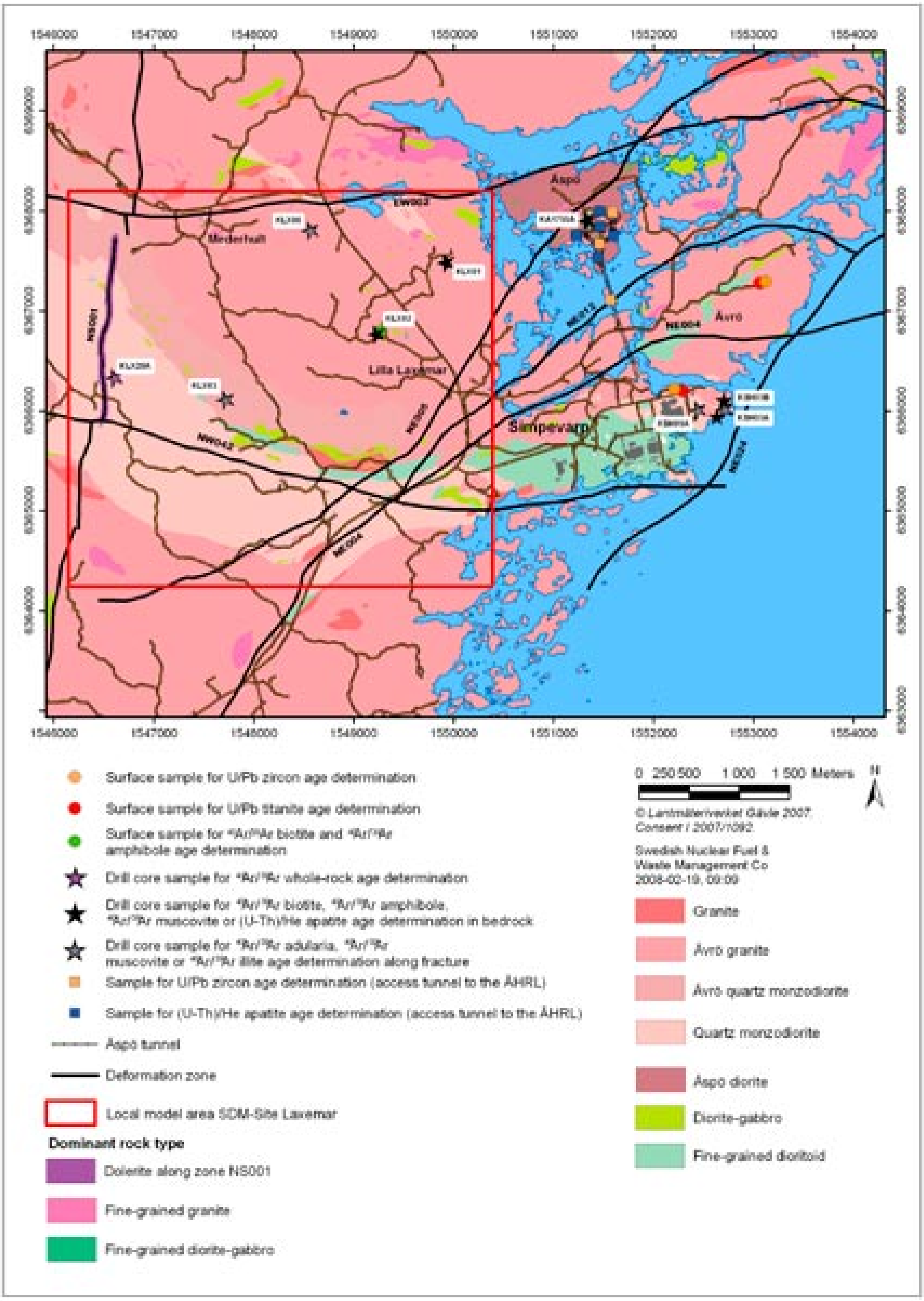


Figure 2-24. Bedrock geological map of the Laxemar-Simpevarp area. The locations of outcrops, boreholes and the access tunnel to the Äspö Hard Rock Laboratory (ÄHRL) that have been sampled for dating of minerals in the bedrock and along fractures, using different isotope systems, are also shown on the map. In both this figure and the text, individual deformation zones are identified according to orientation and number, for example EW002. The prefix letters "ZSM" used for deformation zones in the Laxemar-Simpevarp area have been removed.

Some new apatite fission track (AFT) data from samples in a drill core (KLX02) were also presented in /Söderlund et al. 2008/. However, there are significant differences between the ages calculated from these data and the ages obtained from earlier AFT data in the same borehole /Larson et al. 1999/. As for Forsmark, these serious discrepancies inhibit further geological evaluation of the AFT ages.

2.4.2 Crystallisation of igneous rocks, age relationships and the regional perspective

In strong contrast to Forsmark, the intrusive rocks in the Laxemar-Simpevarp area are more or less well-preserved. Rock types with quartz monzodioritic and granodioritic compositions dominate, but different rock types have been distinguished on the basis of their variable grain size and texture. With these considerations in mind, the dominant rock types are medium-grained, finely porphyritic Ävrö granite (Figure 2-25a), which varies in composition from granite to quartz monzodiorite, and medium-grained, equigranular quartz monzodiorite (Figure 2-25b).

Figure 2-25. *Character of well-preserved rock types in the Laxemar-simpevarp area. a) Ävrö granite with a granodioritic composition. Note the intermediate to mafic enclave in the right part of the picture. b) Characteristic appearance of equigranular quartz monzodiorite. c) Ävrö quartz monzodiorite. Note the darker colour due to higher content of dark minerals compared with the granodioritic variety in (a). d) Diffuse transition between finely porphyritic, grey Ävrö granite (upper part) and equigranular, medium-grained red granite (lower part). The geologist in the photograph is pointing at the diffuse transition.*

However, a quartz monzodioritic variety of the Ävrö granite, i.e. Ävrö quartz monzodiorite (Figure 2-25c), has been distinguished at Laxemar, both at the surface and at depth with the help of modal and geochemical analyses and density logs from the cored boreholes. Minor bodies of equigranular granite, diorite-gabbro and fine-grained dioritoid are also present. Important subordinate rock types are dykes, veins, patches and minor bodies of fine-grained granite, pegmatite and composite intrusions. The latter are composed of a mixture of fine-grained diorite-gabbro and fine-grained granite. Field relationships, including diffuse contacts as well as mixing and mingling relationships, strongly indicate that all these rock types formed close in time and belong to the same igneous event (Figure 2-25d). However, the field relationships also indicate the relative age relationship between the different rock types (Table 2-5).

U-Pb zircon (and titanite) dating of the Ävrö granite (PSM002328) and equigranular quartz monzodiorite (PSM002151), which was carried out in connection with the site investigation work, has yielded crystallisation ages at 1.81 to 1.80 Ga (Table 2-6). The sample locations are shown in Figure 2-24. Although the ages overlap within the uncertainty estimate, they indicate that the Ävrö granite/Ävrö quartz monzodiorite is slightly younger than the equigranular quartz monzodiorite, which is in accordance with the observed field relationships. These ages are also in agreement with earlier U-Pb zircon age determinations for the so-called Äspö diorite, Gersebo granite (Ävrö granite type sampled immediately east of the Götemar granite), Virbo granite (Ävrö granite type sampled c 15 km south-west of Simpevarp) and fine-grained granites (Table 2-6).

The second rock-forming event in the Laxemar-Simpevarp area and its surroundings occurred at c 1.45 Ga (Table 2-6). This event gave rise to the isolated Götemar and Uthammar granites, north and south of Laxemar, respectively, as well as the Jungfrun granite, which is exposed on a small island in the Baltic Sea between Öland and the main land. Finally, at c 900 Ma, mafic magma intruded the western part of the Laxemar-Simpevarp area in the form of dolerite dykes (Table 2-6). These dolerites form the youngest igneous rocks in the region and belong to the regional system of c 1000 to 900 Ma old dolerites with N-S strike that can be followed from Blekinge in the south to Dalarna in the north (Figure 2-8 and /Johansson and Johansson 1990, Söderlund et al. 2005a/).

In a regional perspective, the c 1.80 Ga bedrock in the Laxemar-Simpevarp area in TD5 has the typical lithological characteristics of the GSDG rocks in the Transscandinavian Igneous Belt. These characteristics include evidence for magma-mingling and magma-mixing processes, exemplified by the occurrence of enclaves, hybridization and diffuse transitional contacts between different rock types. These features demonstrate a close temporal and genetic relationship between the different rocks in the c 1.80 Ga suite.

Table 2-5. Relative age relationships between igneous rock types in the Laxemar-Simpevarp area, based on field relationships. SKB rock codes for each rock type are shown in brackets.

Rock type	Relative age
Dolerite (501027)	Youngest
Götemar and Uthammar granites (521058)	
Fine-grained granite (511058) and pegmatite (501061)	
Fine-grained diorite-gabbro (505102)	
Granite, equigranular (501058)	
Ävrö granite (501044)/Ävrö quartz monzodiorite (501046)	
Quartz monzodiorite (501036)	
Diorite-gabbro (501033)	
Fine-grained dioritoid (501030)	Oldest

Table 2-6. Age of crystallisation of igneous rocks in the Laxemar-Simpevarp area and surroundings. TIMS = Thermal Ionisation Mass Spectrometry technique. The locations of borehole KLX20A and the samples from the surface and the Äspö tunnel are shown on Figure 2-24.

Dated rock type	Method	Age	Comment	Reference
Dolerite	$^{40}Ar/^{39}Ar$ whole rock	c 900 Ma	Drill core sample (KLX20A)	/Wahlgren et al. 2007/, /Söderlund et al. in press/
Götemar granite	U-Pb zircon (TIMS)	1452+11/–9 Ma	Surface sample	/Åhäll 2001/
Uthammar granite	U-Pb zircon (TIMS)	1441+5/–3 Ma	Surface sample	/Åhäll 2001/
Jungfrun granite	U-Pb zircon (TIMS)	1441±2 Ma	Surface sample	/Åhäll 2001/
Fine-grained granite	U-Pb zircon (TIMS)	1794+16/–12 Ma	Sample from Äspö tunnel	/Wikman and Kornfält 1995, Kornfält et al. 1997/
Fine-grained granite	U-Pb zircon (TIMS)	1808+33/–30 Ma	Sample from Äspö tunnel	/Wikman and Kornfält 1995, Kornfält et al. 1997/
Äspö diorite	U-Pb zircon (TIMS)	1804±3 Ma	Sample from Äspö tunnel	/Wikman and Kornfält 1995, Kornfält et al. 1997/
Gersebo granite	U-Pb zircon (TIMS)	1803±7 Ma	Surface sample	/Åhäll 2001/
Virbo granite	U-Pb zircon (TIMS)	c 1790 Ma	Surface sample	/Bergman et al. 2000/
Ävrö granite	U-Pb zircon+titanite (TIMS)	1800±4 Ma	Surface sample	/Wahlgren et al. 2004/
Quartz monzodiorite	U-Pb zircon (TIMS)	1802±4 Ma	Surface sample	/Wahlgren et al. 2004/

The intense phase of igneous activity around c 1.80 Ga in the Laxemar-Simpevarp area is characteristic for a large part of TD5 and TD6 in the southern part of the geological reference area (see section 2.2.1 and Figure 2-3a). The rocks in the c 1.80 Ga suite in these tectonic domains formed as a result of an intense period of crustal reworking, in connection with oblique subduction along an active continental margin during the later part of the youngest Svecokarelian tectonic cycle between 1.83 and c 1.79 Ga (see section 2.2.1). The younger granitic magmatism at 1.45 Ga is interpreted to be a far-field effect of Mesoproterozoic tectonic activity further to the west and south, including the Hallandian orogeny in south-western Sweden (see section 2.2.2), while the c 900 Ma dolerites represent an extensional tectonic phase during the later part of the Sveconorwegian orogeny (see section 2.2.2).

2.4.3 Exhumation and cooling history

The time during the geological evolution when the bedrock in the Laxemar-Simpevarp area ultimately cooled beneath the blocking temperature in isotope systems other than the high-temperature, U-Pb zircon system is shown in Table 2-7. The broader implications of these ages for the tectonic evolution in the investigation area are discussed in the following sections 2.4.4, 2.4.5 and 2.4.6.

U-Pb titanite ages

The U-Pb titanite ages (blocking temperature 700 to 500°C) for the Ävrö granite and quartz monzodiorite are 1.80 and c 1.79 Ga, respectively (Table 2-7). The U-Pb zircon and titanite ages are identical for the Ävrö granite (cf. Table 2-6), which is probably due to very rapid cooling after emplacement of the parent magma. In contrast, the titanite age for the quartz monzodiorite is c 10 million years younger than the U-Pb zircon age (cf. Table 2-6), which is commonly found in intrusions due to the lower blocking temperature of the U-Pb titanite system (see also Group D granite at Forsmark). Notwithstanding the interpretation of the titanite ages for these two rock types, it is concluded that these intrusions cooled beneath 700 to 500°C in less than 10 million years after their emplacement.

Table 2-7. Cooling ages of the bedrock in the Laxemar-Simpevarp area based on /Söderlund et al. 2005b, 2008, in press b, Page et al. 2007b/. TIMS = Thermal Ionisation Mass Spectrometry technique. The locations of boreholes and the samples from the surface and the Äspö tunnel are shown on Figure 2-24.

Geological feature	Dated rock type	Method	Age	Comment
Cooling below c 70°C	Ävrö granite, fine-grained granite, fine-grained dioritoid, fine-grained diorite-gabbro, quartz monzodiorite	(U-Th)/He apatite	Surface samples: F_T-corrected ages range between c 313 and 227 Ma Uncorrected ages range between c 211 and 133 Ma Drill core samples: F_T-corrected ages range between c 289 and 120 Ma Uncorrected ages range between c 215 and 85 Ma	Surface or near-surface samples. Drill core samples from KLX01, KLX02, KSH03A/B, and samples from the access tunnel to the Äspö Hard Rock Laboratory In general, the ages decrease with increasing depth in each borehole
Cooling below c 300°C	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	928±6 Ma	Sample from KSH03A (c 300 m borehole length)
	Götemar granite	$^{40}Ar/^{39}Ar$ biotite	1421±4 Ma	Surface sample
	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	1431±6 Ma	Drill core sample from the lowermost part (c 1,605 m) of KLX02
	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	1434±6 Ma	Surface sample close to the Uthammar granite near Fårbo
	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	1479±3 Ma 1484±3 Ma	Samples from the lower part of KSH03A
	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	1481±3 Ma	Drill core sample from the lowermost part (c 1,000 m) of KLX01
	Ävrö granite	$^{40}Ar/^{39}Ar$ biotite	1468±2 Ma, 1486±3 Ma, 1491±6 Ma, 1508±7 Ma	Surface samples or from upper part of KLX01 and KLX02
	Quartz monzodiorite	$^{40}Ar/^{39}Ar$ biotite	1618±7 Ma, 1621±3 Ma	Samples from uppermost part of KSH03A/B
Cooling below c 350°C	Mylonite	$^{40}Ar/^{39}Ar$ muscovite	1406±3 Ma	Drill core sample from KA1755A (Äspö shear zone)
Cooling below c 500°C	Ävrö granite	$^{40}Ar/^{39}Ar$ amphibole	1445±14 Ma	Drill core sample from the lowermost part (c 1,605 m) of KLX02
	Ävrö granite	$^{40}Ar/^{39}Ar$ amphibole	1773±13 Ma	Surface sample close to KLX02
	Quartz monzodiorite	$^{40}Ar/^{39}Ar$ amphibole	1799±4 Ma	Drill core sample from upper part of KSH03A
Cooling below 700 to 500°C	Quartz monzodiorite	U-Pb titanite (TIMS)	1793±4 Ma (upper intercept age)	Surface sample
	Ävrö granite	U-Pb titanite (TIMS)	1800±4 Ma (upper intercept age)	Surface sample

$^{40}Ar/^{39}Ar$ amphibole ages and the onset of greenschist facies metamorphic conditions

The amphibole ages (blocking temperature c 500°C) from surface or near-surface samples in the Laxemar-Simpevarp area fall in the range 1.80 to 1.77 Ga (Table 2-7), i.e. they are very similar to the U-Pb titanite ages and are inferred to be related to the cooling after crystallisation of the Ävrö granite and quartz monzodiorite. It should be noted that the 1.80 Ga age comes from a quartz monzodiorite sample in the upper part of KSH03A in the Simpevarp subarea, while the c 1.77 Ga age is obtained from a surface sample of Ävrö granite close to KLX02 at Laxemar. Although based only on two samples, it is tentatively inferred that the $^{40}Ar/^{39}Ar$ amphibole system either remained open longer at Laxemar relative to the Simpevarp subarea or that the age difference is related to faulting after 1.77 Ga.

In the lowermost part of KLX02, at a borehole length of c 1605 m, a $^{40}Ar/^{39}Ar$ amphibole age of c 1.45 Ga was obtained. The interpretation of this younger age in comparison with the age of the surface sample (Table 2-7) is discussed further in the context of the thermal influence of the Götemar and Uthammar granites (section 2.4.5).

$^{40}Ar/^{39}Ar$ biotite ages and the onset of sub-greenschist facies metamorphic conditions

$^{40}Ar/^{39}Ar$ biotite ages (blocking temperature c 300°C) from surface samples or samples from the upper part of KLX01 and KLX02 at Laxemar range between 1.51 and 1.47 Ga (Table 2-7), whereas a corresponding sample (duplicate analyses of one sample) from KSH03A/B in the Simpevarp subarea has yielded an age of c 1.62 Ga. As for the $^{40}Ar/^{39}Ar$ hornblende ages, the $^{40}Ar/^{39}Ar$ isotope system for biotite closed later in the Laxemar relative to the Simpevarp subarea. The $^{40}Ar/^{39}Ar$ biotite ages in the range 1.51 to 1.47 Ga are interpreted to be related to cooling below c 300°C after reheating of the bedrock, and not to an extremely slow cooling of the protolith from c 1.80 Ga and onwards. There remains a greater uncertainty concerning the cooling history after c 1.80 Ga as represented by the c 1.62 Ga age in the Simpevarp subarea. Further discussion of these ages in the context of the brittle deformation in the Laxemar-Simpevarp area is presented in section 2.4.6.

As expected, the cooling ages in the lower parts of the boreholes are younger than in the corresponding upper parts or at the surface. This can be exemplified by KSH03A/B where the surface samples yielded ages of c 1.62 Ga, whereas samples from the lowermost part of the borehole yielded ages of c 1.48 Ga. In a similar manner, $^{40}Ar/^{39}Ar$ biotite ages in KLX01 decrease from 1486±3 Ma in the uppermost part to 1481±3 Ma in the lowermost part.

Surface samples from the Götemar granite and a TIB rock close to the Uthammar granite as well as from a TIB rock in the lowermost part of KLX02 have yielded ages in the range 1.44 to 1.42 Ga. The implications of these younger ages in the context of the thermal influence of the c 1.45 Ga Götemar and Uthammar granites are also discussed in section 2.4.5. At c 300 m borehole length in KSH03A, a three step plateau age of 928±6 Ma has been obtained. Although the spectra are disturbed, this even younger age is interpreted as dating the cooling below the closure temperature of biotite. The tectonic implications of this age are discussed further in section 2.4.6.

(U-Th)/He apatite ages

(U-Th)/He apatite ages have been obtained from a limited number of surface and near-surface samples, from samples at different depths between c 100 and 1,700 m in boreholes KLX01, KLX02 and KSH03A/B, and from the access tunnel to the Äspö Hard Rock Laboratory (Figure 2-24). The (U-Th)/He data from Laxemar-Simpevarp have been treated in the same manner as the equivalent data at Forsmark (see section 2.3.3) and both F_T-corrected and uncorrected ages are addressed in the text below. The uncertainties in the data from KLX01, KLX02 and the Äspö tunnel are reported with ±2σ, whereas the uncertainties in the data from the surface and from KSH03A/B are reported, as at Forsmark, with ±1σ. There is considerably less variation in the ages obtained from different analyses at each depth in the boreholes compared with those obtained at Forsmark. For this reason, the data from Laxemar-Simpevarp can be interpreted with a higher degree of confidence /Söderlund et al. 2008/. A few highly anomalous old ages, which are probably caused by inclusions in the apatite grains /Page et al. 2007b/, have been excluded from the following data evaluation.

The F_T-corrected (U-Th)/He ages from the few samples at or very close to the surface lie in the range 313±24 to 227±21 Ma, i.e. they lie in the restricted time interval between the Carboniferous and the Middle to Late Triassic in the geological time scale (see Figure 2-2). The corresponding range in uncorrected ages is 211±14 to 133±9 Ma, i.e. Late Triassic to Early Cretaceous.

The data from borehole KLX02 (Figure 2-26) are the most complete and are, therefore, of prime importance for the interpretation of the (U-Th)/He ages in the Laxemar-Simpevarp area. The (U-Th)/He data for KLX01 and the Äspö tunnel are similar to those in KLX02 (Figure 2-26), and all the ages decrease in a systematic manner downwards with depth along the boreholes and the tunnel (Figure 2-26). There is also a decrease in slope on the age-depth diagrams below c 1,400 m in KLX02 (/Söderlund et al. 2005b, Page et al. 2007b/ and Figure 2-26). This corresponds to an age of c 200 Ma (Early Jurassic), if the F_T-corrected ages are used, or between 150 and 100 Ma (Late Jurassic to Cretaceous), if the uncorrected ages are adopted (/Page et al. 2004/ and Figure 2-26).

In the upper part of KLX02, above the change in slope, the youngest, F_T-corrected (U-Th)/He ages at each depth in the borehole lie in the range 260±20 Ma (200 m depth) to 190±14 Ma (1,200 depth) and, below the change in slope, between 198±16 Ma (1,400 m depth) and 120±8 Ma (1,700 m depth). These ages correspond to Permian to Early Jurassic and Early Jurassic to Early Cretaceous, respectively. The corresponding uncorrected ages are 212 to 147 Ma and 136 to 85 Ma, respectively. In the same manner as the uncorrected ages at the surface, they are entirely Mesozoic.

Bearing in mind the uncertainties, there is no difference in age between the F_T-corrected (U-Th)/He ages at the top and bottom of borehole KSH03A on the Simpevarp peninsula. At the top of the borehole (4 m depth), the ages range between 263±18 Ma and 227±21 Ma, i.e. between Permian and Triassic to Jurassic, and at the bottom (866 m depth) between 259±18 Ma and 206±14 Ma, i.e. Permian and Early Jurassic. Furthermore, the (U-Th)/He ages from KSH03A/B indicate an off-set between 130 and 300 m depth that corresponds to the intersection of the deformation zone NE024 (/Page et al. 2007b/ and Figure 2-24). A similar off-set is suggested in KLX01 between 200 and 400 m depth /Page et al. 2007b/.

The broader geological significance of the (U-Th)/He apatite data are addressed below in section 2.4.6. As at Forsmark, alternative lines of approach, using either the F_T-corrected or the uncorrected (U-Th)/He ages, are adopted in this evaluation.

2.4.4 Ductile deformation and the regional perspective

From a structural point of view, the bedrock in the Laxemar-Simpevarp area is dominated by well-preserved intrusive rocks. However, a faint to weak foliation, which is commonly gently dipping but not uniformly distributed over the area, is present. In many cases, it is difficult to decide whether this foliation formed during the igneous evolution, i.e. it represents a flow foliation, or whether it is a solid-state structure. On the basis of the field relationships, it is inferred that the foliation initially developed during a late stage in the igneous evolution, but continued to develop in the solid state after crystallization and solidification of the magmas. All rock types are affected by the foliation, most notably the dyke-like bodies of fine-grained granite and fine-grained diorite-gabbro. The foliation in these rocks formed in the solid state and is more or less strongly developed, particularly in the southern part of Laxemar. In many cases, these dyke-like bodies correspond to ductile shear zones and there is a concentration of this high-temperature strain in the youngest dyke-like intrusions.

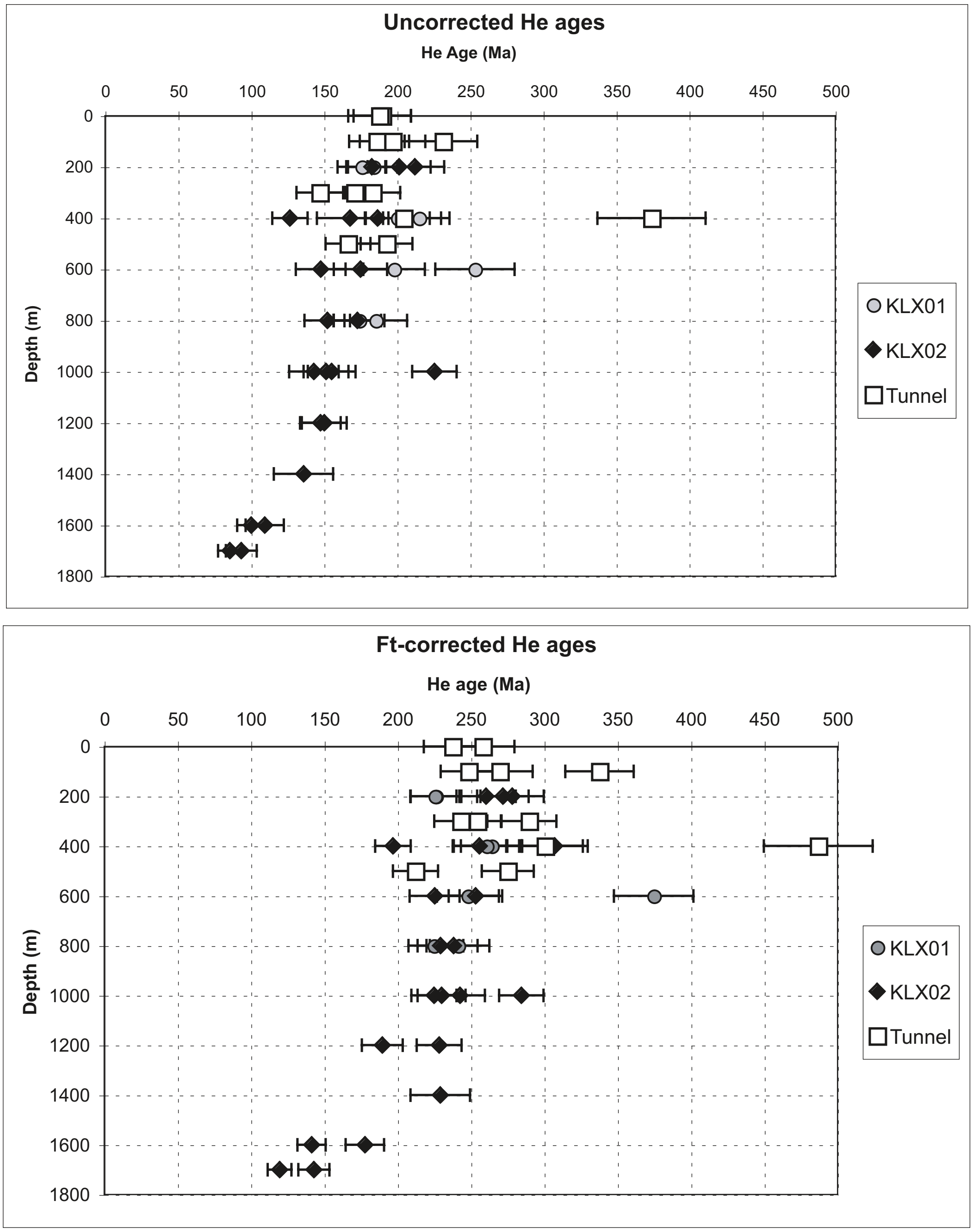


Figure 2-26. *Apatite (U-Th)/He age results from boreholes KLX01, KLX02 and the Äspö tunnel in the Laxemar-Simpevarp area. The upper diagram shows uncorrected ages whereas the lower diagram shows F_T-corrected ages. Uncertainties are reported with ±2σ. /after Söderlund et al. 2005b/.*

Different sets of deformation zones have been identified, modelled and assigned with properties in the Laxemar-Simpevarp area. Although commonly strongly overprinted by polyphase brittle deformation, the majority of these zones contain ductile precursors. This indicates that the gross structural framework was formed when the bedrock still responded to deformation in the ductile regime and discrete, low-temperature, brittle-ductile to ductile shear zones form the most prominent ductile structures in the area.

The brittle-ductile to ductile shear zones vary in size and occur all over the site investigation area. However, the Simpevarp subarea is more strongly affected by such deformation than at Laxemar. This is also indicated in the magnetic anomaly map where the Simpevarp subarea is characterised by a more banded anomaly pattern (Figure 2-27). The most conspicuous concentrations of ductile shear zones occur along two shear belts that strike NE-SW and mark the boundary between the Simpevarp subarea and Laxemar. These belts are referred to as zones NE004 and NE005 (Figure 2-24) and constitute two branches of what has traditionally been called the Äspö shear zone. The shear deformation along these belts is not homogeneous, but they are characterised by a considerably higher frequency of ductile shear zones (Figure 2-28) than in the surrounding country rock.

The ductile shear zones are interpreted to have developed under upper greenschist facies metamorphic conditions /Lundberg and Sjöström 2006/, i.e. at a temperature of c 450 to 500°C. Assuming that the blocking temperature in the $^{40}Ar/^{39}Ar$ amphibole isotope system is c 500°C, the younger $^{40}Ar/^{39}Ar$ amphibole age of 1773±13 Ma constrains the minimum age for the development of the ductile deformation at 1.76 Ga (1.78 Ga, if the 1% revision to older ages is carried out), while the crystallisation age of the rocks (Table 2-6) sets the maximum age for this deformation at 1.81 Ga. A close temporal relationship between the formation of the rocks and the ductile shear deformation is also supported by the variable field relationships between the emplacement of fine-grained granite dykes and the shear deformation. Some of these dykes are affected and cut by ductile shear zones, whereas others are unfoliated and truncate the shear zones /Lundberg and Sjöström 2006/. However, a muscovite that defines the mylonitic foliation in the Äspö shear zone (NE005) has yielded a $^{40}Ar/^{39}Ar$ age of 1.4 Ga (/Drake et al. 2007/ and Table 2-7). This age represents either a resetting of the $^{40}Ar/^{39}Ar$ muscovite system, due to heating by circulating hydrothermal hot fluids that are related to the 1.45 Ga granites, or ductile reactivation of the Palaeoproterozoic mylonite and new growth of muscovite at 1.4 Ga.

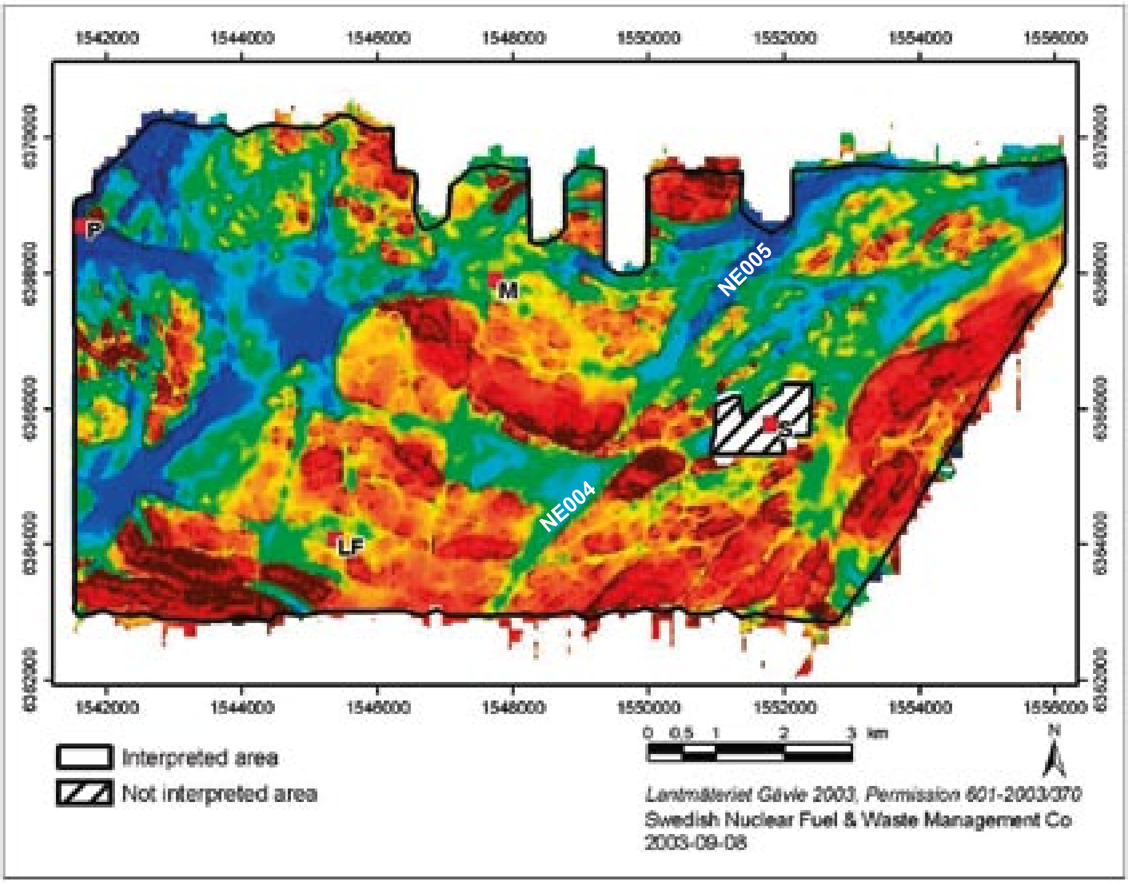


__Figure 2-27.__ Map showing the magnetic total field from the helicopter-borne survey in the Laxemar-Simpevarp area. M = Mederhult, P = Plittorp, S = Simpevarp, LF = Lilla Fjälltorpet

Figure 2-28. *Protomylonitic Ävrö granite within zone NE004 (Äspö shear zone) at Laxemar-Simpevarp.*

The regional scale, most prominent ductile shear zones are subvertical and strike N-S, NE-SW and E-W. A study of their kinematics /Lundberg and Sjöström 2006/ has revealed that the N-S and NE-SW oriented zones are characterised by sinistral strike-slip movement, whereas the E-W shear zones on the Simpevarp peninsula show complex kinematics. This includes both reverse and normal dip-slip as well as sinistral and dextral strike-slip displacements. It has been inferred that the ductile deformation along the various sets of zones formed in response to an approximately northward-directed shortening /Lundberg and Sjöström 2006/. Thus, it is feasible that the ductile shear zones in the Laxemar-Simpevarp area in TD5 formed in response to the same crustal shortening direction as the older ductile shear zones inside the tectonic domains to the north, including the Forsmark area in TD2 (cf. sections 2.2.1 and 2.3.4).

2.4.5 Thermal and structural influence of the Götemar and Uthammar granites

A sample of the Götemar granite has yielded a weighted average $^{40}Ar/^{39}Ar$ biotite age of 1421±4 Ma (Table 2-7), i.e. c 30 million years younger than the U-Pb zircon crystallisation age of 1452+11/–9 Ma (Table 2-6). If the 1% bias correction is applied to the $^{40}Ar/^{39}Ar$ biotite age, this difference will be reduced to c 15 million years. The $^{40}Ar/^{39}Ar$ biotite age is interpreted to reflect cooling of the intrusion through 300°C. In the lowermost part of KLX02 (c 1,605 m borehole length), $^{40}Ar/^{39}Ar$ amphibole and biotite ages of 1445±14 Ma and 1431±6 Ma, respectively, have been obtained. The higher age for the amphibole is consistent with the higher blocking temperature for amphibole. Furthermore, a surface sample of Ävrö granite close to the Uthammar granite near Fårbo yielded a $^{40}Ar/^{39}Ar$ biotite age of 1434±6 Ma.

These ages are inferred to reflect resetting of both the amphibole and biotite $^{40}Ar/^{39}Ar$ isotope systems, in response to a thermal influence in the country rock related to the intrusion of the c 1.45 Ga Götemar and Uthammar granites. It is reasonable to assume that, at increasing distance from, for example, the Götemar intrusion, the temperature in the bedrock after intrusion of this granite was lower, and that the drop in temperature below the respective $^{40}Ar/^{39}Ar$ blocking temperature occurred more rapidly. Thus, the cooling age is closer in time to the actual age of the granite with increasing distance from the intrusion and the youngest $^{40}Ar/^{39}Ar$ biotite age comes from the Götemar granite itself. As mentioned above, the $^{40}Ar/^{39}Ar$ muscovite age from the Äspö shear zone has also been interpreted in terms of either resetting in connection with the intrusion of the c 1.45 Ga granites or ductile reactivation at 1.4 Ga. Samples from c 1,000 m depth in KLX01 have yielded ages older than the intrusion and, for this reason, are interpreted as not being thermally affected.

In contrast to the samples from the lowermost part of KLX02, the c 1.77 Ga $^{40}Ar/^{39}Ar$ amphibole and 1.51 to 1.47 Ga $^{40}Ar/^{39}Ar$ biotite ages at the surface or in the upper parts of KLX02 indicate that the isotope systems in these samples were not reset in connection with the intrusion of the 1.45 Ga granites. Gravity modelling indicates that both the Götemar and Uthammar granites have considerably greater lateral extent in the subsurface relative to that observed at the surface (/Triumf 2004/ and Cruden, personal communication). This can explain why resetting of the $^{40}Ar/^{39}Ar$ isotopic systems in both amphibole and biotite is observed at considerable distances from the surface contacts of the intrusions. The modelled southerly dip of the southern contact of the Götemar granite /SKB 2006a, Wahlgren et al. 2006/ indicates that the lowermost part of the cored borehole KLX02 is situated closer to the Götemar granite than its upper part. Furthermore, the lowermost part of borehole KLX01 is interpreted to be located further away from this intrusion and this is in good agreement with the lack of resetting of the $^{40}Ar/^{39}Ar$ biotite isotope system in this borehole.

It is concluded that the 1.45 Ga Götemar and Uthammar granites are surrounded by thermal aureoles. Within these aureoles, circulating hot hydrothermal fluids were able to reset the $^{40}Ar/^{39}Ar$ isotopic system in both amphibole and biotite. This resetting occurred after establishment of the earlier cooling ages around 1.77 Ga and between 1.51 and 1.47 Ga, respectively.

The emplacement mechanisms and structural influence of the Götemar and Uthammar granites in the surrounding country rock have recently been evaluated (Cruden, personal communication). Based on the $^{40}Ar/^{39}Ar$ amphibole and biotite cooling ages, and assuming a geothermal gradient of 25°C/km, the emplacement depth for these granites is estimated to be between 4.5 and 8 km. Thus, the emplacement of the c 1.45 Ga granites occurred above the brittle-ductile transition. Field observations confirm that both granites are discordant to the structures in their wall rocks.

Both the geometries inferred from gravity modelling (/Triumf 2004/ and Cruden, personal communication) and the structural observations in the field (Cruden, personal communication) are consistent with an interpretation that both granites have the shape of a sill or laccolith (Cruden personal communication). The outward dipping upper contacts formed either by elastic bending of the overlying roof rocks or by magmatic stoping and thermally induced fracturing. Since the emplacements of the granites did not impose any ductile strain on their wall rocks, neither the Götemar nor the Uthammar granite is a "diapir". The apparent conformity of ductile wall rock structures with the southern contact of the Götemar granite is not related to its emplacement, but this structural pattern is rather inherited from the 1.81 to 1.76 Ga ductile deformational history in the surrounding TIB rocks (see section 2.4.4).

Although emplacement did not impose any ductile deformation on the wall rocks at the current level of exposure, elastic bending of the roof of the intrusion during its emplacement would most likely have resulted in brittle reactivation of suitably oriented pre-existing fractures and shear zones in the roof. Furthermore, the possibility that reactivation of pre-existing fractures and shear zones at Laxemar occurred at c 1.45 Ga cannot be excluded, but if so, fault displacement is judged to have been small. Another possibility is that roof bending was purely elastic, and that the elastic stresses were relaxed over time.

Although fracture fillings that are interpreted to be related to the Götemar and Uthammar granites exist (see section 2.4.6), these are mainly documented in boreholes that are located close to these granites, for example KLX06 that is inclined towards the Götemar granite.

However, it is not clear whether the circulating fluids, from which the fillings were precipitated, exploited pre-existing fractures without any shear displacement or whether faulting actually occurred along them at around 1.45 Ga. Stable isotope signatures in fracture minerals and wall rock alteration at Laxemar indicate that fractures were at least affected during the intrusion of these granites /Drake and Tullborg 2007/.

2.4.6 Brittle deformation and the regional perspective

Fracture minerals – relative time relationships and absolute ages

As at Forsmark, the establishment of the relative time relationship between different fracture mineral parageneses is primarily based on cross-cutting relations between fractures and the growth of different fracture minerals as observed in samples from drill cores. Stable isotope analyses on calcite, pyrite, gypsum and barite as well as strontium isotope analyses on calcite, fluorite, gypsum and whole-rock samples have also been carried out in order to investigate the fracture fillings and their relative time relationships. Geochemical analyses have further contributed to the subdivision into different fracture mineral generations. These generations include relatively high temperature minerals such as epidote (greenschist facies), lower temperature minerals such as prehnite (pumpelleyite-prehnite facies) and laumontite (laumontite-prehnite or zeolite facies) and low temperature minerals such as clay minerals. Examples of fracture fillings are displayed in Figure 2-29. The most abundant fracture minerals in the different generations are summarized below in decreasing relative age of formation /e.g. Drake and Tullborg 2007/:

- Generation 1 (oldest) mainly consists of quartz- and epidote-rich mylonite. It also includes muscovite, titanite, Fe-Mg-chlorite and albite. The deformation associated with this generation of minerals varies from ductile to brittle-ductile, in contrast to the deformation during the younger phases (see below) that is entirely brittle in character.
- Generation 2 consists of epidote-rich, green cataclasite with quartz and Fe-Mg-chlorite and a later phase of reddish brown cataclasite that consists of K-feldspar, chlorite, quartz, hematite and subordinate albite.
- Generation 3 consists of euhedral quartz, epidote, prehnite, laumontite, Fe-Mg-chlorite, calcite and adularia, with subordinate pyrite, fluorite, muscovite and amphibole. This is the most common fracture-filling generation in the area and the fractures show intense wall rock alteration with red staining.
- Generation 4 consists of calcite, followed by a dark red/brown filling that consists of adularia, Mg-chlorite, hematite and a later filling that is composed of calcite, adularia, laumontite, Mg-chlorite, quartz, illite and hematite.
- Generation 5 fracture fillings consist of calcite, adularia, Fe-chlorite, hematite, fluorite, quartz, pyrite, barite and gypsum, with subordinate harmotome, REE-carbonate, apophyllite, clay minerals, sulphides and laumontite.
- Generation 6 (youngest) represents the latest fracture minerals and consists of calcite with subordinate pyrite, clay minerals and Fe-oxyhydroxide (near surface). Stable isotopes indicate that these fillings may have precipitated in equilibrium with water similar to the current groundwater, i.e. are possibly Quaternary in age.

The $^{40}Ar/^{39}Ar$ ages for fracture minerals in the Laxemar-Simpevarp area are presented in Table 2-8 and the inferred timing and temperature of formation for the different generations of fracture fillings are displayed in Table 2-9. $^{40}Ar/^{39}Ar$ plateau ages for muscovite (generation 3 including greisen alteration) and for different generations of adularia (generation 3 or younger and generation 5) have been obtained (Table 2-8). Furthermore, a somewhat uncertain age has been obtained for illite from generation 4 or 5 (Table 2-8). $^{40}Ar/^{39}Ar$ dating of generation 3 amphibole and generation 5 apophyllite did not yield plateau ages (Table 2-8). All sampled fractures are situated along deformation zones or within bedrock that is affected by such zones.

Table 2-8. $^{40}Ar/^{39}Ar$ ages for fracture minerals in the Laxemar-Simpevarp area, based on /Drake et al. 2007/. The locations of boreholes are shown on Figure 2-24.

Borehole	Borehole length	Mineral	Fracture orientation	Method	Age
KLX02	676.82–677.00 m	Generation 5 apophyllite	Open fracture	$^{40}Ar/^{39}Ar$	No interpretable age defined
KLX03	970.04–970.07 m	Generation 5 apophyllite	Open fracture in DZ8 in the extended single hole interpretation	$^{40}Ar/^{39}Ar$	No plateau defined in the step-heating spectrum
KSH03A	181.93–181.98 m	Generation 5 adularia	Sealed fracture in zone NE024	$^{40}Ar/^{39}Ar$	400.9±1.1 Ma
KSH01A	256.90–257.10 m	Generation 5 adularia	Sealed fractures in DZ3 in the extended single hole interpretation	$^{40}Ar/^{39}Ar$	425.8±1.7 Ma
KSH03B	14.97–15.32 m	Generation 5 adularia	Sealed fracture	$^{40}Ar/^{39}Ar$	443.3±1.2 Ma 448.0±1.2 Ma
KSH03A	186.52–186.62 m	Generation 4 or 5 illite	Sealed fracture in zone NE024	$^{40}Ar/^{39}Ar$	No plateau defined in the step-heating spectrum. An integrated age of 488.5±1.1 Ma is inferred
KSH03A	863.66–863.84 m	Generation 3 or younger adularia	Sealed fracture cutting mylonite/cataclasite	$^{40}Ar/^{39}Ar$	989±2 Ma
KLX08	933.15–933.30 m	Generation 3 amphibole	Sealed fractures filled with amphibole	$^{40}Ar/^{39}Ar$	No plateau defined in the step-heating spectrum
KLX03	722.72–722.96 m	Muscovite in altered wall rock to fractures filled with generation 3 minerals	Wall rock alteration along sealed fractures oriented 100°/6° and 92°/25° in zone EW946	$^{40}Ar/^{39}Ar$	1417±3 Ma
KLX06	565.22–565.38 m	Generation 3 muscovite	Sealed greisen fracture oriented 328°/34°	$^{40}Ar/^{39}Ar$	1423±3 Ma
KLX06	595.08–595.18 m	Generation 3 muscovite	Sealed fracture oriented 277°/9°	$^{40}Ar/^{39}Ar$	1424±2 Ma
KLX06	535.10–535.26 m	Generation 3 muscovite	Sealed greisen fracture oriented 212°/7°	$^{40}Ar/^{39}Ar$	1424±2 Ma

Table 2-9. Interpreted timing, style and temperature of formation of the different generations of fracture minerals in the Laxemar-Simpevarp area (Drake, personal communication).

Mineral generation	Inferred timing of formation	Inferred style and temperature of formation
Generation 1	> 1.45 Ga	Ductile to brittle-ductile deformation
Generation 2	> 1.45 Ga	Brittle deformation
Generation 3	c 1.45 to 1.40 Ga or older	Brittle deformation, 195–370°C
Generation 4	c 1.40 Ga to 400 Ma (989 Ma)	Brittle deformation, 175–220°C
Generation 5	440 to 400 Ma	Brittle deformation, 80–150°C
Generation 6	400 Ma and younger	Brittle deformation, < 110°C

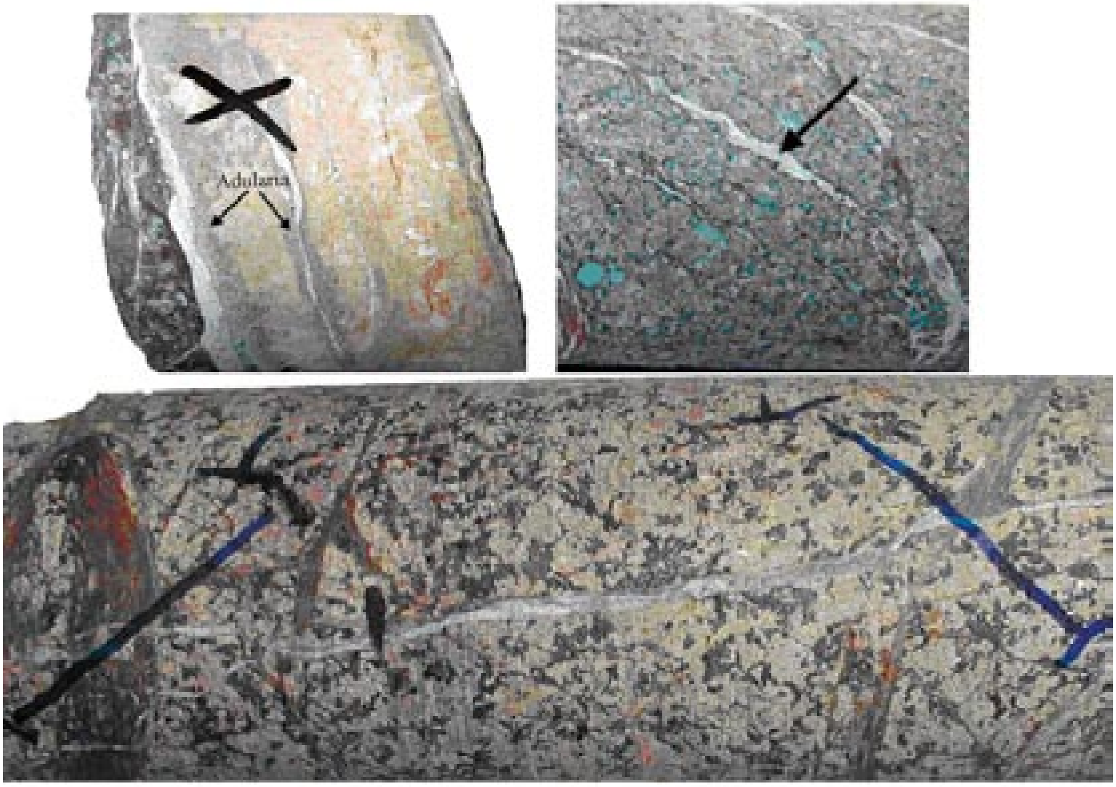


Figure 2-29. Drill core photographs of different fracture fillings in the Laxemar-Simpevarp area /Drake et al. 2007/. Upper left: Cataclasite (generation 2, dark colour, left) is cut by calcite-filled fractures (generation 3, white). The youngest fractures are filled with adularia (generation 5) and laumontite (orange colour). Upper right: Sealed fracture filled with adularia, calcite and hematite. Lower: Sealed fractures (generation 5), filled with calcite, adularia, Mg-chlorite, Fe-chlorite and pyrite etc, cross-cut brown-coloured cataclasite.

^{40}Ar/^{39}Ar dating of generation 3 muscovite from KLX03 (EW946) in southern Laxemar and muscovite from greisen alteration in KLX06 in northern Laxemar has yielded ages between 1.43 and 1.41 Ga (Table 2-8). These ages are interpreted to be related to the circulation of hot hydrothermal fluids that was effected by the intrusion of the Götemar and Uthammar granites, i.e. the far-field affects of the Hallandian orogeny. It is also inferred that the older generation 1 and generation 2 fracture minerals formed prior to 1.45 Ga.

Adularia from a fracture filling in KSH03A, which has been classified to belong to generation 3 or younger /Drake et al. 2007/, has yielded a plateau age on the ^{40}Ar/^{39}Ar step-heating spectrum around 989 Ma (Table 2-8). The age can be interpreted as either the age of crystallisation of the adularia or a complete resetting of the ^{40}Ar/^{39}Ar adularia isotope system /Drake et al. 2007/ in connection with the Sveconorwegian orogeny. If the second alternative is correct, then this generation of adularia is older than the plateau age.

Two splits of a sample of generation 5 adularia from KSH03B yielded plateau ages on the ^{40}Ar/^{39}Ar step-heating spectrum between 440 and 450 Ma (Table 2-8). The same generation adularia from fracture fillings in KSH01A has yielded an ^{40}Ar/^{39}Ar age of c 425 Ma, while an age of c 400 Ma has been obtained for generation 5 adularia from a fracture filling in deformation zone NE024 in KSH03A (Table 2-8). The adularia age from KSH03A also defines the maximum age for laumontite in the same fracture /Drake et al. 2007/. These Silurian to Early Devonian ages are interpreted as the crystallisation ages of the adularia /Drake et al. 2007/ and they are consistent with the inferred Palaeozoic "warm brine" origin of co-precipitated calcite, as revealed by stable isotope analysis (C and O) /Drake and Tullborg 2006a/. Calcite-fluorite fillings in the Götemar granite, which have been dated to 405±27 Ma /Sundblad et al. 2004/, show similar stable isotope results and mineral paragenesis as the fillings in generation 5 (Table 2-9). Illite from NE024 in KSH03A did not yield a plateau age. However, the integrated age of c 488 Ma from the defined $^{40}Ar/^{39}Ar$ step-heating spectrum is interpreted to be reasonable, since it is cut by Palaeozoic calcite /Drake et al. 2007/. On the basis of all these results, it is inferred that the generation 6 fracture minerals formed around or after 400 Ma.

Brittle deformation and hydrothermal fluid activity prior to establishment of the sub-Cambrian unconformity

As mentioned above, the bedrock at the current level of erosion in the Laxemar-Simpevarp area, had cooled below 500°C by 1.76 Ga. However, there remains a greater uncertainty concerning the cooling history after 1.76 Ga, in particular concerning the time when the bedrock passed through the brittle-ductile transition in the crust and entered the brittle realm.

The $^{40}Ar/^{39}Ar$ biotite age of c 1.62 Ga (duplicate analyses of one sample) is not interpreted to indicate slow cooling below 300°C after the crystallisation of the rocks at c 1.80 Ga, but rather that the $^{40}Ar/^{39}Ar$ biotite system closed earlier and was re-opened and subsequently closed again at c 1.62 Ga /Söderlund et al. in press b/. The re-opening of the $^{40}Ar/^{39}Ar$ biotite isotope system may be related to:

- Reheating in connection with the intrusion of 1.71 to 1.66 Ga TIB rocks further to the west during the Gothian tectonic development (see sections 2.2.2 and 2.2.3).
- Loading due to transport of erosional products eastwards from a Cordilleran type TIB mountain range.
- Reheating in connection with the intrusion of 1.65 to 1.47 Ma rapakivi granites and associated igneous rocks during and after the Gothian orogeny (see section 2.2.3). This phase of reheating has also been proposed to explain the $^{40}Ar/^{39}Ar$ biotite ages in the range 1.51 to 1.47 Ga /Page et al. 2007b, Söderlund et al. in press b/.

The hypothesis that involves one or more re-openings of the $^{40}Ar/^{39}Ar$ biotite isotope system, related to the intrusion of younger igneous rocks, implies that the bedrock was able to respond to deformation in a brittle regime a considerable time before 1.62 Ga, and that the c 1.45 Ga Götemar and Uthammar granites were emplaced into a cold, brittle crust. As discussed above (section 2.4.3), it is possible that the consistent differences in $^{40}Ar/^{39}Ar$ amphibole and biotite ages at Laxemar and in the Simpevarp subarea are related to faulting following the closure of these isotope systems, and that different crustal levels are present.

Generation 3 fracture fillings, which are interpreted to be c 1.45 Ga or older (Table 2-9), are common at Laxemar. These fracture fillings are suggested to have formed from circulating hydrothermal fluids which were related to intrusion of the c 1.45 Ga granites. This is supported by the c 1.42 Ga $^{40}Ar/^{39}Ar$ ages for muscovite in "greisen-like" alteration in the wall rock and around sealed fractures, which are mostly subhorizontal /Drake and Tullborg 2007/. It is inferred that hydrothermal activity in connection with brittle deformation was significant in the Laxemar-Simpevarp area during latest Palaeoproterozoic and early Mesoproterozoic time, i.e. during the Gothian and Hallandian tectonic events in the far-field realm.

The effects of Sveconorwegian tectonic activity are indicated by the $^{40}Ar/^{39}Ar$ ages for biotite and adularia of c 928 Ma and c 989 Ma, respectively, from KSH03A in the Simpevarp subarea (/Page et al. 2007b, Drake et al. 2007, Söderlund et al. in press b/ and Table 2-7 and Table 2-8). These data suggest that zone NE024, which dips to the NW in the sea area just outside the Simpevarp peninsula and Ävrö island, as well as fractures in the surrounding wall rock, were reactivated or at least injected by hot hydrothermal fluids as a far-field effect of the Sveconorwegian orogeny in the south-western part of Sweden. An additional indication of Sveconorwegian brittle tectonic activity is provided by the intrusion of c N-S trending, c 0.9 Ga dolerites in the westernmost part of Laxemar, which indicate that this area was affected by extensional deformation in an approximately E-W direction during the later part of the

Sveconorwegian orogeny. The emplacement of dolerite followed, at least in part, pre-existing deformation zones. Thus, the latter were reactivated in connection with the intrusion of the dolerites. However, the extent of the Sveconorwegian brittle deformation in the Laxemar-Simpevarp area is not known.

On the excavated bedrock surface at the drill site for boreholes KLX11A and KLX20A in westernmost Laxemar, N-S oriented fractures with a sinistral component of movement do not displace fractures that strike ENE-WSW and are filled with Cambrian sandstone (Figure 2-30a, /Viola and Venvik Ganerød 2007a/). This suggests that the former are Precambrian in age and have not been reactivated during the Phanerozoic. The strongly fractured dolerite with N-S strike in the deformation zone NS001, which has been intersected in KLX20A, is affected by frequent E-W and N-S oriented shear fractures. The E-W fractures dip gently to moderately, both to the north and south, and show both normal and reverse kinematics, while the N-S shear fractures are steeply dipping and display predominantly strike-slip kinematics /Viola and Venvik Ganerød 2007b/. The timing of this post-dolerite deformation is not known.

An evaluation of the kinematic data in the Laxemar-Simpevarp area with the purpose of developing a conceptual structural model for the area, using the same approach as that adopted in the Forsmark area /Stephens et al. 2007/, is presently ongoing. It is apparent that the kinematic data indicate a complex deformational history along the deformation zones that have been studied in the Laxemar-Simpevarp area. This suggests polyphase reactivation in response to variable stress regimes during the geological evolution.

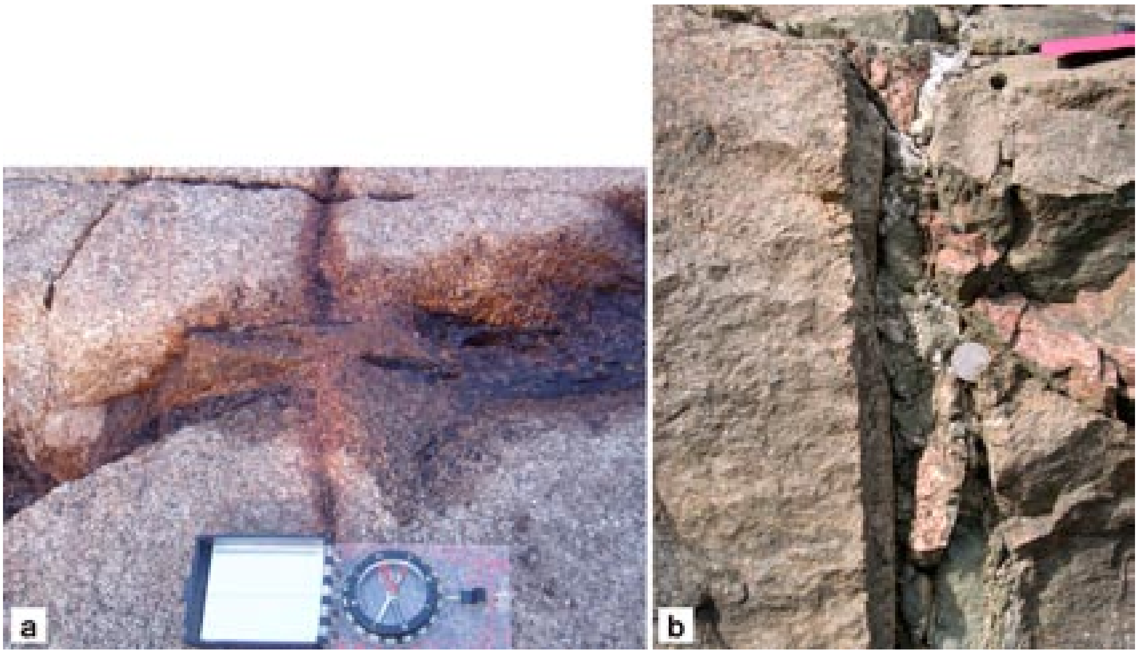


Figure 2-30. *Field relationships of fractures filled with Cambrian sandstone in the Laxemar-Simpevarp area. a) Fracture with ENE-WSW strike (left to right in picture) filled with Cambrian sandstone which is not affected by N-S trending shear fractures. Drill site for KLX11A and KLX20A. b) Brecciated and calcite-healed Cambrian sandstone in a narrow N-S trending fracture zone along a road cut immediately north of reactor 3 at the Oskarshamn nuclear plant. East-side-down displacement after formation of the Cambrian sandstone is indicated by the off-set of the fine-grained granitic dyke. Vertical section, view looking north.*

Faulting and fluid movement after establishment of the sub-Cambrian unconformity

The sub-Cambrian unconformity is a potential marker to demonstrate younger brittle deformation and fluid movement. In general, all pronounced depressions and distinct differences of topographic level in the sub-Cambrian unconformity constitute potential fracture zones or faults along which displacement has occurred after the establishment of this ancient landform.

In the strongly fractured dolerite in KLX20A, calcite of inferred Palaeozoic ”warm brine” type is affected by the shear fractures discussed above (Drake, personal communication). This indicates reactivation of these structures along deformation zone NS001 with N-S strike during the Palaeozoic. The northward extension of this fault affects the Götemar granite. Joints filled with Cambrian sandstone have only been found east of NS001, which indicates that the eastern part of the Götemar granite has been down-faulted with respect to the western part /Kresten and Chyssler 1976/. Thus, two independent lines of evidence indicate Palaeozoic reactivation of this fault in the westernmost part of Laxemar.

Further evidence for Palaeozoic faulting in the Laxemar-Simpevarp area is the documentation of fractures filled with Cambrian sandstone that are overprinted by brittle deformation (Figure 2-30b). Cambrian sandstone, which predates generation 5 mineral fillings, is also found in subvertical fractures in boreholes KLX11C, D and E down to 100 m vertical depth (Drake, personal communication). In addition, a fragment of Cambrian sandstone is present in the cored borehole KSH03A close to the hanging-wall of the NW-dipping deformation zone NE024 in the sea area outside the Simpevarp peninsula and Ävrö island.

Palaeozoic brittle reactivation and flushing of hydrothermal fluids along fractures within and close to zone NE024 in the Simpevarp subarea are also indicated by the $^{40}Ar/^{39}Ar$ ages for generation 5 adularia in the range 448 to 401 Ma (Table 2-8 and Table 2-9). Since generation 5 fracture fillings are present throughout the Laxemar-Simpevarp area /Drake and Tullborg 2007/, it is concluded that brittle reactivation and flushing of hydrothermal fluids during the Silurian or Early Devonian, as a far-field effect of the Caledonian orogeny, was a significant event in this area. This is in agreement with the observations elsewhere in the geological reference area (see section 2.2.3).

In KSH03A/B, an off-set is indicated in the (U-Th)/He age-depth profile (see section 2.4.3). The off-set occurs between 130 and 300 m borehole length. This interval coincides with the deformation zone NE024. It is inferred that movement along this zone displaced the rocks to their current position during a reactivation event sometime after c 180 Ma. Consequently, it is inferred that this deformation zone, apart from reactivation in connection with the Caledonian orogeny, has been reactivated during or after the Mesozoic. A similar off-set in the (U-Th)/He age-depth profile is indicated in KLX01 at Laxemar, suggesting that the rocks below 300 m borehole length have been down-faulted to their present position after c 180 Ma. However, no deformation zone has been identified in the geological single-hole interpretation that can explain the off-set in the (U-Th)/He age-depth profile at this borehole level.

Sedimentary loading and exhumation after establishment of the sub-Cambrian unconformity

The F_T-corrected (U-Th)/He apatite ages at or close to the surface in the Laxemar Simpevarp area indicate that a sedimentary cover was situated on top of the Proterozoic crystalline basement throughout the Late Palaeozoic and the Mesozoic, at least until the Early Cretaceous. If the uncorrected (U-Th)/He apatite ages are used, it is apparent that a sedimentary cover existed even later, from the Late Triassic to the Early Cretaceous. Independent of the difficulties in interpretation of (U-Th)/He apatite ages, both these alternatives indicate the presence of a substantial sedimentary cover sequence in the Laxemar-Simpevarp area during the Mesozoic and possibly also the Late Palaeozoic. Assuming a geothermal gradient of 25°C/km in the sedimentary rocks and a closing temperature for the (U-Th)/He apatite isotope system at 70°C, as carried out in the Forsmark area, it can be inferred that a sedimentary cover with a thickness of c 3 km was present after Palaeozoic time.

The decrease in (U-Th)/He apatite ages with increasing depth trace an exhumation history during the Mesozoic, and the change in slope along the (U-Th)/He age-depth diagram for KLX02 at c 1,400 m depth (see section 2.4.3) marks a change in exhumation and cooling rate /Söderlund et al. 2005b, Page et al. 2007b/. The exhumation rate calculated from the upper part of the drill core is c 17 m/Ma /Söderlund et al. 2005b/, which is close to that calculated for KLX01 /Page et al. 2007b/, whereas the data from the lower part of KLX02 yield a much slower exhumation rate of c 4 m/Ma /Page et al. 2007b/. The inflection point indicates that the slower exhumation rate initiated either during the Jurassic, if the F_T-corrected (U-Th)/He apatite ages are used, or during the Late Jurassic to Cretaceous, if the uncorrected (U-Th)/He apatite ages are adopted. In this context, it is worth noting that a marine transgression and accompanying new loading of sedimentary material took place in southernmost Sweden during the Cretaceous (see section 2.2.2). However, the (U-Th)/He data indicate that no resetting of this isotope system occurred during the Mesozoic /Söderlund et al. 2005b/. As for Forsmark, it is assumed that renewed exhumation of the sub-Cambrian unconformity did not take place until some time during the Cenozoic.

2.5 Summary and comparative evaluation of the bedrock geological evolution in the Forsmark and Laxemar-Simpevarp areas

The bedrock geological evolution in the Forsmark and Laxemar-Simpevarp areas has been evaluated with the help of similar surface and borehole observational data at each site as well as similar age determination data (Figure 2-31). The geochronological work has involved the analysis of different minerals in different isotopic systems with different blocking temperatures. The assembly of these geochronological data has been completed in order to reconstruct the temperature-time history from rock crystallization to the time the rocks were exhumed through the c 70°C geotherm, and to determine the age of certain fracture minerals.

The Forsmark area is situated inside tectonic domain 2 (TD2) in the geological reference area in south-eastern Sweden. An older suite of plutonic, calc-alkaline intrusive rocks formed between 1.89 and 1.87 Ga, and the metagranite inside the tectonic lens, where the target volume is situated, is included within this suite. Amphibolites that intrude the metagranite and a younger suite of calc-alkaline rocks and granites formed between 1.87 Ga and 1.85 Ga. These two suites of intrusive rocks (Figure 2-31) belong to the two Svecokarelian tectonic cycles at 1.91–1.86 Ga and 1.87–1.82 Ga, respectively, that have been recognised in south-eastern Sweden.

Deformation in the Forsmark area initiated between 1.87 and 1.86 Ga (Figure 2-31) with the development of a penetrative grain-shape fabric, with planar and linear components, that formed under amphibolite-facies metamorphic conditions and at mid-crustal depths. The development of broad belts with higher ductile strain that strike WNW-ESE to NW-SE and surround tectonic lenses with generally lower ductile strain also occurred around 1.86 Ga. The amphibolites and other intrusive rocks that belong to the younger suite intruded during the waning stages of and after the development of the penetrative, ductile strain in the area. Regional folding of the variably intense, planar grain-shape fabric also affected the amphibolites. Ductile deformation after 1.85 Ga occurred predominantly inside the belts with higher ductile strain. It successively became more focused along ductile high-strain zones within these belts and cooling ages indicate that ductile strain along these zones probably occurred until at least 1.8 Ga. Dextral transpressive deformation, which is related to bulk crustal shortening in an approximately northward direction during oblique subduction of oceanic lithosphere, is inferred. This subduction occurred beneath an ancient continental margin to the north-east.

The Laxemar-Simpevarp area is situated inside tectonic domain 5 (TD5) in the geological reference area. In strong contrast to Forsmark, the bedrock at Laxemar-Simpevarp formed after the complex geological evolution observed at Forsmark (Figure 2-31) and the intrusive rocks are more or less well-preserved. A c 1.80 Ga suite of intrusive rocks, which belongs to the Transscandinavian Igneous Belt, dominates the area (Figure 2-31). The rocks in this suite show variable composition (granite to quartz monzodiorite to diorite-gabbro), grain size and texture. They have been affected by magma-mingling and magma-mixing processes, and a close temporal and genetic relationship between the different rocks in this suite is inferred. They formed towards the end of the youngest Svecokarelian tectonic cycle in south-eastern Sweden at 1.83–c 1.79 Ga.

Although there is faint to weak ductile fabric in the intrusive rocks, which developed at a late stage in the magmatic evolution but continued to develop in the solid state after crystallization of the magmas, discrete, low-temperature, brittle-ductile to ductile shear zones form the most prominent ductile structures in the area. This deformation affected the area during the time interval 1.81 to 1.76 Ga, in response to an approximately northward-directed shortening. It is inferred that around and after 1.80 Ga, the tectonic regime in south-eastern Sweden continued to be steered by oblique subduction in an approximately northward direction.

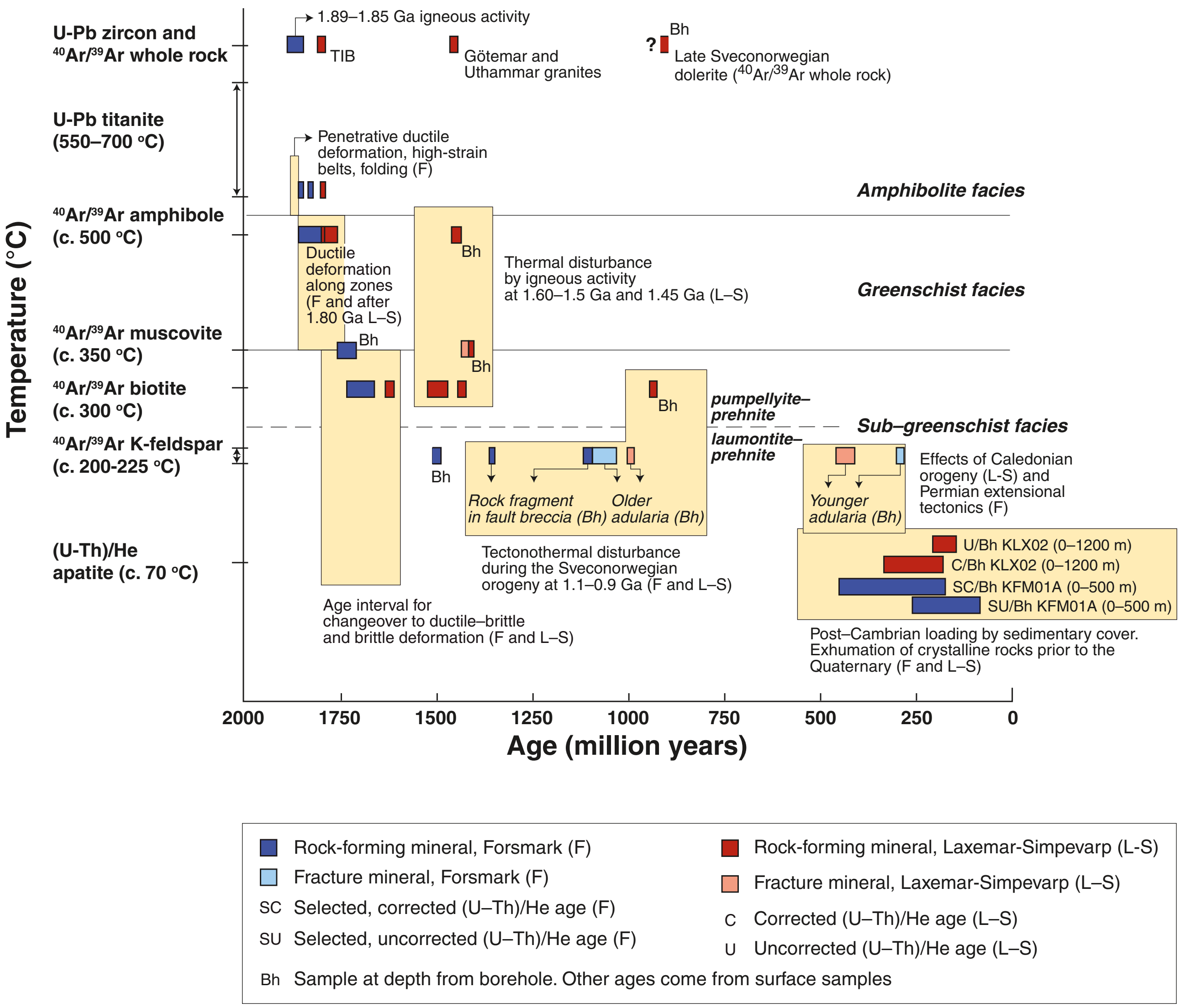


***Figure 2-31.** Summary of the geochronological data that constrain the bedrock geological evolution in the Forsmark and Laxemar-Simpevarp areas. Some $^{40}Ar/^{39}Ar$ and (U-Th)/He data from depth in boreholes are not shown here. As expected, these data are somewhat younger than the equivalent surface and near-surface data.*

In sharp contrast to Forsmark, the Laxemar-Simpevarp area was affected by significant igneous activity later on during the Proterozoic (Figure 2-31). Granitic magmatism at 1.45 Ga is inferred to be a far-field effect of Hallandian orogenic activity further to the west and south, and dolerites with an age of c 900 Ma formed as a result of approximately E-W crustal extension during the later part of the Sveconorwegian orogeny. As indicated by especially disturbances of the $^{40}Ar/^{39}Ar$ isotope system in different minerals (Figure 2-31), both these younger episodes of igneous activity had a significant effect on the thermal evolution of the site. However, the intrusion of the 1.45 Ga granites had only relatively minor effects on its structural evolution.

The brittle deformational history at Forsmark has been evaluated with the help of three lines of approach:

- The use of low-temperature geochronological data that shed light on the exhumation and cooling history (see section 2.3.3 and Figure 2-31).
- The relative time relationships and absolute ages of fracture minerals (see section 2.3.5).
- A comparison of kinematic data from brittle structures along deformation zones, which were evaluated during the geological modelling work at the site, with the tectonic evolution in a regional perspective (see section 2.2).

The same approach has been adopted in the Laxemar-Simpevarp area (see section 2.4.3, section 2.4.6 and Figure 2-31), apart from the use of kinematic data, which, at the present time, are not yet fully evaluated in a regional perspective. In both areas, the sub-Cambrian unconformity forms a key stratigraphic marker horizon. It provides a basis for dividing the brittle deformation and fluid circulation history that took place prior to the late Proterozoic exhumation of this ancient surface, from that which occurred after this exhumation event.

Different generations of fracture minerals have been recognised in both the Forsmark and Laxemar-Simpevarp areas. The more complex pattern at Laxemar-Simpevarp reflects a more complex hydrothermal fluid history relative to that observed at Forsmark. At both sites, an early period of precipitation of a high-temperature mineral assemblage, which includes epidote, was followed by a period of hydrothermal precipitation of different, lower temperature minerals, including adularia (older generation), hematite, prehnite, and calcite. At Forsmark, the fractures that bear epidote formed prior to 1.1 Ga, i.e. are pre-Sveconorwegian in age. In the Laxemar-Simpevarp area, epidote-bearing structures formed prior to 1.45 Ga, and fracture-controlled greisen (quartz, muscovite, fluorite, pyrite and topaz) and intense wall rock alteration developed in connection with the important thermal event at 1.45 Ga. Thermal disturbance around 1.5 Ga is also apparent. The effects of Sveconorwegian tectonothermal activity on the evolution of fracture mineral assemblages are evident at both sites (Figure 2-31). The integrated evaluation that makes use of the different lines of approach outlined above suggests that the different sets and sub-sets of deformation zones in the Forsmark area had formed and were already reactivated during Proterozoic time, in connection with the late Svecokarelian, Gothian and Sveconorwegian tectonic events.

Several lines of evidence indicate faulting after the establishment of the sub-Cambrian unconformity in both the Forsmark and Laxemar-Simpevarp areas. Furthermore, precipitation of younger low-temperature minerals, including sulphides, clay minerals and calcite, occurred during and probably after Palaeozoic time. At Forsmark, circulation of fluids in the crystalline bedrock, which originated from a sedimentary cover rich in organic material during the Palaeozoic, as well as growth of adularia (younger generation) during the Permian have been established (Figure 2-31). In the Laxemar-Simpevarp area, adularia (younger generation) formed during the Silurian or Early Devonian (Figure 2-31), possibly as a far-field effect of the Caledonian tectonic event. The youngest generation of calcite occurs in hydraulically conductive fractures and zones and may have precipitated during a long period including the present.

A conspicuous sedimentary cover was situated on top of the crystalline basement rocks throughout much of the Phanerozoic at both sites (Figure 2-31). However, in this context there are some differences between the two sites. At Forsmark, the crystalline bedrock close to the contact with the sedimentary overburden exhumed through the 70°C geotherm approximately 100 million years earlier relative to that at Laxemar-Simpevarp. Furthermore, although both sites appear to show a change in exhumation rate during the Phanerozoic, an increase in exhumation rate at Forsmark occurred approximately 50 million years earlier than a decrease in exhumation rate at Laxemar-Simpevarp. These changes in exhumation rate occurred either during the Permian or Jurassic at Forsmark and during the Early Jurassic or the Late Jurassic to Cretaceous at Laxemar-Simpevarp. It is assumed that renewed exhumation of the sub-Cambrian unconformity at both sites, with complete denudation of the sedimentary overburden, did not take place until some time during the Cenozoic.

Migration of fluids downwards from the sedimentary cover into the crystalline bedrock is apparent at both sites. At Forsmark, precipitation of, for example, oily asphaltite derived from Cambrian to Lower Ordovician oil shale occurred along fractures in the upper part of the bedrock, while infilling of fractures in the sub-Cambrian unconformity with Cambrian sandstone has been recorded in the Laxemar-Simpevarp area. Fluids, which transported glacial sediment, also migrated downwards and filled new or reactivated fractures at Forsmark during the later part of the Quaternary period.

In conclusion, there are both similarities and significant differences in the bedrock evolution at Forsmark and Laxemar-Simpevarp. Late Svecokarelian deformation along at least some of the deformation zones, and the far-field effects of the Sveconorwegian orogeny, in the form of both brittle deformation and thermal disturbance, are apparent in both areas. Evidence for faulting after the establishment of the sub-Cambrian unconformity and for the presence of a sedimentary cover during the Phanerozoic is also present. Furthermore, downward migration of fluids from the sedimentary cover into the crystalline bedrock is also conspicuous at both sites.

By contrast, the two areas are situated in distinctly different tectonic domains in south-eastern Sweden, with different earlier igneous and ductile deformational histories. In particular, an older and more complex early tectonic evolution took place at Forsmark. However, the younger geological history appears to have been more complex at Laxemar-Simpevarp. In particular, later igneous activity, in the form of the intrusion of granites at 1.45 Ga, which formed as a far-field effect of the Hallandian orogeny, and late Sveconorwegian dolerites, is restricted to the Laxemar-Simpevarp area. Furthermore, the history of hydrothermal activity in the Laxemar-Simpevarp area appears to be more complex. Whereas the far-field effects of early Gothian brittle deformation and hydrothermal flushing during the Permian are apparent at Forsmark, the Laxemar-Simpevarp area was affected by thermal disturbances around 1.6 Ga, 1.5 Ga and 1.45 Ga during the far-field Gothian and Hallandian orogenic events, and by brittle reactivation and flushing of hydrothermal fluids during the Caledonian orogenic event. Furthermore, exhumation of the crystalline bedrock through the 70°C geotherm appears to have occurred at a later stage during the Phanerozoic at Laxemar-Simpevarp. Finally, it needs to be emphasized again (see section 2.2.4) that there is also a major difference in the variation in the thickness of the crust in the parts of south-eastern Sweden where these two sites are located, with little variation in the Forsmark region and a marked thinning of the crust directly south of the Laxemar-Simpevarp area.

3 Geological development during the Quaternary period

3.1 Introduction

The Quaternary is the present geological period, which started 2.6 million years ago. It is characterised by a considerably colder climate than the previous period, called the Tertiary. The Quaternary climate is also characterised by large, sometimes fast, changes of global temperature. One effect of the large climate variation is the waxing and waning of large ice sheets, especially in the mid-latitudes of the Northern Hemisphere. Sweden is one area that has repeatedly been covered by glacial ice, which has had a great impact on the distribution of loose deposits and the shaping and morphology of the landscape. This has in turn affected the near-surface hydrology and the local distribution of soils and vegetation.

This chapter reviews all available site data concerning the development of Quaternary deposits and soils in the Laxemar-Simpevarp and Forsmark areas. Knowledge of past Quaternary environments is used to explain the distribution of Quaternary deposits in the two areas /Sohlenius and Hedenström 2008/. Information about the past can also be used for modelling the future development of the two model areas /SKB 2006bc/. A large part of the results and interpretations discussed in this chapter are based on investigations that have been carried out outside the Laxemar-Simpevarp and Forsmark model areas. The chapter is divided into three sections. The first section provides a review of the Quaternary development of Sweden wheras the second and third sections focus on the history of the Forsmark and the Laxemar-Simpevarp areas, respectively.

In this report, the term "Quaternary deposits" refers to the loose unconsolidated overlying the bedrock. These deposits may also be called regolith or overburden. The term Quaternary deposits is used since all known regolith in the Laxemar-Simpevarp and Forsmark areas was formed during the Quaternary period. Regolith includes all glacial and post-glacial sediments and peat. The upper part of the regolith is referred to as soil. Soils are formed by the interaction between overburden, climate, hydrology and biota.

3.2 Global development

Past variations in environmental factors such as climate and vegetation have affected the composition of the sediments which accumulate on the floors of lakes and sea. The oxygen isotope ratio of glacier ice on e.g. Greenland also varies as an effect of climate change. It has been possible to reconstruct environmental variations during the Quaternary period by studying cores of sediment and ice. Some of these records offer information about past environment on a local scale, whereas others are used to reconstruct the past global environment. Interpretation of the Quaternary development is of fundamental importance in explaining the distribution of regolith in Sweden and other areas that have been glaciated. Moreover, the properties of the soils are an effect of the past environment. The distribution of different soil types can, therefore, provide information on both past environmental conditions and past land use.

A combination of climatic oscillations of high amplitude, together with the intensity of the colder periods, is characteristic of the Quaternary period /Andersen and Borns 1997/. In Sweden, as well as in other areas situated at high and middle latitudes, the climate has alternated between cold glacial and warm interglacial stages. The glacial stages are further subdivided into cold phases, stadials, and relatively warm phases, interstadials (Figure 3-1). At the Geological Congress in London in 1948, the age of the Tertiary/Quaternary transition was determined to be 1.65 million years ago. Another viewpoint, however, suggests that the Quaternary period started c 2.6 million years ago /INQUA 2008, www/. The Quaternary period is divided into two geological epochs: the Pleistocene and the Holocene. The latter represents the present interglacial, which began c 9500 BC (Figure 3-1). There is still an ongoing debate about the rank of the Quaternary. Some authors have suggested to drop the term and to extend the Neogene period into the present. The current formal position of ICS (International Commission on Stratigraphy) is that the Tertiary and Quaternary are sub-era/sub-erathem in rank and Paleogene and Neogene have period/system rank.

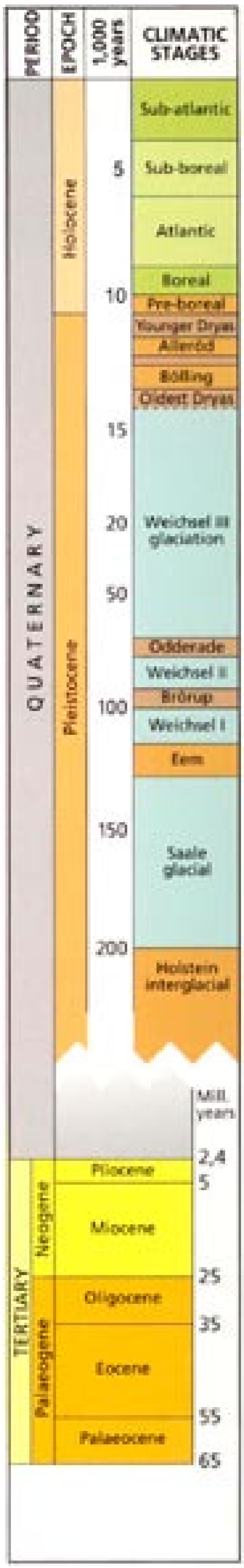


Figure 3-1. The geological timescale showing the subdivision of the late Quaternary period with climatic stages from /Fredén 2002/. The ages are approximate and given in calendar years before present (BP, i.e. before 1950 AD).

The most complete stratigraphies used in Quaternary sience are from the well-dated sediment cores retrieved from the deep sea, which have been used for analyses of e.g. oxygen isotopes /Shackleton et al. 1990/. The marine record has been subdivided into different Marine Isotope Stages (MIS), which are defined based on changes in the global climatic record, including changes in temperature and global ice-volume. Quaternary stratigraphies covering the time before the Last Glacial Maximum (LGM) are sparse in areas that have been repeatedly glaciated, such as Sweden. Furthermore, these stratigraphies are often disturbed by subsequent erosion and are difficult to date absolutely. Our knowledge of the pre-LGM Quaternary history of Sweden is, therefore, to a large extent based on indirect evidence from non-glaciated areas.

Results from the studies of the isotopic composition of deep-sea sediment cores suggest as many as fifty glacial/interglacial cycles during the Quaternary /Shackleton et al. 1990/. The climate during the past c 700,000 years has been colder than the earlier part of the Quaternary, and has been characterised by 100,000 year-long glacial periods interrupted by interglacials lasting for approximately 10,000–15,000 years (Figure 3-2). However, the duration of some interglacials, especially MIS 11, may have been twice as long /e.g. Droxler and Farrell 2000/.

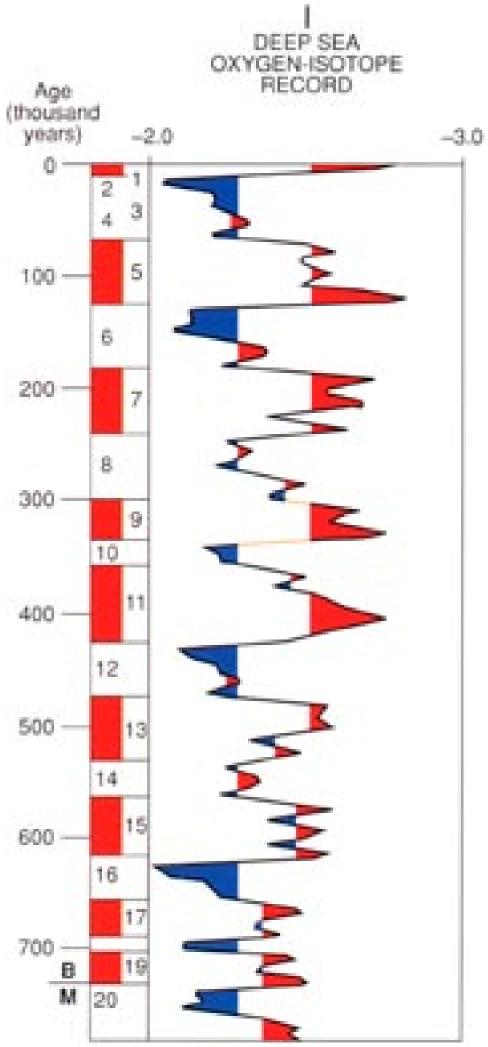


Figure 3-2. *A deep-sea isotope stratigraphy showing climate variations during the past 700,000 years. The red peaks represent warm or relatively warm interstadials and interglacials, whereas the blue peaks represent periods with a relatively cold climate. The interglacials are represented by the most pronounced red peaks /from Andersen and Borns 1997/.*

The coldest climate, and largest ice sheets, occurred towards the end of each of the glacial periods. In the glaciated areas, the mean annual temperature was 10–20°C lower than today during the coldest periods. Most research indicates that long-term climate changes (> 10,000 years) are triggered by variations in Earth's orbital parameters /Milankovitch 1941/. However, these variations are too small to fully explain the large climate variations that occurred during the Quaternary period. The orbital changes may act as a trigger, e.g. affecting the flow of warm air and water from low to high latitudes. For example, during the latest glacial period the warm North Atlantic Drift, a northern branch of the Gulf Stream, did not reach as far north as at present. The warm interglacials are relatively short compared with the glacial periods. It is therefore likely that the present Holocene interglacial will be followed by a long period of colder climate, and Scandinavia will probably be covered by ice again, exemplified by the future scenarios in /SKB 2006c/. However, some scientists argue that the current warm climate may last another 50,000 years, with or without human perturbations /e.g. Berger and Loutre 2002/. Quaternary climatic conditions, with a focus on Sweden, have been reviewed in several SKB reports /e.g. Holmgren and Karlén 1998, Boulton et al. 1999, Morén and Påsse 2001, Hohl 2005/. The anthropogenic burning of fossil fuel is causing increasing atmospheric concentrations of greenhouse gases, mainly CO_2. According to e.g. /IPCC 2007/, these gases will most likely cause a warmer global climate in the future due to an increased greenhouse effect. This effect is expected to cause a greater increase in temperature in Sweden than the global average increase /Ministry of the Environment 2007/. It is possible that the changes in climate will persist for tens of thousands of years /Texier et al. 2003/ and may delay the transition into glacial conditions.

3.3 Quaternary development of Sweden

3.3.1 Regolith in Sweden older than the latest glaciation

In most parts of Sweden, the relief of the bedrock is mainly of Pre-Quaternary age and has only been slightly modified by glacial erosion /Lidmar-Bergström et al. 1997/. Before the onset of the Quaternary glaciations, Sweden was probably covered to a large extent by a layer of weathered bedrock. In Sweden, average erosion during the Quaternary period has been estimated to be equivalent to 12 m of fresh bedrock /Påsse 2004/. In the same report, the average erosion of bedrock during one glacial cycle is estimated to be 1 m. These calculations are based on the volumes of Quaternary deposits present in onshore and offshore areas. The magnitude of the glacial erosion seems, however, to vary considerably geographically. That is evidenced by the pronounced glacial erosion that has taken place during the formation of the Norwegian fjords. Pre-Quaternary deep weathered bedrock occurs in areas such as the inland of eastern Småland, southern Östergötland and the central parts of northernmost Sweden /Lundqvist 1985, Lidmar-Bergström et al. 1997/. The occurrence of deep-weathered bedrock indicates that these areas have only been affected to a small extent by glacial erosion. /Lokrantz and Sohlenius 2006/ recently reviewed the reported occurrences of weathered bedrock in Sweden and their results are summarised in Figure 3-3. The occurrence of weathered bedrock in Sweden has not been systematically studied and the number of sites with such deposits is probably much larger than shown on the map. It is consequently possible that there are other areas, not indicated on the map, where the glacial erosion has been low throughout the Quaternary period. The weathered bedrock is often referred to as saprolite. There are four regions (Figure 3-3) where a large number of sites with weathered bedrock indicate that glacial erosion probably has been of minor importance throughout the Quaternary period:

I) At the border between Skåne and Småland and in easternmost Blekinge, several sites with kaolin-weathered bedrock.

II) Central and eastern parts of the South Swedish Highland, a large number of localities with granular weathered bedrock.

III) Central Sweden, numerous localities with granular weathered bedrock.

IV) Northernmost Sweden and Finland, several localities with granular weathered bedrock.

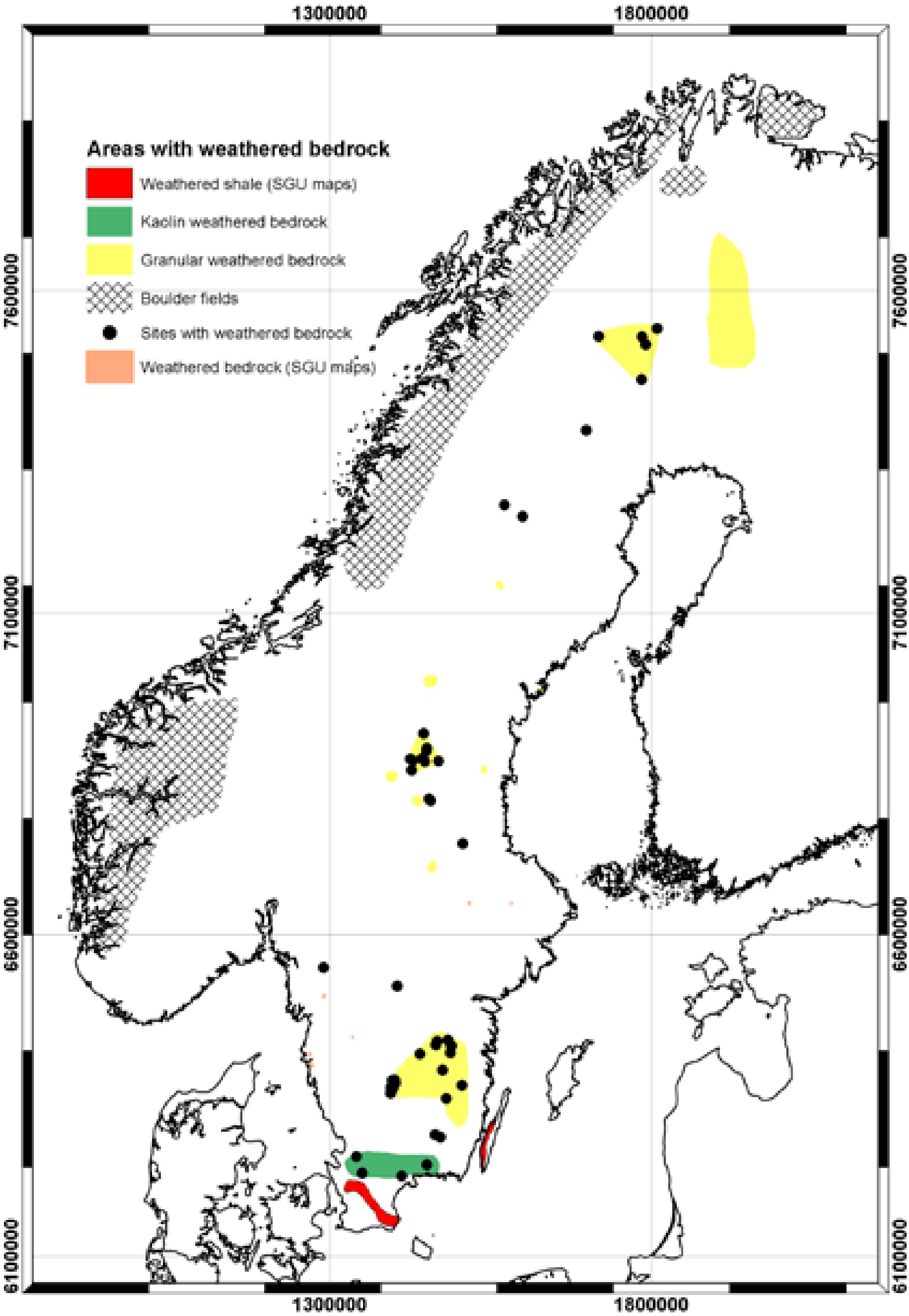


Figure 3-3. *The distribution of areas and sites with different kinds of weathered bedrock in Fennoscandia /from Lokrantz and Sohlenius 2006/. The granular and kaolin-weathered bedrock were probably formed by weathering taking place before the onset of the Quaternary glaciations. These deposits occur in areas which have experienced relatively low glacial erosion. The weathered shale was probably formed as a consequence of weathering that took place after the latest deglaciation.*

Processes taking place after the latest deglaciation probably formed the weathered bedrock in areas with shale (e.g. on Öland and in Skåne and Västergötland, see Figure 3-3). In some areas there are occasional occurrences of granular weathered bedrock (e.g. on the Swedish west coast). The weathered bedrock in these areas has probably been preserved at positions that have been protected from glacial erosion and can therefore not be used as evidence of generally low glacial erosion.

During the latest ice age, the Weichselian, the northern part of Fennoscandia was covered by ice at least three times /e.g. Lagerbäck and Robertsson 1988, Lundqvist 1992/. In some areas, such as in large parts of the interior of northern Sweden, Quaternary deposits and morphological features (e.g. eskers and hummocky moraine) pre-dating the last glacial phase of the Weichselian occur frequently /Kleman et al. 1997, Lagerbäck and Robertsson 1988, Lagerbäck 2007a/ (Figure 3-4). That indicates that the subsequent phases of ice sheet coverage had a low erosional capacity /Hättestrand and Stroeven 2002, Kleman et al. 1997, Lagerbäck and Robertsson 1988/. Such deposits also occur in areas such as Skåne, which has been glaciated for a much shorter period of time. It must be pointed out that stratigraphical studies of Quaternary deposits have not been carried out systematically in the whole of Sweden. Deposits from older glaciations may, therefore, also occur frequently in other parts of Sweden.

3.3.2 Pleistocene development in Sweden

The Pleistocene Epoch, starting 1.8 million years ago, embraces the main part of the Quaternary period, starting 2.6 million years ago and ending at the transition to the present Holocene interglacial, 9500 BC. The global oxygen isotope record indicates numerous glaciations during the Quaternary period. Several of these glaciations have probably affected Sweden. It is, however, at present impossible to state the total number of Quaternary, and possible Pre-Quaternary, glaciations in Sweden.

In Sweden, preserved Quaternary deposits from the period predating the Last Glacial Maximum (LGM) are, as mentioned above, fragmentary. Deposits from that time have mainly been found in areas that have been covered by ice sheets during a relatively short period of time, such as Skåne and Halland /e.g. Påsse et al. 1988/, or where glacial erosion has been low due to cold-based ice conditions. It has been suggested that these latter conditions occurred in the inner parts of northern Sweden during the middle and late parts of the latest glaciation /e.g. Lagerbäck and Robertsson 1988/, the Weichselian. It is possible that pre-LGM deposits are also common in other areas where glacial erosion probably has been low. One such area is parts of South Swedish Highland, where the occurrences of weathered bedrock (Figure 3-3) indicate low glacial erosion. There are some glaciofluvial deposits in Småland that may pre-date the latest deglaciation /Lokrantz and Sohlenius 2006, Alexanderson and Murray 2007/. That issue will hopefully be resolved when the major part of Sweden has been subjected to systematic stratigraphic studies.

Most pre-LGM Pleistocene deposits have been correlated with the stadials and interstadials that occurred during the early Weichselian (Figure 3-4). There are, however, a few sites with older Pleistocene deposits (Figure 3-4). Inorganic deposits such as glacial till have not been dated with absolute methods and such deposits may therefore have been formed at early stages of the Quaternary period.

There are traces of three large glaciations, Elster (MIS 12 or possibly 10), Saale (MIS 6) and Weichsel (MIS 2–5d), that reached as far south as northern Poland and Germany /e.g. Fredén 2002/. There were two full interglacials, Holstein and Eem, between these glacials. The Saale had the largest maximum extension of the Eurasian ice sheets during the Quaternary. It is, however, likely that Quaternary ice sheets reached Poland and Germany more than three times and some of the till beds correlated with Saale and Elster may be of an older age /cf. Andersen and Borns 1997/. Both Saale and Elster were probably characterised by alternating ice-free interstadials and stadials when large parts of Fennoscandia were covered with ice.

Figure 3-4. *Sites with findings of interglacial or interstadial deposits /Fredén 2002/.*

The oldest identified interglacial deposits in Sweden (dated by fossil composition), were probably deposited during the Holstein interglacial (MIS 11, 400,000 years ago or possible MIS 9, 325,000 years ago, see Figure 3-4) /e.g. Garcia Ambrosiani 1990/. Sweden at that time was covered by forest, which according to the composition of pollen was dominated by various coniferous species and a low frequency of broad-leafed trees, at least during some part of the interglacial. The till underlying the Holsteinian deposits may have been deposited during Elster and is the oldest known Quaternary deposit in Sweden. Deposits from the Eemian (Figure 3-4) interglacial (MIS 5e, 130,000–115,000 years ago) are known from several widely spread sites in Sweden /Robertsson et al. 1997/. During the Eemian the climate was periodically 1–2°C warmer than it has been during the present interglacial /Fredén 2002/. Pollen analyses show that the composition of trees was similar to today, but some warmth-demanding species had a more northerly distribution /Robertsson and Garcia Ambrosiani 1992/. The sea level was, at least periodically, higher than at present /Eronen 1989, Robertsson et al. 1997, Funder et al. 2002/ and large parts of the Swedish lowland were probably covered with brackish or marine water (Figure 3-5). There are several findings showing that brackish conditions prevailed in the Baltic Sea during the Eemian interglacial /Robertsson et al. 1997/. /Funder 2000/ studied the mollusc faunas in Eemian deposits from the Baltic Sea. He concluded that the Baltic had a salinity 5–10‰ higher than at any time during the present interglacial /see Westman et al. 1999/. Several authors have suggested that a connection existed between the Baltic Sea and the White Sea (Figure 3-5) during the Eemian interglacial /Eronen 1989/. That may explain the relatively high salinity during that time.

The latest glacial, the Weichselian, started c 115,000 years ago. It was characterised by colder stadials, interrupted by phases with milder climate, interstadials. Numerous sites with deposits from the early part of the Weichsel are known from the inner parts of northern Sweden. The models presented by e.g. /Lundqvist 1992/ and /Fredén 2002/ are often used to illustrate the history of Weichselian glaciation (Figure 3-5). The climate records from Fennoscandia have been correlated with records from other parts of western Europe (Figure 3-6). Terrestrial records have been further correlated with results from isotope analyses of deep-sea sediments (Figure 3-6). Two interstadials took place during the early part of the Weichsel, approximately 100,000–90,000 (MIS 5c) and 80,000–70,000 years ago (MIS 5a). Most of Sweden was free of ice during these interstadials, but the climate was considerably colder than today and tundra with shrub vegetation probably characterised northern Sweden /Lagerbäck 2007a/. Southern Sweden may have been covered with coniferous forests during the first of these interstadials. The second interstadial (correlated with MIS 5a) was colder /e.g. Lagerbäck 2007a/ and the vegetation in southern Sweden was probably characterised by sparse birch forest.

It can be assumed that permafrost condition prevailed in large parts of Sweden during the Weichselian interstadials and frost processes probably had a large impact on the regolith. There are only a few publications reporting evidences of frost processes during the Weichselian interstadials. /Hättestrand 1994/ suggests that boulder depressions in northern Sweden have been formed as an effect of frost processes taking place before the latest Weichselian glacial phase. In northernmost Sweden, /Lagerbäck 1988/ found frost-shattered bedrock and ice-wedge casts, which are assumed to have formed during the second Weichselian interstadial. Lagerbäck also found stones and boulders that probably have been polished by wind blown snow during the same interstadial. These so called ventifacts indicate a climate considerably colder than the present.

Most researchers agree that the ice sheet did not reach further south than the Mälaren Valley during the Early Weichselian stadials. The ice advanced south and covered southern Sweden first during the Mid Weichselian (c 70,000 years ago). Most of Sweden was thereafter probably covered by ice until the deglaciation. Parts of Skåne were, however, free of ice until a few thousand years before the LGM.

The models presented by /Fredén 2002/ and /Lundqvist 1992/ (Figure 3-5) have been debated /cf. Lokrantz and Sohlenius 2006/. Most researchers agree that at least two interstadials, with ice-free conditions in most of Sweden, did occur within the Weichselian glaciation. However, since the dating of such old deposits is problematic, the timing of these interstadials is uncertain.

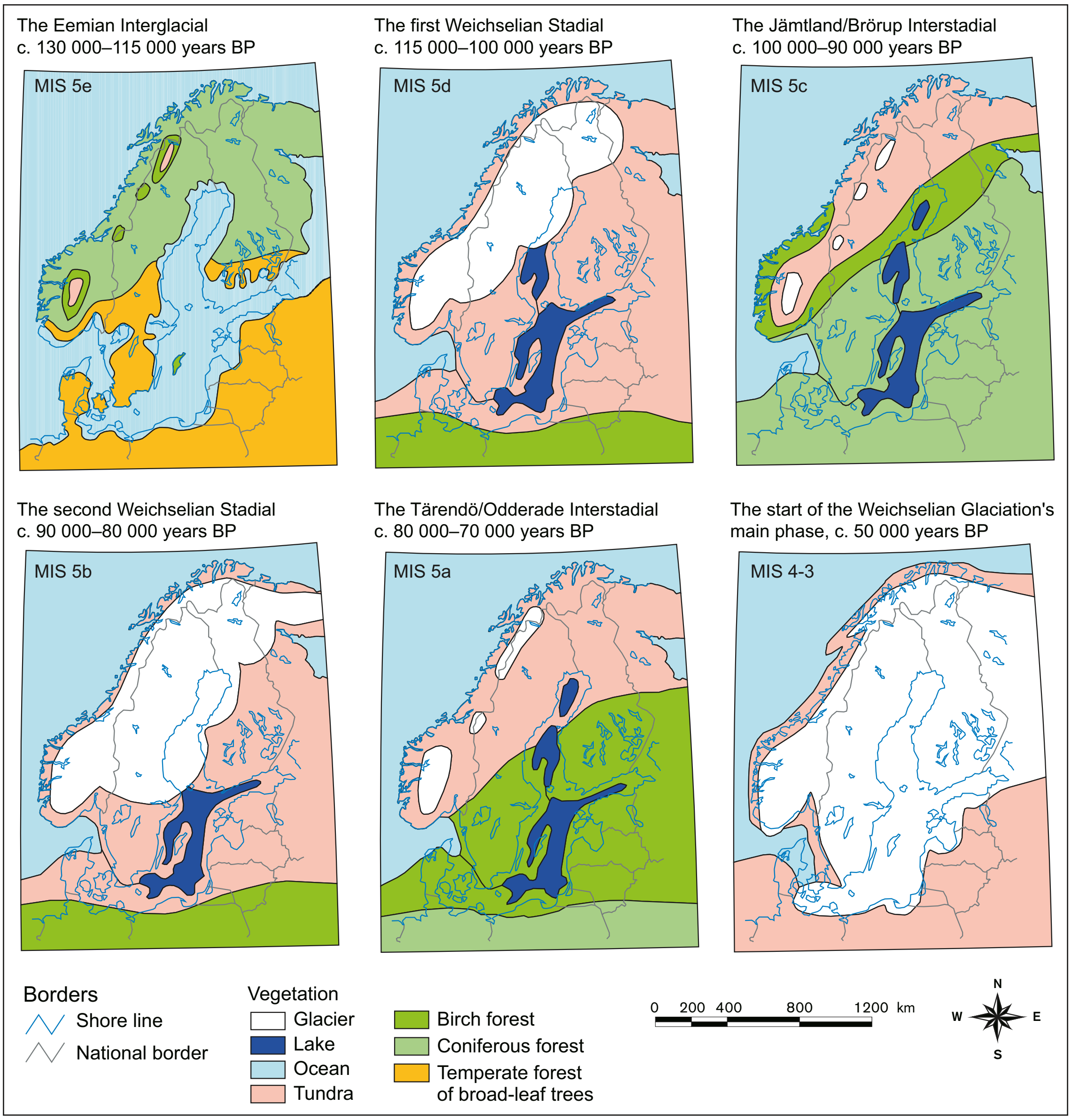


Figure 3-5. *The development of vegetation and ice cover in northern Europe during the latest interglacial (Eem) and first half of the latest ice age (Weichsel). The different periods have been correlated with the Marine Isotope stages (MIS). The maps should be regarded as hypothetical due to the lack of well dated deposits from the different stages /from Fredén 2002/.*

Investigations from both Finland and Norway suggest that large parts of the Nordic countries may have been free of ice during parts of Mid Weichselian (MIS 3) /e.g. Olsen et al. 1996, Ukkonen et al. 1999, 2007/. These new findings, however, are contradicted by the Danish OSL-based glaciation chronology /Houmark-Nielsen and Kjær 2003/, for the Weichselian. That may also imply that the second of the interstadials attributed to the Early Weichselian by /Fredén 2002/ could have occurred during the Middle Weichsel. In large parts of Sweden, the total time of ice cover during the Weichsel may therefore have been considerably shorter than previously suggested by e.g. /Fredén 2002/ and /Lundqvist 1992/.

During the Last Glacial Maximum (LGM), c 18,000 BC (MIS 2), the continental ice reached its southernmost extent (Figure 3-7). The Weichselian ice sheet reached as far south as the present Berlin, but had a smaller maximum extent than the two preceding glacials (Saale and Elster). A comprehensive compilation of interpreted ice sheet fluctuations during the Weichselian is found in /Lokrantz and Sohlenius 2006/.

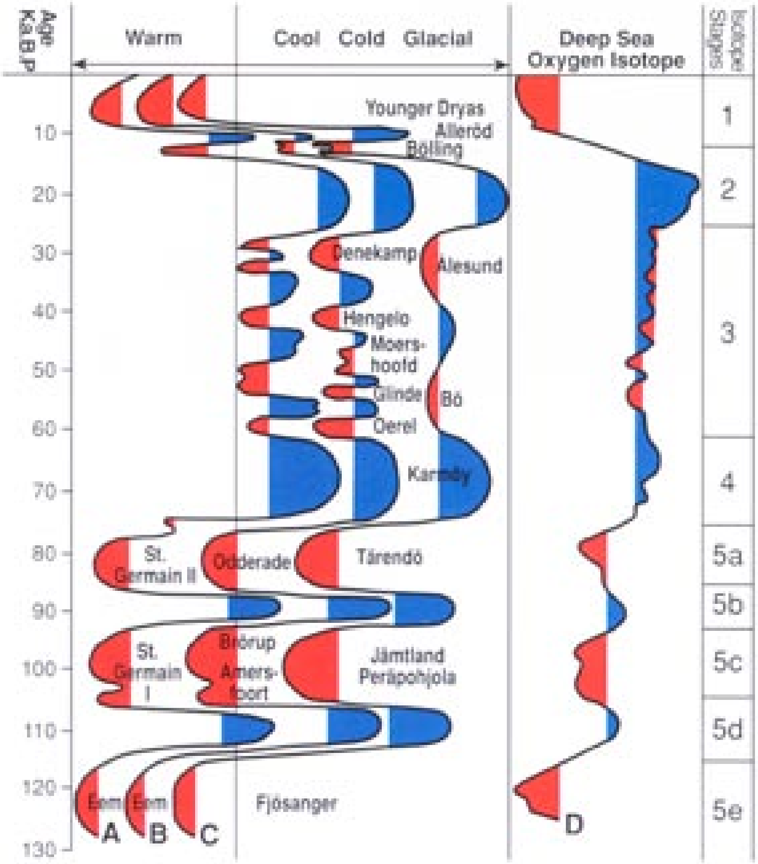


__Figure 3-6.__ Climate fluctuations recorded from three areas in western Europe in combination with the climate record from the deep sea. A, Northern France (pollen-analysed bog deposits), B, Holland and northern Germany (pollen analyses), C, Fennoscandia (litho- and biostratigraphical studies), D, Deep-sea oxygen-isotope curve. The red peaks represent warm or relatively warm periods and the blue peaks represent cold periods /from Andersen and Borns 1997/.

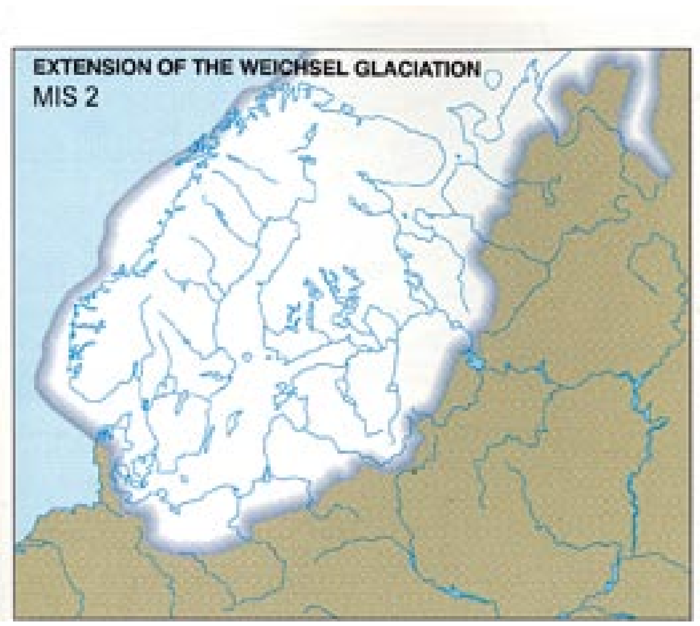


__Figure 3-7.__ The maximum extent of the latest ice age, the Weichselian, approximately 18,000 BC /from Fredén 2002/.

A large amount of freshwater was stored in the global ice sheets throughout the last ice age. The global sea level was therefore lower than at present and it is likely that the Baltic Basin was isolated from the sea and characterised by freshwater conditions (Figure 3-5). Several researchers /e.g. Lagerlund 1987/ have suggested that the Baltic was drained by a river which was situated in the Alnarp Valley in Skåne during parts of the Weichselian interstadials.

3.3.3 Latest deglaciation

A change to a warmer climate took place about 16,000 BC, shortly after the LGM. Consequently, the ice sheet started to withdraw, a process that was completed after some 10,000 years (Figure 3-8).

***Figure 3-8.** The deglaciation of Sweden /from Fredén 2002/. The timing of the deglaciation was determined with ^{14}C dates on the west coast and with clay varve chronology on the east coast. The ages have been converted to calibrated years BP (Before Present). Red numbers = calendar years BP, blue numbers = clay varve years BP, black numbers = ^{14}C years BP.*

The timing of the deglaciation of Sweden has been determined by ^{14}C dates and clay-varve chronology. The latter dating method is based on correlation of annually deposited sedimentary layers, which often are present in the glacial clay /De Geer 1912/. The deglaciation chronology of eastern Sweden, including the Laxemar-Simpevarp and Forsmark areas, has mainly been established by using clay-varve chronologies /e.g. Kristiansson 1986, Strömberg 1989, Brunnberg 1995, Ringberg et al. 2002/, whereas the timing of the deglaciation in other parts of Sweden has mainly been determined by ^{14}C dates. These two chronologies have recently been calibrated to calendar years /Lundqvist and Wohlfarth 2001, Fredén 2002/.

There were several standstills and even readvances of the ice front during the deglaciation of southern Sweden. In western Sweden, zones with end moraines (ridges formed parallel to the ice front) reflect these oscillations (Figure 3-9). In south-eastern Sweden, less clear and continuous end moraines developed, partly because a lot of stagnant ice remained in front of the retreating ice sheet. The correlations of ice marginal zones across Sweden are, therefore, problematic and it has, therefore, not been possible to reconstruct the exact timing of the deglaciation in all areas of Sweden.

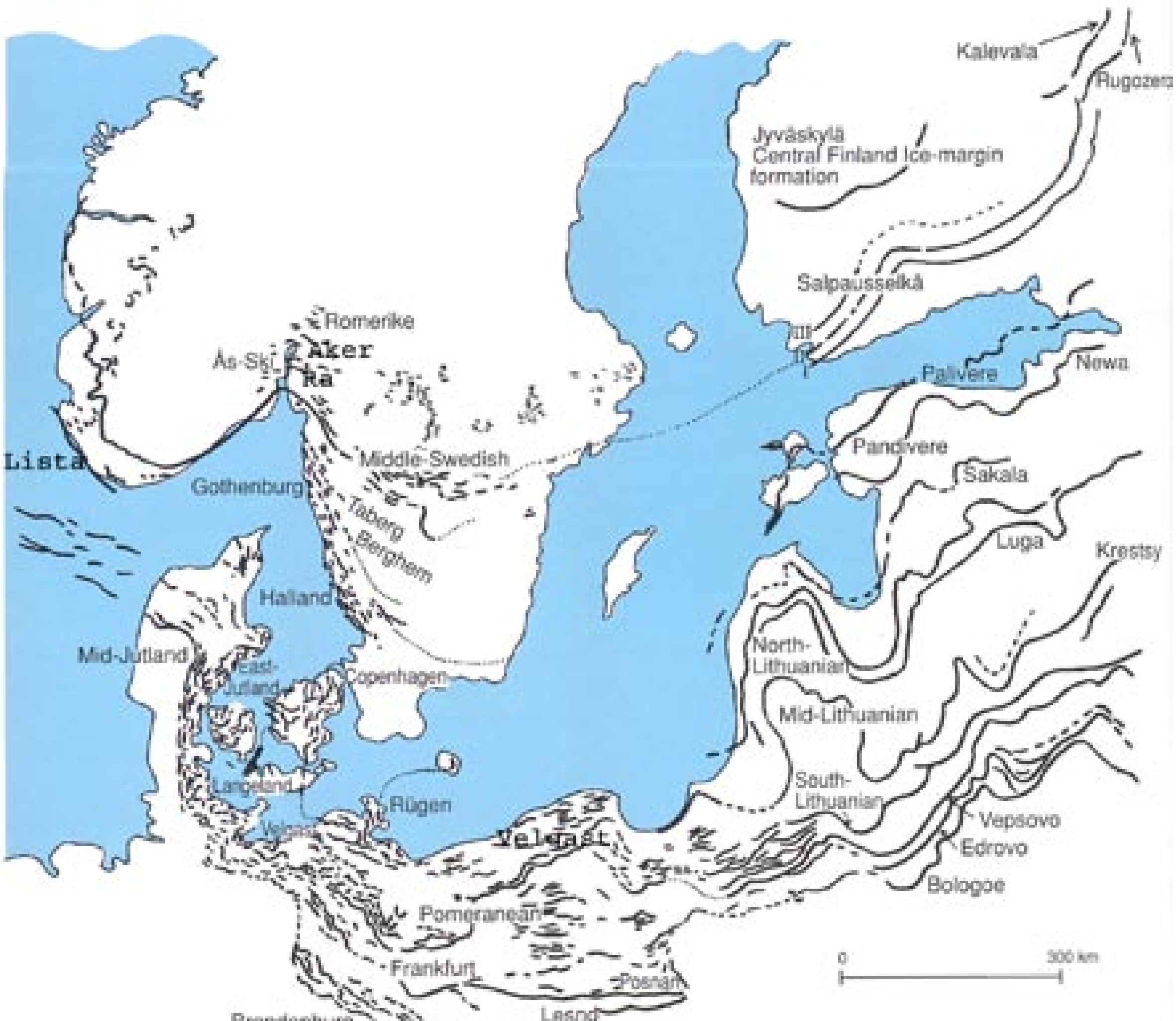


__Figure 3-9.__ End moraines formed during the Last Glacial Maximum (LGM) and the latest deglaciation. The solid lines indicate marginal formations and the dashed lines correlations between known marginal formations /from Andersen and Borns 1997/. Approximate radiocarbon ages in years BC: Brandenburg-Leszno: 18,000; Frankfurt-Poznan 15,000; Pomeraneian: 13,000; Mid-Lithuaneian-Velgast-Copenhagen: 12,000; Luga-Rügen-Halland-Lista: 11,500; Pandivere-Gothenburg: 10,500; Berghem: 10,300; Taberg: 10,000; Ra-Middle Swedish-Salpausselkä: 9000–8300 (8500); Aas-Ski: 8500–8200; Aker: 7800; Romerike-Jyväskylä: 7600–7500. Some of the moraines are not well dated. Moreover, the correlations between e.g. Sweden and the eastern Baltic area are uncertain.

During a cold period called the Younger Dryas (c 12,850–11,650 years ago), there was a major standstill, and in some areas a readvance, of the ice front. At that time, the ice front had an east-west extension across Dalsland, Västergötland and Östergötland (Figure 3-8). The end of Younger Dryas marks the onset of the present interglacial, the Holocene. The ice retreated more or less continuously during the early part of the Holocene and the last ice remnants disappeared from northern Sweden c 7000 BC.

3.3.4 Climate after the latest deglaciation

At several sites in southern Sweden there are relict tundra polygons (i.e. a pattern of fissures on the surface of the ground) and other features, which formed during the Younger Dryas as an effect of permafrost /Svensson 1982/. However, since the Forsmark area was not yet deglaciated and the Laxemar-Simpevarp regional model area was completely covered by water during that period, there is no reason to suggest that any of these areas were affected by permafrost during Younger Dryas. The timing and climatic development of the transition between the Pleistocene and the Holocene has been discussed by e.g. /Björck et al. 1996/ and /Andrén et al. 1999/. It has been shown that the onsets of the cold Younger Dryas stadial and the early Holocene warming were extremely rapid, with substantial temperature changes within a period of less than a hundred years. According to /Björck et al. 1996/, the fast decline in temperature at the onset of Younger Dryas was due to the input of large amounts of freshwater into the North Atlantic, which lowered the salinity and inhibited the flow of warm surface water from the south (the Gulf Stream). When the input of freshwater later was sufficiently reduced due to the lowered temperature, warm water from the south was again transported northwards along the European coast, and the temperature increased. There was a cooling of the early Holocene climate during the so-called Preboreal oscillation, which was a 150-year-long cooling period, c 200 years into the Holocene /Björck et al. 1996/.

The Holocene climate of northern Sweden has been studied by e.g. /Karlén et al. 1995/. They recognised more than ten small oscillations between relatively warm and cold climate during the Holocene. The summer temperature in northern Sweden was 1°C warmer than at present during the warm periods and 1°C colder during the cold periods.

Northern Sweden was deglaciated during the early part of the Holocene when the climate was relatively warm. These areas were therefore covered by forest, mainly birch and pine, shortly after deglaciation. During the Holocene thermal maximum, between 5500 and 2000 BC, the summer temperature in southern Sweden was approximately 2° warmer than at present /Antonsson and Seppä 2007/. Forests with *Tilia* (lime), *Quercus* (oak) and *Ulmus* (elm) then covered large parts of southern Sweden. The temperature decreased after this warm period, and the forests became increasingly dominated by coniferous trees. However, cold events occurred during the warm early and middle Holocene as well. Results from Greenland ice cores presented by /Alley et al. 1997/ show that a cold event half the amplitude of the Younger Dryas occurred at 6200 BC. /Davis et al. 2003/ have reconstructed the Holocene climate in Europe from pollen data. They concluded that the warmer climate during the Mid-Holocene was restricted to north-western Europe, whereas the climate further south was similar to or even colder than today.

The past Quaternary climate has been affected by orbital changes described by /Milankovitch 1941/. These changes will probably affect the future climate as well. The future climate will, however, most probably also be affected by an anthropogenic impact. Most researchers agree that the global temperature will rise during the coming decades as an effect of increasing atmospheric concentrations of greenhouse gases /IPCC 2007/. There is also a general consensus suggesting that the global temperature has already started to rise. However, some authors e.g. /Karlén 1998/ suggests that there is no evidence of an anthropogenic impact on the present climate. /Berger and Loutre 1997/ argued that the atmospheric CO_2 concentration had a major impact on the climate in the past as well. An enhanced greenhouse effect may, therefore, cause a significant delay of future periods of permafrost and glaciations /e.g. Texier et al. 2003/. According to /IPCC 2007/, that delay depends on the magnitude of future emissions of green-house gases. Modelling results suggest that it may take up to 100,000 years before the ice sheets are back to the size that they would have been without an anthropogenic increase of greenhouse gases /cf. Lahdenperä 2006/.

3.3.5 Development of the Baltic Sea after the latest deglaciation

A major crustal phenomenon that has affected and continues to affect northern Europe, following the melting of the Weichselian ice sheet, is the interaction between isostatic recovery on the one hand and eustatic sea level variations on the other. Isostatic recovery is an ongoing process and is an effect of the unloading of the Weichselian ice. The rate of recovery has decreased significantly since deglaciation. The eustatic level is dependent on the amount of water in the world's oceans, which changes as an effect of the amount of water bound in the world's glaciers and ice sheets. During the latest glaciation, the global sea level was in the order of 120 m lower than at present, due to the large amounts of water stored in ice /Fairbanks 1989/.

In northern Sweden, the heavy continental ice load depressed the Earth's crust by as much as 650 m below its present elevation, c 18,000 BC /Påsse and Andersson 2005/. As soon as the pressure started to decrease due to thinner ice coverage, the crust started to rebound (isostatic land uplift). This uplift started before the final deglaciation and is still an active process in most parts of Sweden. In Sweden, the highest identified level of the Baltic Sea or the West Sea is called the highest shoreline (Figure 3-10). This former shoreline is situated at different elevations throughout Sweden, depending on how much the crust was depressed and the level of the global sea-level at the deglaciation. The highest levels, nearly 300 metres above sea level (m.a.s.l.), are found along the coast of northern Sweden, and they decrease to levels less than 20 m.a.s.l. in southernmost Sweden. The highest shoreline was formed gradually as the ice-front retreated towards the north, which means that this shoreline never existed synchronously. The highest level covered by marine water on the Swedish West Coast and by brackish Littorina Sea water in the Baltic Basin is called the marine limit. On the West Coast that limit coincide with the highest shoreline.

The development of the Baltic Sea since the latest deglaciation is characterised by changes in salinity, which have been caused by interplay between variations in the relative sea level and the isostatic uplift. This history has therefore been divided into four main stages /Munthe 1892, Björck 1995, Fredén 2002/, summarised in Table 3-1 and Figure 3-11. Three of these stages; Yoldia, Ancylus and Littorina, are named after molluscs, which reflect the salinity of the stages. Freshwater conditions prevailed during most of the deglaciation of Sweden. The first Baltic Sea stage, the Baltic Ice Lake, was characterised by freshwater conditions. Weak brackish conditions prevailed c 9300–9100 BC, during the middle part of the Yoldia Sea stage /e.g. Andrén et al. 2000, Wastegård et al. 1995/. The saline water entered the Baltic basin through the narrow straits in Västergötland and Närke. The maximum salinity was between 10‰ and 15‰ in the western part of the Yoldia Sea /Schoning et al. 2001/. The straits in Middle Sweden were, however, disconnected from the sea due to a fast isostatic recovery. The Yoldia stage was consequently followed by the freshwater Ancylus Lake stage, which lasted until the onset of the brackish Littorina Sea stage around 7500 BC /Fredén 2002/.

Variations in salinity during the Littorina Sea stage have mainly been caused by variations in freshwater input and changes of the cross-sectional areas in the Danish Straits /cf. Westman et al. 1999/. Salinity was probably low during the first c 1,000 years of the Littorina Sea stage but started to increase at 6500 BC. Earlier studies evaluating salinity variations since the onset of the Littorina Sea have been reviewed by /Westman et al. 1999/. The resulting salinity curve for the open Baltic proper presented by /Westman et al. 1999/ (Figure 3-12) is based both on biostratigraphic evidence /e.g. Munthe 1910/ and results from isotopic analyses of shells /e.g. Punning et al. 1988/. The most saline period occurred at 4500–3000 BC when the surface water salinity in the Baltic proper (south of Åland) was 10–15‰, compared with approximately 7‰ today /Westman et al. 1999/. The salinity curve presented by /Westman et al. 1999/ has recently been challenged by /Kortekaas et al. in press/, who claim that true brackish conditions were established in the Baltic c 4500 BC. That conclusion is based on the results of optically simulated luminescence (OSL) datings. This study is the first attempt to use OSL results to date Baltic Sea sediments, and future investigations will hopefully resolve the issue, if this method produces reliable ages of these sediments.

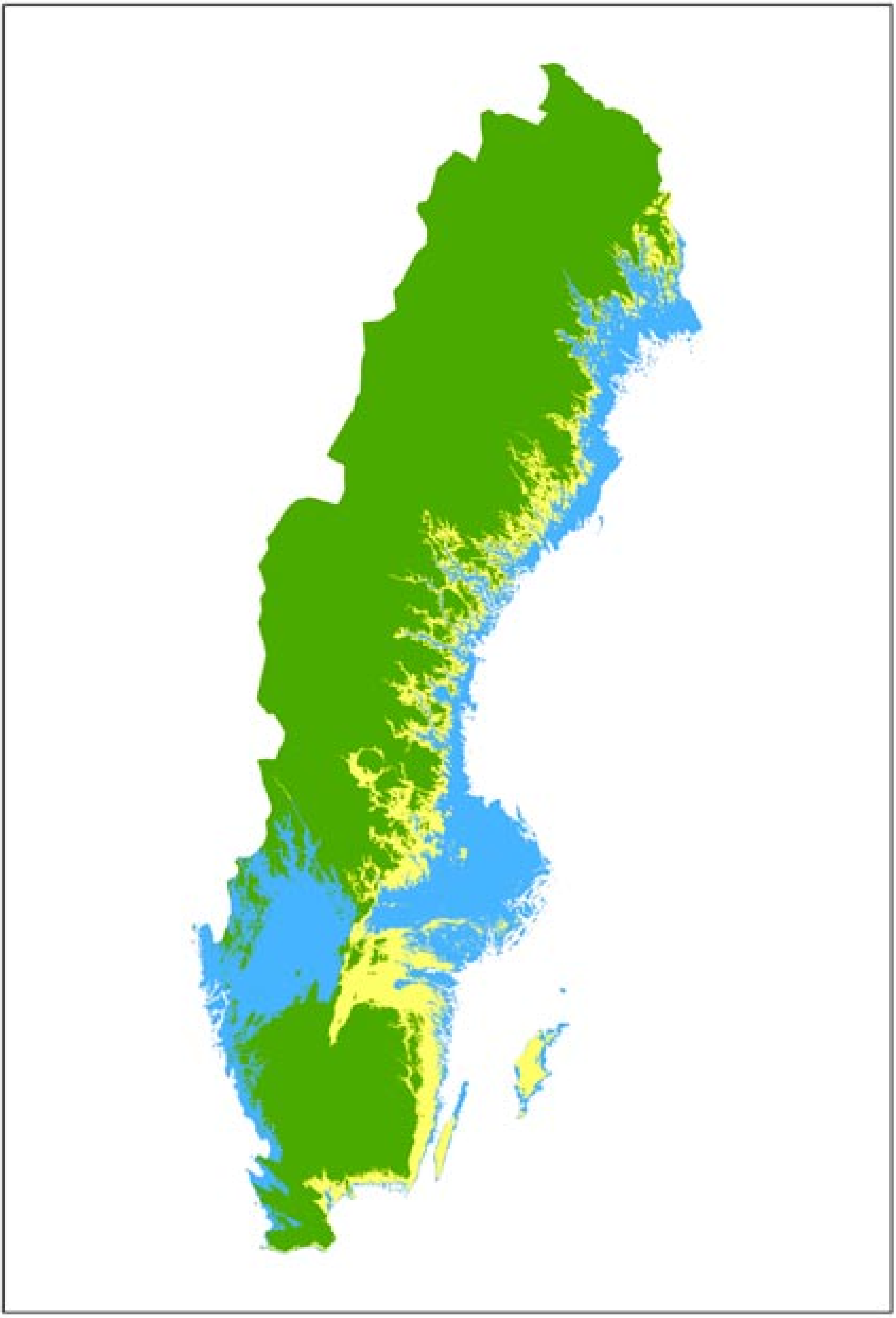


Figure 3-10. *Areas situated below the highest shoreline (yellow and blue) and marine limit (blue) (modified by Jirner Lindström (SGU) from /Påsse and Andersson 2005/. The highest shoreline is the highest level of the Baltic Sea and the sea along the West Coast since the latest deglaciation.*

Figure 3-11. *Four main stages characterise the development of the Baltic Sea since the latest deglaciation: A) the Baltic Ice Lake (13,000–9500 BC), B) the Yoldia Sea (9500–8800 BC), C) the Ancylus Lake (8800–7500 BC) and D) the Littorina Sea (7500 BC-present) (modified from /Fredén 2002/). "F" and "L" shows the location of Forsmark and Laxemar-Simpevarp, respectively. Fresh water is symbolised by dark blue and marine/brackish water by light blue.*

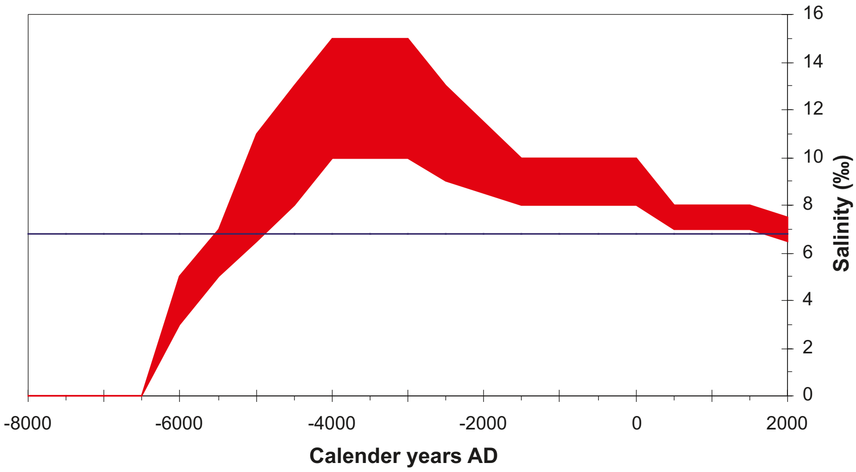


Figure 3-12. *Salinity variations in the Baltic proper off Oskarshamn during the past 10,000 years. Maximum and minimum estimates are derived from /Westman et al. 1999/ and /Gustafsson 2004ab/. The present salinity in the area is shown as a horizontal reference line.*

The palaeosalinity of the northern part of the Baltic Sea has been reconstructed by reference to the isotopic composition of strontium in molluscs /Widerlund and Andersson 2006/. According to this study, salinity during the Littorina Sea stage was 4.8–10.3‰ in the Bothnian Bay, whereas it was 7.3–10.3‰ in the Bothnian Sea. These values agree well with the results of earlier biostratigraphic studies /e.g. Munthe 1894/.

The late Weichselian and early Holocene shoreline displacement in Sweden has been studied by numerous researchers /e.g. Eronen 1983, Svensson 1989, Risberg 1991, Hedenström and Risberg 1999/. The shoreline displacement in northern Sweden has been mostly regressive due to a large isostatic component. Along the southern part of the Swedish east and west coasts, the isostatic component was smaller and declined earlier during the Holocene, resulting in a complex shoreline displacement with alternating transgressive and regressive phases. Shoreline displacement in Sweden has been summarised by /Påsse 2001/ and /Påsse and Andersson 2005/. Shoreline displacement following deglaciation has also been simulated by Global Isostatic Adjustment models /e.g. SKB 2006c/.

Several authors have suggested that the level of the Baltic Ice Lake was lowered by c 25 m in 1 to 2 years around 9500 BC /Jakobsson et al. 2007/, when the ice sheet margin retreated from Billingen in Västergötland /e.g. Björck 1995/. That event has been recognised as being related with a sharp drop in the shoreline displacement curves around the Baltic basin /e.g. Svensson 1989/. This drainage event was followed by the Yoldia Sea stage, which was characterised by a regressive shoreline displacement in the whole Baltic Sea. In the southern part of the Baltic Sea, the onset of the following Ancylus Lake stage was characterised by a transgression. The Ancylus Lake was isolated from the sea and the transgression was caused by a faster isostatic component in the north compared with the south. The Baltic Basin has been at the same level as the sea from the onset of the Littorina Sea stage. In the southern Baltic Sea there have been several transgressive phases since the beginning of the Littorina Sea stage /Risberg et al. 1991, Berglund 1971/. These transgressions were caused by a eustatic component dominating the isostatic component.

The drainage of the Baltic Ice Lake has recently been questioned by /Påsse and Andersson 2005/. They suggest that the fast shoreline displacement during the final phase of the Baltic Ice Lake stag was caused by a fast isostatic component. /Påsse and Andersson 2005/ suggest that the Baltic Ice Lake was at the same level as the sea. They therefore propose that the whole period encompassing the Baltic Ice Lake and Yoldia Sea phase should be called the Baltic Ice Sea phase. The mathematical models used by Påsse have recently been questioned by /Lambeck 2006/. This issue will probably be a matter of debate in the near future.

Isostatic land uplift will continue for many thousands of years, although the rate will steadily decrease. The future shoreline displacement will, however, also be determined by eustatic sea level. Global warming caused by the greenhouse effect may cause a eustatic sea level rise.

Table 3-1. The four main stages of the Baltic Sea. The Littorina Sea here includes the entire period from the first influences of brackish water 7500 BC to the present Baltic Sea.

Baltic stage	Calendar year BC	Salinity
Baltic Ice Lake	13,000–9500	Glacio-lacustrine
Yoldia Sea	9500–8800	Lacustrine/Brackish/Lacustrine
Ancylus Lake	8800–7500	Lacustrine
Littorina Sea *sensu lato*	7500–present	Brackish

3.3.6 Development of soils after the latest deglaciation

Soil formation in Sweden has been proceeding since the end of the last glaciation period, when the ice retreated and exposed the land in areas above the highest shoreline (Figure 4-10). Below this level, the land was submerged until it rose from the sea due to isostatic uplift. The soils in Sweden are generally very young and there is a gradient in soil age from the coast to the inland. The time since the sea withdrew and left the land exposed can be determined based on the elevation and shoreline displacement curves, which describe the retreat of the sea during post-glacial time /Påsse 1997, 2001, Påsse and Andersson 2005/. At coastal sites such as Laxemar-Simpevarp and Forsmark, the time for soil-forming processes has consequently been shorter than at higher elevations. The soils in coastal areas can, therefore, display a relatively high pH and a high content of easily weathered minerals. Furthermore, the content of organic material and nitrogen is generally low in the uppermost soils at sites that have recently risen above the sea. The properties of soils in the coastal areas of Sweden are probably similar to the soil properties of current inland areas directly after the deglaciation, when unweathered minerogenic soils were exposed to weathering processes in newly deglaciated areas.

Since nitrogen is essential for plants, some plants growing on soils low in nitrogen, for example in coastal areas, can fix nitrogen directly from the atmosphere. Areas that have been covered by vegetation for some decades will gain a topsoil layer that is rich in organic material and nitrogen. The accumulation of soil organic matter depends on the input of litter and the decomposition of soil organic matter. The enrichment of organic material will continue in wetlands, whereas other areas are characterised by equilibrium between accumulation and mineralisation of organic matter. The time required for this equilibrium to establish varies, but may be up to 10,000 years /Birkeland et al. 1999/. For Scandinavian forest soils this time has been reported to be approximately 2,000 years /Liski et al. 1998/. Reference field data from the Swedish National Forest Soil Inventory (NFSI) from the period 1993–2002 has been used to describe the development of carbon and nitrogen stocks in forest soil during the post-glacial time. The results of that study are reported in /Löfgren 2008/ and indicate that the total carbon and nitrogen stocks in Podzol soils reaches equilibrium after approximately 2,500 years. At deeper soil layers the carbon concentration seems to increase for c 6,000 years and then level off. The results are uncertain though, because of the large variability in the data

The accumulation of organic material in wetlands will cause the formation of a peat layer and the associated soil type, Histosol, which is common in present or former fens and bogs. Formation of Histosol takes hundreds of years, and that soil type cannot be expected to exist in wetlands that recently have risen above sea level. /Starr 1991/ studied the effects of soil formation at sites in Finland that have risen above sea level during the past 5,000 years. The results show that Podzol formation is rapid during the first 2,500 years. The soil-forming processes are thereafter much slower. /Olsson and Melkerud 1989/ studied chemical and mineralogical changes during the genesis of a Podzol. They determined the average rate of weathering since the latest deglaciation and suggested that the weathering rate has increased recently, possibly due to the influence of acid rain.

Young soils may have high contents of easily weathered minerals (e.g. calcite), which is favourable for forest growth and agriculture. The concentrations of these minerals will decrease over time in the uppermost soil horizon. That will cause a drop in pH and in the concentrations of many of the nutrients needed by plants. However, fertiliser can be used to compensate for some of the losses of nutrients from the soils. Carbonate-rich soils occur in several areas of Sweden, for example in northern Uppland. In many such soils, the carbonate will be or has been leached out from the uppermost soil layers as an effect of chemical weathering. That process will continue for thousands of years. /Ingmar and Moreborg 1976/ studied the effect of carbonate weathering in a transect from the coast to the interior of northern Uppland. They found that carbonate has been leached out from the uppermost decimetres of the young soils situated in coastal areas. At inland sites, which have been exposed to weathering for several thousand of years, all carbonate has been leached out from the uppermost metres of the soils. The decreasing carbonate content of the soils causes a decreasing alkalinity and pH in the surrounding lakes

/Ingmar and Moreborg 1976/. The recently uplifted carbonate-rich soils at the Forsmark site are good examples of soils that has been affected by soil forming processes for a short period of time. These soils are still rich in calcite, and the average pH of the B-horizon is consequently 6.7 at Forsmark compared to 4.9 in the rest of Sweden /Lundin et al. 2004/.

The distribution of soils in Laxemar-Simpevarp and Forsmark has been investigated and described by /Lundin et al. 2004/ and /Lundin et al. 2005/, respectively. For a thorough description of soil classification, the reader is referred to /WRB 1998/.

3.4 Quaternary development of the Forsmark area

This section summarises the Quaternary development of the Forsmark area in particular, based on site-specific data derived from the site investigations at Forsmark as well as information from the region. All information from the site indicates that the regolith in the Forsmark regional model area was deposited during, or after, the Weichselian glaciation.

3.4.1 Before the latest glacial phase

Preserved Quaternary deposits older than the latest glacial phase are rare in Sweden in general, hence the duration and extent of early Quaternary glaciations is poorly known. During the two glaciations preceding the latest glacial cycle, the ice cap reached into northern Poland and Germany, which means that the Forsmark area was covered by ice at least during the Elster (MIS 12 or 10) and Saale (MIS 8–6 or possibly 10–6) glaciations. A large number of excavations performed in north-eastern Uppland /Lagerbäck et al. 2004a, 2005a/ and in the Forsmark candidate area /Sundh et al. 2004/ did not reveal any traces of older glacial phases. Nor are there any records of sediments preserved from the Holsteinian (MIS 11 or 9) or Eemian (MIS 5e) interglacials in the Forsmark region.

During the latest interglacial, the Eemian (MIS 5e, 130,000–115,000 years ago), the Baltic Sea level was higher than at present, and the glacio-isostatic component was probably more pronounced after the Saale glaciation than after the Weichselian. It is therefore likely that the Forsmark area was covered with brackish water during a large part of that interglacial /Robertsson et al. 1997/.

3.4.2 Latest glacial phase (Weichselian)

The latest glacial phase, the Weichselian, is subdivided into three stadials and at least two main interstadials as described in section 4.2.2. During the first stadial (MIS 5d, c 117,000–105,000 years ago), the glaciers advancing over the post-Eemian surface are known to have left significant erosive and morphological traces in the Norrbotten area /cf. Lagerbäck 1986/. The ice cap was restricted to the alpine region /Fredén 2002, SKB 2006c/, which means that the Forsmark area was probably free of ice during the first Weichselian stadial (MIS 5c, c 100,000–90,000 years ago). The vegetation in the Forsmark area during the first Weichselian interstadial was possibly dominated by coniferous forest, whereas the second interstadial (MIS 5a, c 80,000–70,000 years ago) was colder, the forest probably sparser and dominated by *Betula* (Birch). The extension of the ice sheet during the second Weichselian stadial has generally been assumed to have grown much larger and possibly reached as far south as the Stockholm region (Fredén 2002, Figure 3-5). However, there is no stratigraphical information from the Forsmark region supporting this assumption (Robertsson et al 2005).

In Forsmark, sediments that may have been deposited during the second or third Weichselian stadial have been found during excavations within the candidate area /Sundh et al. 2004/. In the western part of the candidate area, north-east of Lake Gällsboträsket at PFM002581, a clayey till was revealed under a sandy-silty till at a depth of 1.9 m. The contact between the two till beds is sharp and erosive, with occasional sharp-edged lumps of the underlaying hard clayey till incorporated into the base of the overlying sandy-silty till (Figure 3-13). The high degree of consolidation of the clayey till was apparently already present before deposition of the overlaying sandy-silty till. The most striking physical property of the clayey till is its extreme degree of consolidation, to the extent that it even resisted ordinary mechanical excavation methods. The hard clayey till observed during the site investigations at Forsmark, as well as during the construction of the Forsmark nuclear power plant /Agrell and Björnbom 1978/, is tentatively correlated with a till unit observed at several sites in central and northern Sweden /Björnbom1979, Robertsson et al. 2005/.

Figure 3-13. *Due to erosive contact between the two till-beds, sharp-edged lumps of clayey till intercalate into the base of overlying sandy-silty till (PFM002581).*

Since absolute dating of glacial sediments is generally problematic, the hard clayey till found at Forsmark was analysed for reworked microfossils in order to provide a relative age of the unit /Robertsson 2004/. The pollen grains found in the sediment are interpreted as having been eroded from the ground and incorporated in the till during the glacial phase and should not be regarded as primary deposition. The samples analysed showed a typical interglacial signature containing high frequencies of tree pollen dominated by *Betula* (Birch), *Alnus* (Alder) and *Corylus* (Hazel) together with minor occurrences of *Picea* (Spruce), *Quercus* (Oak), *Tilia* (Lime) and *Carpinus* (Hornbeam). The composition points to an originally interglacial pollen flora, in contrast to an interstadial signature which would show higher frequencies of shrubs and herbs such as *Betula nana*-type (Dwarf birch) and *Artemisia*, not present in the Forsmark samples /Robertsson 2004/. Based on the reworked pollen grains, the maximum age of the hard clayey till is post-Eemian, i.e younger than 115,000 years. Present knowledge about the extent of the Weichselian ice sheet during the different phases suggests that the lithological unit represented by a dark clayey till found in central and northern Sweden could be correlated with the unit found at Forsmark. The most recent interpretation of the age of the dark clayey till is that it was deposited during MIS 4 (c 75,000–60,000 years ago) /cf. Robertsson et al 2005/. Based on its stratigraphic position and pollen composition, the only conclusion about the age of the hard clayey till is that it is older than the latest ice advance /cf. Sundh et al. 2004/.

During the stadials when the ice sheet did not reach Forsmark, it has been assumed that tundra conditions prevailed during ice-free parts of the stadials /Fredén 2002/. The exact timing and extent of the Mid-Weichselian (MIS 4) glaciation is uncertain and there are indications of ice-free conditions in large parts of Fennoscandia during parts of the Mid-Weichselian /cf. Lokrantz and Sohlenius 2006/. The total time of ice coverage in the Forsmark area may therefore have been considerably shorter than in the model presented by /Fredén 2002/.

The main glaciation during the Weichselian was the latest advance. The greatest extent of the Weichselian ice sheet, the Last Glacial Maximum (LGM), was reached c 16,000 BC /Fredén 2002/. According to mathematical and glaciological models, the maximum thickness of the ice cover in the Forsmark region was up to c 3 km during the LGM /SKB 2006c/.

Glacial striae on bedrock outcrops are formed at different stages of the glaciations, so several generations of striae may be identified. The oldest glacial striae observed in the region of north-eastern Uppland are orientated from the north-west, a younger system from the north-north-west and the youngest striae were formed by an ice sheet moving approximately from the north /Persson 1992/.

A somewhat different system of glacial transport is recorded in the Forsmark candidate area. A northerly direction is recorded both in the oldest glacial striae and the oldest documented directional transport of the till material as recorded in clast fabric analysis /Sundh et al. 2004/. However, the overall dominating system shows transport and deposition from the north-west, allthough a younger system from the north was recorded at a few localities /Sohlenius et al. 2004/. The boulders and gravel fraction in till samples were analysed with regard to petrographic composition and compared with the local bedrock /Bergman and Hedenström 2006/. It was concluded that the majority of the boulders consisted of local bedrock types with a suggested dominant transport direction from the north-west. However, a high percentage of Ordovician limestones in the gravel fraction suggests that these grains may have originated from the north /Bergman and Hedenström 2006/.

During a late stage of the latest glaciation, or during the deglaciation, the environment beneath the ice sheet was favourable for the deposition of laminated fine-grained sediments under uplifted blocks of bedrock (cf. Chapter 4). These spectacular sediment-filled open fractures in the upper part of the bedrock were identified under till during the site investigations in Forsmark /Leijon 2005/ as well as during the construction of the Forsmark power plants /Stephansson and Ericsson 1975, Carlsson 1979/. Both the processes behind and the age of the formation are uncertain. With the same approach as that used for the hard clayey till, the sediment incorporated beneath uplifted bedrock blocks was analysed with regard to reworked microfossils and compared with the pollen spectra in the overlying till /Robertsson 2004/. Analyses of pollen in the sediment showed an interglacial signature, similar to a sample of reworked clay of Eemian origin identified at a site north of Uppsala /Robertsson 2000/. A suggested maximum age of the laminated glacial sediment is therefore post-Eemian. The sediment-filled fractures are interpreted as having been formed during a late stage of the glacial phase, when large amounts of sediment-loaded meltwater collected beneath and inside the retreating ice /cf. Stephansson and Ericsson 1975, Leijon 2005/ (see section 3.3.2).

3.4.3 Latest deglaciation

After the LGM, the deglaciation started with melting of the continental ice sheet. The front of the melting ice margin reached Forsmark c 8800 BC (10,800 years ago, cf. Figure 3-8) /Strömberg 1989, Persson 1992, Fredén 2002/ during the Preboreal chronozone. The ice at the front was in the order of 300 m thick, retreating into the open water of the final freshwater phase of the Yoldia Sea (cf. Figure 3-11).

In the Forsmark area, a glaciofluvial esker, the Börstilåsen esker, was deposited when stones, gravel and sand were transported by the meltwater in a tunnel beneath the ice. The information from the Forsmark site investigations shows that the esker, at least at the investigated sites, is located directly on top of the bedrock, indicating that any till deposited prior to the formation of the esker has been eroded. When the ice retreated further, varved clay was deposited in deeper basins. One varve represents accumulation during one year and is composed of a summer layer with coarser material (silty) and a fine-grained winter layer. The sediments provide annual resolution and has often been analysed through clay varve measurements in order to establish the chronology of the deglaciation /cf. Strömberg 1989/. Along the Swedish east coast, clay varve investigations have provided a continuous sequence known as the Swedish time scale /De Geer 1912, Strömberg 1989, Lundqvist and Wolfarth 2001/. Forsmark is located c 40 km east of the sites where local clay varve chronologies were established /De Geer 1940/. According to extrapolations between investigations from central and northern Uppland and Åland, the rate of ice recession was c 300–350 m per year in northern Uppland, as compared with c 150–300 m per year in Laxemar. In several of the corings performed in lakes and small ponds in the Forsmark model area, distinctly varved clay was observed, however not chronologically interpreted /Hedenström 2003/.

A marker horizon of the late glacial sediments in Uppsala area is known as the “spot zone” /Strömberg 1989/. The unit consists of distal (thin) varves of glacial clay with a 5–10 cm thick layer containing white, red or green fragments (spots) of Ordovician limestone. The spot zone has been observed at excavations close to the Börstilåsen esker south of the Forsmark model area /Lagerbäck et al. 2004a/ as well as in a sediment core collected at PFM004396, offshore from Forsmark /Risberg 2005/. A common interpretation of the spots is that they are till material transported and deposited from drifting icebergs after the ice front had left the area.

3.4.4 Coastal area after the latest deglaciation

The highest shoreline in the region was formed in connection with the deglaciation during the final freshwater phase of the Yoldia Sea stage of the Baltic (Figure 3-10 and Figure 3-14). The closest shore/land area at that time was situated c 100 km to the west of Forsmark, where the highest shoreline has been identified at c 190 m.a.s.l. At the deglaciation, the Forsmark area was initially covered by approximately 150 m of glacio-lacustrine water.

The Holocene shoreline displacement in northern Uppland has been studied with stratigraphic methods by /Robertsson and Persson 1989/ and /Hedenström and Risberg 2003/. The methods used are based on diatom stratigraphy of lake sediments for identification of the isolation event of the basin, together with radiocarbon dating and determination of the elevation of the isolation threshold of the basins. Since there are no elevated (and old) areas close to Forsmark, the stratigraphic investigations only cover the last 6,500 years.

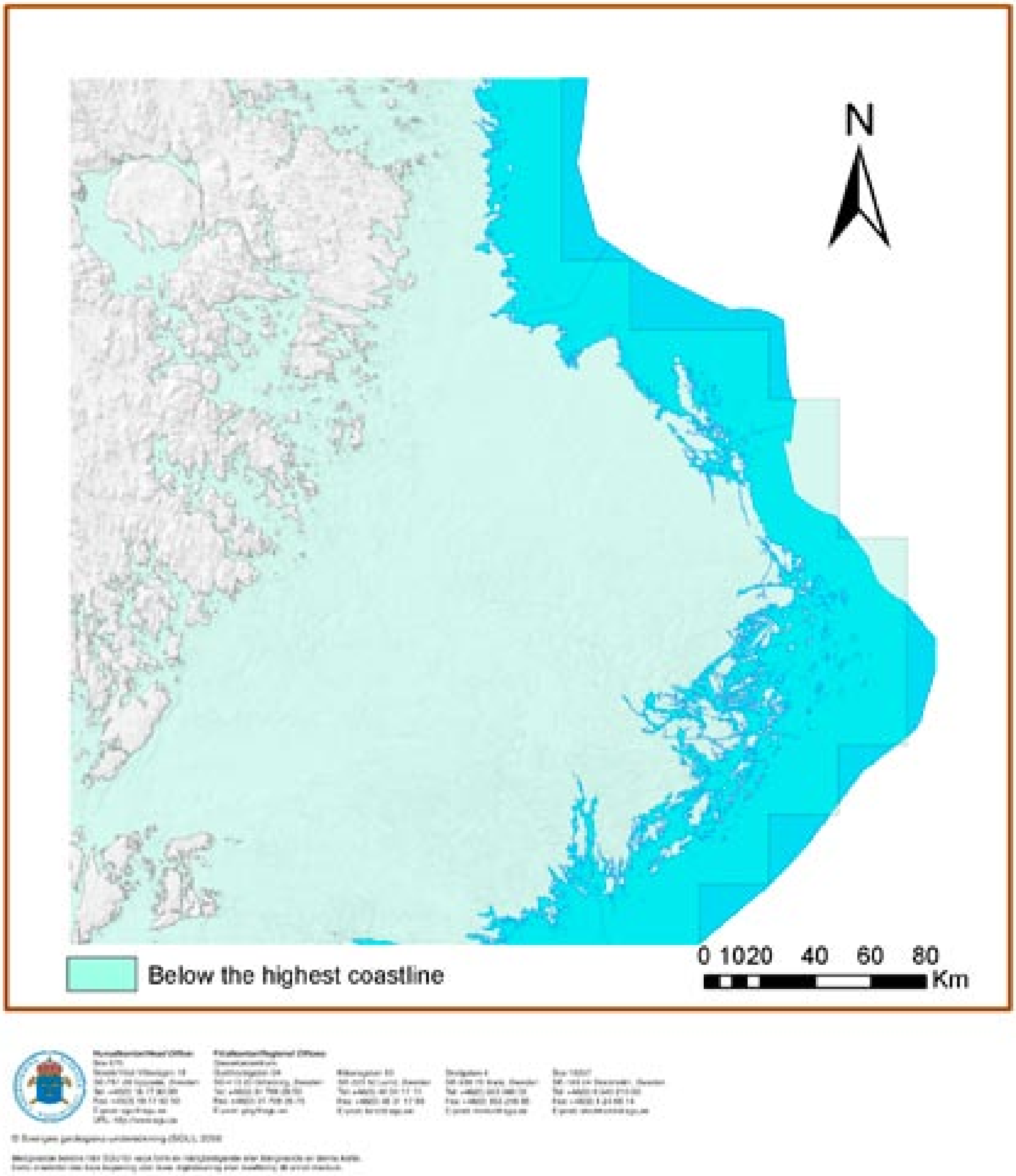


Figure 3-14. *Palaeogeographic map showing the areas located above (white) the highest shoreline in the region of Eastern Svealand and South Eastern Norrland (based on /Påsse and Andersson 2005/).*

/Påsse 2001, 1997/ has described shoreline displacement in Fennoscandia during Holocene in a mathematical model. Påsse's model has been adjusted to the Forsmark site by using input data from sites north, south and east of Forsmark. The modelled curve is presented in Figure 3-15, together with the results from dated isolation events of lakes and mires in the vicinity /Hedenström and Risberg 2003/. As can be seen, the modelled curve and the ages based on stratigraphical investigations are in agreement. In contrast to the southern parts of the Swedish coast, where the relative sea level was both transgressive and regressive during the Holocene, the shoreline in Forsmark and further north has been continuously regressive since the deglaciation. Initially, during the Yoldia Sea and Ancylus Lake stages of the Baltic, the average regression rate was in the order of 3.5 m/100 years, and this has diminished to a present rate of c 0.6 m/100 years (Figure 3-15).

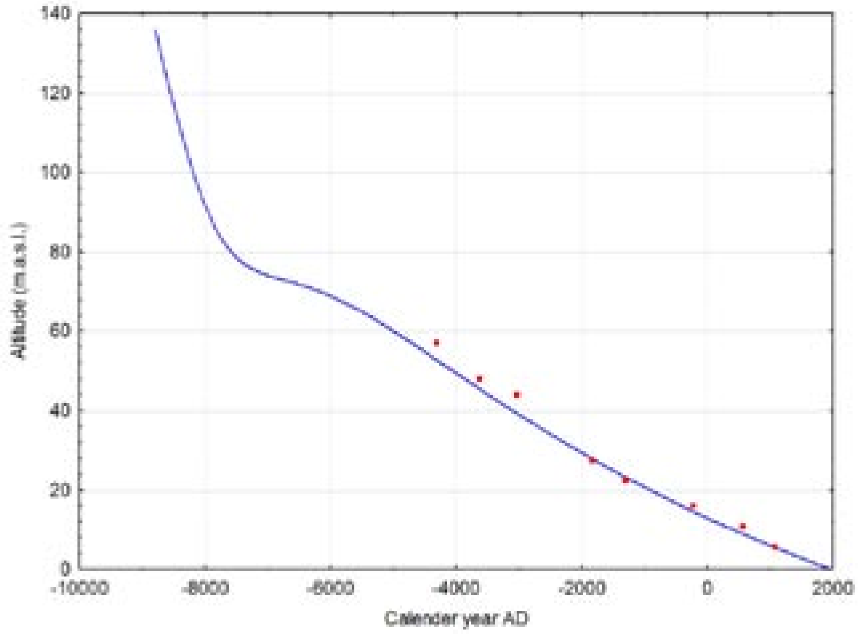


Figure 3-15. Shoreline displacement curve for the Forsmark area after the latest deglaciation. The red symbols are from dating of the isolation events of lakes and mires /Hedenström and Risberg 2003/. The blue solid curve was calculated using a mathematical model /Påsse 2001/.

The modelled curve covers the time span from deglaciation until present, and can also be extended into the future. The accuracy of the curve is generally assumed to be best in the more recent parts, since most input data are from the last c 7,000 years. The absolute altitude of the highest shoreline at the sites where land occurred at the time for the deglaciation is assumed to be relatively reliable (±5 m). Since the closest field observations available are from c 100 km west of Forsmark (cf. Figure 3-14), the exact water depth at Forsmark at the deglaciation is more uncertain.

The stratigraphical investigations and radiocarbon dates from the Forsmark area are concentrated to the last 6,500 years /Hedenström and Risberg 2003/. The most accurate data are probably from the last c 4,000 years. The reason for this is that the isolation events of the younger sites have been dated using modern technique (AMS radiocarbon dates) applied on terrestrial macrofossils, in combination with detailed stratigraphical investigations, whereas the older sites have been dated using conventional radiocarbon dates on bulk sediment samples. Generally, the accuracy in altitude determinations of the investigated sites is high (±0.5–1 m), whereas the estimated uncertainty in isolation age is between ±150 years (the younger sites) to approximately ±300 years at the older sites.

The brackish water phase of the Yoldia Sea lasted c 120 years in southern and central Sweden, as recorded by ostracods and foraminifers in varved clay /Wastegård et al. 1995, Schoning et al. 2001/. Since the deglaciation of the Forsmark region took place late during this Baltic stage, and due to the freshwater flow from the melting ice, the influence of saline water in north-eastern Uppland during this stage was only minor, if any. Stratigraphic investigations of a sediment core collected offshore from Forsmark at PFM004396 showed that no calcareous fossils were preserved in the sediments, even though a relatively high lime content in the clay (11%) would favour preservation /Risberg 2005/. If the saline water had reached Forsmark, ostracods or foraminifers would most probably have been observed in the sediment. The stratigraphic investigations of the sediment core served as a basis for the compilation of a qualitative model of the post-glacial marine environment in the Bothnian Sea offshore from Forsmark (Figure 3-16).

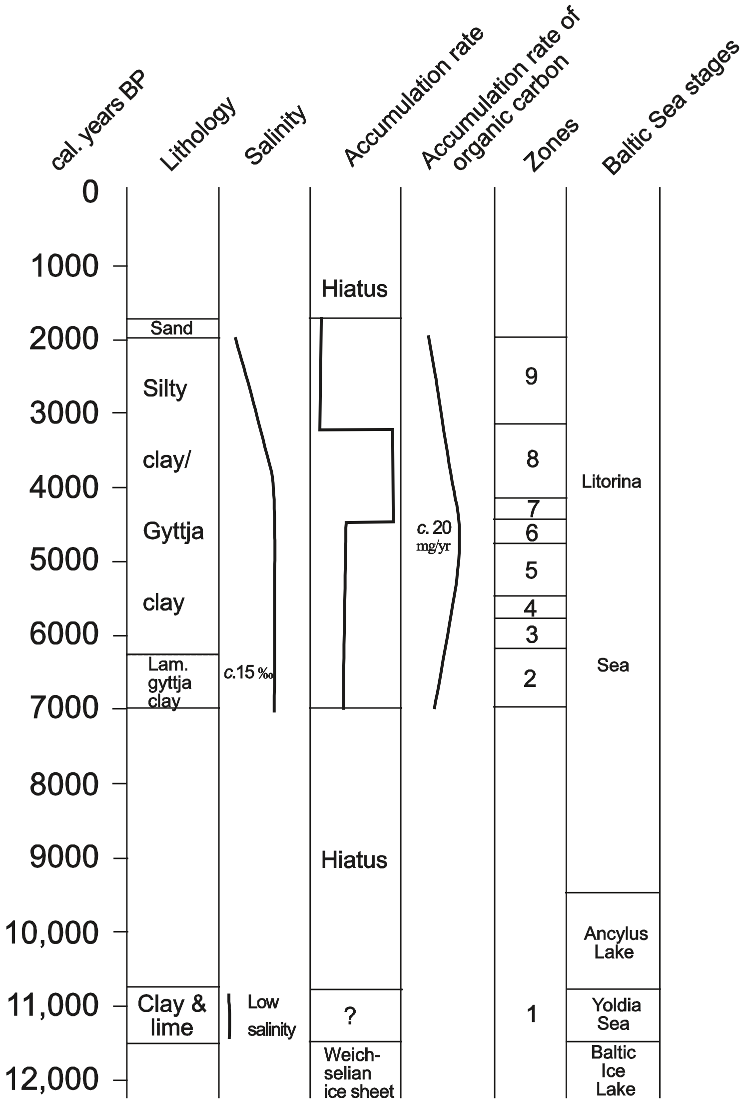


Figure 3-16. *Qualitative model for the post-glacial marine environment offshore from Forsmark /Risberg 2005/ based on stratigraphic analyses and radiocarbon dating of one sediment core at PFM004396. The salinity variations and accumulation rates should be regarded as rough estimates.*

Despite the scattered occurrences of brackish water-living diatoms, no observations of foraminifers or ostracods were made in the sediments accumulated in the Yoldia Sea (zone 1 in the sediment from PFM004396). This can probably be explained by relatively low salinity, cold water and/or a high accumulation rate /Schoning 2001/. Furthermore, low abundances of all types of siliceous microfossils characterise the Yoldia Sea sediments at PFM004396, as well as the sediments in Lake Eckarfjärden /Hedenström and Risberg 2003/.

The next Baltic stage, the Ancylus Lake, was lacustrine with initial outlet through the Lake Vänern basin (Figure 3-11C). Since the Forsmark area is located north of the outlet, there was no isostatically generated Ancylus transgression in this region, in contrast to the Simpevarp-Laxemar-Simpevarp area. Instead, a regressive shoreline characterises this Baltic stage as well (cf. Figure 3-15). It is noteworthy that no sediments deposited during the Ancylus lake stage have been identified in the stratigraphic investigations performed within the region /Bergström 2001, Hedenström and Risberg 2003, Risberg 2005/.

Ongoing global eustatic sea level rise, in combination with a decrease in the rate of isostatic uplift in the southern Baltic basin, enabled marine water to enter the Baltic basin through the Danish straits, marking the onset of the Littorina Sea *sensu lato* (Figure 3-11D). In Uppland, this stage includes an initial phase when the salinity was stable and low, the Mastogloia Sea, which lasted for approximately 1,000 years before the onset of the brackish water Littorina *sensu stricto* /Hedenström 2001/. The salinity variations in the open Bothnian Sea, offshore from Forsmark, since the onset of the Littorina Sea are presented in (Figure 3-17).

As indicated by the hiatus in Figure 3-16, the sediment sequence is affected by erosion until c 5000 BC. This agrees with the post-glacial sedimentary pattern observed in the region. In the terrestrial region in particular, only small areas are covered with fine-grained post-glacial deposits. The geographic location has caused erosive forces to dominate. The relatively flat topography, combined with strong currents, may possibly have resulted in a still-ongoing transport of fine-grained particles towards the east, to deeper parts of the Baltic basin /cf. Elhammer and Sandkvist 2005a/. Till and other coarse-grained deposits still dominate in near-shore areas today /cf. Persson 1985, 1986/, see Chapter 6.

In northern Uppland, the first land areas emerged c 6,500 years ago /Robertsson and Persson 1989, Bergström 2001, Hedenström and Risberg, 2003, Risberg et al. 2005/, during the most saline phase of the Littorina Sea, which correlates with the Holocene climatic optimum during the Atlantic climatic stage /Westman et al. 1999/. A weak trend of increasing salinity was recorded in the stratigraphy at PFM004396 c 5000–2400 BC whereas the uppermost sediments seem to indicate somewhat lower salinities from c 2400 to 0 BC. The diatom composition in the analysed sediment core indicates the lowest salinity in the upper part of the sediment. This is probably a result of the reduction of saline inflow through the Öresund Strait /Westman et al. 1999/.

In Forsmark, however, it was not until c 500 BC before the first islands started to form. The flat upper surface, in combination with the relatively rapid land uplift (presently 6 mm/year), resulted in a rapid growth of new land areas and major geographical changes over time. One effect of the continuous regressive shoreline displacement is that once the new land areas and lakes have been isolated from the Baltic, they have not been flooded again. For a description of the development of the landscape and the vegetation, see Chapter 6.

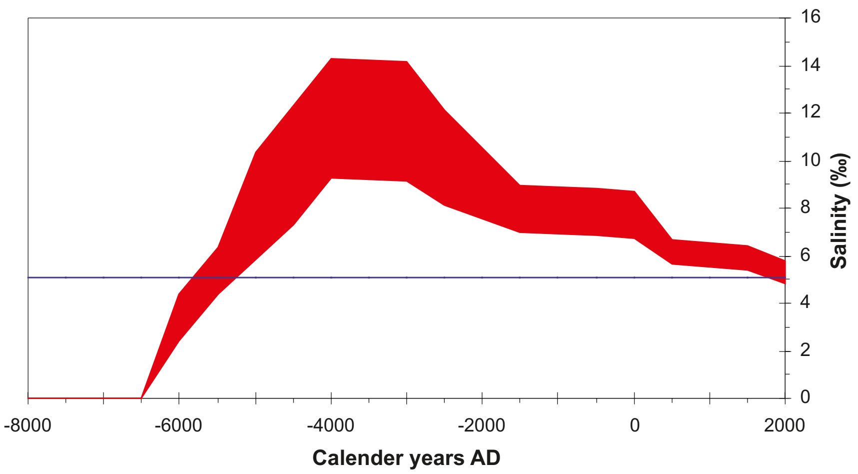


Figure 3-17. *Salinity variations in the open Bothnian Sea during the past c 9,000 years. Maximum and minimum estimates are drived from /Westman et al. 1999/ and /Gustafsson 2004ab/. The present salinity in Forsmark is shown as a horizontal reference line.*

The ongoing change in the distribution of land and sea continues with the emergence of new land areas, forming new and larger islands. The distribution of minerogenic Quaternary deposits is affected by soil-forming processes at the surface, but no major redistribution has taken place since the area was isolated from the Baltic. The most notable change isobserved in the distribution of organic deposits, for example the sedimentation of gyttja in the lakes and the formation of peat in the wetlands. The isolation age and the duration of the lacustrine phase of the lakes in Forsmark are presented in a model for landscape development /Brydsten 2006/ (cf. Table 6-1). According to the model, the lake phase of Lake Eckarfjärden will continue for another 5,100 years, whereas the small pond Kungsträsket will be filled in with sediment within 200 years.

3.4.5 Development of the model area as recorded by the distribution of Quaternary deposits

The Quaternary development in the Forsmark area is reflected by the present distribution of the Quaternary deposits (Figure 3-18). For a description of the properties of the regolith, see /Hedenström and Sohlenius 2008/ and for a description of the spatial distribution, a depth model of the regolith in Forsmark is presented in /Hedenström et al. 2008/.

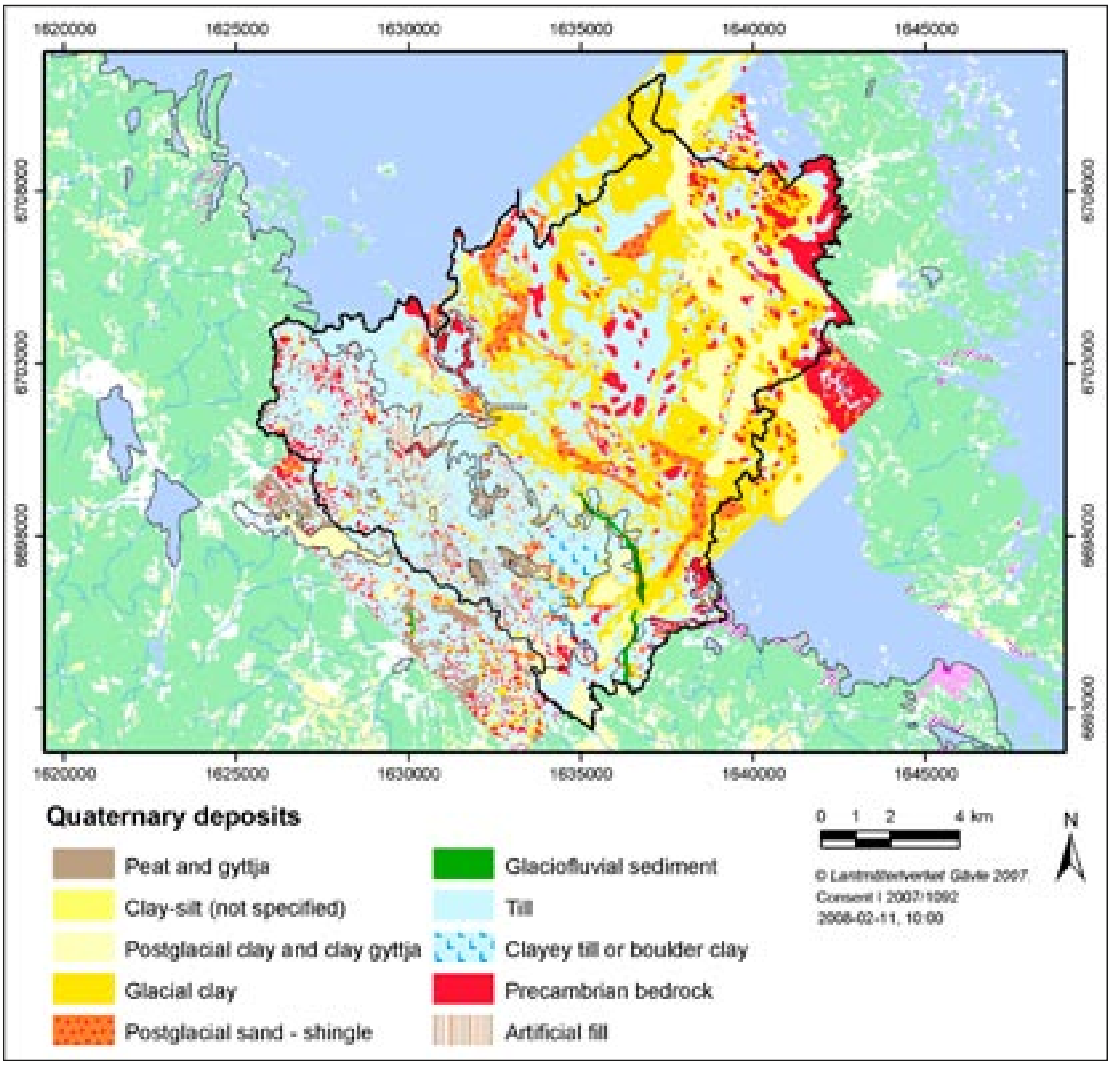


Figure 3-18. The distribution of Quaternary deposits in the Forsmark regional model area. The map presents a compilation from several data sources originally presented at various scales. From /Hedenström and Sohlenius 2008/.

In the terrestrial area, stratigraphic investigations from soil/rock drilling and excavations have been the main source of information to describe the stratigraphy of the Quaternary deposits /Johansson 2003, Sundh et al. 2004, Hedenström et al. 2004/. In the marine area, the stratigraphic investigations are based mainly on interpretation of geophysical investigations /Elhammer and Sandkvist 2005a/ and only one sediment core of post-glacial sediment has been analysed /Risberg 2005/.

The spatial distribution of the Quaternary deposits (Figure 3-18) is highly dependent on the bedrock morphology. A digital elevation model of the bedrock surface is presented in Figure 3-19 /Hedenström et al. 2008/. The surface of the elevated areas in the western part are dominated by till and bedrock outcrops, indicating that these areas have been subject to erosion from currents and wave washing. The fine-grained sediments and post-glacial deposits generally have the same stratigraphy in the terrestrial area and in the offshore part of the Forsmark area. Based on the investigations a conceptual model has been constructed, including a general stratigraphy for Forsmark (Table 3-2).

The upper bedrock has been observed to be fractured, as evidenced by the high hydraulic conductivity of the transition between bedrock and till. Unconsolidated sediments have been identified beneath bedrock blocks at sites in the central part of the candidate area /Leijon 2005, Albrecht 2005/. Thus, the transition between bedrock and Quaternary deposits may be described as a zone rather than a distinct line. In Forsmark, the grain size composition and the till fabric

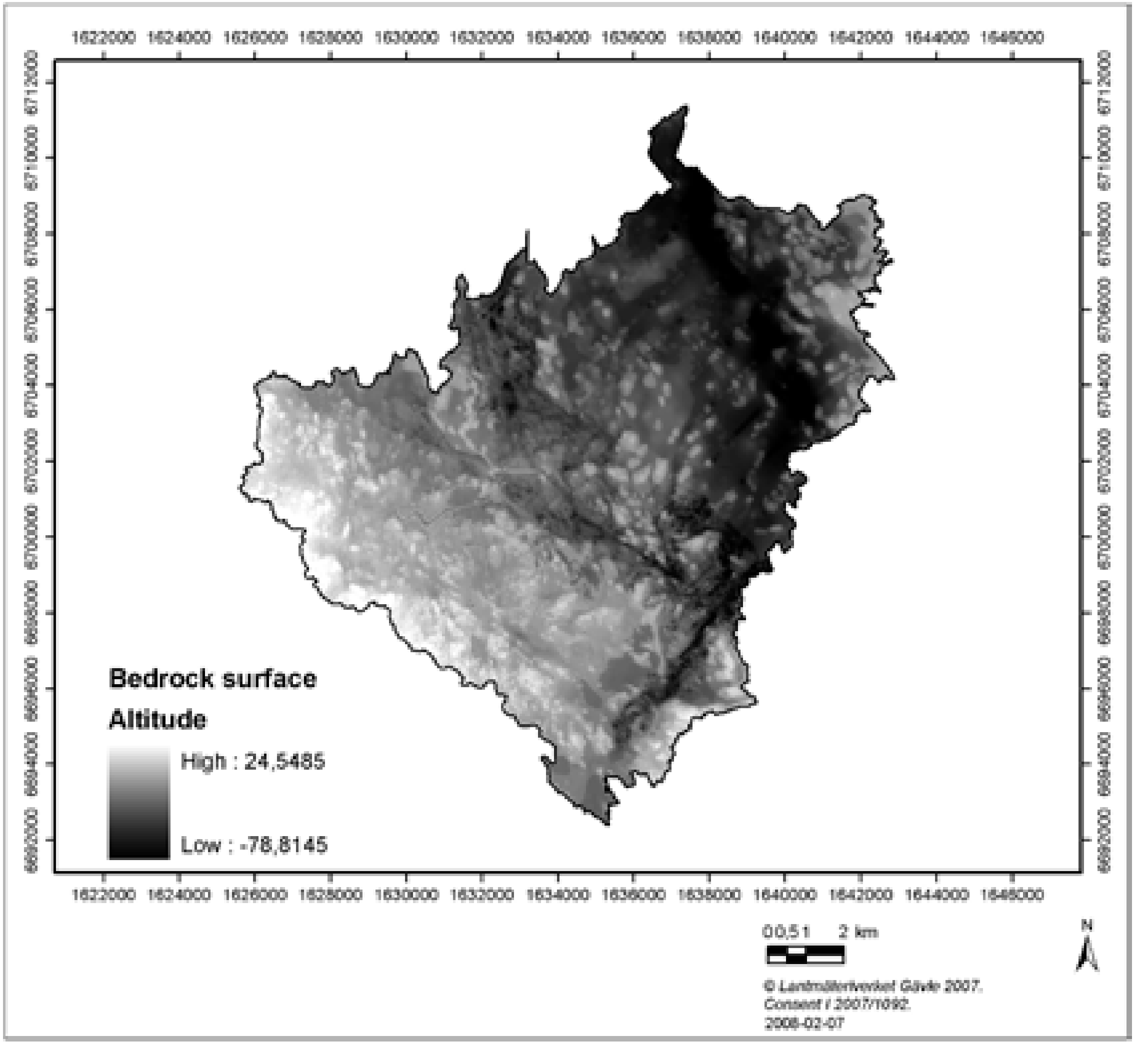


***Figure 3-19.** Digital elevation model, DEM, of the bedrock surface at Forsmark /from Hedenström et al. 2008/.*

Table 3-2. General stratigraphic distribution of the Quaternary deposits in the Forsmark area. Note that not all deposits are present at all sites.

Environment	Lithology	Relative age
Bog	Bog peat	Youngest
Fen	Fen peat	
Freshwater lake	Gyttja/Calcareous gyttja	↑
Freshwater lake and coastal basin	Algal gyttja	
Post-glacial Baltic basin	Clay gyttja	↑
Coast	Post-glacial sand and gravel	
Post-glacial Baltic basin	Post-glacial clay	↑
Late glacial Baltic basin	Glacial clay	
Late glacial	Glaciofluvial sediment	
Glacial	Till	Oldest
	Bedrock	

analyses indicate that there is more than one generation of till (cf. section 3.4.2). The stratigraphy is complex, with sandy till observed on top of clayey or silty till in the western part and the reverse stratigraphy in the eastern area. In the boundary between sandy and clayey till, the two till types have been nested into each other in a more or less random way /Sundh et al. 2004/. At the sites where the hard clayey till has been observed, this till unit has been located beneath a sandy till /cf. Sundh et al. 2004, Albrecht 2005/.

The few corings performed at the Börstilåsen esker showed that the glaciofluvial sediment is also deposited directly on the bedrock, probably after erosion of the till layer /Werner et al. 2004/. At SFM0061, c 7 m glaciofluvial sediment, dominated by gravel and stones, was retrieved, indicating sedimentation in a high-energy environment.

Glacial and post-glacial clay has accumulated in the deeper valleys, particularly on the floor of the sea. Glacial clay was deposited in deep water during the latest deglaciation. In Forsmark, varved glacial clay has been identified in the deeper sediments of several of the lakes and ponds, for example Lake Eckarfjärden. A typical characteristic of this unit in Forsmark is distinct varves (especially at sites located close to the Börstilåsen esker), together with a high clay and lime content and a low organic content /cf. Hedenström and Risberg 2003, Hedenström 2004/. The glacial clay in Forsmark was deposited during the Yoldia Sea stage of the Baltic. As mentioned above, there are no biostratigraphic observations supporting the presence of clay from the Ancylus Lake stage. It is most probable that erosive phases occurred in these areas as well, as indicated in the sediment core PFM004396 /Risberg 2005/. A major hiatus was also identified between the glacial clay and sub-recent sediment in Lake Eckarfjärden /Hedenström and Risberg 2003/. A general trend of more accumulation bottoms in the deeper valleys offshore than in more elevated areas can be seen in the bottom substrate. Till and bedrock in the surface layer are less frequent in the marine areas (c 35%) than in the terrestrial areas (c 75%).

As a result of the regressive shore displacement, the water depth decreased and bottom currents found new routes. Erosion was initiated by the currents and a layer of sand and gravel was transported and deposited on the glacial clay. Post-glacial clay was deposited in the deeper areas. This unit consists of redeposited clay particles with incorporation of organic matter. In Forsmark, this unit in the marine area consists of gyttja-clay, with an organic content of 3–6% /Risberg 2005/, whereas the sediments deposited in the shallow areas close to the shore are mainly clay-gyttja /Bergkvist et al. 2003/.

The wetlands in the Forsmark area consist of both fens and bogs. However, the bogs are few in number and still young, while rich fens are the dominant type /Göthberg and Wahlman 2006/. The bogs are located in the most elevated part of the area. Below are some results are presented from a stratigraphic investigation of peat /Fredriksson 2004/.

Stenrösmossen (AFM001245) is one of the older mires, located NW of Lake Eckarfjärden. Based on the shore displacement model, an approximate isolation age of the basin is c 700 AD /Påsse 2001/. The mire is today to a large extent a horizontal forest fen developed from a shallow stagnant water body. The main part of the mire is influenced by minerotrophic nutrient-rich groundwater from surrounding Quaternary deposits. Today the north-western and southern parts of the fen are covered with forest vegetation, which is dominated by pine and spruce in the north-west and predominantly birch, alder and aspen in the south. The open central parts of the fen are mostly covered with different *Carex* species mixed in a bottom layer of brown mosses and a scattered distribution of more nutrient-demanding *Sphagnum* species together with *Ledum palustre*, *Myrica gale*, *Calluna vulgaris* and *Empetrum nigrum*. This part of the mire has today relatively nutrient-poor vegetation and the surface can be classified as a nutrient-poor fen (Fredriksson 2004).

A generalised diagram of the peat stratigraphy in the Stenrösmossen mire is shown in Figure 3-20. The stratigraphy is characterised at the bottom by a thin layer of gyttja or clay-gyttja deposited directly on till. This indicates that erosion was active until shortly before, or until the time of, the isolation of the basin from the Bothnian Sea. A thin layer of pure low-humified light yellow *Phragmites* peat, normally mixed with *Equisetum* remnants, often overlies the gyttja or clay-gyttja, representing the infilling and overgrowing of the basin. Above these layers the peat normally consists of medium to highly decomposed *Carex* peat with wood, *Carex* peat, *Carex-Bryales* peat and *Carex-Sphagnum* peat. These layers also largely represent the present vegetation of the fen, except in the northern part, where the densely forested mire show a higher humification of the remaining peat layers, due to ditching and oxidation. In some of the open parts of the fen there is also a 0.5 to 1 m thick pure low-humified *Carex* peat.

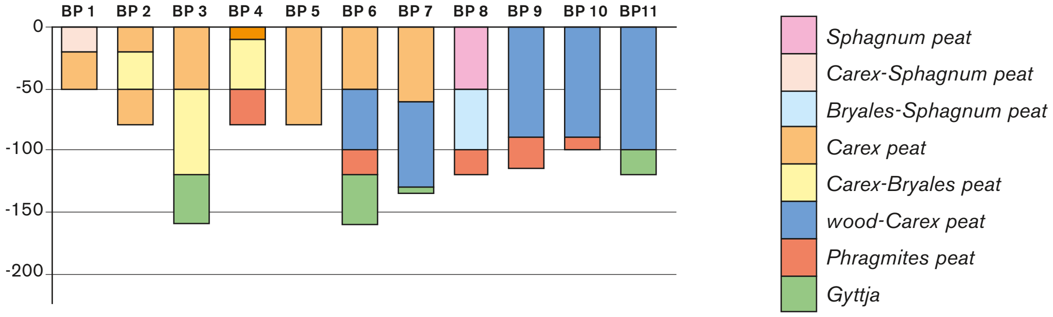
In order to quantify the recent and long-term rates of sediment and peat deposition, three sites in the Forsmark area have been analysed using radiometric dating methods /Sternbeck et al. 2006/. The long term accumulation rates were determined by ^{14}C dating, whereas the 20th century accumulation was analysed using ^{210}Pb (Table 3-3).

As noted above, the sub-recent sediments were dated using ^{210}Pb. Two cores were used, PFM005785 from Tixelfjärden and PFM005784 from Kallrigafjärden. The estimated mass accumulation rates in the two basins during the 20th century are 1,070 and 1,080 g C m^{-2} yr^{-1}, respectively. The long-term accumulation rate for Kallrigafjärden is lower, 250 g C m^{-2} yr^{-1} /Sternbeck et al. 2006/. The recent accumulation rates are in agreement with previous measurements on the Swedish coast (400–1,900 g C m^{-2} yr^{-1}) /El-Daoushy 1986/.

Table 3-3. Average mass accumulation rates (g m^{-2} yr^{-1}). The ^{210}Pb record covers the 20th century and the ^{14}C dates have been used to calculate the long-term accumulation rate /from Sternbeck et al. 2006/. (S = sediment, P = peat).

Site	^{210}Pb, average (g m^{-2} yr^{-1})	^{210}Pb, range (g m^{-2} yr^{-1})	Average long term (^{14}C) (g m^{-2} yr^{-1})	Long term cal yrs ago
Kallrigafjärden (S)	1,070	500–1,500	250±125	0–500
Tixelfjärden (S)	1,080	200–1,900		
Rönningarna (P)			69±18	0–1,600

a)



b)

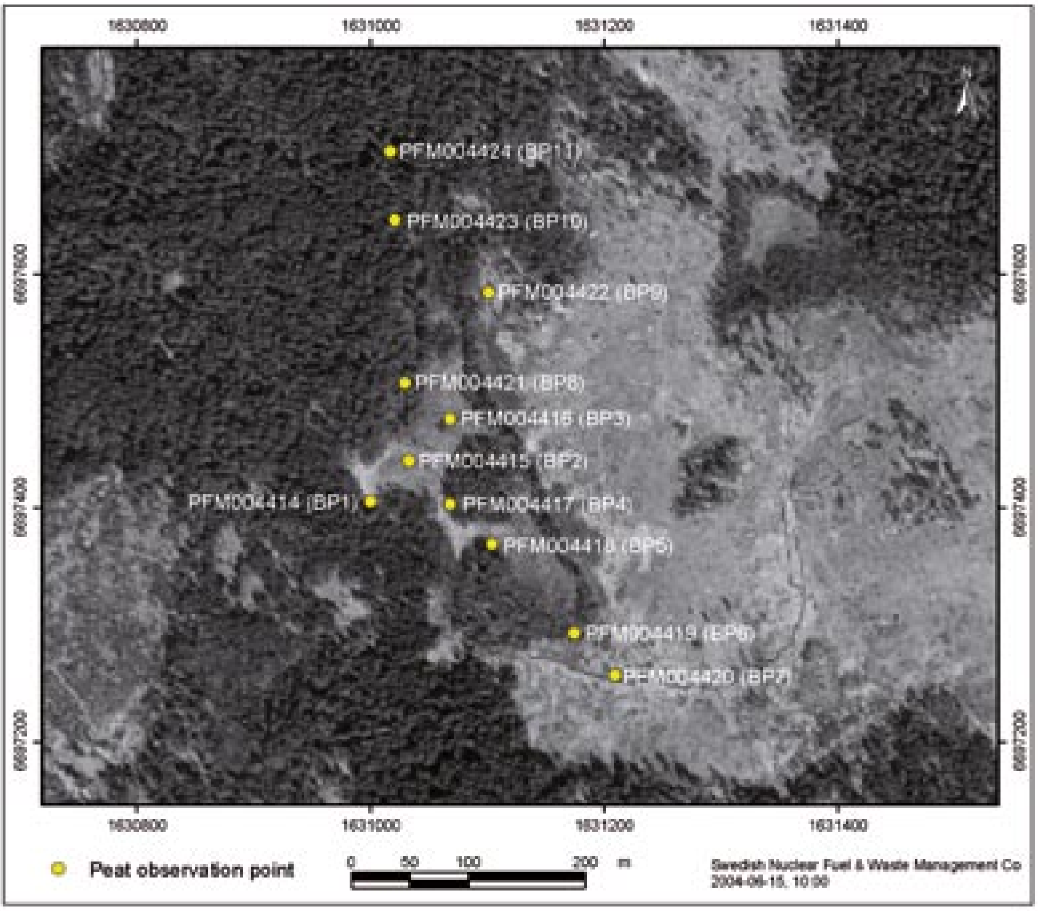


Figure 3-20. *a) Generalised stratigraphy of the organic sediments and peat in Stenrösmossen, AFM001245. The depths are in cm. b) Locations of the coring points /from Fredriksson 2004/.*

The carbon accumulation rate was quantified for sub-recent time for Kallrigafjärden and Tixelfjärden, and the long-term accumulation rate of the elements was determined for Kallrigafjärden and the Rönningarna mire (Table 3-4).

Table 3-4. Average organic carbon accumulation rates from /Sternbeck et al. 2006/. The long-term averages are shown in bold (S = sediment, P = peat).

Depth, cm	Organic carbon accumulation rate (g C m^{-2} yr^{-1}) Mean	Standard deviation
Kallrigafjärden (S)		
2–4	101	13
16–18	71	14
32–34	38	7
0–70	14	7
Tixelfjärden (S)		
2–4	118	15
10–12	92	12
16–18	67	9
32–34	13	2
Rönningarna mire (P)		
0–190	**38**	**11**

3.5 Quaternary development of the Laxemar-Simpevarp area

This section reviews the Quaternary development of the Laxemar-Simpevarp area in particular, whereas the Quaternary development of Sweden in general is described above. The reconstruction of the Quaternary development of the Laxemar-Simpevarp area is based both on results from older studies and results obtained in the site investigation.

The climate development of Northern Europe shows that numerous cold periods with glaciations have occurred. It can therefore be concluded that the Laxemar-Simpevarp area has been covered by ice sheets several times, although the exact timing is almost impossible to deduce. Future glaciations can therefore be expected. In Laxemar, the onset of a colder climate will probably initiate a long period of tundra conditions, which later may be followed by a period of ice coverage.

Since the latest deglaciation there have been several large, mostly regressive, variations of the water level in the Baltic Sea, which have had a great impact on coastal areas like the Laxemar-Simpevarp area. Such variations have probably been significant for large parts of the Quaternary period and may affect the Laxemar-Simpevarp area in the future as well.

3.5.1 Before the latest glacial phase

The marine isotope record /e.g. Shackleton 1997, Shackleton et al. 1990/ suggests that there were numerous glaciations during the Quaternary period (cf. Figure 4-2). The absolute number of past ice sheets covering the Laxemar-Simpevarp area is, however, unknown. End moraines from three glaciations are known from northern Poland and Germany /e.g. Andersen and Borns 1997/. It can therefore be concluded that the Laxemar-Simpevarp area was glaciated at least three times, but probably more, during the Quaternary period.

The climate during the interglacials probably resembled the present interglacial. The sea level was higher than at present during the latest interglacial, the Eemian (130,000–115,000 years ago), and it is therefore likely that the local model area was covered with brackish water during most of that interglacial.

As previously mentioned, the models presented by /Fredén 2002/ and /Lundqvist 1992/ are often used to illustrate the development of the Weichsel (Figure 3-5). The Laxemar-Simpevarp area was most probably free of ice during the two early Weichselian stadials and interstadials, MIS 5d–5a (Figure 3-5). The length and timing of ice-free conditions in Fennoscandia during these interstadials are not known /Lokrantz and Sohlenius 2006/. It has been assumed that tundra conditions prevailed during the stadials /Fredén 2002/. The vegetation during the first Weichselian interstadial was probably dominated by coniferous forest, whereas the second interstadial was colder, with sparse forests dominated by birch (*Betula*). Figure 3-5 suggests that the ice advanced south and covered the Laxemar-Simpevarp area first during the Middle Weichselian (MIS 4 c 70,000 years ago). The exact timing of the Middle Weichselian glaciation is, however, unknown and there are indications of ice-free condition in large parts of Fennoscandia during interstadial parts of MIS 3 /Ukkonen et al. 1999, 2007/, and summer temperatures as warm as the present /Helmens et al. 2007/. It is thus possible that the MIS 5a map shown in Figure 3-5 represents the palaeogeography during a middle Weichselian interstadial rather than the early Weichselian. The total time of ice coverage in the Laxemar-Simpevarp area may therefore have been considerably shorter than in the model presented in Figure 3-5.

In the Laxemar-Simpevarp model area there is no evidence of Quaternary deposits that were deposited before the last phase of the Weichselian glaciation. The stratigraphic distribution of Quaternary deposits (Table 3-6) shows the same succession as can be expected in an area where the deposits were formed since the latest ice age /Sohlenius et al. 2006/. It is, however, not possible to determine the absolute age of the glacial till in the area. Older glacial till and fluvial sediment of unknown age were discovered during the SGUs mapping of Quaternary deposits in Västervik, c 40 km north of Laxemar-Simpevarp /Svantesson 1999/. Water-laid deposits covered by till on the south Swedish Highland have been described by /Rydström 1971, Daniel 1989, Jönsson 1979/. /Rydström 1971/ suggested that these water-laid deposits were deposited during a Weichselian interstadial. /Lagerbäck 2007b/ has recently found indications suggesting that certain stones and boulders in southern Sweden were deposited before the last glacial phase and remains at in situ positions. Therefore, it can not be excluded that Quaternary deposits older than the last Weichselian glacial phase also exist in the Laxemar-Simpevarp area.

/Lagerbäck et al. 2004b, 2005b, 2006/ searched for traces of possible late- or post-glacial faulting in the Oskarshamn region. The results were also used to discuss the age and stratigraphy of the Quaternary deposits in the area. The study includes results from stratigraphic descriptions made in machine-cut trenches, studies of bedrock exposures, possible post-glacial faults and interpretations from aerial photos. The results from studies of bedrock outcrops show that the degree of glacial erosion is low in the area. The machine-cut trenches were all situated close to glaciofluvial eskers, and at several sites a diamicton (i.e. unsorted material with large variation in particle size) covering the glacial clay was recorded. It is suggested that the diamicton may be glacial till. This supposed till was probably deposited during the latest glacial phase. The underlying glacial clay and glaciofluvial deposits may consequently have been deposited during a deglaciation older than the latest. One of the machine-cut trenches, studied by /Lagerbäck et al. 2005b/, was situated close to the Tuna esker in the western part of the Laxemar-Simpevarp area. The stratigraphic results suggest that the Tuna esker and the surrounding sediments were deposited during the latest glaciation. In the Laxemar-Simpevarp area there is no stratigraphic evidence of Quaternary deposits from the time before the latest glacial phase. However, the widespread occurrence of deposits that may have been deposited before the last phase of the Weichselian glaciation further suggests that such deposits may occur also in the Laxemar-Simpevarp area.

Furthermore, several sites with weathered bedrock (saprolites) of Pre-Quaternary age are known in the interior of Småland, the closest c 50 km west of the regional model area /Lidmar-Bergström et al. 1997/. These deposits indicate that the intensity of glacial erosion has been low in the areas west of Laxemar. The occurrence of such "old" saprolites in the regional model area can therefore not be excluded.

The bedrock surface in the model area is often rough and rich in fissures indicating a low degree of glacial erosion /Rudmark et al. 2005/. The absence or at least low frequency of overburden predating the latest glacial cycle indicates that the Quaternary glaciers have eroded older loose deposit in the model area.

Results from high-resolution ice sheet modelling further suggest that the Weichselian ice had a low erosional capacity on the inland of Småland /Näslund et al. 2003/. Results from the same modelling suggest high ice velocities during parts of the deglaciation and basal melting conditions in the Laxemar-Simpevarp area during the Weichselian glaciation. This suggests that the ice had a high erosional capacity in the coastal areas (e.g. Laxemar). However, there is no field evidence from the regional model area to support these results.

3.5.2 Latest glacial phase (Weichselian)

According to a reconstruction of the Weichselian ice sheet by ice-sheet modelling, the maximum thickness of the ice cover in the Oskarshamn region was about 2.4 km during the Last Glacial Maximum /SKB 2006c/. The stratigraphic studies indicate that the till in the Laxemar-Simpevarp area was deposited during the latest glacial phase /Rudmark et al. 2005, Sohlenius et al. 2006/. The characteristic of the till indicates a short distance of glacial transport and the mineral composition of the till probably reflects that of the local bedrock /Sohlenius et al. 2006/. /Bergman and Sohlenius 2007/ showed that most of the boulders and gravel in the till are of local origin. Most boulders have been transported 100 metres or less from the original bedrock position. However, some individual boulders have been transported 4.5 km or more /Bergman and Sohlenius 2007/. Also the chemical composition of the till indicates that the till has been transported only a short distance /Lindroos 2004, Sohlenius and Hedenström 2008/.

The direction of glacial striae and results from fabric analyses of three till samples have been used to reconstruct the direction of ice movements during the Weichselian /Rudmark et al. 2005, Sohlenius et al. 2006/. Glacial striae on bedrock outcrops indicate a youngest ice movement from N30°W–N45°W and N40°W–N60°W in the Västervik and Oskarshamn areas, respectively /Svantesson 1999, Rudmark 2000/. Similar results are presented on an old SGU map of the Laxemar-Simpevarp area /Svedmark 1904/. Results from the site investigation concerning measurements of glacial striae /Rudmark et al. 2005/ also indicate a youngest ice movement from the north-west (N50°W–N40°W). At six localities, two distinct systems of striae with a somewhat more northerly striae direction have been observed (N35°W–N15W°). These striae probably indicate somewhat older ice movements or local deviations caused by the bedrock morphology. Glacial striae indicating an ice movement from the north-east (N45°E and N15°E) have been observed at two sites in the Laxemar-Simpevarp model area (PSM007166 and PSM005407). Both of these observations were made below the till at the bottom of machine-cut trenches. Glacial striae indicating ice movements from the north-east have previously been observed in the archipelago of Småland /Rudmark 2000/. The fabric analyses at PSM007166 indicate that the till at that site was deposited from N10°E. At PSM005407, the striae from the north-east are overlain by clayey till. That till has a fabric indicating deposition from N15°W. However, the high clay content in that till rather indicates transport from the Baltic depression, i.e. from the east or north-east.

One fabric analysis and two striae observations indicate a relatively old direction of ice movement from the north-east. Most other striae observations indicate that the latest active ice moved from the north-west. It is therefore suggested that an ice sheet moving from the north-west followed the ice moving north-east.

/Bergman and Sohlenius 2007/ studied the distribution of different bedrock types in the till and showed that till has been transported from the north. It was not possible to determine the direction of glacial transport in detail based on these results. The till in two samples from the same site (PSM007171 and PSM007173) contains calcium carbonate. The remaining 46 till samples from the Laxemar-Simpevarp area did not contain any detectable amounts of calcite.

The closest limestone areas are on the floor of the Baltic Sea, east and north-east of the area investigated here. The presence of calcite therefore further supports the interpreted ice movement from the north-east.

There are three small and one large (the Tuna esker) glaciofluvial deposits in the regional model area (Figure 3-21). During the latest deglaciation the glaciofluvial material was deposited in tunnels beneath the ice sheet by meltwater running from the north. The occurrence of subglacially formed eskers indicates basal melting conditions during the deglaciation. Stratigraphical studies along the coast of Småland have shown that some of the eskers and surrounding Quaternary desposits are covered by diamict material, probably till. It can therefore not be ruled out that some eskers were deposited during a deglaciation older than the latest /cf. Lagerbäck et al. 2006/. The large Tuna esker and the surrounding deposits lack a till coverage and that esker was consequently most probably deposited during the latest deglaciation.

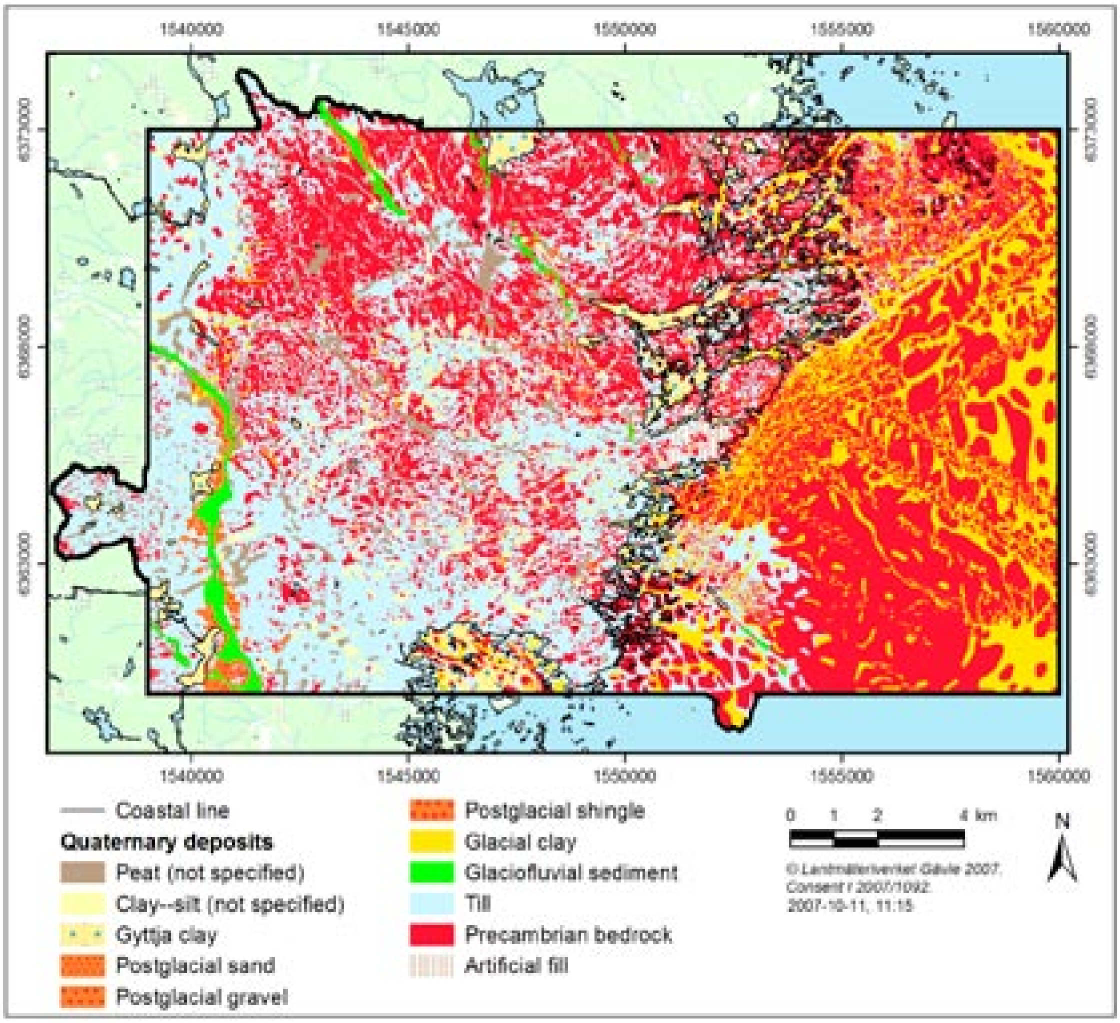


Figure 3-21. *The distribution of Quaternary deposits on the sea floor and in the terrestrial part of the Laxemar-Simpevarp regional model area (essentially outlined by the black rectangular area) /Ingvarson et al. 2004, Rudmark et al. 2005, Elhammer and Sandkvist 2005b/. The areas with Precambrian bedrock may at some sites be covered with up to 0.5 m of Quaternary deposits.*

3.5.3 Latest deglaciation

According to the calibrated clay-varve chronology, the Oskarshamn area was deglaciated around 12,000 BC /Lundqvist and Wohlfarth 2001/. The latest deglaciation of southern Sweden, as interpreted from /Lundqvist and Wohlfarth 2001/, is shown in Figure 3-22.

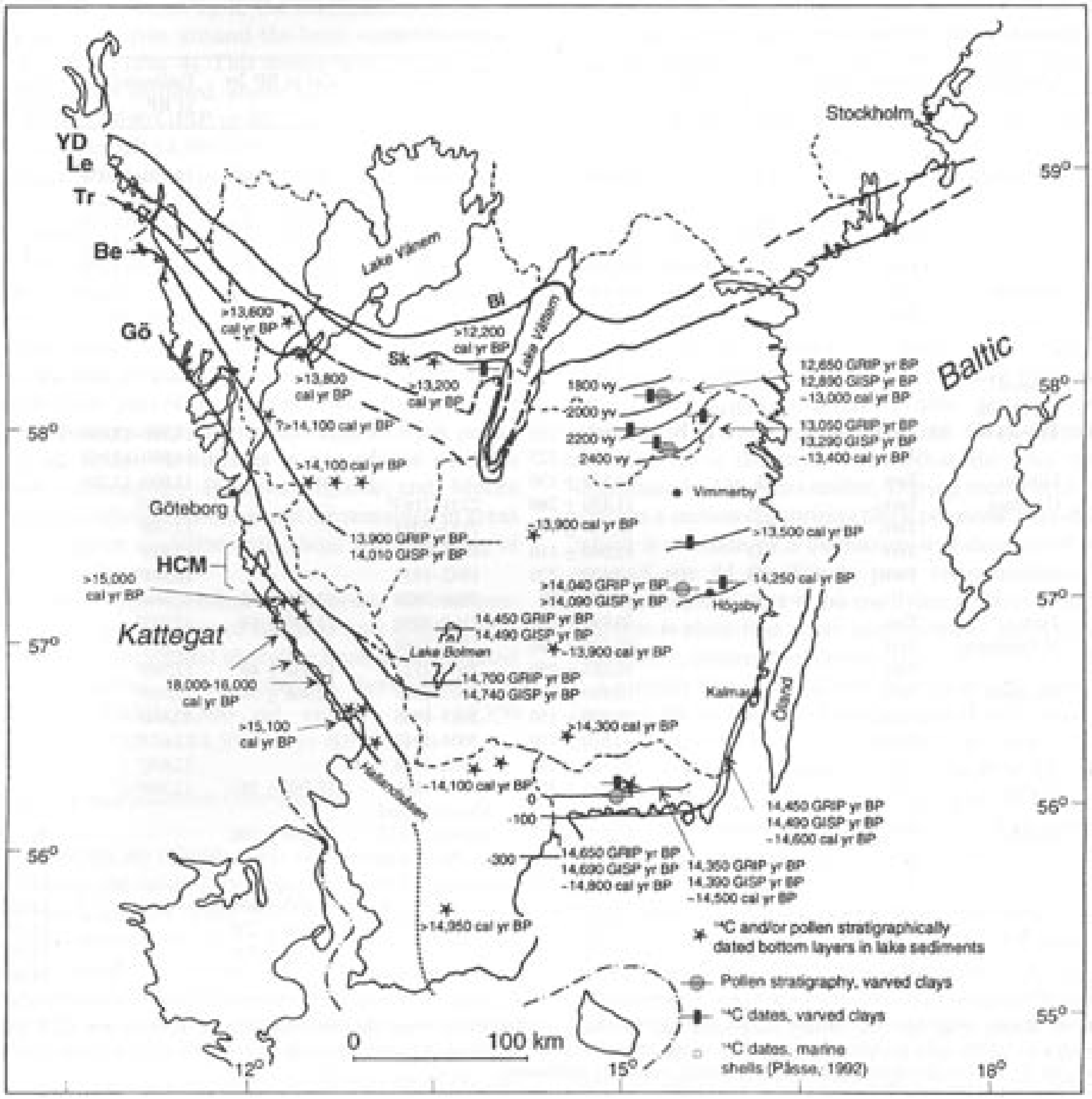


__Figure 3-22.__ The latest deglaciation of southern Sweden with age-equivalent west-east correlations of the ice marginal lines. Ages determined by different techniques have been calibrated to calibrated years BP. GISP and GRIP refer to ages determined for climate changes identified in ice cores from Greenland summit /from Lundqvist and Wohlfarth 2001/. HCM = Halland coastal moraines, Gö = Göteborg moraine, Be = Berghem moraine, Tr = Trollhättan moraine, Le = Levene moraine, YD = Younger Dryas moraines (constituted by Sk = Skövde moraine, Bi = Billingen moraine).

The ice front had a north-east/south-west direction during the deglaciation, which is perpendicular to the latest ice movement (see above). Results from studies of clay-varves along the coast of Småland indicate that the ice margin retreated more or less continuously with a velocity of c 125–300 m/year /Kristiansson 1986/. There are, however, indications of an ice-marginal oscillation in the Vimmerby area, 40 km north-west of the regional model area /Agrell et al. 1976/. This oscillation has resulted in a series of ice-marginal deposits which can be followed to Vetlanda c 50 km south-west of Vimmerby /Lindén 1984, Malmberg Persson et al. 2007/. This presumed oscillation may have taken place during or after the Older Dryas chronozone (c 12,000 BC). It is also possible that the till covering sediments on the South Swedish Highland (see above) was deposited during oscillations of the ice front during the latest deglaciation /Rydström 1971/.

3.5.4 Coastal area after the latest deglaciation

The highest shoreline in the Oskarshamn region is located c 100 m above present-day sea level /Agrell 1976/. Accordingly, the whole regional model area is situated below the highest shoreline (Figure 3-23). The highest shoreline is situated c 20 km west of the model area. In the Laxemar-Simpevarp region, shoreline regression has prevailed and the rate of land uplift during the past 100 years has been c 1 mm/year /Ekman 1996/.

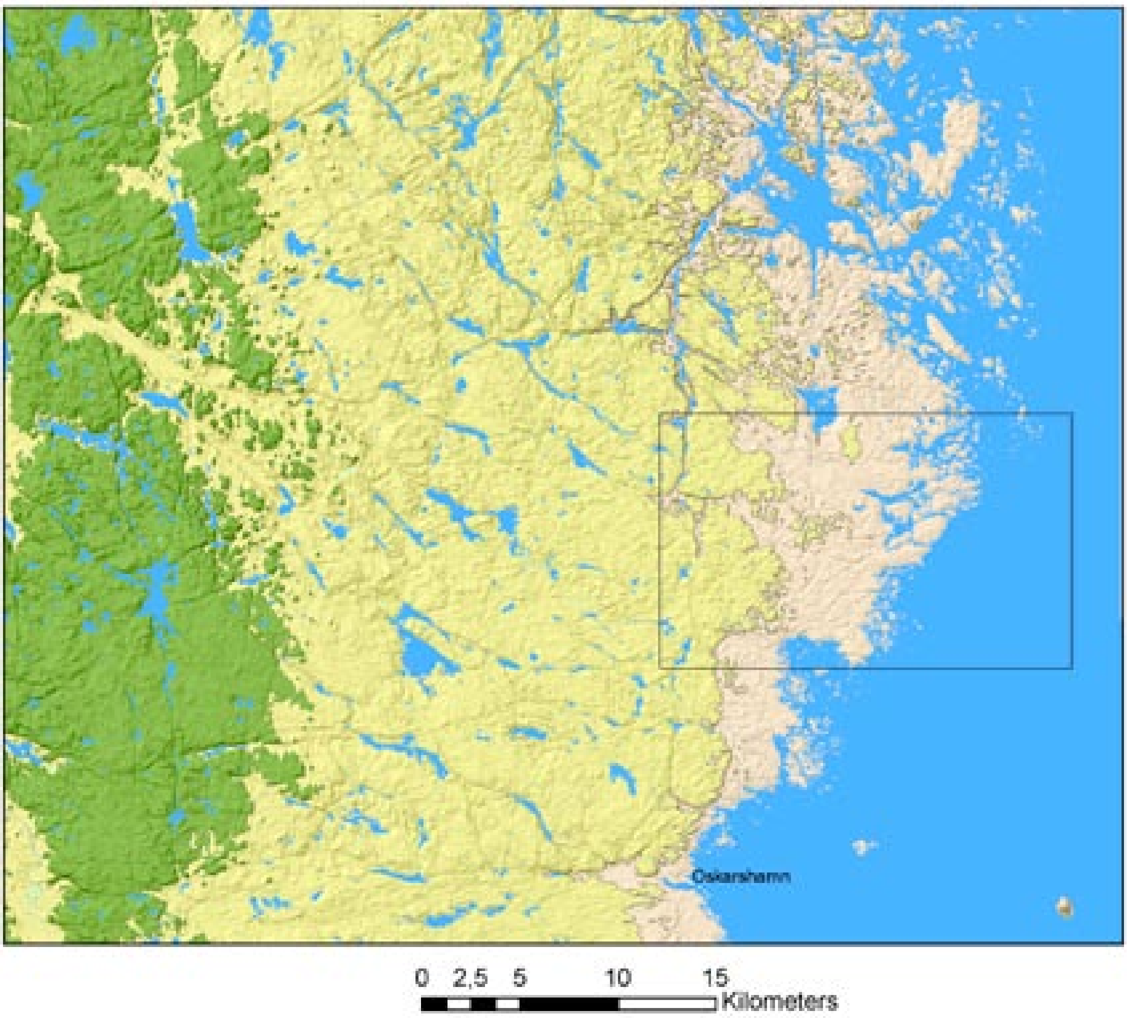


Figure 3-23. The highest shoreline and marine limit in eastern Småland. The Laxemar-Simpevarp regional model area is enclosed in a rectangular area (modified by Jirner-Lindström (SGU) from /Påsse and Andersson 2005/).

The late Weichselian and early Holocene shoreline displacement in the Oskarshamn region has been studied by stratigraphic methods by /Svensson 1989/. According to /Svensson 1989/, and several other publications /e.g. Björck 1995/, the shoreline dropped instantaneously c 25 m due to drainage of the Baltic Ice Lake at 9500 BC. The drainage was followed by the Yoldia Sea stage, which was dominated by freshwater conditions, but was influenced by brackish water for a period of about 100–150 years. The Laxemar site has experienced at least two periods with negative land growth, i.e. transgressions. The first transgression took place during the Ancylus Lake stage and was a lacustrine transgression caused by a tilt of the Baltic basin. The more recent transgression, which was caused by increased global sea level, took place during the early part of the Littorina Sea stage when the sea water was slightly saline /Robertsson 1997/. However, more detailed stratigraphic studies of sediments from areas north (Södermanland) and south (Blekinge) of the Laxemar-Simpevarp area have shown that three and six transgressions, respectively, occurred during that period /Risberg et al. 1991, Berglund 1971, Berglund et al. 2005/. It is therefore likely that several transgressions occurred also in the model area during the Littorina Sea stage.

The estimated shoreline displacement since the latest deglaciation was more recently reviewed and reinterpreted by /Påsse 1997, 2001, Påsse and Andersson 2005/. The shoreline displacement curve for the Laxemar-Simpevarp area presented here (Figure 3-24) is based on modelling of data obtained from radiocarbon dates and stratigraphical studies of lake sediments /Påsse 2001/. Input data to the modelling consist mainly of the data presented in /Svensson 1989/. The work by Svensson is, however, completely focused on the shoreline displacement before the onset of the Littorina Sea. The displacement curve during the last 9,500 years may consequently be more complex than illustrated by the curve in Figure 3-24. Furthermore, the area investigated by /Svensson 1989/ is situated 20–30 kilometres south of the Laxemar area and there may be some minor differences between the two areas. Moreover, the accuracy of the radiocarbon method has improved significantly since that work was carried out, and it is possible that a modern investigation would give slightly different results than those presented by Svensson. Another uncertainty which is difficult to account for is the transformation of radiocarbon ages to calendar years. There are several alternative transformation methods available which give somewhat different results, and if another method than that used by /Påsse 2001/ is applied, the resulting shoreline displacement curve may look somewhat different.

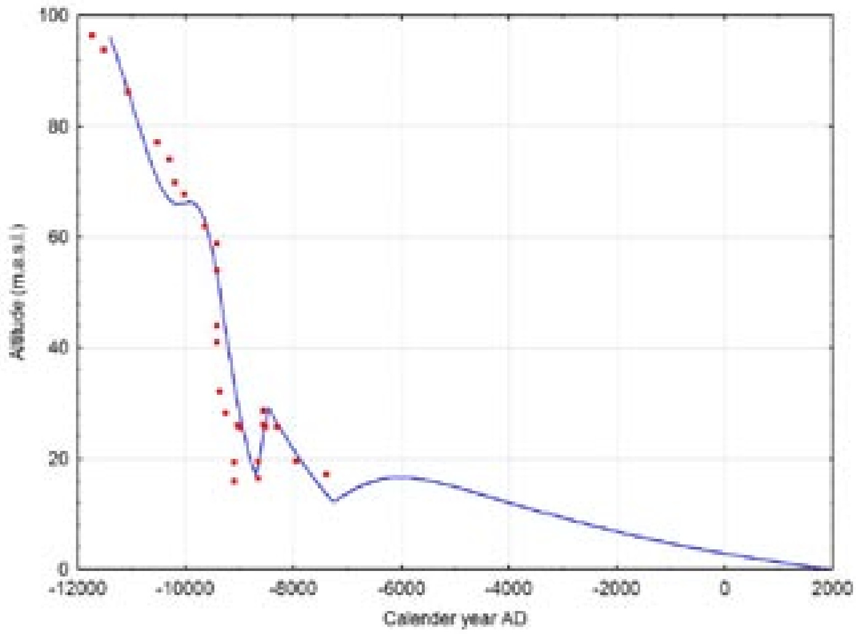


Figure 3-24. *The shoreline displacement in the Laxemar-Simpevarp area after the latest deglaciation. The red symbols show the results from dating of lake sediments in the region /Svensson 1989/. The blue curve was calculated using a mathematical model /Påsse 2001/.*

Påsse's curve is similar to the curve presented by /Svensson 1989/. Påsse suggests, however, that the rapid shoreline displacement during the end of the Baltic Ice Lake was caused by a fast isostatic component and not a sudden drainage as has been suggested previously /e.g. Svensson 1989, Björck 1995/. Påsse's interpretations have not gained any consensus among other researchers, and the mathematical models used by Påsse have recently been questioned by /Lambeck 2006/.

Salinity variations in the open Baltic proper, offshore from Oskarshamn, since the onset of the Littorina Sea, are shown in Figure 3-12. However, since the Laxemar-Simpevarp area was situated close to the coast during most of the Littorina stage, it can be assumed that salinity was generally lower than is shown in Figure 3-12.

/Brydsten 2006/ has used Påsse's mathematical model to calculate the age of some of the lakes in the Laxemar-Simpevarp area from lake elevations today and the shoreline displacement equations (Table 3-5, see also section 6.4.2). Isostatic rebound will continue in the future as well, and Påsse's equation has been used to calculate future shoreline displacement /Brydsten 2006/. It is, however, difficult to predict future eustatic changes of the sea level and thereby future shoreline displacement. An increased greenhouse effect may cause a warmer climate and a higher global sea level. Simulation with a Global Isostatic Adjustment model suggests that the Laxemar-Simpevarp area may be subjected to continued regression even if the Greenland ice sheet were to melt and increase the global sea level due to global warming /SKB 2006c/. On the other hand, the onset of a colder glacial climate will cause a lower global sea level. That will probably lead to the isolation of the Baltic Basin from the sea, which was the case during the Weichselian interstadials when the Baltic Basin consituted a freshwater lake (Figure 3-5).

3.5.5 Development of the model area as recorded by the distribution of Quaternary deposits

The properties and stratigraphy of the Quaternary deposits reflect the Quaternary development of the area /Nilsson 2004, Sohlenius et al. 2006/. For a thorough description of the distribution and properties of the Quaternary deposits the reader is referred to /Sohlenius and Hedenström 2008/. The results from the stratigraphic studies of Quaternary deposits and soil/rock drilling show that the till rests directly upon the bedrock surface. The following general stratigraphy was observed from the ground surface: peat, clay gyttja, sand, glacial clay and till (Table 3-6). The stratigraphic distribution of Quaternary deposits is more or less the same in terrestrial areas as in areas covered by lake or sea water /Sohlenius et al. 2006, Rudmark et al. 2005, Elhammer and Sandkvist 2005b, Johansson and Adestam 2004/. There are several previous investigations from bays and wetlands that describe the same general stratigraphy /Borg and Paabo 1984, Landström et al. 1994, Aggeryd et al. 1995, Risberg 2002/.

The geographical distribution of the Quaternary deposits (Figure 3-21) is highly dependent on the bedrock morphology of the model area /Rudmark et al. 2005/. The distribution of clays is mostly restricted to the long and narrow valleys which are characteristic for the investigated area. The highest topographical areas have been subjected to erosion by waves and streams. Periods of erosion have occurred also in the valleys, but it is evident that long periods of deposition of fine-grained material have also occurred in these areas.

Table 3-5. Estimated time for isolation from the Baltic Sea for some of the lakes in the Laxemar-Simpevarp area /Brydsten 2006/.

Lake	Year of isolation from the Baltic Sea
Frisksjön	1200 AD
Plittorpsgöl	6000 BC
Söråmagasinet	900 AD
Fjällgöl	6000 BC

Table 3-6. The general stratigraphic distribution of Quaternary deposits in the Laxemar-Simpevarp area /Sohlenius et al. 2006/.

Quaternary deposit	Relative age
Bog peat	Youngest
Fen peat	↑
Gyttja clay/clay gyttja	
Sand/gravel	↑
Glacial clay	
Till	↑
Bedrock	Oldest

The oldest fine-grained deposits, glacial clays, were deposited during the latest deglaciation when the water was relatively deep. Glacial clay is referred to here as clay with low organic content, often below 0.5%, and includes both clay deposited during the deglaciation and younger clay deposited during the early Holocene phases of the Baltic Sea (the Yoldia Sea and Ancylus Lake). The clays deposited during the deglaciation of the Baltic Sea are typically varved. In the Laxemar area, however, results from stratigraphic studies in trenches show that the glacial clay almost completely lacks varves /Sohlenius et al. 2006/. At one site, c 0.5 cm thick varves were, however, recorded in the lowermost part of the glacial clay. There are earlier reports of varved glacial clay close to Västervik north of the Laxemar-Simpevarp area /e.g. Svantesson 1999/. It is not known why the depositional environment in the investigated area has been unfavourable for the formation of varves. The lowermost glacial clay is often brownish, and overlain by bluish glacial clay. It is possible that the bluish colour is due to diagenetic processes taking place after the deposition of the glacial clay. The sediments overlying the glacial clay are often rich in organic matter, which may have caused reducing conditions and the reduction of iron in the uppermost (bluish) glacial clay. Fragments of limestone, probably of Ordovician age, were found in the glacial clay. The closest limestone areas are situated on the floor of the Baltic Sea, east and north-east of the area investigated here.

As the water depth decreased, streams and waves started to erode the uppermost glacial clay and deposited a layer of sand/gravel on top of the clay. The transition from glacial clay to sand/gravel is sharp and of erosive nature. Currents probably deposited this layer when the sites were situated below the level of the sea. The sand and gravel have been re-deposited during erosion of till and glaciofluvial deposits.

At many sites a bed of clay gyttja or sometimes gyttja overlies the sand and gravel layer. There is a successive transition from silt-gravel to clay gyttja. The gyttja-rich sediments were deposited during a coastal bay stage shortly before the sites emerged from the sea. At one site (PSM007190), bands of mollusc shells were found in the gyttja /Sohlenius et al. 2006/. These shells represent species that indicate deposition in a brackish water environment (Erik Wijnbladh, SKB, pers. com.). At another of the sites investigated by /Sohlenius et al. 2006/ (PSM007170), the clay gyttja contained several diatom species which were common in the bays of the Littorina Sea (e.g. *Epithemia sorex*) (Anna Hedenström, SGU, pers. com.).

Figure 3-25 shows the shoreline during three different periods of the Holocene. The maps clearly show that areas currently covered by gyttja clay coincide with areas that were once sheltered bays. The processes of erosion and deposition are still active on the sea floor and along the present coast. Results from the marine geological survey /Elhammer and Sandkvist 2005b/ show that a sand layer often overlies the glacial clay on the sea floor. The surface of the sand is often characterised by ripples, which show that currents are actively redistributing that layer. /Sternbeck et al. 2006/ have studied the past and present rates of organic sedimentation on the floors of lakes and bays (see below). The floors of many of the valleys are former or present wetlands. The areas consisting of wetlands have, however, decreased significantly due to artificial drainage.

In the lakes, the clay gyttja is overlaid by gyttja, which is still accumulating /Sternbeck et al. 2006/. In the present wetlands, a layer of fen peat covers the gyttja sediments /Nilsson 2004/. At some sites the fen peat has been covered by bog peat. As mentioned above, artificial ditches have drained most of the former wetlands, but in general they are still covered by a peat layer.

The stratigraphy from Långenmossen /Nilsson 2004/ differs from the one presented in Table 3-6. At that site a clay layer was recorded sandwiched between gyttja layers (PSM006564, 19 m above the present sea level). This clay layer may possibly represent the Ancylus transgression, more than 8000 BC (Figure 3-24), when the water depth in the area increased by c 11 metres /cf. Påsse 2001/

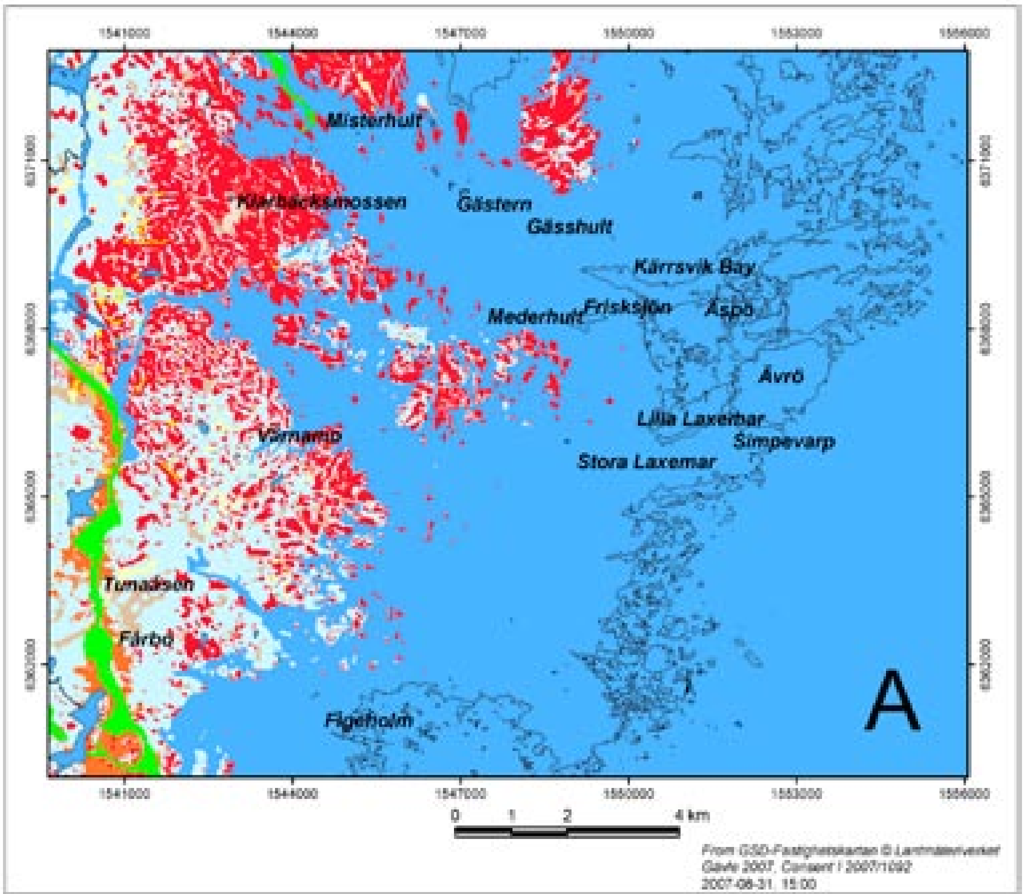
In all investigated lakes, the contents of C (carbon), S (sulphur) and N (nitrogen) show an increasing trend from the oldest to the youngest sediments /Nilsson 2004/. The total contents of all these elements are relatively low in the glacial clay. The sulphur content is higher than 1% in most sediment overlying the glacial clay and the highest values, almost 4%, were recorded in the organic-rich gyttja sediments. Sulphur in the sediments may in part be associated with organic material, but most sulphur in post-glacial organic-rich sediments is bound in iron sulphides /cf. Sternbeck and Sohlenius 1997/. The sulphides were formed in an anoxic environment on the bottom or below the sediment/water interface. The iron sulphides were precipitated after reduction of ferric iron and sulphate during the anaerobic breakdown of organic matter. Some of the organic-rich lake sediments are low in sulphur, however, indicating a low content of iron sulphides. That may be due to oxidising bottom conditions and/or the relatively low sulphate content in fresh water.

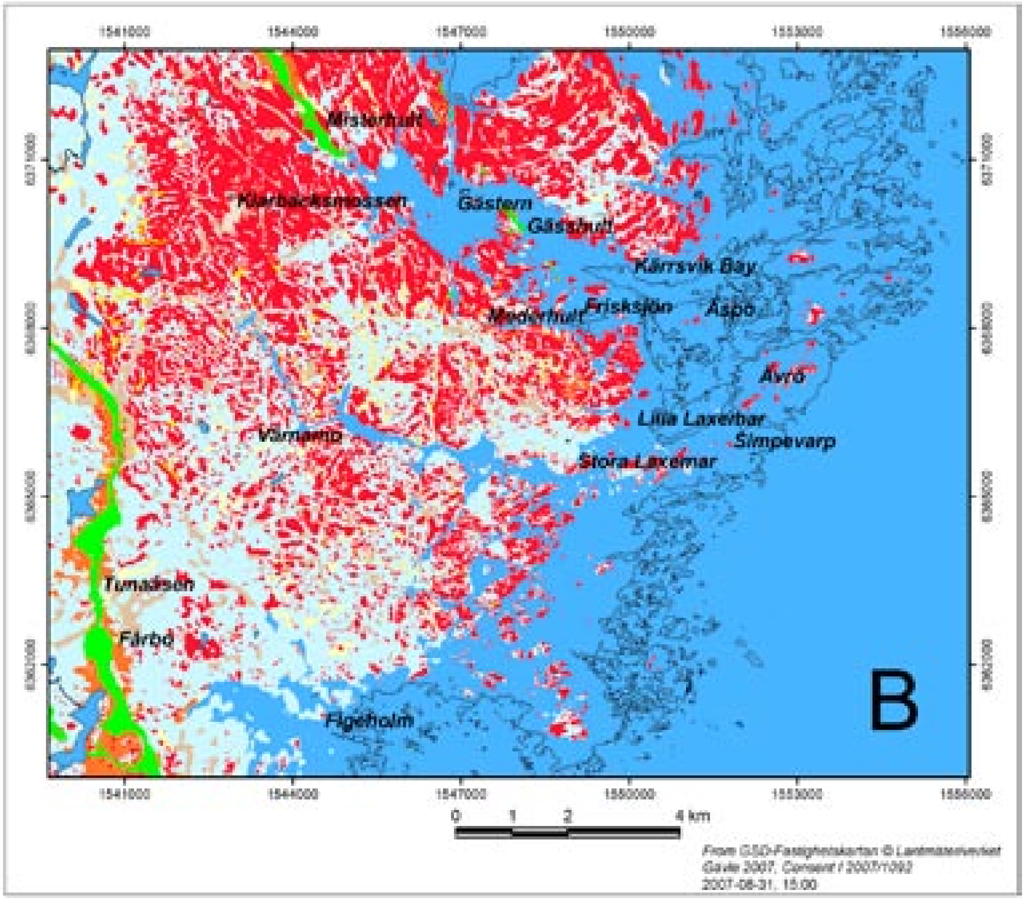
Results from three radiocarbon datings of sediment cores /Risberg 2002/ show that the gyttja overlying the sand/gravel layer in Borholmsfjärden started to accumulate c 1000 BC. The average accumulation rate for the 3,000-year period, calculated from the ^{14}C analyses, is c 1.2 mm/yr. The sand/gravel is underlain by glacial clay that accumulated shortly after the deglaciation when the water depth at the site was great. The sand/gravel layer represents a period of 7,000 years when no fine-grained sediments were deposited. The gyttja sediment started to accumulate when rising land areas sheltered the site.

The recent and long-term rates of sediment and peat accumulation in the Laxemar-Simpevarp area have been studied by /Sternbeck et al. 2006/ (Table 3-7 and Table 3-8). The average long-term accumulation covers a period of several thousand years and the accumulation rates probably varied considerably throughout that period. Lake Frisksjön was isolated from the sea around 2,000 years ago /Brydsten 2006/ and the long-term accumulation rates reflect a period when the present lake was connected to the Baltic Sea. The long-term and recent carbon accumulation rates in Lake Frisksjön and Borholmsfjärden are considerably higher than in the open Baltic Sea /Emeis et al. 2000, 2003/. These two basins have to a great extent been surrounded by land for a long period of time and may therefore have properties similar to lakes. That may explain the high carbon accumulation rates in these basins. In Lake Frisksjön, the rates of carbon accumulation during the bay stage and the present lake stage were similar.

Table 3-7. Average mass accumulation rates (g m^{-2} yr^{-1}). The ^{210}Pb record covers the 20th century and the ^{14}C dates have been used to calculate the long-term accumulation /from Sternbeck et al. 2006/. (S = sediment, P = peat).

Site	^{210}Pb, average (g m^{-2} yr^{-1})	^{210}Pb, range (g m^{-2} yr^{-1})	Average long term (^{14}C) (g m^{-2} yr^{-1})	Cal yrs ago
Lake Frisksjön (S)	410	300–600	400±30	2,600–4,060
Borholmsfjärden (S)	680	470–1,000	680±100	3,300–4,400
Norrefjärd (S)	740	200–1,100		
Granholmsfjärden (S)	380	200–650		
Klarebäcksmossen (P)	450	300–600	56±6	0–8,400


1541000
1544000
1547000
1550000
1553000
1556000
Misterhult
Klarbäcksmossen
Gästern
Gässhult
Kärrsvik Bay
Frisksjön
Mederhult
Äspö
Ävrö
Lilla Laxemar
Simpevarp
Stora Laxemar
Värnamo
Tunaåsen
Fårbo
Figeholm
A
0
1
2
4 km
From GSD-Fastighetskartan © Lantmäteriverket
Gävle 2007, Consent I 2007/1092
2007-08-31, 15:00


1541000
1544000
1547000
1550000
1553000
1556000
Misterhult
Klarbäcksmossen
Gästern
Gässhult
Kärrsvik Bay
Frisksjön
Mederhult
Äspö
Ävrö
Lilla Laxemar
Simpevarp
Stora Laxemar
Värnamo
Tunaåsen
Fårbo
Figeholm
B
0
1
2
4 km
From GSD-Fastighetskartan © Lantmäteriverket
Gävle 2007, Consent I 2007/1092
2007-08-31, 15:00

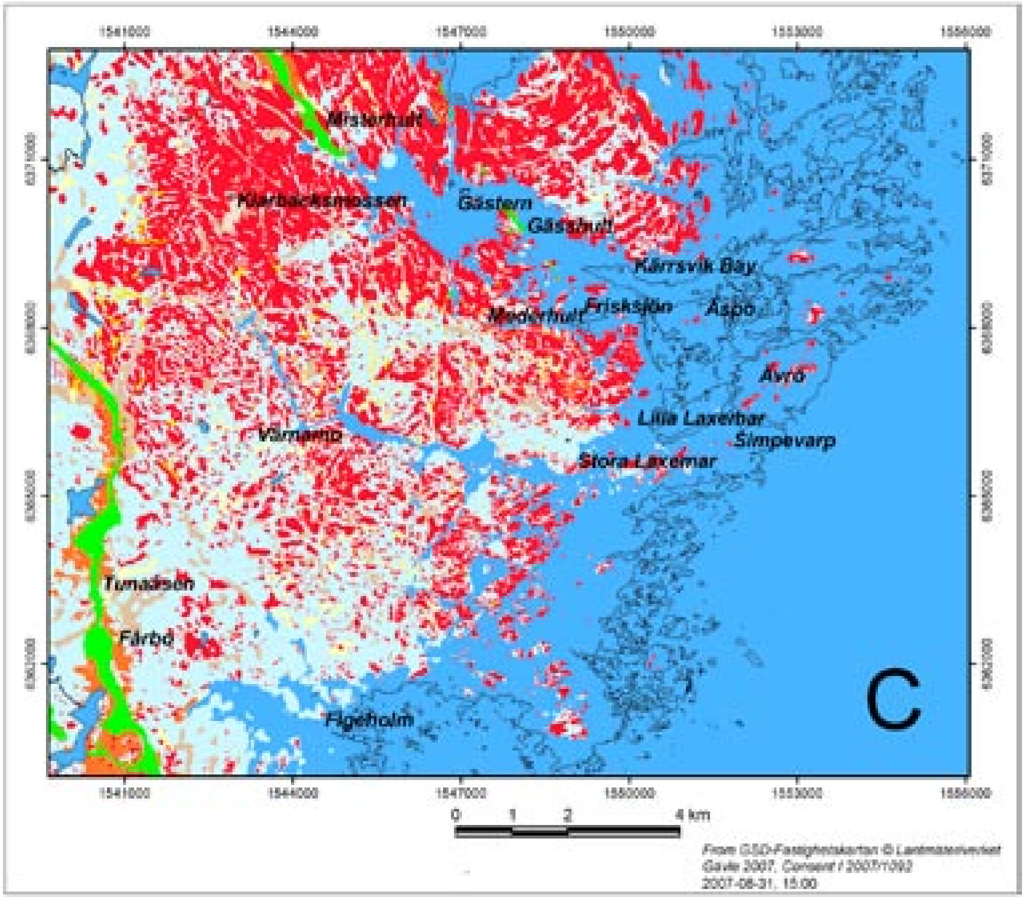


Figure 3-25. Distribution of land and sea in the Laxemar-Simpevarp area at three different times during the Holocene, A) 7800 and 8650 BC, B) 3900 BC, C) 1100 BC. The sea level was 19 (A), 12 (B) and 5 (C) meters higher than at present at the three times shown on the maps. Figure A represent two different occasions, one before and one after the Ancylus transgression.

Table 3-8. Average organic carbon accumulation rates in Lake Frisksjön, in the marine basin Borholmsfjärden and in the wetland Klarebäcksmossen /Sternbeck et al. 2006/. Long-term averages are shown in bold (S = sediment, P = peat).

Depth, cm	Organic carbon accumulation rate (g C m^{-2} yr^{-1}) Average	Standard deviation
Lake Frisksjön (S)		
20–22	79	14
188–431	**74**	**13**
Borholmsfjärden (S)		
20–22	67	8
280–560	**95**	**18**
Klarebäcksmossen (P)		
33–35	137	17
0–300	**29**	**4**

/Kaislahti Tillman and Risberg 2006/ studied the long-term accumulation rate of sediments in two sediment cores sampled outside the Laxemar archipelago (PSM002118 and PSM002123). They concluded that the organic carbon accumulation rate was < 1 g m^{-2} yr^{-1} during the Baltic Ice Lake and rose to c 3.5 g m^{-2} yr^{-1} during the Ancylus Lake/the Mastogloia Sea stages. During the Littorina Sea stage, values varied between 10–56 g m^{-2} yr^{-1}. These values are lower than the values obtained by /Sternbeck et al. 2006/ and more similar to values calculated from other parts of the open Baltic Sea /Emeis et al. 2003/. The sites investigated by /Kaislahti Tillman and Risberg 2006/ are situated outside the archipelago where sedimentary conditions are less favourable for carbon accumulation compared with the more sheltered lakes and bays, and this may at least partly explain the lower accumulation rate as found by /Sternbeck et al. 2006/.

In Klarebäcksmossen, the long-term peat accumulation rate is similar to the accumulation rates calculated for mires in Finland /Turunen et al. 2002/. The recent peat accumulation rate in Klarebäcksmossen is much higher than the long-term accumulation rate. Similar results have been obtained in other studies of peat accumulation in /Shotyk et al. 2005/.

/Risberg 2002/ investigated the microfossil record (diatoms) in a sediment core from Borholmsfjärden south of Äspö. The sediment sequence consisted of brownish clay overlain by bluish clay, sand/gravel and gyttja, which is in accordance with the general stratigraphy of the area (Table 3-6). The results show that both the bluish and brownish clays were deposited during the brackish phase of the Yoldia Sea. It is, however, not known if corresponding brownish and bluish clays described from other sites in the regional model area /Nilsson 2004, Sohlenius et al. 2006/ were also deposited in the Yoldia Sea. /Kaislahti Tillman and Risberg 2006/ investigated the diatom record in two sediment cores outside Laxemar. The diatom composition showed that the sediments were deposited during all four main Baltic Sea stages.

3.6 Summary

The Quaternary climate is characterised by large and sometimes rapid changes in global temperature. Ice sheets covered larger areas during the cold periods than at present. The Forsmark and Laxemar-Simpevarp areas have consequently been covered by glacier ice at least three times. However, the total number of glaciations that affected the model areas is not known. The cold glacial periods were much longer than the warmer interglacial periods, which are characterised by a climate similar to the present. However, long ice-free periods have also existed during the glacials. During these ice-free periods the climate was colder than today and tundra conditions probably prevailed in large parts of Sweden. Consequently, it can be assumed that permafrost has prevailed in the model areas for long periods of time. The latest glaciation (Weichselian) started c 115,000 years ago, and there is geological evidence for at least two periods when a large part of Sweden was free of ice. However, the onset of the latest glacial coverage at the two sites and the exact timing and duration of the ice-free periods at the sites are unknown. By contrast, the timing of the latest deglaciation is rather well established along the coast to the Baltic Sea.

The present interglacial, the Holocene, started at the deglaciation of Mid-Sweden when the ice margin had already retreated from Laxemar-Simpevarp but before it had reached Forsmark. The climate during the deglaciation became successively warmer, although some phases with colder climate did occur. In southern Sweden, the warmer climate caused a gradual change from tundra vegetation to forest dominated by decidious trees. The Mid-Holocene climate was characterised by temperatures a few degrees higher than today. The forests in southern Sweden have subsequently been dominated by coniferous forest. The areas covered by forest began to decrease c 3000 BC due to the introduction of agriculture. However, the areas used as arable land are decreasing today and the forested areas are increasing.

The development of the Baltic Sea after the latest deglaciation has been characterised by ongoing shoreline displacement. The interaction between isostatic recovery and eustatic sea level variations has caused varying depth in the straits connecting the Baltic Sea with the

Atlantic Ocean in the west, which has, in turn, caused varying salinity throughout the Holocene. At 4500–3000 BC, the salinity of the Baltic Basin was almost twice as high as it is today in Laxemar-Simpevarp and Forsmark. Figure 3-26 summarises the post-glacial development of the two areas. The Forsmark area was deglaciated more than 3,000 years after the Laxemar-Simpevarp area and did consequently not experience the brackish phase of the Yoldia Sea. The land growth curves (brown) clearly show that the Forsmark area started to emerge from the Baltic much later than the Laxemar-Simpevarp area. Laxemar-Simpevarp has experienced two periods with trangressive shoreline displacement (blue curve), causing a negative land growth. Most researchers agree that the level of the Baltic Sea instantaneously dropped 25 metres at the transition from the Baltic Ice Lake to the Yoldia Sea stage. That fast drop is not clearly reflected in the shoreline displacement curve for the Laxemar-Simpevarp site.

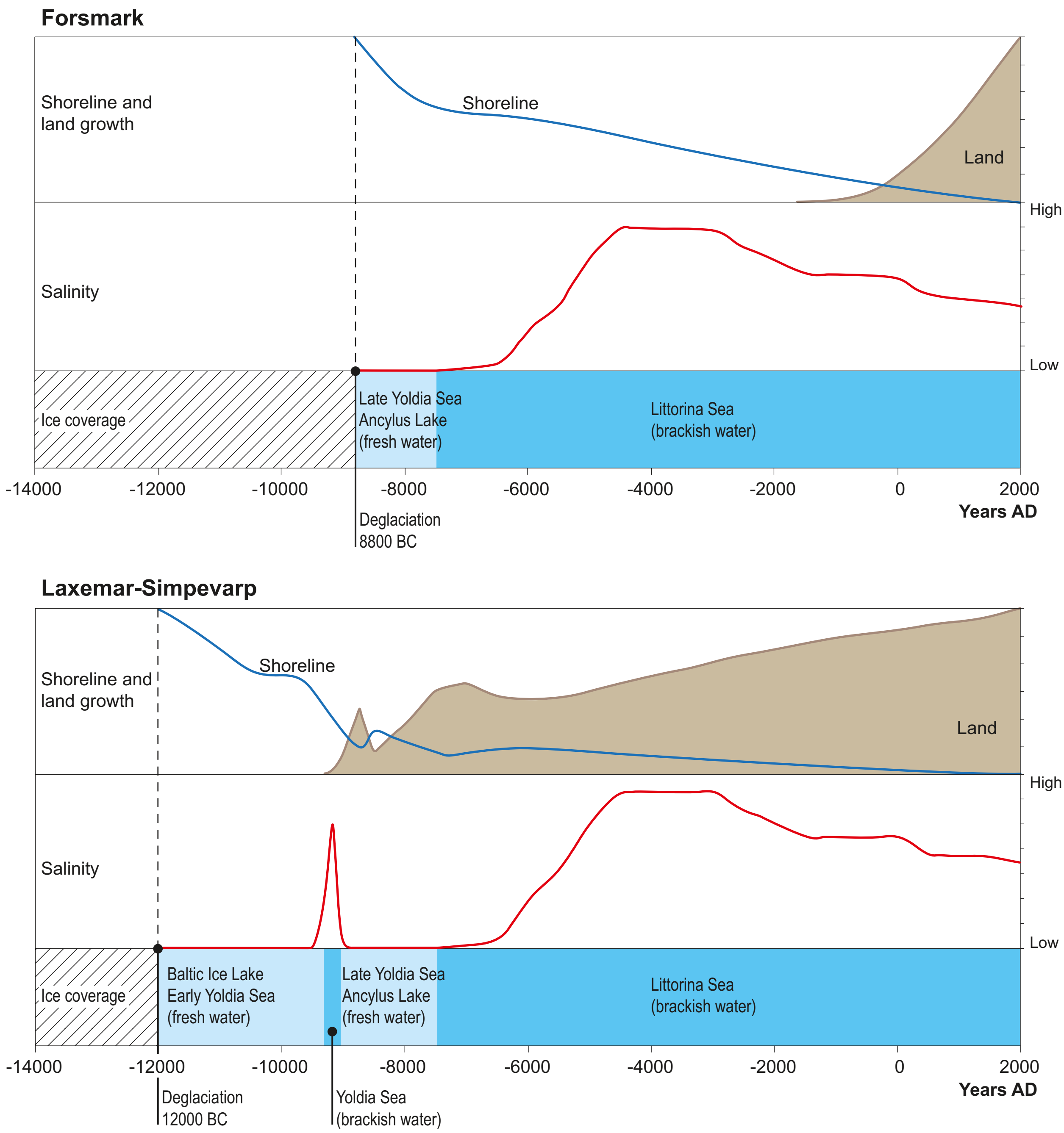


Figure 3-26. *The development of the Forsmark and Laxemar-Simpevarp areas from the latest deglaciation to the present. The red curves show variation in salinity of the Baltic Sea at the two sites (the Bothnian Sea for Forsmark and the Baltic proper for Laxemar-Simpevarp).*

It is suggested that all known loose deposits in both of the model areas were deposited during the last phase of the latest glaciation and after the following deglaciation. In Forsmark, a till unit consisting of overconsolidated silty-clayey till was deposited during an earlier phase of the latest glaciation. However, the possibility of the occurrence of older deposits cannot be excluded, and there are indications of older deposits in neighbouring areas.

Till and glaciofluvial material was deposited both directly by the ice sheet and by glacial meltwater. Both the Laxemar-Simpevarp and Forsmark regional model areas are completely situated below the highest shoreline and were consequently covered by water after the latest deglaciation, from c 12,000 BC and 8800 BC, respectively. During the deglaciation, glacial clay was deposited in the lowest topographical areas. The following shoreline displacement has had a great impact on the distribution and relocation of fine-grained Quaternary deposits. The most exposed areas have been subjected to wave washing and currents on the bottom. Sand and gravel have consequently been eroded from older deposits, transported and deposited at more sheltered locations. Periods of erosion have occurred also at sheltered locations, which have caused erosion of fine-grained deposits such as glacial clay. Gyttja clay is commonly occurring in the terrestrial valleys and was deposited when these valleys were narrow bays. Shoreline displacement is an ongoing process and new areas are currently exposed to erosion, whereas sheltered bays with conditions favourable for deposition of clay gyttja have formed in other areas.

Lakes and wetlands are gradually being covered by fen peat, which at some locations is being covered by bog peat. In Forsmark, the mires are generally small and too young for raised bogs to develop. In Laxemar, many wetlands have been drained by ditches for agricultural purposes and the peat is consequently being oxidised.

4 Palaeoseismicity and seismicity during the Quaternary period

4.1 Introduction

An earthquake is the result of a sudden release of energy through movement (faulting) along a deformation zone, resulting in the emission of seismic waves. This movement is normally the result of stresses that have accumulated over a certain time interval in a particular volume. Fault movement and the generation of an earthquake imply that the applied shear stresses in the rock along the fault have exceeded the stresses that friction and the intrinsic material strength of the rock could withstand, i.e. the Mohr-Coulomb failure envelope has been exceeded. The part of a fault which moves in a given earthquake is limited, both in depth and in areal extent.

Information on earthquake activity prior to recordings in historical time is provided indirectly with the help of geological studies of faults exposed at the present level of erosion, along which it has been possible to make estimates of both the character and timing of fault movement. These observations are referred to as *palaeoseismological studies*. During historical time, but prior to the use of modern instrumentation (seismometers), approximately 100 years ago, earthquakes were detected solely by the direct observation of effects at the surface, including ground motions felt by people and damage to buildings etc caused by vibrations. The size of the effects observed that were reported in, for example, newspapers of the time can be used to assess the location, depth and magnitude of the event. Studies of such phenomena are referred to as *macroseismic studies*. Both the palaeoseismological and macroseismic studies can be used to link the pre-instrumental observations to the instrumental ones, but both types of study are far less reliable than modern *seismological instrumental information* using seismometers. Nevertheless, they are of considerable importance, bearing in mind the very limited time period for which instrumental data are available.

This chapter addresses palaeoseismicity and seismicity in the Fennoscandian Shield during the Quaternary period. Section 4.2 summarises the causes of seismic activity, i.e. the driving forces. Section 4.3 addresses the palaeoseismological information relevant to late- or post-glacial faulting. A short overview of this phenomenon in Sweden is followed by a summary of the results of detailed studies designed to evaluate the occurrence of such faulting in both the Forsmark and Laxemar-Simpevarp areas. These studies were completed in connection with the respective site investigation programmes in the two areas. The next part of the chapter, in section 4.4, addresses macroseismic and seismological instrumental information that has been compiled in historical time from 1375 up to 2005, and from 1904 to 2005, respectively. This description stems from the assessment of earthquake activity in Sweden that has recently been completed for SKB by /Bödvarsson et al. 2006/. The predominantly editorial and other modifications to this text are the responsibility of one of the authors of this report (Stephens). Finally, a summary of material in this chapter is provided in section 4.5.

4.2 Earthquakes and relationship to plate tectonics and post-glacial isostatic rebound

Earthquakes are not evenly distributed on the planet, but are largely concentrated along limited seismogenic zones. These zones generally correspond to the boundaries between plates that form the Earth's outer cold and rigid shell, the so-called lithosphere (Figure 4-1). The plates are in constant slow motion relative to each other, and earthquakes predominantly occur as a consequence of these motions. Since the plates are relatively strong and rigid, stresses are maintained for great distances and earthquakes can even occur far away from the plate boundaries in tectonic domains inside plates, so-called intra-plate earthquakes. Sweden is situated at the present time (cf. Chapter 2) within the large Eurasian plate and the nearest plate boundary, the mid-Atlantic ridge, is more than 1,000 km away.

Second-order phenomena, which are significant in generating earthquakes, include activity associated with mantle plumes, where warm material from the Earth's mantle forces its way up towards the surface, or activity in areas which have recently been loaded or unloaded by sediment, water or ice. In particular, the northern part of Europe has been affected by several glaciations and deglaciations during the last c 2 Ma (see Chapter 3), and it has been inferred that major earthquake activity occurred in connection with the retreat of continental glaciers (see section 4.3 below). Earthquakes generated during isostatic rebound after the latest glaciation have been explained by the release of stress that accumulated earlier during glacial loading in connection with tectonic plate motions (see, for example, /Johnston 1987, 1993/). The release of stress occurred during unloading, in connection with the rapid removal of the ice. More recently, modelling work has indicated that the high horizontal stresses induced by flexure in connection with loading by ice, together with the ambient tectonic stress field, can cause fault instability /Wu and Hasegawa 1996ab, Wu et al. 1999, Lund 2005, 2006/.

Finally, since, for example, blasting associated with mining activity or loading by water in connection with reservoir construction can trigger earthquakes, there is a need to separate these anthropogenic activities from crustal deformational features in the analysis of seismological instrumental data.

4.3 Palaeoseismic activity related to late- or post-glacial faulting

4.3.1 Overview – Sweden

Far away from any plate boundaries, the current seismicity in Sweden is generally low (see section 4.4) and regional uplift due to isostatic rebound after depression of the crust during the latest glaciation prevails. This situation contrasts markedly with the conditions that prevailed some 10,000 years ago, when it has been inferred that at least northern Sweden and the adjacent parts of Finland and Norway were affected by major faulting, in connection with the disappearance of the latest inland ice-sheet. A significant number of late- or post-glacial, reverse fault scarps have been identified in northern Fennoscandia (e.g. /Lagerbäck 1979, 1990, Kuivamäki et al. 1998, Olesen et al. 2004/ and Figure 4-2) and it has been inferred that the accompanying earthquakes reached magnitudes of up to M8 or even larger on the Richter magnitude scale /e.g. Muir Wood 1993, Arvidsson 1996, Mörner 2003/. An extensive compilation of the current knowledge concerning late- or post-glacial faulting was recently provided in Appendix 3 in /Munier and Hökmark 2004/.

When loosely packed, a water-saturated, frictional sediment that is affected by strong ground shaking, for example an earthquake, can liquefy. As a consequence of this process, the primary sedimentary structures will be destroyed and replaced by a variety of deformational features, which can be recognised in stratigraphical studies. Thus, fault movements may be indicated either directly by distinct displacements, manifested in the bedrock surface or covering regolith, or indirectly by seismically derived deformation of Quaternary sediment. For this reason, abundant liquefaction structures in the fault region, developed in sandy or silty sediment, are consistent with late- or post-glacial faulting and palaeoseismic activity.

Since the vertical relief along the late- or post-glacial faults in northern Fennoscandia generally exceeds 5 m and the fault scarps stand out as anomalous features in the generally, glacially smoothed landscape (Figure 4-2), they are relatively easily detected by means of the interpretation of aerial photographs. A brief investigation by means of aerial photograph interpretation was not able to identify similar features in central Sweden /Lagerbäck 1979/.

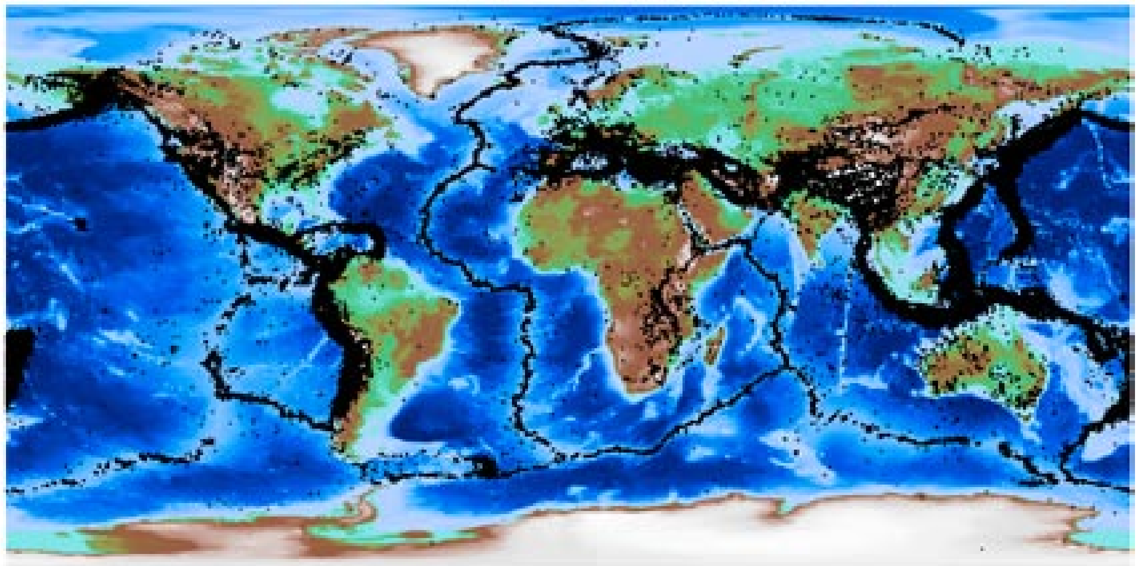


__Figure 4-1.__ Distribution of earthquakes with a magnitude (M) > 3 recorded during the last 30 years on the Earth. Note the strong concentration of earthquakes along seismogenic zones that generally lie along or in the vicinity of plate boundaries (after /Munier and Hökmark 2004/, Figure A3-5).

__Figure 4-2.__ The inset map shows late- or post-glacial faults in the northern part of Finland, Norway and Sweden, including the Pärvie fault (adapted from /Munier and Hökmark 2004/). The photograph shows the Pärvie fault escarpment which is 150 km long and was formed during the latest deglaciation of northernmost Sweden /Lundqvist and Lagerbäck 1976/. The main escarpment is c 10 m high and cuts the glacially smoothed landscape. Photograph from Robert Lagerbäck (SGU) with view along the fault escarpment to the south-west.

However, arguments for the occurrence of late- or post-glacial palaeoseismic activity in southern Sweden have been put forward /e.g. Mörner 1990, 2003/, based on the presence of structures identified as being caused by seismically induced liquefaction phenomena. As yet, conclusive evidence for corresponding fault movements is lacking and the interpretations have been questioned /e.g. Muir Wood 1993/. Two other types of indirect evidence for late- or post-glacial faulting have been used. These include irregular isostatic uplift during the Holocene and the occurrence of bedrock caves.

/von Post 1929/ suggested irregular isostatic uplift during the Holocene in the area north of Lake Vänern. This interpretation has later been confirmed by a study from the same area using modern dating techniques. The isolation events for several lake basins that are located in different bedrock blocks were dated and it was demonstrated that the individual blocks had emerged at different times during the Holocene /Risberg et al. 1996/. Similar conclusions were made following a study conducted in Blekinge by /Björkman and Trägårdh 1982/. Recently, /Risberg et al. 2005/ have demonstrated irregular uplift in the eastern part of central Sweden since the onset of the Littorina Sea (7500 BC). The irregular shoreline displacement north of Lake Vänern and in Blekinge may also be related to post-glacial faulting in the investigated areas. However, no post-glacial faults have been recognised in any of these areas and it remains uncertain whether or not the irregular isostatic uplift is related to palaeoseismic activity during the Holocene.

Bedrock caves and fractured bedrock occur sporadically throughout Sweden. Several bedrock caves have been described from the region around Forsmark and there are at least three bedrock caves north of Laxemar /Sjöberg 1994/. It has been suggested that these caves formed in connection with palaeoseismic activity shortly after the latest deglaciation /Sjöberg 1994/. If ancient earthquakes formed such caves, similar features should be present in other areas in the crystalline bedrock, which were affected by seismic activity in historical time. However, evidence is lacking for the existence of similar caves in these areas /e.g. Muir Wood 1993/.

In a study of fractured bedrock and bedrock caves in the region around Forsmark in northern Uppland, /Lagerbäck et al. 2005a/ discovered that these structures often occur in areas with boulder-rich till and poorly exposed bedrock. They also showed that the boulders around the caves have been glacially transported. Furthermore, several of the boulders in the rock mass that forms one of the caves are stacked in a manner indicating the effects of an overriding ice sheet. Thus, the fracturing probably predates the latest deglaciation. /Lagerbäck et al. 2005a/ suggested that the boulder caves and boulder-rich till were formed in connection with changes in the ice-induced stress pattern in the surficial parts of the bedrock near to the margin of the receding ice sheet. To what extent this process was glaciological in origin or simply due to release of stress in the bedrock during unloading when the ice was removed (or to both these phenomena) awaits further investigation. In this context, the results from drill site 5 at Forsmark, discussed in the following section, are highly relevant.

4.3.2 Forsmark area

A targeted site investigation programme, which aimed to trace possible, major late- or post-glacial fault movements in and around the Forsmark area, was initiated in 2002 /Lagerbäck and Sundh 2003/ and extensive field investigations were conducted during 2003 and 2004 /Lagerbäck et al. 2004a, 2005a/. A summary of all the results is provided in /Lagerbäck et al. 2005a/. In this context, the term "major faulting" was defined as a displacement in the order of several metres along a fault that is several kilometres in length. Faults of these dimensions may, if conditions are favourable, be detected by means of the interpretation of aerial photographs. Furthermore, if motion along such a fault was instantaneous, it would have generated high magnitude earthquakes, which, in turn, could have produced characteristic distortions in water-saturated sandy or silty sediment, so-called liquefaction structures.

An interpretation of aerial photographs was carried out in a relatively large area (Figure 4-3) in north-eastern Uppland, with the purpose of looking for morphologically conspicuous lineaments that are candidates for being late- or post-glacial faults. Several fairly prominent escarpments and crevasses were noted but, when later studied in the field, these features turned out to be more or less strongly, glacially abraded, i.e. they are not late- or post-glacial in age.

In order to search for liquefaction structures, all gravel and sand quarries in operation within the investigation area were examined (Figure 4-3). In addition, 48 trenches with a total length of c 900 m were excavated at 18 different sites, the majority of which were located along the Börstil esker to the south-east of Forsmark. Strongly contorted and folded sequences of glacial clay were encountered at several localities (Figure 4-4), but the disturbances were interpreted to be caused by sliding. Conclusive evidence for a palaeoseismic origin for the sliding was not found, although such an origin was not excluded /Lagerbäck et al. 2004a, 2005a/. Since no major distortions that could be associated with seismically induced liquefaction were identified (Figure 4-5), it was concluded that no major (magnitude > 7 on the Richter scale) earthquakes had occurred in the Forsmark area after the retreat of the latest inland ice sheet.

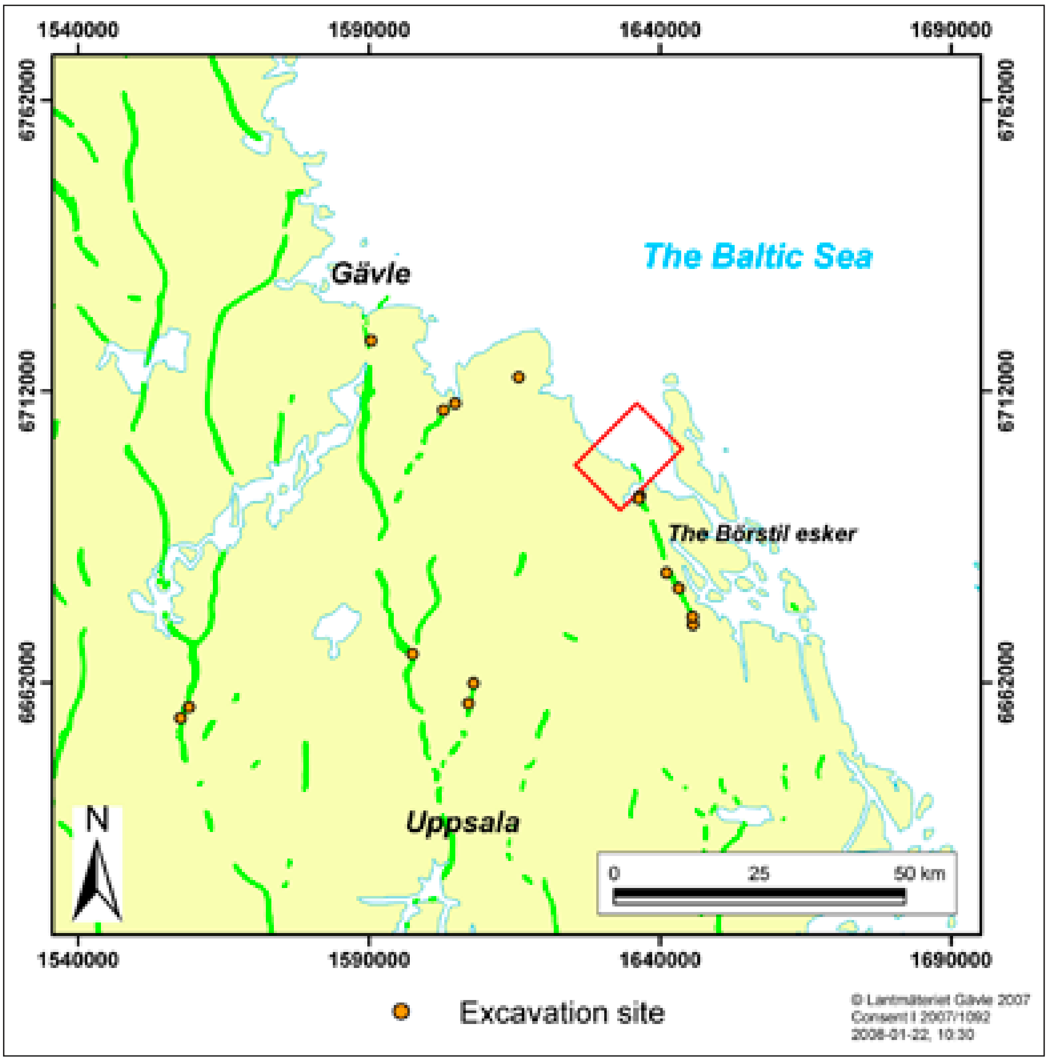


Figure 4-3. *Map of the area investigated for the detection of late- or post-glacial faults in north-eastern Uppland. Glaciofluvial deposits are marked in green. The Forsmark regional model area is marked as a red rectangle.*

Figure 4-4. *Chaotically mixed slide deposits of fine sand, silt and glacial clay along the Börstil esker to the south-east of Forsmark.*

Figure 4-5. *Section along a trench that is typical of the stratigraphy along the Börstil esker to the south-east of Forsmark. The section shows a bed of fine sand and coarse silt covered by a bed of clay-laminated silt. Extended excavation revealed loosely packed and saturated glaciofluvial sand to a depth of at least 5 m. Although the stratigraphy is considered to have been highly susceptible to liquefaction, if it had been saturated with water, no disturbances related to seismically induced liquefaction were discovered here or elsewhere along the esker.*

Excavation of the Quaternary cover till during preparation of drill site 5 at Forsmark revealed freshly fractured bedrock with displacement of bedrock blocks and the occurrence of several fractures filled by glacial sediment (/Leijon 2005/ and Figure 4-6a). These features strongly resemble those identified in the superficial rock mass close to the Forsmark nuclear power plant, where vertical displacements close to the ground surface up to nearly 1 m have been documented (/Carlsson 1979/; see also section 2.3.5). A preliminary evaluation suggested that the fracturing at drill site 5 was a result of the formation and/or reactivation of fractures during glacial- or post-glacial time and that the observations at the drill site are important from the point of view of safety assessment. For this reason, it was decided to carry out a series of more detailed investigations at the drill site, in order to provide information on the character and possibly the origin of these structures /Leijon 2005/. These investigations addressed the Quaternary cover sequence, the bedrock at the ground surface, and the subsurface bedrock down to a depth of c 130 m.

Detailed mapping of the bedrock at the surface verified the occurrence of a high frequency of open fractures compared with other areas at Forsmark. Most of these open fractures exhibit signs of either formation or reactivation under late-glacial conditions, although judgements in this respect were in many cases uncertain. The most prominent features documented were a number of fractures that strike NE-SW and dip gently to the SE. These fractures had apertures ranging up to about 20 cm and were typically filled with unconsolidated sediment (Figure 4-6b). The bedrock in the hanging wall to these fractures was uplifted and, in some cases, was rotated slightly relative to the bedrock in the footwall. Investigations of the filling material revealed a composition resembling that observed in the till overburden. It has been inferred that sediment-bearing water flowed into the fractures and was followed by quiet sedimentation of the material.

Drilling and ground penetrative radar surveys were carried out to determine whether the disturbances observed at the surface persisted at depth. The presence of anomalously wide and sediment-filled fractures was verified down to a maximum depth of 10 m. Below this depth, there were no signs of conditions that deviate from those typically encountered within the tectonic lens at Forsmark. Based on these observations, it was concluded that the disturbances observed are surface-related phenomena confined to the superficial rock mass and are not related to faults deeper down in the crust (see also /Carlsson 1979/). The relationship between fractures, glacial striation, fracture infill and glacial sediment indicate that the fracturing occurred during a late stage of the local deglaciation /Lagerbäck et al. 2005a/.

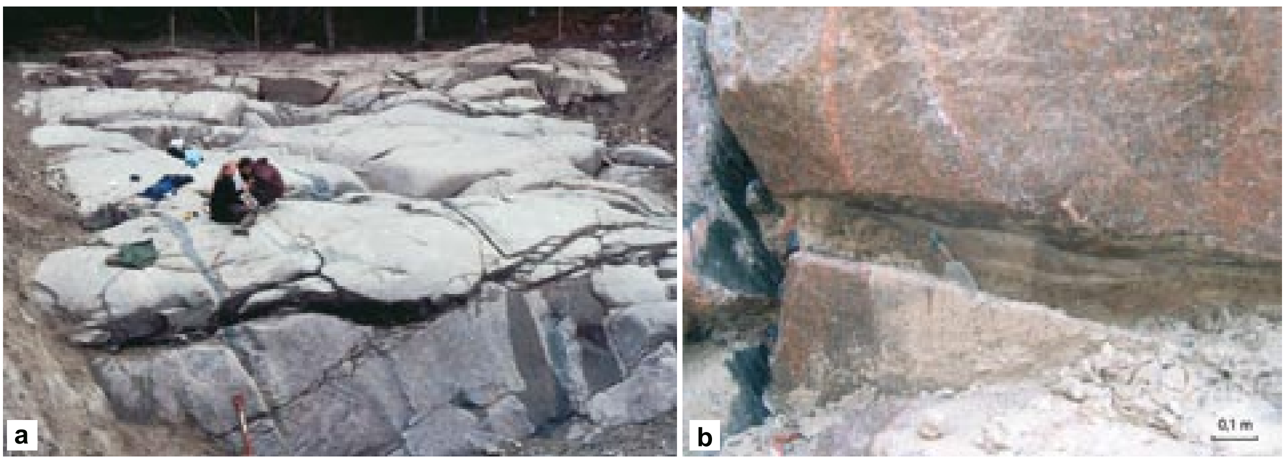


Figure 4-6. *Character of bedrock and fractures at drill site 5, Forsmark. The site was originally covered with till that has been removed. (a) Glacially smoothed and striated bedrock. Freshly fractured bedrock is common along the exposed surface. The major fracture in the foreground, which lacks signs of glacial abrasion, was filled with laminated silty sandy sediment. (b) Laminated silt in an open fracture in the north-western part of the excavated area at drill site 5.*

/Carlsson 1979/ concluded that, if a sufficient difference in stress arose around the time of the latest deglaciation due to a more rapid relaxation of the vertical rather than of the horizontal stresses, then the tensile strength of the rock mass would have been exceeded and failure would have ensued. In this manner, the stress accumulated earlier in the bedrock would have been released close to the ground surface when the ice retreated from the area. The significant differences in the structural and hydrogeological character of the bedrock at Forsmark, particularly above c 200 m depth, have also been related to the effects of release of stress /Olofsson et al. 2007, Stephens et al. 2007/. The effects of hydraulic jacking have also been discussed in the context of these near-surface features /Pusch et al. 1990, Munier and Hökmark 2004/. The results of the site investigation work at Forsmark, including the detailed investigations at drill site 5 /Leijon 2005/, in combination with those carried out nearly 30 years ago at the nuclear power plant /Carlsson 1979/, emphasize the need for extreme care in the use of surface phenomena for the identification of palaeoseismic activity (see also /Munier and Hökmark 2004/).

4.3.3 Laxemar-Simpevarp area

Several studies have addressed the possible occurrence of late- or post-glacial faulting in the Laxemar-Simpevarp area and its surroundings /Lagerbäck et al. 2004b, 2005b, 2006/. The aim of these studies was to establish if any major late- or post-glacial faulting had occurred in the Laxemar-Simpevarp area or in its vicinity. The terminology and methodology used in these studies are identical to those used at Forsmark (see above).

The interpretation of aerial photographs was carried out in a relatively large area in eastern Småland and southern Östergötland in the region that includes Laxemar-Simpevarp (Figure 4-7). Several features, which may have been caused by recent fault movement and given rise to palaeoseismic activity, were indicated by this study. Field checks showed that most of the escarpments in the mainland part of the investigation area are more or less glacially abraded and striated or strongly weathered. It has been inferred that they did not form during post-glacial time. Field reconnaissance of some minor escarpments in the archipelago, which were identified in the aerial photographs, suggested that these features are generally the result of glacial plucking, governed by vertical joints and horizontal sheet structures, rather than faulting. However, one of the most prominent escarpments identified in the mainland part of the investigation area, a 700 m long feature at Klevaberget, some 25 km south-west of Sävsjö, was not glacially abraded. A field check in this area revealed that the vertical cliff was so severely weathered that a late- or post-glacial age for this feature is unlikely. The only morphological feature that remains under suspicion for late- or post-glacial faulting in the investigation area is a minor but prominent escarpment on the island of Öland /Lagerbäck et al. 2004b/. However, it has not been possible to draw any conclusions regarding the genesis of this feature, since no stratigraphical studies could be carried out.

Boulders in unstable positions along sloped surfaces occur rather frequently in parts of the investigation area, preferentially above the highest coastline. It has been argued /Lagerbäck et al. 2005b/ that such boulders would probably not have remained in position, if they had been subjected to a major earthquake.

As at Forsmark, a second line of approach has involved the excavation of trenches. Altogether 53 trenches with an overall length of some 740 m were excavated and investigated at 14 different sites in the eastern part of the investigation area. The trenches were excavated on the flanks of glaciofluvial deposits, mainly eskers, with the intention of reaching sandy or coarse silty deposits, covered ideally by a moderately thick bed of finer-grained sediment. The trench walls were described stratigraphically. All trenches were excavated in level or only gently sloping ground and are 1.5 to 4.5 m in depth. Most of the excavation sites are located fairly high above the present sea level, and emerged above the ancient sea level soon after deposition of the glacial sediments. The deglaciation of the investigation area occurred approximately 12,000–11,500 years BC /Lundqvist 2002/ and most of the excavation sites were uplifted above

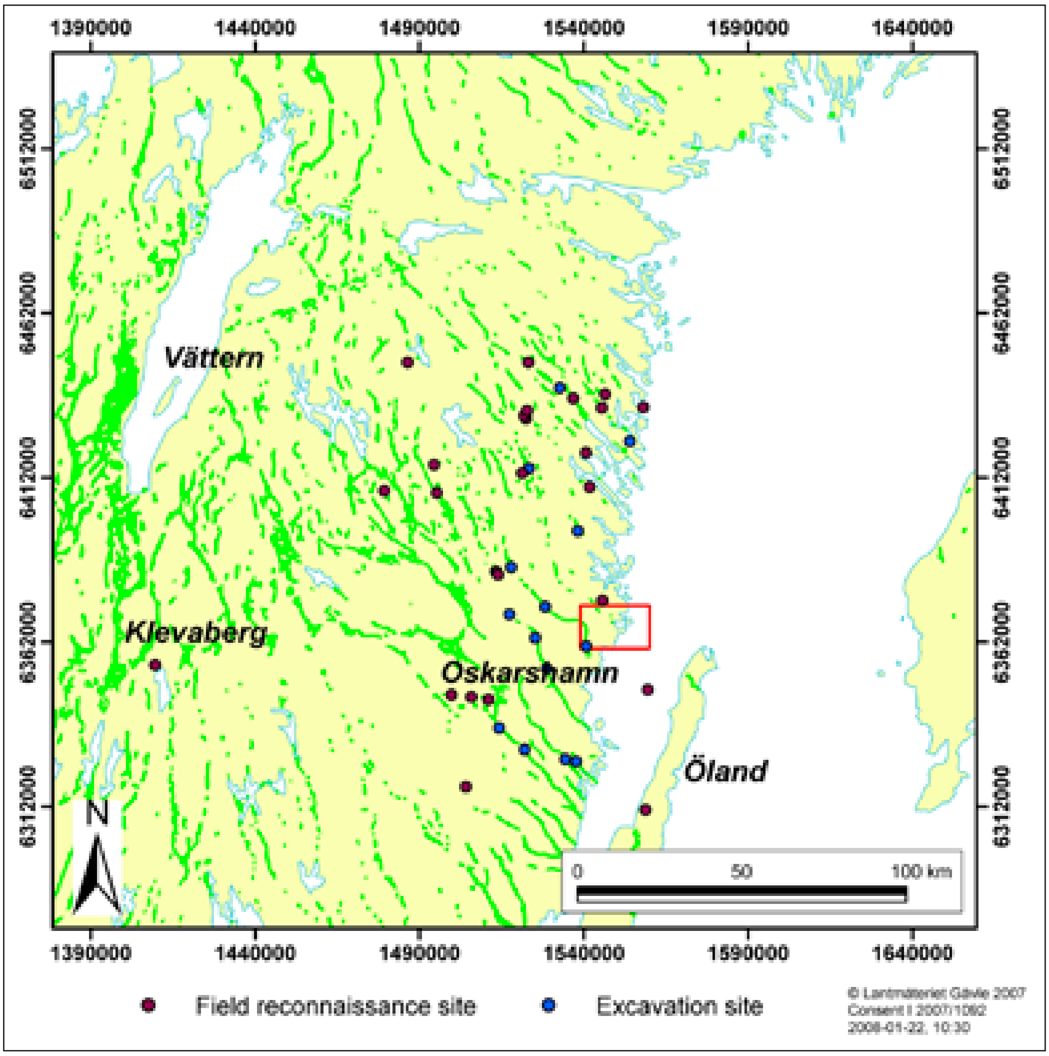


Figure 4-7. Map of the area investigated for the detection of late- or post-glacial faults in eastern Småland and southern Östergötland. Glaciofluvial deposits are marked in green. The Laxemar-Simpevarp regional model area is marked as a red rectangle.

sea level before 9000 years BC /e.g. Påsse and Andersson 2005/. For this reason, it is inferred that the deposits were entirely saturated with water during only a short period of time. However, a fairly high groundwater table at some of the sites indicates that the deposits at these sites have, to some degree, remained susceptible to liquefaction throughout the Holocene.

In many of the trenches, deposits of loosely packed sand or coarse silt, i.e. deposits susceptible to liquefaction, are either missing or are covered by diamict deposits of unknown origin. These trenches yield no information bearing on the presence of late- or post-glacial faulting in the area. In the trenches where deposits susceptible to liquefaction are present, no deformational features that could be unambiguously related to seismic shaking were noted. Features, such as sliding and faulting, which may have been initiated by earthquake activity during or after the latest deglaciation, are present. However, there remains some uncertainty concerning the interpretation of these features. One such slide was recorded close to the Tuna esker in the Laxemar model area.

4.3.4 Concluding statement

The investigations of late- or post-glacial faulting in the Forsmark and Laxemar-Simpevarp areas have used the same methodology as that used in the northern part of Sweden to identify such faulting. The investigations show that definitive evidence for late- or post-glacial faulting in these two areas, which gave rise to major earthquakes, is lacking. The results from an excavation at drill site 5 at Forsmark also emphasize the need for extreme care in the use of surface features for the identification of palaeoseismic activity. The effects close to and along the ground surface of processes related to both the release of stress in the bedrock during ice retreat or glaciological phenomena need to be evaluated more carefully.

4.4 Seismicity in historical time

4.4.1 Nomenclature

Magnitude

Magnitude is a measure of the size of an earthquake. It is related to the amplitude of the observed ground vibrations at some distance from the source, due to the seismic waves generated by the event. The well known Richter magnitude scale is logarithmic. A relatively shallow magnitude 6 earthquake generates elastic (seismic) waves containing about 32 times more energy than those from a magnitude 5 event, and about 1,000 (32×32) times greater than that from a magnitude 4 event. The Richter scale usually refers to local magnitude (M_L), which addresses the size of relatively small seismic events within approximately 600 km from the recording station and at depths of less than approximately 70 km. For large earthquakes, it refers to surface wave magnitude (M_S) or moment magnitude (M_W). The latter is essentially the slip area multiplied by the slip magnitude.

The size of an earthquake depends on a number of parameters including the rupture area of the fault, the amount and velocity of slip between the two sides of the fault, and the elastic properties of the surrounding rocks. Since only the upper part of the crust is brittle and since this part of the crust has a finite strength, the size of earthquakes is limited. The largest observed seismic events on the Earth have a magnitude of approximately 9.5 on the Richter scale, e.g. the Great Chilean earthquake of the 22nd May, 1960. In general, the number of observed events decreases by a factor of ten for every unit increase in earthquake magnitude (Gutenberg-Richter relationship).

Hypocentre and epicentre

The hypocentre (or focus) of an earthquake is the rupture point of an earthquake along a fault, where strain energy is initially converted to elastic wave energy. The point on the Earth's surface that is directly above the hypocentre of an earthquake is referred to as the epicentre.

Focal mechanism

The focal mechanism of an earthquake is a summary of the movement on the fault plane associated with the earthquake event. It provides direct information bearing on the orientation of the fault that moved and the kinematics of the shear slip along the fault. In many cases, a physically based description of the magnitude of the event, such as moment magnitude, is part of the focal mechanism estimate. This magnitude is estimated from the recorded seismograms, and from it the active fault area and magnitude of slip can be calculated. Geologically ancient fractures or planes of weakness in the bedrock usually determine the orientation of the rupture plane, but the sense of movement (kinematics) is predominantly controlled by the stress field in the volume at the time of the earthquake event.

4.4.2 Earthquakes in Sweden in historical time

Data quality

The inferred epicentre and magnitude of earthquakes that occurred in the northern part of Europe between 1375 and 2005, based on all the data available at the time of the compilation in /Bödvarsson et al. 2006/, are shown in (Figure 4-8). Confident interpretation of the spatial and temporal distribution of earthquakes in this area is restricted by the use of data sets of different quality that have been obtained throughout historical time (see also section 4.1). Seismological instrumental observations commenced in Sweden during 1904 and radical improvements in the quality of seismometers have taken place several times during the last century. A modern seismological network, the Swedish National Seismic Network (SNSN), has been established during the last few years. In mid 2007, this network consisted of 59 recorder stations with two stations under construction (Figure 4-9).

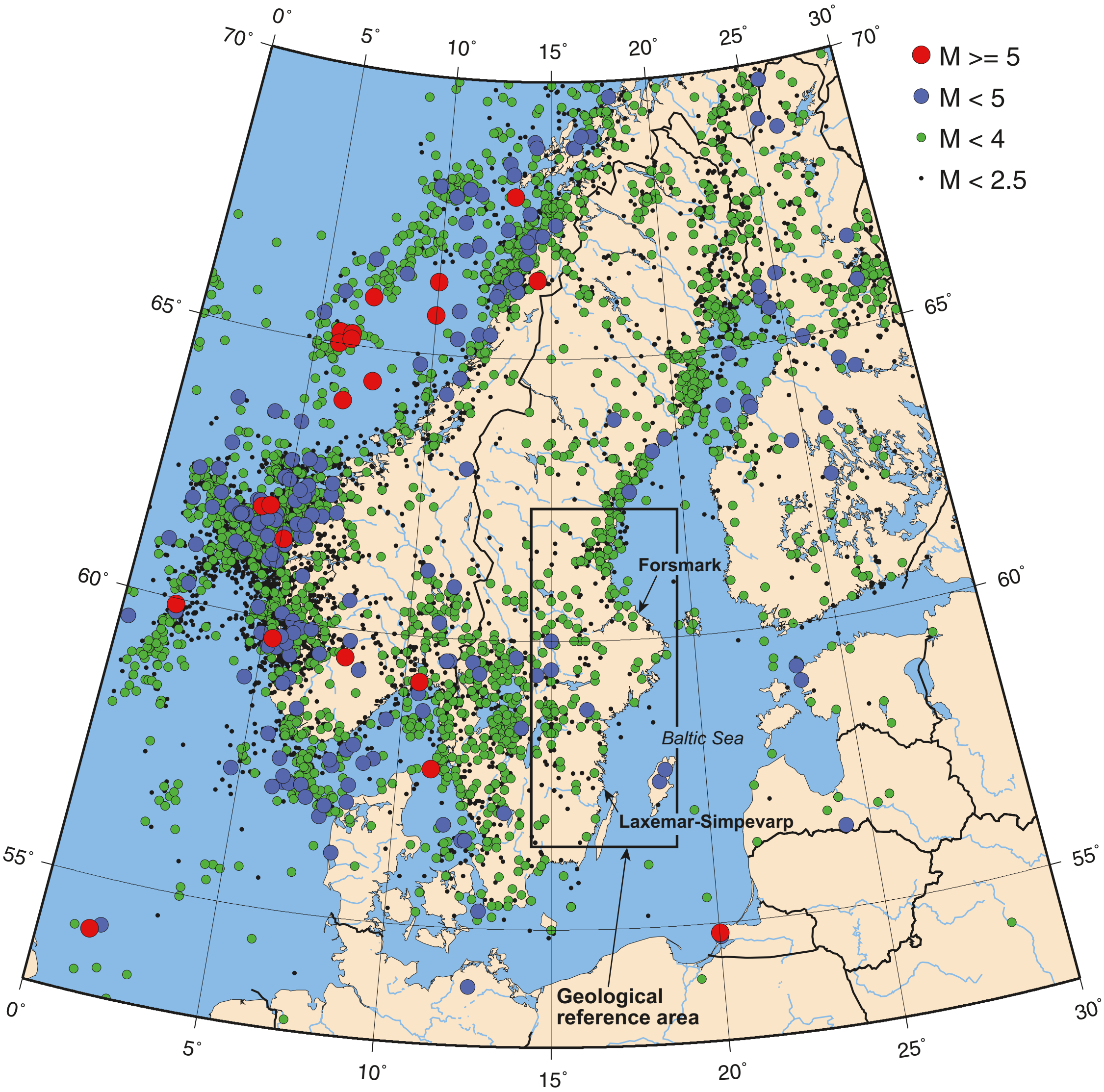


Figure 4-8. *Epicentre and magnitude of earthquakes in the northern part of Europe between 1375 and 2005. Note that earthquake data for the neighbouring countries to the south of the Baltic Sea are not complete (modified after /Bödvarsson et al. 2006/). The geological reference area, as defined in section 2.1, is shown.*

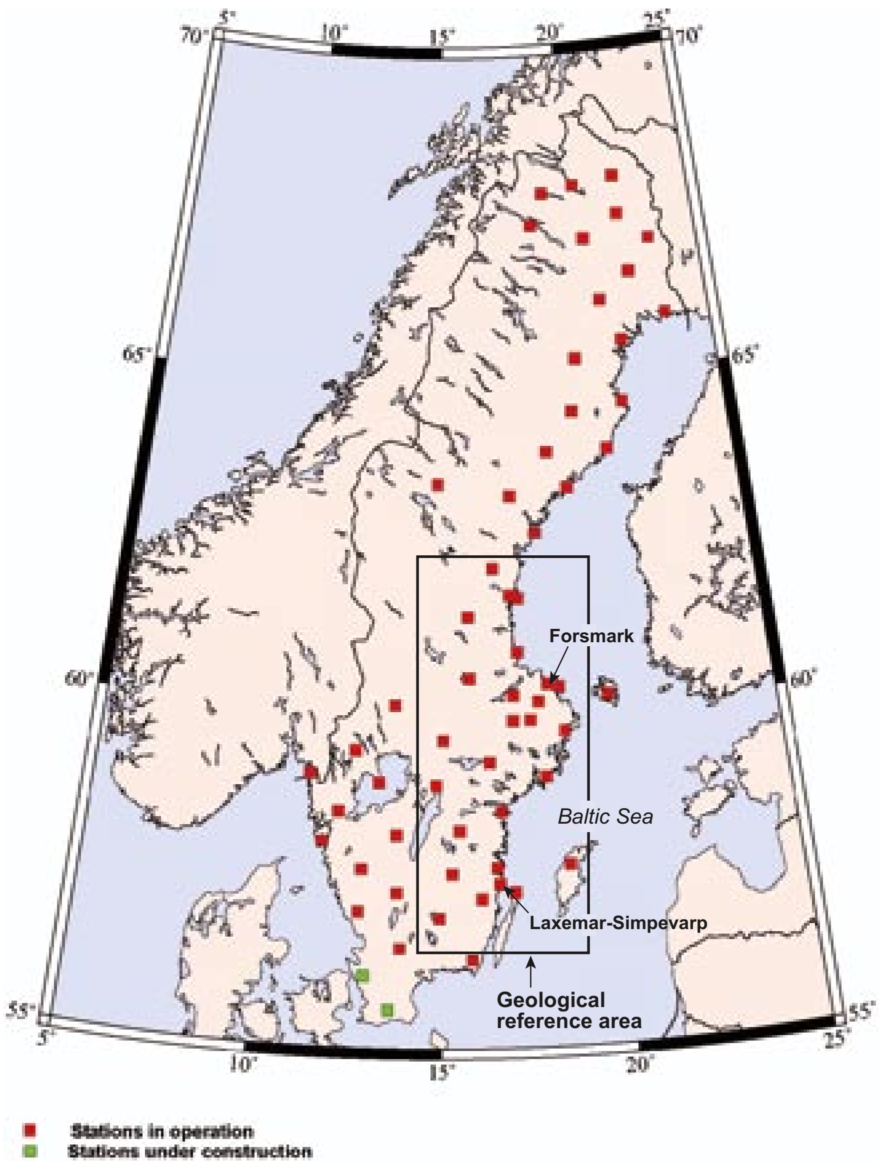


Figure 4-9. *Recorder stations in the Swedish National Seismic Network (SNSN). Figure from /Bödvarsson 2007/. The geological reference area, as defined in section 2.1, is shown.*

The ability to detect smaller events has increased over time, especially recently with the deployment of the new network, but not geographically in an even manner. In large parts of the country, events of magnitude well below 2.5 are now detected. However, these are shown only as very small points on Figure 4-8, and, for this reason, do not dramatically affect the image. The time evolution of the data means that no precise level of completeness for the presented data can be given. However, for more recent time, corresponding to the bulk of the data, the image is essentially complete to magnitude 2.5, and since the events smaller than this do not dramatically alter the image, it provides a balanced picture of the distribution of seismicity for the whole area. The new network will shortly provide a major improvement in the documentation of earthquakes in the south-western part of Sweden, the seismicity of which is presently under-represented in the SNSN data. Thus, the level of completeness for most of Sweden will soon be well below magnitude 2.5, probably 1 or even less. It is worth emphasizing that the relatively high level of seismicity along the Baltic Sea coast is not an artefact of station distribution or some other factor. The seismicity here, and in the south-western part of Sweden, is genuinely relatively high.

Spatial variability and possible causes

As described in Chapter 2, the major part of Sweden is situated in a shield area, which implies that it is an ancient, stable part of the Earth's crust, far away from any plate boundary at the present time. As expected, there are generally few earthquakes in this area, compared with the frequency along plate boundaries (Figure 4-1). Furthermore, there is an absence of earthquakes with a magnitude ≥ 6 (Figure 4-8). The largest earthquake that has been documented in the vicinity of Sweden during historical time, based on both macroseismic /Wahlström 1990/ and instrumental /Slunga 1991, Bödvarsson et al. 2006/ data, occurred offshore along the Oslo rift, close to the coast of south-west Sweden (Figure 4-8). This earthquake occurred during 1904 and had a magnitude of M_S 5.4. In more recent time, the largest recorded earthquake, offshore Kaliningrad on the 21st September 2004, had a magnitude of M_S 5.2. Although earthquakes are observed every day in and around Sweden, they are normally very small and do not affect constructions.

Seismic activity that has been recorded in Sweden over historical time is not evenly distributed over the country. Areas of relatively high activity are conspicuous along several linear alignments in the northern part of Sweden and in a broader region in south-western Sweden, around lake Vänern and along the south-west coast (Figure 4-8). There is also a higher concentration of earthquake epicentra in the southernmost part of the country in Skåne, relative to, for example, the area immediately to the north-east along the Baltic Sea coast (Figure 4-8). Much of the geological reference area (see Chapter 2), including the Forsmark and Laxemar-Simpevarp areas, shows relatively little seismic activity (Figure 4-8).

The linear alignments of earthquakes, at least in the northernmost part of Sweden and in adjacent areas in Finland and Norway, have been related /Bödvarsson et al. 2006/ to the late- or post-glacial faults that have been recognised with the help of palaeoseismic studies (see section 4.3.1). Since it is inferred that these faults have been significantly active at some point during the last few thousand years, it is not surprising that they still show small but very significant levels of activity today. However, it is unclear if this activity reflects an exponentially decreasing relaxation process after the inferred larger motions along these faults, or if there is still a significant risk of large movements along them. The linear alignment along the coast of Norrland occurs where both land uplift related to post-glacial isostatic rebound is greatest (Figure 4-10) and where there is also a decrease in crustal thickness from the central part of Finland north-westwards towards and into Sweden (see section 2.2.4).

A correlation between an increased frequency of seismic events and crustal thinning associated with relatively young tectonic activity was suggested by /Kinck et al. 1993/. It is apparent that the strong concentration of earthquakes in south-western Sweden and the less pronounced concentration in southernmost Sweden occur in regions where there are significant changes in crustal thickness, probably in connection with the development of the Permo-Carboniferous Oslo rift and the Permo-Carboniferous and younger tectonics along the Sorgenfrei-Tornquist Zone, respectively (section 2.2.4 and Figure 2-13). The lack of earthquakes along a major part of the so-called Protogine Zone, in the central southern part of Sweden, does not support a simple relationship between increased seismic activity and this ancient geological structure as suggested by /Slunga 1991/.

The distribution of earthquakes in Sweden with depth indicates at least three seismically different layers in the crust /Slunga 1991/. A marked overall decrease in the frequency of earthquakes occurs beneath c 18 km depth in southern Sweden and shallower, beneath c 13 km depth, in northern Sweden. The upper crustal layer also shows a larger proportion of small earthquakes. /Slunga 1991/ speculated that this change may be caused by a lithological discontinuity in the crust. Beneath c 35 km throughout Sweden, the crust is seismically quiet and this changeover is most probably related to the more ductile character of the crust beneath this depth /Slunga 1991/. Based on the assumption that the brittle-ductile transition in the crust occurs close to the boundary between greenschist and sub-greenschist facies metamorphic conditions, i.e. around 300 to 400°C, these data indicate an average geothermal gradient of approximately 8 to 12°C/km at the current time. This estimate is considerably lower than that inferred to have existed when the crystalline bedrock was covered by sedimentary material during the Phanerozoic (see sections 2.3.5 and 2.4.6).

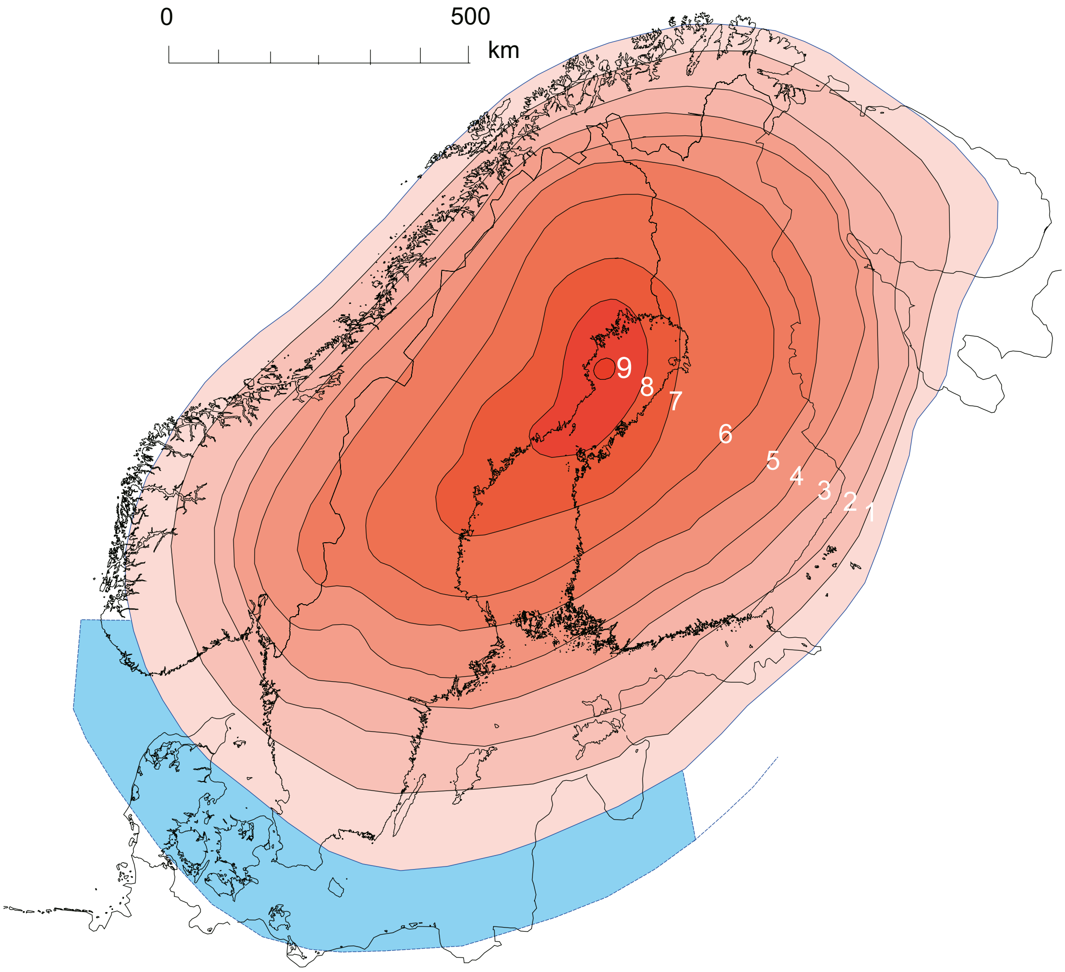


Figure 4-10. Recent rate of land uplift in Finland, Norway and Sweden, expressed in mm per year /after Ojala et al. 2004/.

Temporal considerations

Seismicity is generally episodic in character and there are several indications that this is also true for Sweden /Slunga 1991, Kijko et al. 1993/. Earthquake occurrence rates can be expressed with the help of the frequency-magnitude, or Gutenberg-Richter, relationship, which describes the number of events equal to or larger than a certain magnitude in a specific data set. It is usually expressed as $\log_{10}N = a - bM$ where M is the magnitude, N is the number of events equal to or larger than magnitude M, a is the intercept, which depends on the number of events in the time and region sampled, and b is approximately 1. The b-value is the inferred slope in the frequency-magnitude plot. In areas of low earthquake frequency and limited instrumental observation time, for example in Sweden, there are major uncertainties with frequency-magnitude analyses, especially when the analysis is carried out in restricted geographical areas.

Notwithstanding the difficulties indicated above, frequency-magnitude relationships for the Forsmark and Laxemar-Simpevarp areas have been presented in /Bödvarsson et al. 2006/ and are shown in Figure 4-11. The choice of reference areas with different radius is addressed in /Bödvarsson et al. 2006/. Only data from 1904 until today is used from the catalogue for northern Europe. The higher sensitivity of the SNSN data with respect to small earthquakes is apparent (Figure 4-11). The step-like behaviour of the SNSN line at larger magnitudes is due to the short period of observation. Very few events above magnitude 3 have been recorded in the SNSN data and, for this reason, the curve is very unreliable above approximately magnitude 3. The calculation of the b-values has taken account of such biases in the data.

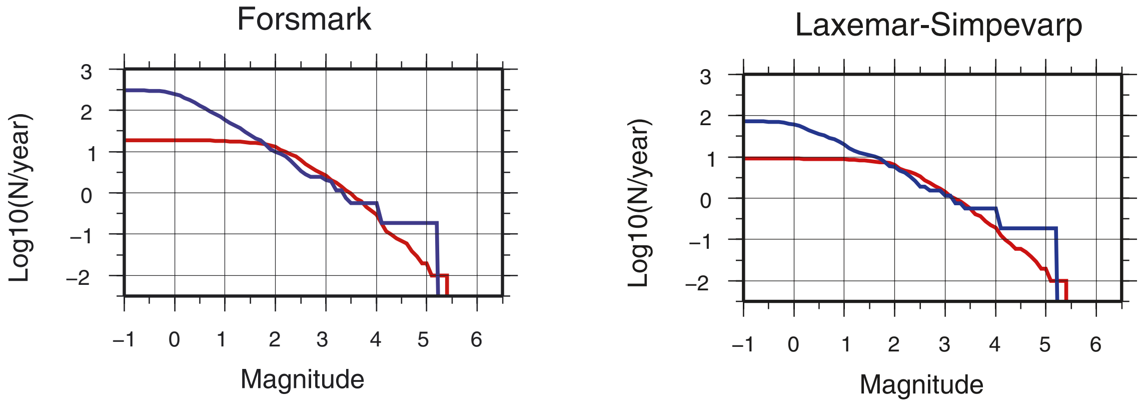


Figure 4-11. *Frequency-magnitude relationships using number of events per year (N/year). SNSN data are shown by blue lines, historical (1904–2005) data from northern Europe are shown by red lines. (a) Forsmark. Events within a 650 km radius from the area. (b) Laxemar-Simpevarp. Events within a 500 km radius from the area. Figure modified slightly after /Bödvarsson et al. 2006/.*

A least-squares fit to the slope in the frequency-magnitude plots yields the b-values. For Forsmark, the SNSN data gives b = 0.75 and the historical data for northern Europe indicates b = 0.97. For Laxemar-Simpevarp, the SNSN data gives b = 0.60 and the historical data for northern Europe indicates b = 0.87 /Bödvarsson et al. 2006/. The smaller the b-value is, the higher is the occurrence rate of large earthquakes compared with small earthquakes. Although apparently different, /Bödvarsson et al. 2006/ conclude that it is not possible to confirm that the b-values of the two data sets are statistically different.

The b-values above are generally lower than those reported by /Kijko et al. 1993/ who, for Sweden south of latitude 60°, indicate b = 1.04 ± 0.05 and for north of latitude 60° b = 1.35 ± 0.06. Furthermore, /Slunga et al. 1984/ reported a b-value of 0.75 for a latitude south of 56.5° and longitudes between 12° E and 14° E in southernmost Sweden. Due to the larger amount of data in the more recent analyses, these earlier estimates /Kijko et al. 1993, Slunga et al. 1984/ are intrinsically less robust than the more recent estimates. However, more data are required in order to improve the statistical reliability of the results. Further analysis of frequency-magnitude relations, not least where it concerns the probabilities of future earthquakes, is addressed in /Bödvarsson et al. 2006/.

4.4.3 Crustal deformation

Seismic and aseismic deformation

When the rigid upper part of the crust is submitted to stress, it can deform both elastically throughout the entire stressed volume and as shear slip along faults. Both slow, stable slip, which is aseismic in character, and sudden, seismic slip induce larger strains in the volume than those caused by regional elastic deformation. In general, ongoing tectonic deformation, where stresses and stress changes are transmitted from plate boundaries into plate interiors, is elastic in the upper part of the crust until sufficient shear stress has been accumulated along a fault. Once the strength of the fault is overcome, the fault moves and either an earthquake or aseismic creep on the fault occurs. The extent of crustal deformation that is related to sudden, seismic slip is strongly correlated with the magnitude of the seismic event. Smaller events with M_L less than 1 typically correspond to lateral movements of 0.001–1 mm, whereas larger events with magnitude around 5 have slips of 50–500 mm. These rapid, seismic movements occur on a limited area on the fault plane, for example a roughly circular area with a radius between 30 and 900 m /Lay and Wallace 1995/.

In general, slower fault motions, with a relative velocity along the fault plane of less than possibly 0.1 mm/s, do not generate seismic signals of sufficient amplitude that can be detected by normal seismometers and the deformation takes the form of aseismic creep. The properties of the fracture and the surrounding rock medium, and the characteristics of the local stress field determine whether or not an initiated movement is dynamically unstable and thereby accelerates into seismic slip. In situations where rapid acceleration (as opposed to slow slip) does not occur, the movement ceases when the shear stress has been reduced to a value corresponding to less than the dynamic friction of the fracture. In general, only in cases of seismic motion (10–1,000 mm/s) does the inertia of the rock mass become significant.

Aseismic fault creep is most commonly observed at plate boundaries, such as the creeping section of the San Andreas fault or "slow earthquakes" along subduction zones /Bödvarsson et al. 2006/. If aseismic movements are of significance in the within-plate region in Sweden, then movement along faults in this region may be very much greater than that deduced by simply summing the motions of observed earthquakes along them. Significant aseismic sliding along faults was proposed by /Slunga 1991/, based on a study of the temporal and spatial behaviour of microearthquakes in both southern and northern Sweden. This sliding accumulates stress at localities along the faults which, when they break, cause microearthquakes. /Slunga 1991/ estimated that, during the time interval 1980 to 1984, aseismic horizontal deformation occurred in southern Sweden at the rate of 1 mm/year/100 km.

Regional stress field inferred from focal mechanisms

At the time that /Bödvarsson et al. 2006/ presented their compilation, the focal mechanism for roughly 2,000 seismic events in Norway, Sweden, Finland and around the Baltic Sea was available. The size of these events varies from about $M_L = 0$ to 5 and their focal depths are generally between 7 and 35 km. Strike-slip displacement with inferred maximum and minimum principal stress axes in the horizontal plane, according to the fault model of /Anderson 1951/, are prominent. A dominant set of strike-slip fault solutions and subordinate reverse dip-slip or oblique-slip fault solutions were also identified by /Slunga 1991/ for more than 200 seismic events in Sweden in the range $M_L = 0.6$–4.5.

Since seismic events predominantly occur along geologically ancient fractures or planes of weakness in the bedrock, the orientation of these structures has an influence on the focal mechanism. Overall changes in the orientation of these structures in different parts of the Fennoscandian Shield will influence the variability in fault plane solutions inside the shield. It is also important to keep in mind that the solutions discussed above pertain to crustal stress at seismogenic depths. Considerable evidence points to a reverse sense of movement in the uppermost part of the crust (c 1,000 m) in large parts of Sweden, with a vertical or subvertical minimum principal stress /e.g. Stephansson et al. 1991/.

The maximum principal stress as inferred from the seismic data is oriented WNW-ESE in the horizontal plane and is in agreement with earlier analyses of seismic events in Sweden /Slunga 1991, Gregersen et al. 1991/. This direction is in accordance with that expected from plate tectonics with ridge push forces from the mid-Atlantic ridge (see also section 2.2.2). These considerations provide strong support to the hypothesis that ongoing plate tectonic processes are important for an understanding of recent seismic activity.

Since both Forsmark and Laxemar-Simpevarp share similar loading and unloading cycles (see section 2.5) and are experiencing, at the present time, the same WNW-ENE ridge push forces from the mid-Atlantic ridge, differences in the measured stress state on a large scale between the two sites and on a local scale within a particular site need to be explained with the help of other factors. As far as large-scale variations between Forsmark and Laxemar-Simpevarp are concerned, differences in the long-term geological evolution and crustal thickness variations at the two sites, as summarized in section 2.5, need to be taken into account. The possible influence of differences in crustal thickness variations on the measured stress state above 1,000 m at the two sites has already been addressed in /Martin and Christiansson 2007/.

Direct measurements of deformation at the ground surface

The surface deformation associated with larger earthquakes can be directly observed using geodetic methods that measure surface topography with high precision (Interferometric Synthetic Aperture Radar or InSAR, GPS etc). However, most events in the Fennoscandian Shield are at considerable depth (7–35 km) compared with the deduced dimensions of the slip area. If an event has a maximum slip of 10 mm (e.g. $M_L = 3$) and a slip radius of 300 m, then the deformation would have decreased to a value of less than 0.1 mm at a distance of only 300 m from the event /Bödvarsson et al. 2006/. The permanent deformation at the surface due to such movements at depth cannot be geodetically observed using currently available technology.

During the last 15 years, networks of permanent GPS stations in Sweden (SWEPOS), Finland and Norway were incorporated into the BIFROST project /e.g. Johansson et al. 2002/ in order to provide data for glacial isostatic adjustment (GIA) analysis on a regional scale. The BIFROST analysis shows a maximum vertical rebound velocity of approximately 11 mm/year and horizontal movements which exceed 2 mm/year at several sites. Formal uncertainties are as low as 0.1 mm/year for the horizontal rate and 0.2 mm/year for the vertical rate at most stations /Johansson et al. 2002/. The velocity estimates are constant rates fitted to the time series data of each GPS station, in agreement with GIA which should not have rate changes over a ten year period. The deformation rates observed by the BIFROST project agree very well with predicted deformation rates from models of the GIA process, both vertically and horizontally /Milne et al. 2004/. By removing the modelled GIA deformation from the observed deformation field, the BIFROST group have estimated residual movements of up to 2 mm/year at Kuusamo, in Finland, and 0.5–1 mm/year in southern Sweden /Milne et al. 2004/. Further discussion of residual movements, which can be related to fault slip and earthquake activity, can be found in /Bödvarsson et al. 2006/.

On a more local scale, more detailed GPS measurement campaigns, including the Äspö GPS monitoring network experiment in the Laxemar-Simpevarp area, have been carried out in Sweden /Pan and Sjöberg 1999, Pan et al. 1999, Sjöberg et al. 2004/. These studies have yielded local deformation rates in the order of 1–4 mm/year. More recently (2005), seven GPS stations have been established in the Forsmark area /Gustafson and Ljungberg 2006/, inside three different bedrock blocks, i.e. south-west of the Forsmark deformation zone, inside the tectonic lens at Forsmark between the Eckarfjärden and Singö deformation zones, and north-east of the Singö zone /see Stephens et al. 2007/. The first evaluation of the data from these GPS stations will be completed during 2008.

The Laxemar-Simpevarp area was studied by GPS campaign measurements during 2000–2004 /Sjöberg et al. 2004/. The GPS network was located on both sides of an E-W fault. Most of the data could not demonstrate statistically significant deformation. However, a sub-set of the data did provide an apparently statistically significant result, albeit on the limit of available resolution. This was interpreted as indicating possible slip along the fault at a rate of about 1 mm/year, with the northern side moving eastwards, i.e. a component of dextral strike-slip displacement. This is consistent with the inferred general orientation of the current stress field in southern Sweden with the principal maximum stress in a WNW-ESE direction in the horizontal plane. However, no seismicity was observed in the area. If the geodetic data does indeed correspond to lateral movements of the surface, and if these movements do reflect motion also at greater depths, then significant aseismic movement can be inferred /Bödvarsson et al. 2006/.

According to /Bödvarsson et al. 2006/, measurements in local campaigns are hampered by high uncertainties and it is not possible to verify the data obtained from these experiments with the help of the high resolution regional networks, since the latter are simply insufficiently dense. Nevertheless, /Johansson et al. 2002/ explicitly concluded that there is no evidence for the relative horizontal motions inferred by /Pan and Sjöberg 1999/. It is also important to keep in mind that there are probably intrinsic difficulties in the geological interpretation of movement data from the ground surface in the Fennoscandian Shield, bearing in mind the bedrock movements close to the surface that have been recognised at, for example, Forsmark (see /Carlsson 1979, Leijon 2005, Stephens et al. 2007/ and section 4.3.2 in this report). Such movements are related to release of stress close to the ground surface, diminish rapidly at depth and are not related to deeper seismic or aseismic events along active faults.

4.5 Summary

An earthquake is the result of a sudden release of energy through movement (faulting) along a deformation zone, resulting in the emission of seismic waves. This movement is normally the result of stresses that have accumulated over a certain time interval in a particular volume. An overview of palaeoseismic activity in Sweden during the latest part of and after the Weichselian glaciation, with special focus on the Forsmark and Laxemar-Simpevarp areas, is presented here. This is accompanied by an assessment of seismic activity in historical time from 1375 up to 2005, over the northern part of Europe. The part of the chapter concerned with activity in historical time is based upon and, with predominantly editorial modifications, is largely extracted from the assessment of earthquake activity in Sweden that has recently been completed and published by SKB.

Palaeoseismic activity has been inferred directly by, for example, distinct displacement of the surface that separates the crystalline bedrock from the Quaternary cover or indirectly by seismically derived deformation of Quaternary sediment. The interpretation of aerial photographs provides a tool to identify morphologically conspicuous lineaments that are candidates for late- or post-glacial faults. A significant number of late- or post-glacial, reverse fault scarps have been identified in the northern part of Sweden and it has been inferred that the accompanying earthquakes reached magnitudes of up to M8 or even larger on the Richter magnitude scale. As yet, conclusive evidence for such fault movements is lacking in the southern part of Sweden.

With the help of a similar methodology to that used in the northern part of Sweden, detailed investigations to evaluate the occurrence of palaeoseismic activity in and around the Forsmark and Laxemar-Simpevarp areas have been carried out in the context of the site investigation work. None of the morphological lineaments that have been recognised have been inferred to represent late- or post-glacial faults. Furthermore, no deformational features in Quaternary sediment have been unambiguously related to seismic activity. On the basis of these results, evidence in the geological record for major earthquakes in these two areas is lacking.

Compared especially with plate boundaries in other parts of the world, there is, in general, a low frequency of earthquakes throughout historical time in the within-plate region of northern Europe, and an absence of earthquakes with a magnitude ≥ M6 on the Richter scale. However, seismic activity in Sweden throughout historical time is not evenly distributed over the country. Areas of relatively high activity are conspicuous along linear alignments in the northern part of Sweden, in a broader region in south-western Sweden and, less conspicuously, in the southernmost part of the country (Skåne). By contrast, much of the geological reference area in south-eastern Sweden, including the Forsmark and Laxemar-Simpevarp areas, shows relatively little seismic activity.

The linear alignments of earthquakes, at least in the northernmost part of Sweden and in adjacent areas in Finland and Norway, have been related to the late- or post-glacial faults that have been recognised with the help of palaeoseismic studies. The linear alignment along the coast of Norrland occurs where both land uplift related to post-glacial isostatic rebound is greatest and where there is also a tendency for a decrease in crustal thickness. A correlation between an increased frequency of seismic events and crustal thinning is apparent in south-western and southernmost Sweden. The crustal thinning occurs in areas where Late Palaeozoic and younger extensional tectonics has taken place. In this context, it is worth recalling the significant decrease in crustal thickness immediately south of the Laxemar-Simpevarp area (see section 2.2.4). The crust in Sweden below c 35 km is seismically quiet and this changeover is most probably related to the more ductile character of the crust beneath this depth. If correct, an average geothermal gradient of approximately 8 to 12°C/km is inferred at the current time.

Although strike-slip movement is the dominant focal mechanism, irrespective of where in Sweden the seismic event occurred, reverse dip-slip or oblique-slip fault plane solutions are also present. Since seismic events predominantly occur along geologically ancient fractures or planes of weakness in the bedrock, the orientation of these structures has an influence on the focal mechanism. It is also important to keep in mind that the solutions discussed above pertain to crustal stress at seismogenic depths. Considerable evidence points to a reverse sense of movement in the uppermost part of the crust (c 1,000 m) in large parts of Sweden, with a vertical or subvertical minimum principal stress.

The maximum principal stress as inferred from the seismic data is oriented WNW-ESE. This direction is in accordance with that expected from plate tectonics with ridge push forces from the mid-Atlantic ridge. These considerations give support to the hypothesis that ongoing plate tectonic processes are important for an understanding of recent seismic activity. Palaeoseismic activity has been explained by the release of stress that accumulated earlier during glacial loading in association with long-term tectonic plate motions. An alternative mechanism that involves the release of high horizontal stresses induced by flexure during loading, in combination with the ambient plate tectonic stresses, has also been discussed. The release of stress and fault instability occurred during unloading and the rapid removal of the ice. Since both Forsmark and Laxemar-Simpevarp share similar loading and unloading cycles (see section 2.5) and are experiencing, at the present time, the same WNW-ENE ridge push forces from the mid-Atlantic ridge, differences in the measured stress state on a large scale between the two sites and on a local scale within a particular site need to be explained with the help of other factors. As far as large-scale variations between Forsmark and Laxemar-Simpevarp are concerned, differences in the long-term geological evolution and crustal thickness variations at the two sites, as summarized in section 2.5, need to be considered.

An attempt to document local surface deformation with the help of detailed GPS measurements has recently been completed in the Laxemar-Simpevarp area and is presently in progress at Forsmark. Bearing in mind the occurrence of significant bedrock movements close to the ground surface, which are related to release of stress and diminish rapidly at depth, there are intrinsic difficulties in relating ground measurements to deeper seismic or aseismic activity along active faults. This observation also emphasizes the need for extreme care in the use of surface phenomena for the interpretation of palaeoseismic activity.

5 Groundwater evolution during the Quaternary period

5.1 Introduction

Climatic changes in the past are of fundamental importance for understanding the groundwater evolution in the Fennoscandian crystalline basement. The variation in climate has been dramatic during the period from the Eem interglacial, starting around 128,000 years ago, until the present period, the Holocene. This is evident in the Forsmark and Laxemar-Simpevarp areas where cyclic brackish marine, meteoric and glacial conditions have affected the groundwater composition. Significant imprints from these climatic variations are still preserved to various degrees in the bedrock aquifer, in the connected matrix pore fluids, and in the boundary with the deep saline groundwater /Laaksoharju et al. 2008, Follin et al. 2008/.

Accordingly, there is a significant variation in the characteristics of the present groundwaters, with imprints of glacial waters, meteoric waters and typically marine waters, depending on the prevailing conditions at the time of formation. The groundwater infiltration and formation in the basement is governed by the local hydraulic driving forces. Chemical and isotopic patterns in the water indicate that extreme events, such as the maximum melting of the inland ice, saline sea water stages, dominating wet periods, has left imprints on the bedrock groundwater. Another factor affecting groundwater formation has been the length of the climatic cycles. During stagnant hydrological conditions or periods with stable groundwater conditions, the pore waters in the rock matrix will have been affected also due to concentration gradients between the porewater and fracture water.

As a consequence of the cyclic pattern and the change in recharge conditions due to shoreline displacement, the most recently recharged water tends to flush out older water types. The hydraulic conditions are therefore continuously changing and water remnants from earlier recharge can be preserved in localised areas of low permeability. Thus the hydrogeochemistry provides an archive which reflects an important framework for understanding the bedrock hydrogeochemical evolution and the hydrogeological dynamics of the bedrock system.

In the sections below, effects of the climate evolution and shoreline displacement on the groundwater evolution are discussed, together with the effects of groundwater mixing and water-rock interactions. The post-glacial development is the basis for the present conceptual thinking concerning groundwater evolution at the sites. The measurable effects of these events in the groundwater are addressed.

5.2 Influence of climatic changes on groundwater evolution

Change in sea level is one of the major consequences to glaciation and deglaciation processes. This is caused by an interaction between the isostatic recovery of the basement rocks and eustatic sea level variations. The net effect of these two processes in terms of elevation is called shoreline displacement (cf. Chapter 3). A detailed picture of the post-glacial development at Forsmark and Simpevarp, including shoreline displacement and the development of the Baltic, is given in Chapter 3, and is summarised below.

In northern Sweden, the heavy continental ice depressed the Scandinavian Shield as much as 800 m below its present altitude. Shortly after the last glacial maximum (LGM), a marked climatic change started about 18,000 years ago, and the ice started to retreat, a process that was completed after some 10,000 years. The end of this cold period around 9500 BC marked the onset of the present interglacial, the Holocene. The ice retreated more or less continuously during the early part of the Holocene.

As soon as the vertical stress decreased after the ice recession, the basement and crustal rocks started to slowly rise (isostatic land uplift). The rate of uplift differs between the two sites, and the process is described in Chapter 3 of this report; see also /Påsse 1997/.

The development of the Baltic Sea after the last deglaciation is characterised by a series of brackish and freshwater reflecting changes in sea level. This evolution (see Chapter 3 of this report) has been divided into four main stages; the Baltic Ice Lake (13,000–9500 BC), the Yoldia Sea (9500–8800 BC), the Ancylus Lake (8800–7500 BC) and the Littorina Sea (7500 BC–present). The scenario for groundwater evolution differs slightly between Forsmark and Laxemar, and this is considered in the conceptual models for the evolution of the two sites presented in Figure 5-1 and Figure 5-2.

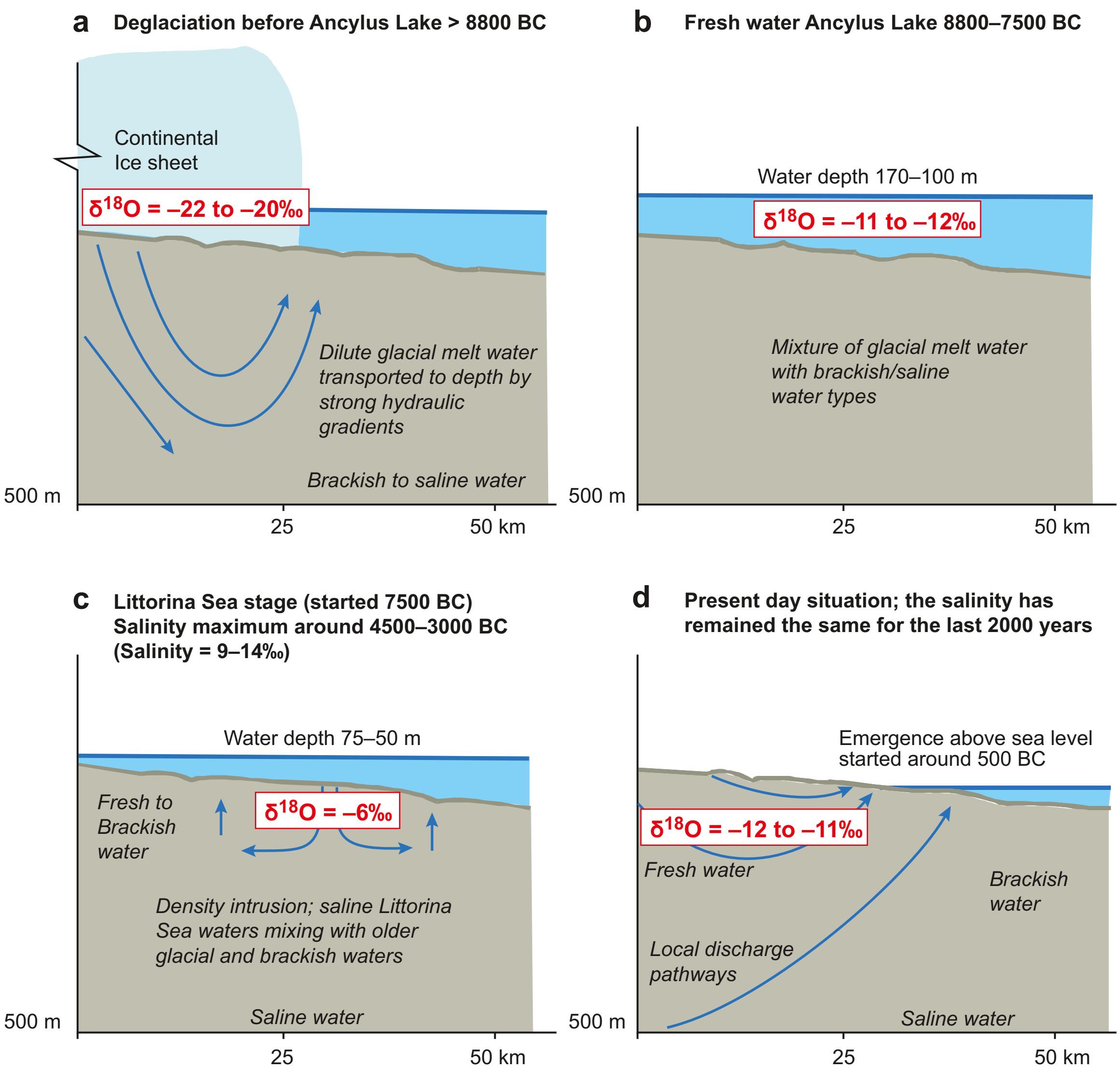


__Figure 5-1.__ Conceptual model for groundwater evolution in the Forsmark area. A sequence of pictures illustrate the post-glacial development of the area a) the deglaciation before the Ancylus Lake (> 8800 BC), b) the freshwater Ancylus Lake between 8800–7500 BC, c) density driven intrusion of Littorina sea water between 7500 BC to 0 AD, and d) the present day situation. Blue arrows indicate the flow pattern of the groundwater.

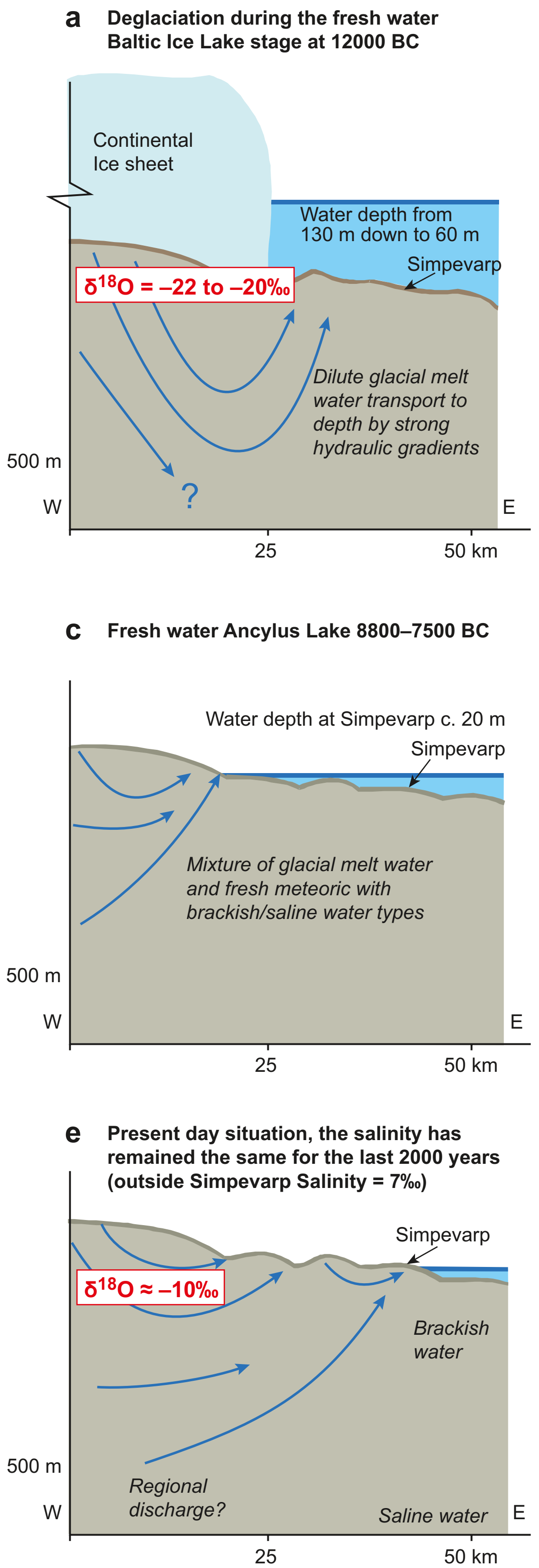


Figure 5-2. *Conceptual model for groundwater evolution in the Laxemar-Simpevarp area. A sequence of pictures illustrate the post-glacial development of the area a) the deglaciation during the Baltic Ice Lake stage at about 12,000 BC, b) the Yoldia Sea period (9500–8800 BC), c) the freshwater Ancylus Lake between 8800–7500 BC, d) showing the penetration due to density driven intrusion of Littorina sea water between 7500 BC to 0 AD, and e) the present-day situation. Blue arrows indicate flow pattern of the groundwater.*

5.3 Palaeohydrogeochemical signatures traceable in the groundwater

Hydrogeochemical studies underline the importance of major components and isotopes (e.g. chloride, magnesium and $\delta^{18}O$) as a tool to classify the main groundwater types and trace their interactions and origins /SKB 2005e/. Four key end-member water types are identified and contribute to the Forsmark and Laxemar/Simpevarp groundwater system and chronologically comprise /after Follin et al. 2008/: *Highly Saline Water* (oldest) > *Last Deglaciation Meltwater* > *Littorina Sea Water* (→ *Baltic Sea Water*) > *Present-day Meteoric Water* (most recent), cf. Figure 5-1 and Figure 5-2. Using the parameters chloride, magnesium and $\delta^{18}O$ these four water types can be classified as follows:

Highly Saline Water
Strong saline source → high chloride content (> 20,000 mg/L)
Non-marine origin → low magnesium content (< 20 mg/L)
Depleted in $\delta^{18}O$ (> –9‰ SMOW)

Last Deglaciation Meltwater
Non-saline source → low chloride content (< 8 mg/L)
Non-marine origin → low magnesium content (< 8 mg/L)
Significantly depleted $\delta^{18}O$ (< –20‰ SMOW)

Littorina Sea Water
Brackish saline source → moderate chloride content (max. ~ 6,500 mg/L)
Marine origin → high magnesium content (~ 450 mg/L)
Depleted $\delta^{18}O$ (–6‰ SMOW)
(The chloride content of the present-day *Baltic Sea Water* is ~ 2,500–3,800 mg/L)

Present-day Meteoric Water
Non-saline, fresh source → low chloride content (< 200 mg/L)
Non-marine origin → low magnesium content (< 20 mg/L)
Intermediate depleted $\delta^{18}O$ (–12 to –10‰ SMOW)

The *Present-day Meteoric Water* and *Littorina Sea Water* type groundwaters are based on hydrogeochemical measurements /SKB 2005e/. Imprints of the Littorina water type are scarce in the Laxemar subarea, but are more common at the Simpevarp peninsula, which is situated in a more coastal area, and in the Forsmark area. The *Higly Saline Water* type groundwater is based on measured data from the Laxemar subarea /SKB 2006d/ and the *Last Deglaciation Meltwater* type groundwater is characterised according to information from the open literature /e.g. Brown 2002/. As pointed out in the section 5.5 below, the original water types have undergone mixing and alterations (water/rock reactions) after their introduction into the bedrock. Moreover, the *Last Deglaciation Meltwater* type groundwater only exists as a residual component in the deeper brackish *Littorina Sea Water*. Non-marine brackish to saline groundwaters are found even deeper in the basement, below the Littorina Sea water. No obvious residual meltwater components with depleted $\delta^{18}O$ are evident in the *Highly Saline Water* type groundwater. In contrast, this water tends to be enriched in $\delta^{18}O$, possibly due to water/rock interactions in the groundwater in bedrock fractures, and/or influence from pore water in the intact bedrock. Generally, the groundwaters sampled in the bedrock consist therefore of a complex mixture of the above major water types.

The chemical composition of a hypothesised additional water type referred to as a mixture of *Old Meteoric ± Glacial and Saline Waters* can only be speculated upon, but its general presence has been confirmed both in groundwater in fractures and in the pore water in the rock matrix at Forsmark (Appendix 7 in /Laaksoharju et al. 2008/). However, since it is conceived as a melange of ancient water influences, it may not be possible to define as a particular water type. Nevertheless, the concept of a residual, pre-Weichselian, water influence is of considerable importance in understanding the palaeohydrogeological evolution in the Fennoscandian Shield.

Therefore five sources of end members for the hydrochemistry observed are suggested, with the following relative chronology in terms of hydrogeochemical influence: *Deep Saline Water* (oldest) > *Mix of Old Meteoric, Glacial and Saline Waters* (hypothetical) > *Last Deglaciation Meltwater* > *Littorina Sea Water* > *Present-day Meteoric Water* (most recent) /Laaksoharju et al. 2008, Follin et al. 2008/. The western and central parts of the Laxemar regional model area that never were covered by the Littorina Sea, have instead experienced a continuous period of Meteoric Water recharge over the order of 10,000 years.

5.4 Groundwater evolution by mixing and reactions

The groundwater evolution in the Baltic coastal areas can be described as the result of several different processes involving mixing as well as reactions /e.g. Laaksoharju et al. 2008/. The chemical and isotopic data collected from the different groundwaters provide a fingerprint of these processes. To understand and interpret these data and the groundwater evolution, the following issues need to be considered (cf. Figure 5-3).

1) *The original composition of the recharge water entering the bedrock.*

   Because both of the studied areas are situated close to the Baltic Sea coast, it is evident that both fresh, meteoric water, and brackish, marine waters of different salinities, have played important roles. Fresh meteoric waters originating from very different climatic conditions (i.e. from temperate to glacial) have been recharged repeatedly.

2) *Reactions taking place in the soil cover and upper bedrock, which modify the original signature of the recharge water.*

   Examples are water/rock reactions such as silicate weathering, ion exchange, calcite dissolution/precipitation and microbially mediated reactions involving, for example Mn, Fe and sulphide/sulphate.

3) *The hydraulic conditions which steer the mixing and reactions that largely determine the resulting groundwater chemistry, especially for the conservative elements.*

   Topography, bedrock permeability, water-density differences and glacial ice loading/unloading, all contribute to the hydraulic conditions. The diffusion gradients created between fracture groundwaters and matrix pore waters can result in a chemical modification of the fracture and matrix groundwaters over long time intervals. Changes in diffusion gradients may be triggered by periodic changes in recharging groundwaters.

5.5 Groundwater evolution of the Forsmark and Laxemar-Simpevarp areas

At all sites investigated for groundwater chemistry in the circum-Baltic area, an increase in salinity versus depth is encountered, although the shape and steepness of the salinity gradients varies considerably between the sites.

At Forsmark, saline groundwaters with traceable marine components (i.e. brackish marine groundwaters) are found at a depth of approximately 300–600 m (depending on location). The brackish non-marine groundwater (5,000–10,000 mg/L Cl) usually found at 400–700 m depth (depending on location) and sometimes even deeper, is influenced by mixing, reactions and interaction with pore fluids in the rock matrix (diffusion processes). Furthermore, isotope and chemical data suggest that portions of these waters have been preserved in the bedrock for very long periods of time (i.e. at least 1.5 Ma). In the depth interval of 700 m to at least 1,000 m, saline groundwaters of similar minimum ages are found, and at even greater depths (~ 1,500 m) at Laxemar, highly saline groundwaters (also of similar minimum age) have been encountered.

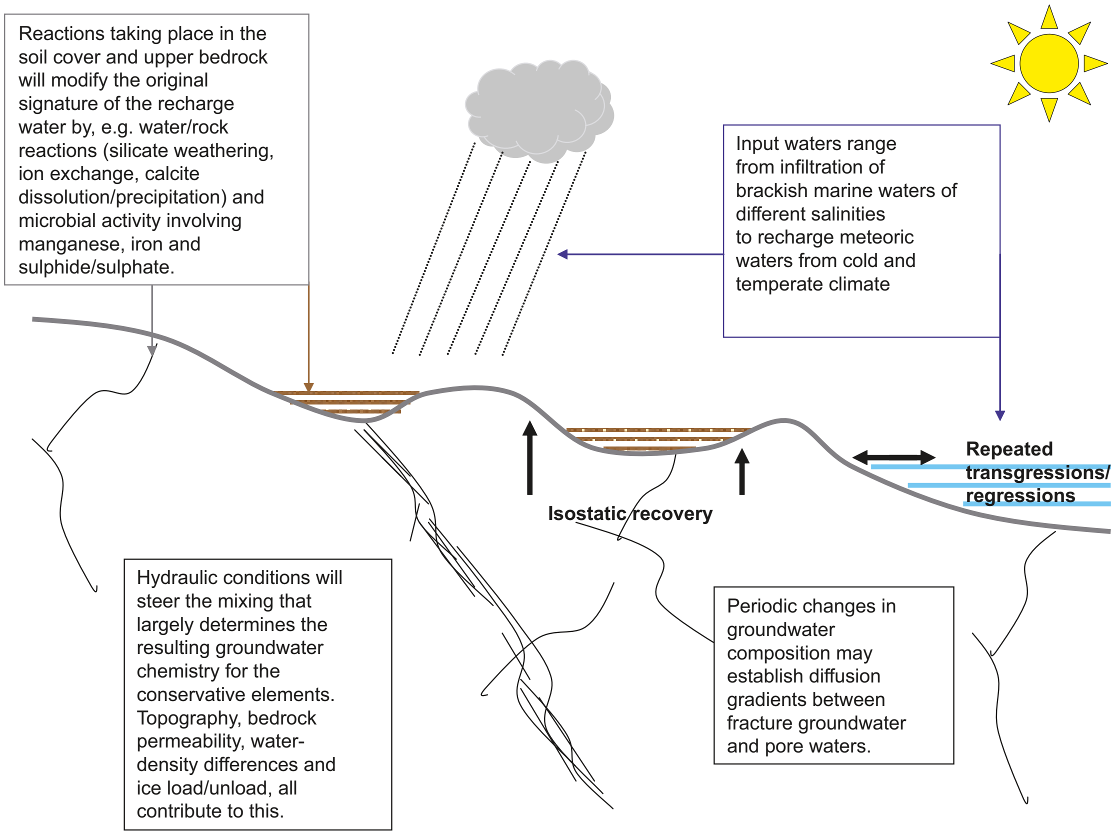


Figure 5-3. *Sketch showing the most important factors controlling the groundwater evolution in coastal areas of Sweden.*

Residence times for these deep Laxemar groundwaters have been sufficient to change the $\delta^{18}O$ and $\delta^{2}H$ ratios, causing deviation from the Global Meteoric Water Line. Groundwaters at Forsmark and Laxemar-Simpevarp at depths greater than 1,500 m are most likely brine in character and of unknown age and origin.

Figure 5-4, Figure 5-5 and Figure 5-6 outline the hydrogeochemical conceptualisation of the Forsmark and Laxemar-Simpevarp areas. Figure 5-4 describes conditions during the Late Palaeozoic stage which the two areas have in common. The presence of very saline (~ 20 wt%, mainly Ca-Cl) fluids at this time is indicated by studies of fluid inclusions in calcite of Palaeozoic origin /Sandström et al. 2008, Drake et al. 2008/. Therefore, it can be assumed, that during the Late Palaeozoic when several kilometres of marine and terrestrial sediments covered the areas (cf. Chapter 2), brine solutions were formed, allowing highly saline waters to penetrate and saturate the underlying crystalline bedrock.

Subsequent erosion slowly reduced this sedimentary cover, and in the Late Tertiary the present bedrock was exposed once again /Lidmar-Bergström 1996/. This re-exposure of the crystalline rock has resulted in a flushing out and dilution of the brine in the upper 1,000 m (or more) of the bedrock, due to the effect of subsequent glaciations and interglaciations during the Quaternary. In addition, close to the present-day coast of the Baltic Sea, repeated transgressions and regressions have caused oscillations between marine, non-marine and meteoric groundwater environments. This means that both areas are influenced by several generations of meteoric waters, intruded into the bedrock during both cold and temperate periods. Portions of these different waters are still present today, especially in the less hydraulically conductive parts of the bedrock. Also Baltic Sea waters from different evolution stages of the Baltic region prior to the last Weichselian glaciations have affected the groundwater.

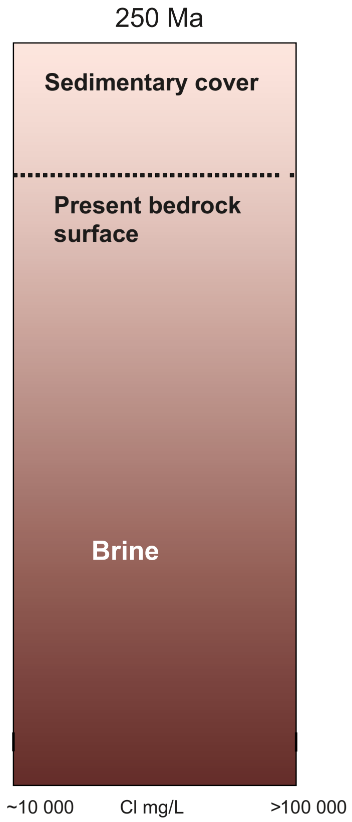


Figure 5-4. *A simplified sketch of the groundwater situation during the Late Palaeozoic when the Forsmark and Laxemar-Simpevarp areas were covered by marine and terrestrial sediments of large thickness /Cederbom et al. 2000/.*

Figure 5-5a and Figure 5-6a show a tentative distribution of groundwater types and salinity gradients in the Forsmark and Laxemar-Simpevarp areas before the intrusion of meltwater from the last deglaciation. At that time it is assumed that there must have been a presence of old meteoric waters, comprising components derived from both temperate and cold climate events. These water types have probably gradually been mixed with deeper, more saline groundwaters. In more hydraulically conductive parts of the basement rock, however, meltwater from the latest deglaciation was intruded to several hundreds of metres depth (Figure 5-5b and Figure 5-6b), and therefore more or less fresh water dominated the upper 400 to 500 m in the most conductive zones.

During the subsequent Littorina Sea stage (Figure 5-5c and Figure 5-6c), the Forsmark area and the coastal parts of the Laxemar-Simpevarp area were covered by brackish sea water estimated to be at around 6,500 mg/L Cl (twice the present salinity of the Baltic Sea), slightly higher than value estimated for Forsmark. The maximum salinity occurred between c 4500 and 3000 BC. Due to density differences, the Littorina Sea water intruded into the deformation zones and fractures previously filled with fresh water of glacial and old meteoric character (Figure 5-5c and Figure 5-6c). The Littorina Sea stage did not affect areas in Laxemar above the highest shoreline (Figure 5-6c).

The present-day situation is shown in Figure 5-5d and Figure 5-6d, which illustrates the flushing of the brackish Littorina Sea water in the upper part of the bedrock by recharged meteoric groundwaters during the last 1,000 years. At this juncture, meltwater from the last deglaciation can no longer be identified as a major component in the bedrock, but rather constitutes a minor part in the Littorina Sea water due to mixing. Locations at Laxemar which are not affected by Littorina Sea water have generally a more dilute groundwater at a larger depth, compared with areas covered by the Littorina Sea (see Figure 5-6d).

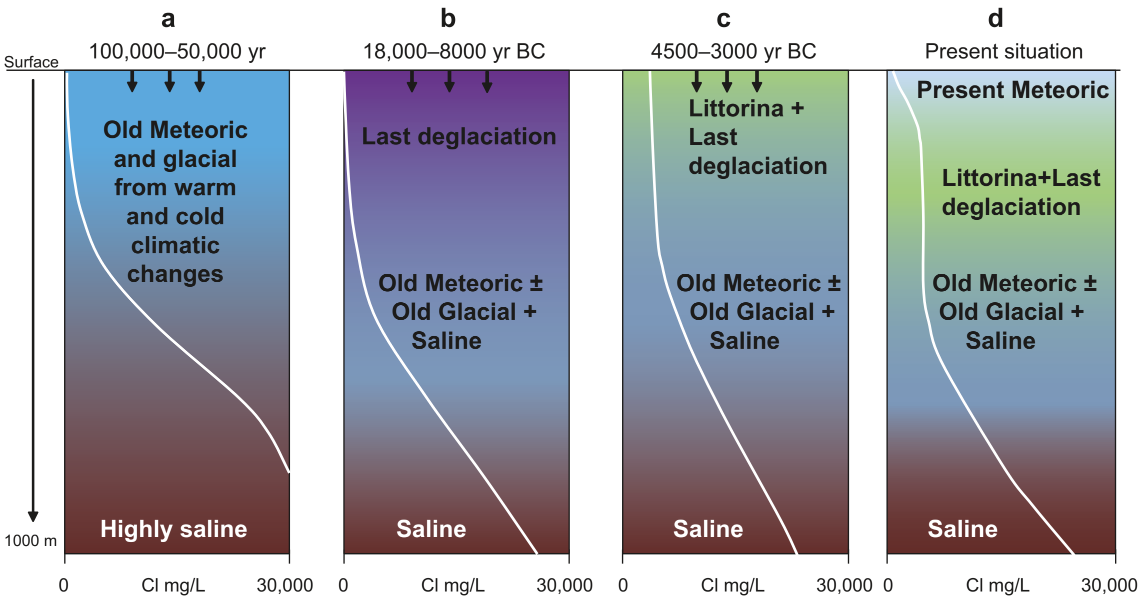


Figure 5-5. Sketch showing tentative salinities and groundwater-type distributions versus depth for the transmissive zones at Forsmark. From left to right: a) situation prior to the last deglaciation, b) deglaciation and intrusion of Late Weichelian meltwater, c) the Littorina Sea water penetration caused by density intrusion, and d) the present situation.

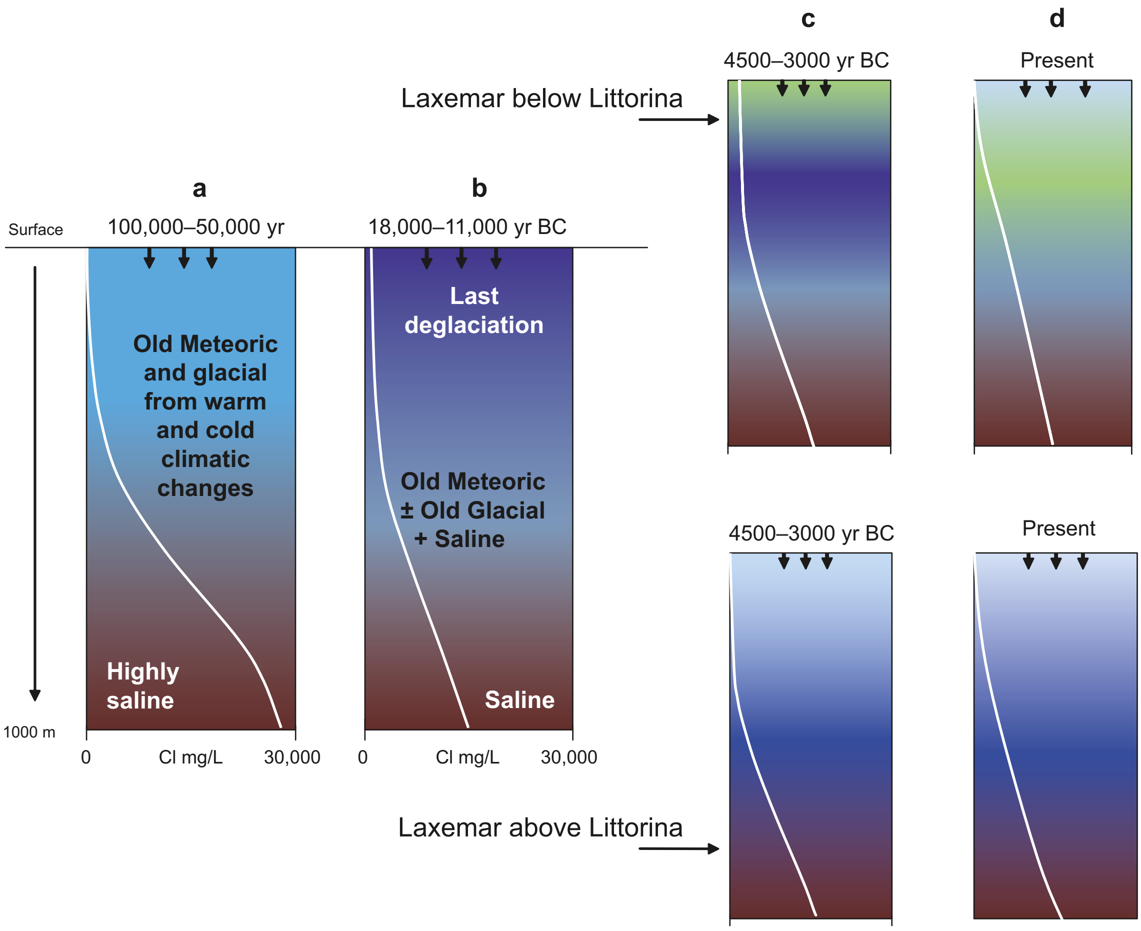


Figure 5-6. Sketch showing tentative salinities and groundwater-type distributions versus depth for the transmissive zones at Laxemar. From left to right: a) situation prior to the last deglaciation, b) intrusion of last deglaciation meltwater, c) part of Laxemar covered/not covered by Littorina Sea water, d) and the present situation.

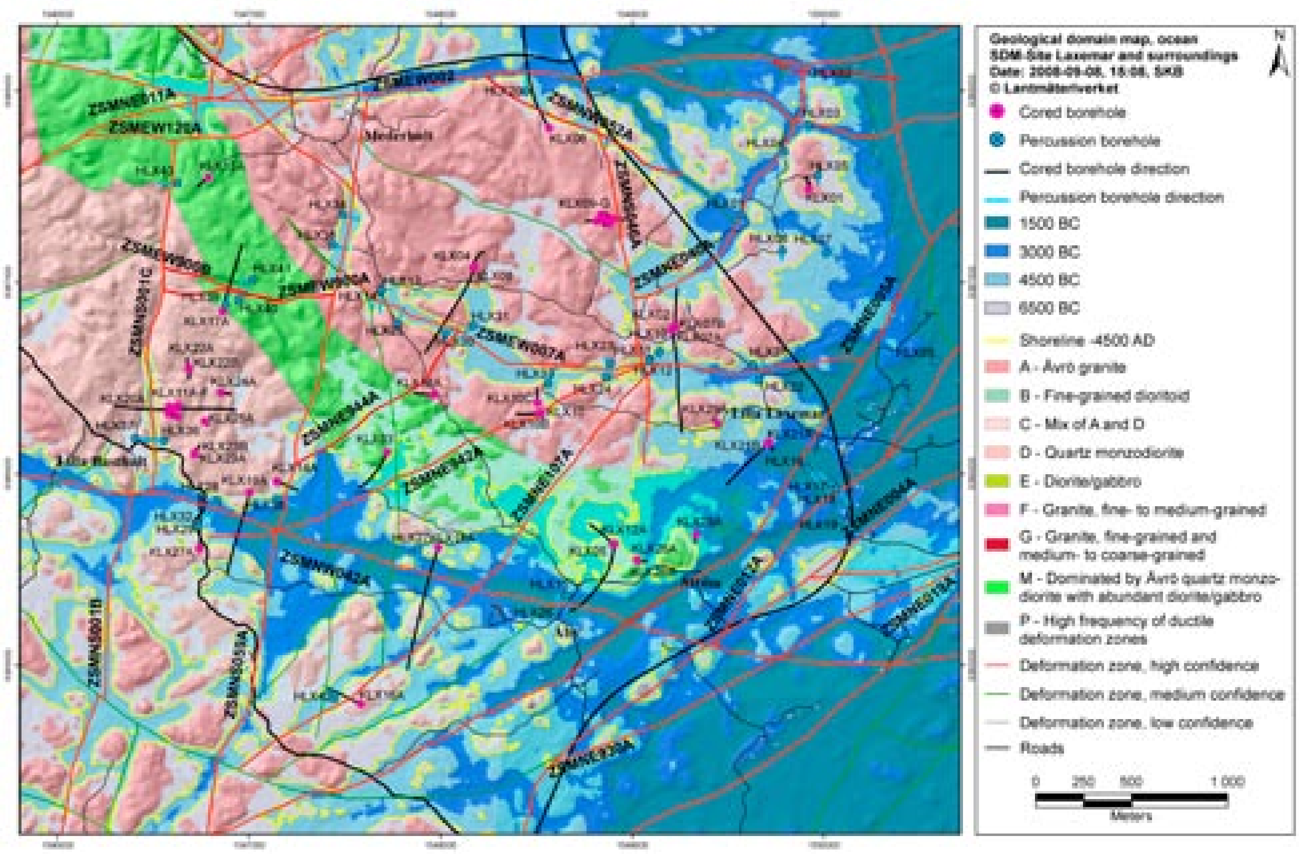


Figure 5-7. *Shoreline changes in the Laxemar-Simpevarp area during the Littorina period. The maximum salinity in the Baltic during the Littorina period occurred between 4500 BC and 3000 BC.*

The Littorina imprint shows different patterns in the Laxemar-Simpevarp and Forsmark areas due to the fact that the Littorina Sea covered the entire Forsmark area, but only parts of the Laxemar subarea (Figure 5-7). Littorina seawater pervaded the Laxemar subarea mainly along the deeper E-W valleys and entered the bedrock via large sub-vertical deformation zones which are topographically expressed at the surface by these valleys. This resulted in a mixing between the Littorina with fresh water of glacial and meteoric character resident in these zones. During the last few thousands of years, when the Laxemar subarea has risen above sea level, meteoric water has replaced most traces of Littorina water by flushing.

5.6 Summary

The groundwater evolution in the Forsmark and Laxemar-Simpevarp areas has been strongly affected by climate changes in the past. Investigations have shown that the groundwaters observed today have different origins, including glacial meltwater, meteoric water and marine water, depending on the prevailing conditions. Shoreline displacement plays an important role in understanding the infiltration mechanism for these waters. It is particularly important for the intrusion of the saline Littorina Sea water into the bedrock, as well as for the subsequent flushing processes in the upper, more permeable bedrock horizons. It seems that the most recently recharged water tends to flush older water types, especially in the upper permeable part of the bedrock. However, hydraulic conditions vary over time, and remnants of earlier climatic fluctuations can be preserved in localised areas of low permeability. Thus, palaeohydrogeochemistry thus provides an important framework for understanding the bedrock hydrogeochemical evolution which is crucial for the hydrogeochemical and hydrogeological understanding of the site.

Waters of very different residence times have been documented, ranging in age from recent tritiated meteoric waters (< 50 a), to (late) marine waters (3000–4000 BC), to low $\delta^{18}O$ glacial water (last deglaciation around 8800 BC in Forsmark and 12,000 BC in Laxemar-Simpevarp), to deeper, ancient waters isolated from the atmosphere for more than 1.5 Ma. This means that the changes in hydraulic conditions during at least the Quaternary period have left their imprints in the fracture and pore waters. However, most fracture groundwaters observed today originate from the last glaciation/deglaciation cycle and the subsequent Holocene period, whereas data or imprints from earlier cyclic events, prior to the last Weichselian maximum, are few. The mixing processes and the reactions affect the groundwater composition and may modify the palaeosignatures of the groundwater; these processes have to be understood when interpreting the groundwater data. In contrast, porewaters reflect a much less dynamic system so that palaeo-signatures can still be detected, providing important input to site understanding.

6 Development of ecosystems during the late Quaternary period

6.1 Introduction

Long-term ecosystem development or change in inshore land and sea areas of Fennoscandia is driven mainly by two different factors; climate change and shoreline displacement. During the Quaternary period the climate has changed repeatedly and it has thereby changed the conditions for biota that define the ecosystems. Such climatic changes have directly changed the conditions for ecosystem formation, e.g. mire- and bog complexes, and have caused north- and south-ward migration of species and ecological communities. Changes of species distributions have the potential of affecting whole ecosystems, i.e. the emergence or disapperance of species which may have a key function in the ecosystem, such as the mega herbivores that are thought to have kept the forests fairly open, or a predator which directly may alter the food web and thereby the whole ecosystem. In this perspective, human historical land use is also an important component that in many ways has shaped the landscape of today. Human land use is treated separately in Chapter 7. The second important factor, shoreline displacement, has strongly affected both Forsmark and Laxemar-Simpevarp since the latest deglaciation and still causes a continuing and relatively predictable change in the abiotic environment, e.g. in water and nutrient availability. It is therefore appropriate to describe the origin and succession of some major ecosystem types in relation to shoreline displacement, i.e. the ontogeny of a lake and its further development into wetland. Below, the first section has a general perspective on the long-term ecosystem development in Fennoscandia, whereas the subsequent sections describe ecosystem development from the regional perspectives of Forsmark and Simpevarp.

6.2 Ecosystem development in Sweden after the latest deglaciation

6.2.1 Climate and terrestrial vegetation

The ecosystem succession in southern Sweden after the latest deglaciation was primarily controlled by climatic changes and the formation of new land areas, but also human activities have influenced the ecosystem development, especially during the last few millennia. Shortly after the ice retreat, which started in southernmost Sweden c 15,000 BC, the landscape was free of vegetation and can be characterised as polar desert. Relatively soon, the ice-free areas were colonised, first by lichens and mosses, which were followed by tolerant grasses and herbs. Pollen investigations from southern Sweden have shown that a sparse Birch (*Betula spp*) forest covered the landscape soon after the deglaciation /e.g. Björck 1999/.

During the period called the Younger Dryas (c 11,000–9500 BC) there was a decrease in temperature and the climate became arctic. Large areas of the deglaciated parts of Sweden were affected by permafrost, and much of the previously established flora and fauna disappeared. Only the most tolerant species remained and herb tundra developed. At the beginning of the Holocene c 9500 BC, the temperature increased again and southern Sweden was covered by forests, first dominated by Birch and later by Scots pine (*Pinus sylvestris*) and Hazel (*Corylus avellana*).

Northern Sweden was deglaciated during the early part of Holocene when the climate was relatively warm. These areas were therefore covered by forest, mainly consisting of Birch and Scots pine, shortly after deglaciation. There was a cooling of the early Holocene climate during the so-called Preboreal oscillation, which was a 150 year long cooling period /Björck et al. 1996/. During the mid-Holocene, between 7,000 and 5,000 years ago, the summer temperature in southern Sweden was approximately 2°C warmer than at present. Forests with Lime (*Tilia cordata*), Oak (*Quercus robur*) and Elm (*Ulmus glabra*) covered large parts of southern Sweden.

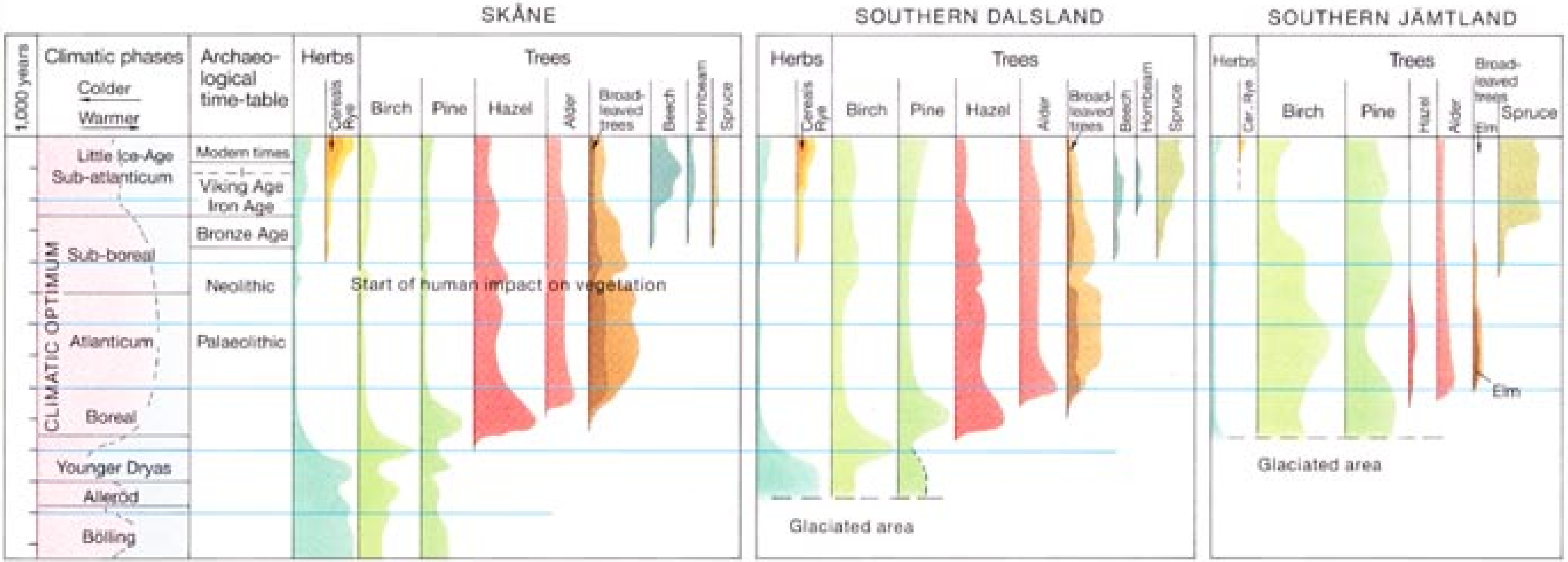


Figure 6-1. *Pollen diagram showing how the composition of vegetation has changed from the latest deglaciation to the present. The diagrams were made after analyses of sediment cores from Skåne, Dalsland, and Jämtland. The past summer temperature was somewhat higher than the present, something which is reflected by higher frequencies of pollen from broad-leafed trees (c 5–8 thousand years ago). In southern Sweden agriculture was introduced c 3000 BC, which is shown as an increase in the frequency of pollen from herbs /from Fredén 2002/.*

These trees then had a much more northerly distribution than at the present day. However, cold events occurred also during the warm mid-Holocene. Results from Greenland ice cores presented by /Alley et al. 1997/ show that a cold event, half the amplitude of the Younger Dryas, occurred around 6200 years BC. In a study of the Holocene climate of northern Sweden, /Karlén et al. 1995/ recognised more than ten small oscillations between relatively warm and cold climate. The summer temperature during the warm periods was generally 1°C warmer than at present, and during the cold periods it was 1°C colder than at present.

After the warm mid-Holocene, the temperature decreased and the forests have subsequently become more dominated by coniferous trees. Norway spruce (*Picea abies*) has successively spread from northernmost Sweden towards the south during the Holocene. This species has not yet spread naturally to parts of Skåne and the Swedish west coast /e.g. Lindbladh 2004/. /Davis et al. 2003/ reconstructed the Holocene climate in Europe from pollen data. They concluded that the warmer climate during the mid-Holocene was restricted to north-western Europe, whereas the climate further south was similar to or colder than that today. The ecological history of Sweden during the last 15,000 years has been reviewed by e.g. /Berglund et al. 1996a/. In Figure 6-1, tree pollen diagrams from three Swedish regions show the vegetation succession from the latest deglaciation to the present.

During the last few thousand years, the composition of the vegetation has changed not only due to climatic changes and the formation of new land areas, but also due to human activities. In southern Sweden, the introduction of agriculture and the subsequent opening of the landscape started c 5,000 years ago. It is often assumed that Sweden was more or less covered by forest before the introduction of agriculture. However, /Vera 2000/ suggested that grazing animals kept the European landscape relatively open. Some of the grazing animals which were common in the early Holocene have decreased or disappeared completely. /Lindbladh et al. 2003/ have suggested that also fires kept some forest types more open before humans started to have an impact on the forests in northern Europe.

6.2.2 Fauna

The climate variations have also affected the faunal composition. There are several early findings of mammal species such as reindeer and mammoth, which lived in southern Sweden shortly after the deglaciation. In the cold but nutrient-rich sea along the Scandinavian west coast, the mammal fauna was characterised by arctic species, e.g. polar bear and a variety of seal and whale species. During the shift to warmer climate at the beginning of Holocene the early mammal species disappeared, and the open landscape in the southern parts of Sweden was dominated by large grazers, e.g. bison, wild horse and aurochs. Certain animal species, which today occur further south, lived in southern Sweden during the warmest phase of the Holocene (e.g. the Pond Turtle, *Emys orbicularis*). Most of the present mammal fauna was established in southern Sweden during the early Holocene. Some of the early established species, such as the aurochs and the bison, are however now extinct in Sweden /Berglund et al. 1996b/.

6.2.3 Coastal ecosystems

After the latest deglaciation the environment in the Baltic Sea has varied due to climatic and salinity variations. These variations have in turn affected the ecosystems. That is reflected in the remnants of organisms found in sediment and raised shorelines from the different Baltic Sea stages. In fact the Yoldia Sea, Ancylus Lake and Littorina Sea are all named after different molluscs, which reflected the different salinities characterising these stages /Munthe 1892/. More recent investigations have used variations of the diatom flora as recorded in sediments to reconstruct salinity variation after the latest deglaciation /Sohlenius et al. 1996/. The development of the Baltic Sea after the latest deglaciation is further discussed in section 3.3.5.

The Baltic Sea was deglaciated during the Baltic Ice Lake, Yoldia Sea and Ancylus Lake stages (Figure 3-11). Freshwater conditions prevailed during most of that time. However, during the Yoldia Sea, a short period (c 120 years) with brackish conditions occurred. This is confirmed by the findings of foraminifers and of the marine bivalve *Portlandia (Yoldia) Arctica* from this period. During the following Ancylus Lake, the Baltic was characterised by freshwater conditions, which is reflected by findings of the freshwater gastropod *Ancylus fluviatilis*, and by the composition of the diatom flora recorded from numerous sediment cores /e.g. Sohlenius et al. 1996/. The first c 1,000 years of the Littorina Sea was characterised by low salinity. This low salinity phase is sometimes referred to as the Mastogloia Sea after the diatom *Mastogloia smithii* /Thomasson 1927/. The Littorina Sea is named after the gastropod *Littorina littorea*. That gastropod had a more northerly distribution than at present during the most saline phase of the Littorina Sea. The high salinity during the mid-part of the Littorina Sea period is further supported by the diatom flora as recorded in sediment cores /e.g. Andrén et al. 2000/. The last c 3,000 years has been characterised by lower salinity. That stage is sometimes referred to as the Limnaea Sea after the mollusc *Limnaea ovata baltica* /Sauramo 1958/. The salinity variations in the Baltic proper since the onset of the Littorina Sea is shown in Figure 3-12.

It has been shown that the bottoms of the Baltic basin were anoxic below the halocline during a large part of the Littorina Sea stage /e.g. Sohlenius and Westman 1998/. The anoxic conditions probably caused high concentrations of nutrients in the bottom water. There are several studies of sediment cores showing that the primary productivity in the Baltic proper increased during the transition from the freshwater Ancylus Lake to the brackish water Littorina Sea /e.g. Sohlenius et al. 1996/. That increase was caused by displacement of the nutrient-rich bottom water to the photic zone. It is also possible that phosphorus-rich oceanic water contributed to the relatively high productivity in the Baltic during the Littorina Sea stage. The periods with highest productivity seem to coincide with the most saline phase of the Littorina Sea. There are several papers reporting that nitrogen-fixing cyanobacteria have occurred in the Baltic since the onset of the Littorina Sea /Bianchi et al. 2000, Westman et al. 2003/. The occurrence of these bacteria indicates that the concentration of phosphorous, at least occasionally, has been high in the surface water since the beginning of the Littorina Sea.

6.2.4 Lake ecosystems

Lake basins may be formed in many different ways, often related to catastrophic events in the history of Earth. Lakes appear wherever a threshold is formed that obstructs the passage of runoff water. /Hutchinson 1975/ defined eleven main classes and characterised totally 76 sub-classes of lake basins, based on the processes involved in their formation. Lake basins found in Sweden include e.g. tectonic basins, basins formed by glacial activity, by fluvial action and by meteorite impact, as well as by man-made dams. The most common types of lake basins in Sweden are those that have been formed directly or indirectly by glacial activities during and after the Pleistocene glaciations. New lakes are still continuously formed along the coast, as the land is rising from the depression that occurred during the last glaciation period (cf. section 3.3.5). This is the case especially in Forsmark but also in the Laxemar-Simpevarp areas.

6.2.5 General successional trajectories in shoreline displacement areas

Succession is a directional change of ecosystem structure and functioning, which may occur over time scales from decades to millenia. Succession may be a result of new land emerging (primary succession) or by disturbance such as after a clear-cut (secondary succession). The vegetation development and the species community through time are constrained by the availability of dispersal propagules and the local abiotic conditions /i.e. Rydin and Borgegård 1991, Löfgren and Jerling 2002/. In the investigated coastal areas, the overall regressive shoreline displacement transforms the near-shore sea bottom to new terrestrial areas or to freshwater lakes. The subsequent development of these terrestrial areas and lakes may follow different trajectories depending on factors such as fetch during the marine shore stage, slope and surrounding topography. A schematic illustration of some of the main trajectories is shown in Figure 6-2, where the sea bottom is the starting point and the end point is an inland bog or a forest locality.

The structure of the drainage network is important for ecosystem development, since it determines, or at least strongly affects, groundwater levels and water content in the upper soil layers. However, processes which may have affected the drainage network mainly took place prior to or during the latest glacial period. It is therefore reasonable to assume that no major topographical changes due to e.g. erosion or sedimentation have occurred after the investigated sites emerged above the sea level, with the exception of sedimentation in lakes. Sediment accumulation probably has not changed the drainage areas, since thresholds generally are formed in glacial till or bedrock. Peat formation may lead to damming, resulting in expanding peatlands. However, damming due to peat formation is considered to be of minor importance for the drainage-network development in the investigated areas, and it is probably only in the most elevated parts that peat formation may have caused any changes in the drainage pattern.

Almost all vegetation types in southern Sweden have been strongly influenced by human activities in historical time and also today. This influence has varied over time depending on the size of human population. Some vegetation types, such as agricultural land, are man-made, whereas other types are kept at a successional stage otherwise found during a restricted period following the shoreline displacement, e.g. a meadow.

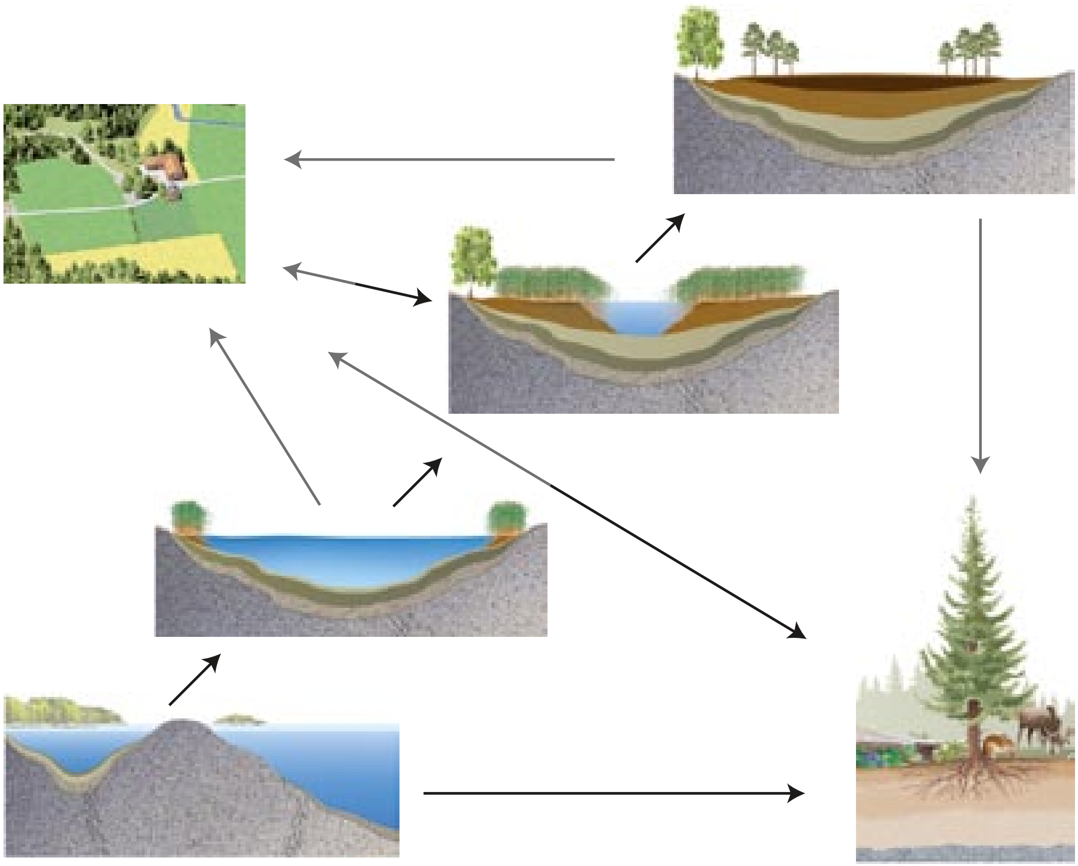


Figure 6-2. A schematic illustration of the major ecosystems that may be found at certain points during the temporal development, where the original sea bottom slowly is turned into inland due to shoreline displacement. Black arrows indicate natural succession, whereas grey arrows indicate human-induced changes to provide new agricultural land or improved forestry. Agricultural land may be abandoned and will then develop into forest or, if the hydrological conditions are suitable, into a fen. A forest may be "slashed and burned" and used as agriculture land.

Sea bay/shore

The starting conditions for ecosystem succession from the original sea bottom in a coastal area are strongly dependent on the topographical conditions. Deep bottoms accumulate sediments (accumulation bottoms) at a higher rate than shallow bottoms (transport bottoms). In near-coast locations, the degree of wave-exposure determines whether sediments will be accumulated or not; the bottoms in sheltered bays accumulate organic and fine-grained inorganic material, whereas the finer fractions are washed out from more wave-exposed shorelines with a large fetch.

During regressive shoreline displacement, a sea bay may either be isolated from the sea at an early stage and thereafter gradually turned into a lake as the water becomes fresh, or it may remain as a bay until it is uplifted by the shoreline displacement and turned into a wetland or a forest. The Baltic Sea shore can be divided into four main shore types: rocky shores, shores with more or less wave-washed till, sandy shores and shores with fine sediments. Wave-exposed shores will be subject to a relocation of earlier allocated sediments and these shores will emerge as wave-washed till. The grain-size of the sediments left will therefore be a function of the fetch or the wave-exposure at the specific shore.

In the Forsmark area, shores with wave-washed till are the most common, but also rocky shores and shores with fine sediments do occur (Figure 3-18). In the Laxemar-Simpevarp area, rocky shores are the most common, followed by shores with wave-washed till, and shores with fine sediments also occur. These shores later turn into forests (see below). In coastal basins that will later develop into lakes, there is a threshold in the mouth of the basin towards the open sea. This threshold allows settling fine material to accumulate in the deeper parts of the basin. Provided that the water depth is less than 2–3 m, different macrophyte species (e.g. *Chara* sp) colonise the illuminated sediments. Along the shores, *Phragmites* and other aquatic vascular plants colonise the system, and a wind-sheltered littoral zone is developed. In both these habitats, the colonisation of plants reduces the water currents, resulting in increased sedimentation and accelerated terrestrialisation of the bay. When the treshold is lifted above the sea level, inflow of fresh surface- and groundwater slowly changes the system from a brackish to a freshwater stage.

Lake

All present-day lakes in the investigation areas originated from depressions in the bottom of the coastal system, and where the shoreline displacement is regressive new freshwater lake basins are continuously formed along the coast of the Baltic Sea. The lake ecosystem gradually matures in an ontogenetic process which includes subsequent sedimentation and deposition of allochthonous (transported from the surrounding catchment area) as well as autochthonous (originating from/produced within the lake) substances. Hence, the long-term ultimate fate for all lakes is an inevitable fill-up and conversion to either a wetland or a drier land area, the final result depending on local hydrological and climatic conditions. A usual pattern for this ontogeny, which is often referred to, is the sequential development of more and more eutrophic (nutrient-rich) conditions as the lake depth and volume decreases /Wetzel 2001/. In later stages, aquatic macrophytes speed up the process by colonising large areas of the shallow sediments, and finally more terrestrial plant communities can colonize and grow there. Accordingly, the peat layers developed during this ontogenetic process follow some bottom-up order with more limnic character in the bottom with *Phragmites* peat, followed by *Equisetum* and then sedge-fen peat, likely over-grown by bog peat /Sjörs 1983/. However, various environmental conditions may alter this general ontogenetic pattern, and there are examples of lake ontogeny that include a transition to more oligotrophic (nutrient-poor) conditions /Engstrom et al. 2000/, as well as to more dystrophic (low pH, brown-water) conditions /Brunberg et al. 2002, Brunberg and Blomqvist 2003/.

Dystrophic conditions are typical for small forest lakes in large areas of Sweden. These lakes are characterised by high input of allochthonous carbon from the drainage area and often by short water turnover time /Brunberg and Blomqvist 2000/. The development into dystrophic conditions starts with colonisation by *Sphagnum* mosses in areas with macrophytes in the sheltered littoral. As the growth of *Sphagnum* proceeds in an outward direction and organic accumulation underneath these plants increases, a mire/floating-mat littoral zone is successively developed. This mire-littoral is important in that it may alter the groundwater flow and/or the chemistry of the inflowing groundwater and turn the system increasingly acidic. Thus, the invasion of the sheltered littoral by *Sphagnum* should, at least theoretically, have a profound effect on the functioning of the lake ecosystem. In a later stage of succession, the accumulation of organic detritus in the lake basin completely covers the previously illuminated benthic area. At this stage, the *Sphagnum* littoral alone dominates the metabolism of the system, as most of the previously benthic habitat has been lost through accumulation of peat. The whole ecosystem; the mire-littoral as well as the open water, is now acidic. The area of open water is continously reducing due to the expansion of the floating mats. The floating mats fill in the lake from the top, meaning that bog-like peat can be deposited directly at the lake bottom (with some mud layer in between), as the weight of the growing peat pushes the lower parts downwards /Sjörs 1983/. The final stage of this ontogenetic process is the raised bog ecosystem (Figure 6-3E).

Wetland

Mires are formed basically through three different processes; terrestrialisation, paludification and primary mire formation /Rydin et al. 1999, Kellner 2007/. Terrestrialisation is the filling-in of shallow lakes as described above. Paludification, which is the predominant way of mire formation in Sweden, is an ongoing water logging of more or less water-permeable soils, by expanding mires or as a result of beaver activities. Primary mire formation is when peat is developed directly on fresh soils after emergence from water or ice. All three types of processes are likely to have occurred or to occur in the Forsmark and Laxemar-Simpevarp areas, but peatland filling in lakes (terrestrialisation) /von Post and Granlund 1926/ is probably the most common type of peatland development in the areas around the investigated sites.

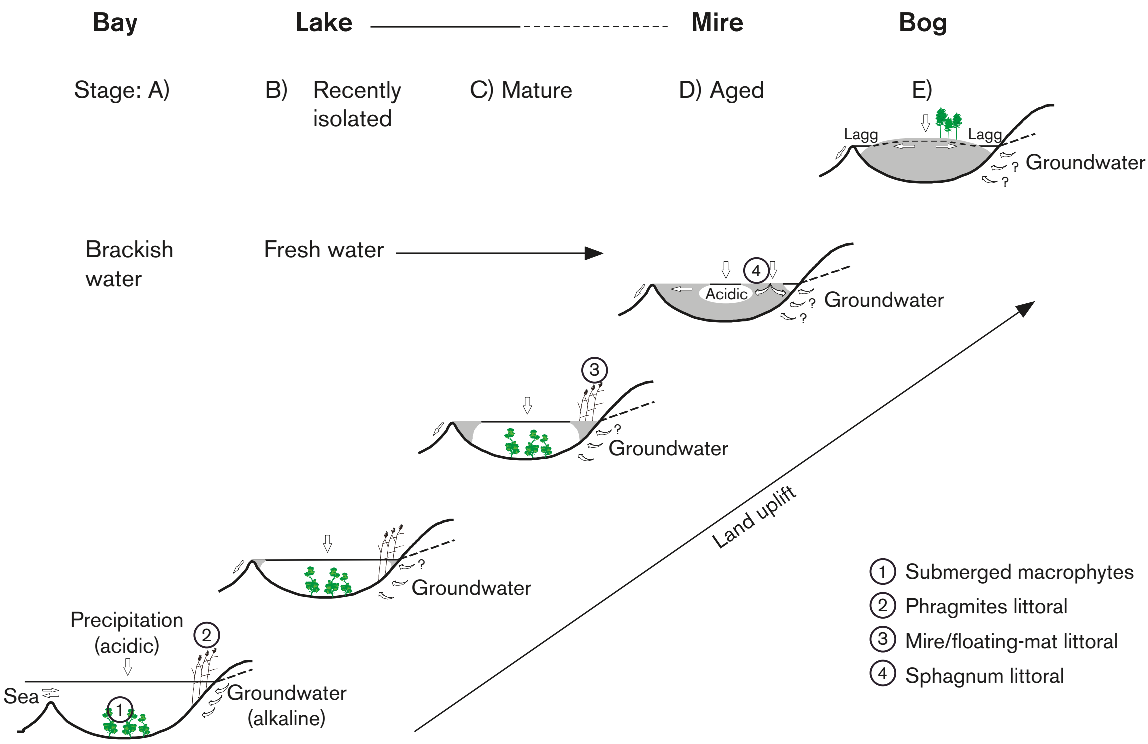


Figure 6-3. Schematic description of the ontogeny of a closed-off bay of the sea to a mire. The figures represent different important components of the ecosystem. Modified from /Brunberg and Blomqvist 2000/.

Wetlands are often described as ecotones, i.e. transitional spatial gradients between adjacent aquatic and terrestrial environments /Mitsch and Gosselink 2000/. Thus, wetlands can be considered as transitional in both space and time. As wetlands show a hydrological gradient, they usually interact strongly with varying abiotic factors from both ends of the gradient. These factors may drive a wetland towards its terrestrial neighbour if, for example, the water level falls, or toward its aquatic neighbour if the water level rises. Alternatively, plant production of organic matter may raise the level of the wetland, resulting in a drier environment in which new species can succeed. Accordingly, fluctuating hydrologic conditions are the major factor controlling the vegetation pattern in wetlands /Niering 1989/.

The richer types of mires will undergo a natural long-term acidification, when turning into more bog-like mires. It seems that the final result of mire development in the boreonemoral and southern boreal areas of Sweden is a bog /Rydin et al. 1999/. The bog can, however, have trees of Scots pine on it, if the peat can support their weight, and some studies (e.g. /Gunnarsson et al. 2002/ and references therein) indicate that Scots pine have established and become more common on bogs in recent years.

Historically, mires have often been drained for forestry, and in Sweden such activities peaked in the 1930s. Traditionally, mires were also used for haymaking, and in this context the rich fens were more important than the poor fens. Haymaking slows down or stops the succession of the rich fen, resulting in poorer fen-like stages due to the inhibition of peat formation /Elveland 1978/. Mires have also been used for agriculture purposes, and such use was, during the 1850s and subsequently, often preceded by ditching to ensure the best possible conditions for the crops cultivated. This resulted in lowering of the water table, inducing a switch from anaerobic to aerobic conditions, which initiated decomposition and erosion of peat-dominated soil.

Forest

The first pioneer woody species on the shoreline are, in Forsmark, Hawthorn (*Hippophaë rhamnoides*), and, in Laxemar-Simpevarp, Blackthorn (*Prunus spinosa*) and the tree Alder (*Alnus glutinosa*). These species have a litter that is rich in nitrogen, and this nutrient supply facilitates the establishment of many other species. From the establishment of bushes and trees, a varied light environment and new habitats are created. In this way, the vegetation composition is steadily changing, but with a relatively high degree of determinism /e.g. Svensson and Jeglum 2000/. In most areas with a thicker soil layer in southern Sweden, the Norway spruce forest has to be regarded as the climax vegetation type. The occurrence of Scots pine would probably be more restricted, mainly to areas with a shallower, more nutrient-poor soil layer, if forestry management was to decrease and fire, again, was to become a natural disturbance in the landscape /Sjörs 1967, Engelmark and Hytteborn 1999/.

Agricultural land

Before agricultural modernisation, mainly fairly dry soils were cultivated. Heavy clays and wetlands were instead used for mowing, whereas less fertile areas, such as stone-ridden tills and areas with a thin soil layer, were grazed. In Nynäs in Södermanland, it was found that also thin soils on bedrock were used for cultivation close to the villages in the 17th and 18th centuries /Cousins 2001/. As management intensity and population increased, more of the medium fertile soils were used for agriculture whereas the poorest soils were assigned to livestock /Rosén and Borgegård 1999/. However, this trend came to an end as management was rationalised by using fertilisers and better equipment in the early 20th century. This development of farming and the development of forest tools and machinery altered the utilization of land and thus its previous association with different soils. The distribution of agricultural land in Sweden is today largely associated with post-glacial deposits /Angelstam 1992, Sporrong et al. 1995/.

The seminatural grassland was earlier intensively used, but is today mainly a part of the abandoned farmland following the nationwide general regression of agricultural activities.

If these areas are left unattended, they will eventually develop into forests that in most cases will be dominated by Norway spruce. During the latter part of the 1900s, farmers were encouraged to plant coniferous trees on arable land, thereby accelerating the succession into forest.

6.3 Ecosystem development at Forsmark

When the latest deglaciation in Forsmark took place approximately 8800 BC, the closest shore was situated c 100 km to the west of Forsmark. At that time, the Forsmark area was situated c 150 m below the surface of the Yoldia Sea (cf. section 3.4.4). Since the major part of the Forsmark regional model area was covered by water until c 500 BC, the post-glacial development of the area is determined mainly by the development of the Baltic basin and by shoreline displacement.

At around 500 BC, a few scattered islands situated in the western part of the regional model area were the first land areas to emerge from the brackish water of the Bothnian Sea (Figure 6-4). The surface of these first islands was covered by sandy till and exposed bedrock, i.e. similar to the present situation on the islands outside Forsmark. Palaeo-ecological studies from the Florarna mire complex, situated c 30 km west of the regional model area, indicate a local humid and cold climate at approximately this time /Ingmar 1963/.

At 0 BC, the Bothnian Sea still covered the Forsmark candidate area, whereas the islands in the western part of the regional model area had expanded in size (Figure 6-4). Land areas presently covered by peat had emerged and, at that time, these newly isolated basins were small and shallow freshwater lakes/ponds, similar to the near-shore lakes which can be found in the area today. The apparent isolation of Lake Bruksdammen in the western part of the area around 0 BC is an artefact caused by the use of today's lake thresholds when constructing the map; the lake was probably created by man in the 17th century by damming the river Forsmarksån /Brunberg and Blomqvist 1998/.

At 1000 AD, the mainland had expanded further in the south-western part of the area (Figure 6-4). The isolation process of the Lake Eckarfjärden basin was initiated (see Figure 6-5 for the location of present-day lakes in the area), but the bay still had an open connection with the Baltic in the northern part /cf. Hedenström and Risberg 2003/. The area west of Lake Eckarfjärden presently occupied by the Stenrösmossen mire had emerged, and a short lake phase was succeeded by infilling of reed /cf. Fredriksson 2004/. The Börstilåsen esker and the most elevated areas at Storskäret (see Figure 1-2) constituted some small islands in the east, exposed to waves and erosion.

At 1500 AD, a considerable part of the regional model area had emerged from the Baltic and several freshwater lakes were isolated, e.g. Lake Eckarfjärden and Gällsboträsket (Figure 6-4). A shallow strait connected the bays that today are Lake Bolundsfjärden and Lake Fiskarfjärden. The northern part of this archipelago was heavily exposed to wave action, whereas the southern part was relatively protected. The area covered by clayey till at Storskäret formed a large island, partly protected from wave exposure by the Börstilåsen esker. Hundred years later, the strait between Lake Bolundsfjärden and Lake Fiskarfjärden had been cut off, and there were two bays with different conditions. At around 1650 AD the major part of the candidate area was situated above sea level.

The post-glacial development of ecosystems in the Forsmark area is principally determined by the climate, the development of the Baltic basin and the shoreline displacement, as described above and in Chapter 4. The first terrestrial ecosystems appearead around 500 BC, and the succession of both the terrestrial and aquatic ecosystems have in all essentials followed the general patterns outlined above. Site-specific information that can be added to the general successional trajectories include the regional vegetation development, the local and regional lake ontogeny, and some comments upon the development of terrestrial areas.

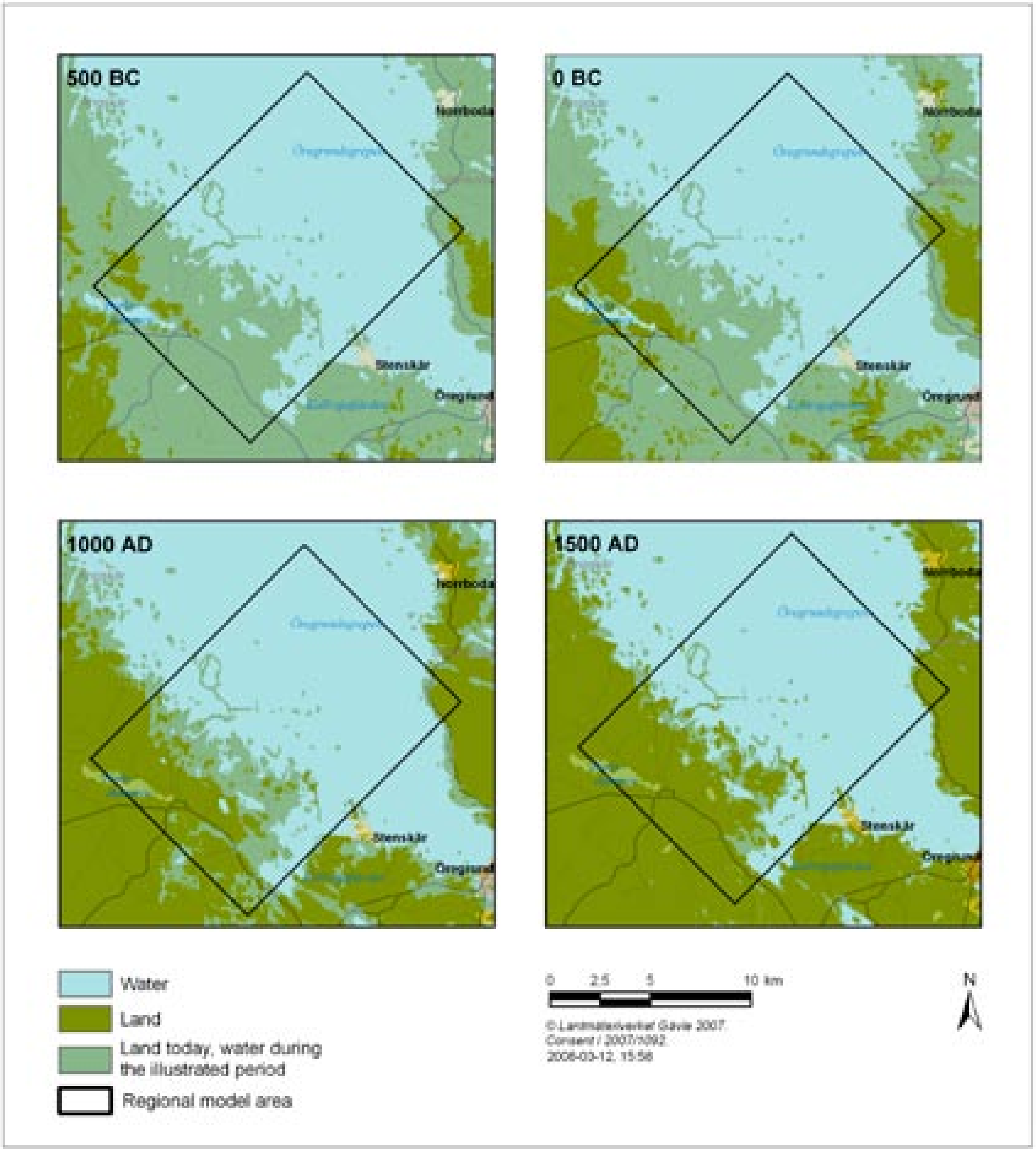


Figure 6-4. The distribution of land and sea in the Forsmark area at 500 BC, 0 BC, 1000 AD and 1500 AD.

6.3.1 Regional vegetation development

In order to describe the Holocene vegetation history in a longer time span, the area for collecting data must be expanded to include more elevated regions such as the western part of the county of Uppland. /Karlsson 2007/ has recently compiled published investigations on pollen analyses from Uppland, together with results from stratigraphical investigations performed in connection with archaeological investigations for the construction of 90 km of new highway (E4) in northern Uppland. The following description is based mainly on the associated compilation of 12 pollen diagrams /Karlsson 2007/, and focuses on the vegetation history during the Stone Age in Uppland (c 5500–2300 BC). Palaeoecological description of the type region South-Central Sweden /Berglund et al. 1996a/ is also used for the regional description.

In western Uppland, the first areas to emerge were mainly covered by till, bare bedrock and eskers. In all pollen diagrams, Pine (*Pinus*) and Birch (*Betula*) are the dominant trees when the sites were located in the outer archipelago, while a mixed deciduous forest containing e.g. Peduculate oak (*Quercus robur*), Aspen (*Populus tremula*) and Lime (*Tilia cordata*) spread at sites located in the inner archipelago. Along the shores and in bays, Alder (*Alnus*) and Willow (*Salix*) were common, while in sheltered positions on fine-grained Quaternary deposits a temperate- and nutrient demanding tree flora consisting of Elm (*Ulmus glabra*) and Hazel (*Corylus avellana*) was widespread.

Flat rocks and crevices close to the shore probably hosted a light demanding flora such as Common juniper (*Juniperus communis*), Heather (*Calluna vulgaris*) and Sheep's Sorrel (*Rumex acetosella*). A pioneer shrub found from the Mesolithic and onwards is Sea-buckthorn (*Hippophaë rhamnoides*), which is one of the typical shrubs along the Forsmark coast today. Sea-buckthorn is very sensitive to competition from other plants and needs to colonize un-weathered minerogenic deposits. These conditions are only found where new, un-weathered and uncolonised land areas emerge, i.e. where the shore displacement is faster than approximately 5 mm/year.

When the land areas grew and the islands became part of the main land, also the number of pollen taxa found in the sediments increased, reflecting that a more diverse flora was developed at the sites. An event that is often identified in pollen diagrams from north-western Europe is the decline of Elm-pollen at c 3000 BC, known as the Elm decline /Huntley and Birks 1983/. There are a number of suggested causes for the Elm decline; climatic changes, elm disease, human activity or a combination of these. In the pollen diagrams from Uppland, the Elm decline can be traced in more than 50% of the diagrams and is dated c 2500 BC /Karlsson 2007/.

To obtain information on the local vegetation history, there are only few investigations available. At the Hållnäs peninsula, c 35 km north of the Forsmark regional model area, biostratigraphical investigations were performed in connection with archaeological investigations /Ranheden 1989/. These investigations indicate traces of forest clearing from c 600–700 AD. Extensive land use and settlements from the Viking age and medieval period were identified in the fossil record, i.e. humans have been occupying the archipelago successively as new land emerges from the Baltic.

A pollen investigation of sediment collected in the Kallrigafjärden has been performed /Bergkvist et al. 2003/. The sampling site was located close to the outlet of the River Olandsån, thus the pollen record in the sediments will give a regional vegetation history. Norway spruce (*Picea abies*) is present in the bottom layer of the sediment, indicating that the whole sediment sequence was deposited after the immigration of spruce at c 0 AD/BC /Berglund et al. 1996a/. Heather and sea-buckthorn pollen reflect the vegetation at the shores. High values of lime pollen may indicate that this species was important for fodder production and therefore was favoured by humans /Bergkvist et al. 2003/. Other traces of humans are corn (*Hordeum* sp) from far down in the sediment, indicating cultivation within the area. There are no radiocarbon dates of the analysed sediments from Kallrigafjärden, thus no absolute ages are known.

6.3.2 Long-term development of lakes in the region

Ontogeny of oligotrophic hardwater lakes in the Forsmark area

All lakes existing in the Forsmark investigation area today (see Figure 6-5), as well as a number of previously small and shallow lakes which over time have been converted to wetlands due to the ontogenetic process, can be classified as oligotrophic hardwater lakes. Accordingly, they are characterised by high pH (pH 7–8), low phosphorous concentration (tot-P often lower than 0.015 mg/L), high concentrations of major ions and high electrical conductivity /Sonesten 2005/. This is a combined effect of the calcium-rich Quaternary deposits, the recent emergence from the Baltic Sea and the shallow lake depths, resulting in high primary production at the light-illuminated sediment surface and very low production in the water mass /Brunberg et al. 2002/. The high primary production at the sediment surface results in high benthic pH, which in turn causes benthic precipitation of $CaCO_3$ and co-precipitation of phosphorous. Much of the precipitated phosphorous is more or less permanently locked in the sediments by high pH and high O_2 concentration /Brunberg et al. 2002/.

/Brydsten 2006/ used the lake elevation today together with the shoreline equation model by /Påsse 2001/ and estimated the sedimentation rate to model the isolation time and the duration of the lake phase for the lakes in the Forsmark area. The oldest of the present-day lakes in the area emerged from the Baltic Sea around 1100 AD (Table 6-1), whereas the largest lake in the area, Lake Bolundsfjärden, and several of the small near-shore lakes in the area, are still affected by occasional intrusions of sea water (cf. section 4.1.1 in /Tröjbom et al. 2007/). Due to both chemical and biological processes in the lake water, the amount of nutrients available in the lakes is effectively reduced by co-precipitation together with calcium-rich particulate matter. Because of this, the phosphorous concentration in lakes and streams is generally low. The nitrogen concentration, on the other hand, tends to be high, or even very high, due to a combination of high input and low biotic utilisation /Brunberg and Blomqvist 1999, 2000/. These conditions, together with shallow lake depths, gives rise to the unique type of lakes in the Forsmark area, the oligotrophic hardwater lake.

As described above, all lakes can in the long-term be regarded temporary since they eventually will be filled-up and converted to either a wetland or drier land area. However, provided that the lake is deep enough, also the oligotrophic hardwater stage may be of a temporary nature.

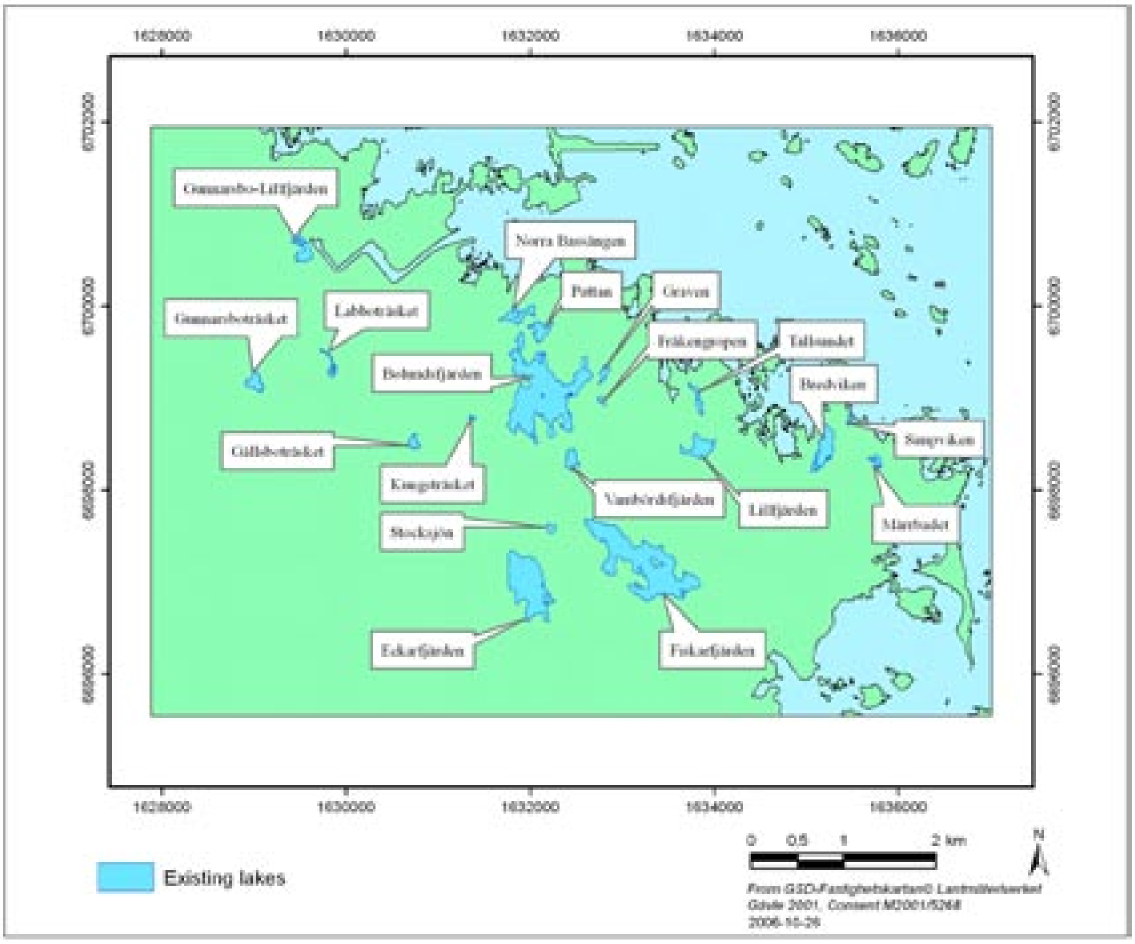


Figure 6-5. Existing lakes at the Forsmark site.

Table 6-1. Time for isolation from the Baltic Sea and estimated time at conversion to wetland for existing lakes in the Forsmark area (modified from Table 3-1 in /Brydsten 2006/). For identification of catchments and sub-catchments, see /Brunberg et al. 2004/.

Catchment	Sub-catchment	Lake	Lake isolation time (Year AD)	Time at conversion to wetland (Year AD)
Forsmark 1	1:3-4	Labboträsket	1400	2200
	1:1-4	Gunnarsbo-Lillfjärden	1700	2900
Forsmark 2	2:8	Gunnarsboträsket	1100	2900
	2:10	Eckarfjärden	1200	7100
	2:9-10	Stocksjön	1500	2400
	2:7	Kungsträsket	1600	2200
	2:8	Gällsboträsket	1700	2500
	2:5	Fräkengropen	1800	2200
	2:6	Vambördsfjärden	1800	3000
	2:4-5	Graven	1900	2500
	2:11	Puttan	1900	3200
	2:1-10	Norra Bassängen	1900	3400
	2:3-10	Bolundsfjärden	1900	7600
Forsmark 3	3:1	Tallsundet	2000	2600
Forsmark 4	4:2	Lillfjärden	2000	3700
Forsmark 5	5:1	Bredviken	2000	5900
Forsmark 6	6:1	Simpviken	2000	2200
Forsmark 7	7:2-4	Märrbadet	2000	2300
Forsmark 8	8:1	Fiskarfjärden	1900	7600

/Brunberg et al. 2002/ proposed that light conditions at the sediment surface may have a major influence on nutrient conditions in this type of lake. If the lake water during the ontogenetic process turns more brownish, reduced benthic photosynthesis may contribute to a change from an oligotrophic hardwater stage into a more eutrophic stage. Additionally, it is only the minerogenic Quaternary deposits, such as glacial till and glacial clay, and not the bedrock, that contain carbonates and coupled anions, and thus these sources will be depleted with time. The system will reach a point when the precipitation of $CaCO_3$ from the lake water will no longer take place. At that point, there will be no co-precipitation of important plant micronutrients (e.g. phosphorous) or essential trace elements (e.g. iron, manganese). Instead, these elements, and especially phosphorous, will contribute to the production of organisms in the lake system and there will be a rapid change towards eutrophic conditions. This change will, in turn, lead to increased amounts of sedimenting organic matter (i.e. increased filling), increased decomposition rates, at least until anoxic conditions are reached, and enhanced nutrient recycling /Brunberg and Blomqvist 2000/.

However, due to the shallow depths of both previous and present-day lakes in the Forsmark area, it is unlikely that they reached or will reach a stage of increasing eutrophication before they are completely filled with material. Instead, a likely ontogeny of the shallow hardwater lakes in Forsmark is growth of reed around the lakes and a succession towards a reed swamp, a fen and finally a bog ecosystem. This idea is supported by the fact that mires (fens) constitute a large part of the Forsmark area today (10–20% of the area in the three major catchments). It is also supported by the fact that the riparian zone of most existing oligotrophic hardwater lakes in the area is dominated by mires. Interestingly, this was also supported by a vascular plant inventory of different mire types /Göthberg and Wahlman 2006/, where the number of indicator species for bog increased with the height above sea level (section 4.1.1 in /Löfgren 2008/).

Ontogeny of brown-water lakes in the region

Today there are no brown-water lakes in the Forsmark area. However, investigations of lakes in the nearby catchment Forsmarksån /Brunberg and Blomqvist 2000, 2003/ showed that lakes in the vicinity of the Forsmark area may develop to brownwater lakes after passing through an oligotrophic hardwater stage, but may also form brownwater lakes directly after isolation. From an ontogenic point of view, the catchment of River Forsmarksån, and thereby also its lakes, may be divided into two parts with differing ontogeny; the area upstream and downstream, respectively, of the 13 m high waterfalls at Lövstabruk /Brunberg and Blomqvist 2000/.

Palaeoecological studies by Tord Ingemar et al. (referenced in /Brunberg and Blomqvist 1998/) show that the upstream Lake Vikasjön passed through an oligotrophic hardwater stage after its isolation from the Baltic Sea, a period when "cyanophycée-gyttja" was formed. This corresponds to the present situation in the oligotrophic hardwater lakes along the coast, e.g. Lake Eckarfjärden and Lake Bolundsfjärden in the regional model area. In Lake Vikasjön, this stage lasted for about 1,000 years, and was followed by a period of 1,000–2,000 years when the lake sub-basins successively were isolated from each other and partly grown over by mires. The sediments in the remaining lake basins then switched to "dy" sediments, i.e. lake sediments mainly consisting of humic compounds, transported to the lake from the terrestrial surroundings.

The lakes situated below the 13 m fall in Lövstabruk have a different history. Due to the substantial difference in the topography, they were isolated from the Baltic Sea at least 2,000–2,500 years later than the upstream lakes. At that time, the upstream lakes had passed the oligotrophic hardwater stage, and were already more or less brownwater systems. The inflowing water from the upstream areas to the newly formed lakes was thus brownish and less alkaline. This water from the main river constituted a major component of the inflowing water to the newly formed lake basins. The large flow of water dominated, and still dominates, the hydrology of the systems, thus diluting and washing out the contributions from the land areas in the close vicinity of the newly formed lakes. Consequently, no oligotrophic hardwater stage occurred in the chain of lakes situated along the main river below Lövstabruk. Instead, they developed to brownwater flow-through lakes more or less directly after isolation /Brunberg and Blomqvist 2000/.

Ontogeny of deep eutrophic lakes in the region

There are no deep eutrophic lakes in the Forsmark area today, but the deepest parts of Öresundsgrepen will in the future develop into a number of deep lakes which will differ considerably from the present-day lakes in the Forsmark area (/Kautsky 2001/, cf. Table 5-1). There are a few deeper lakes in the region, and the ontogeny of two deeper lakes in the vicinity of the Forsmark area, Lake Erken and Lake Limmaren, was assessed by /Brunberg and Blomqvist 2000/. Both of these lakes are relatively eutrophic today. In investigations of sediments from Lake Limmaren, /Brunberg et al. 2002/ found no signs of changing trophic status after isolation from the Baltic Sea, despite the fact that the lake surroundings, like the Forsmark lakes, have calcareous soils. It seems likely that neither Lake Erken nor Lake Limmaren have passed an oligotrophic hardwater stage, and the main reason is probably that, due to their larger depths, dark conditions prevail at the sediment surface. Thus, benthic photosynthesis is prevented and instead pelagic photosynthesis dominates /Brunberg et al. 2002/.

For Lake Erken, the accumulation of sediments in the deepest parts of the basin is maximally 1 m over the 2,500 years that have passed since the lake was isolated from the Baltic Sea. Assuming the same rate of sediment deposition, the accumulation of sediments during the next 10,000 years would be 4 m. The accumulation of sediments in other parts of the lake would be considerably less. Thus, even 10,000 years from now, Lake Erken will be a large and, for the region, relatively deep lake (maximum depth c 16 m).

The situation in Lake Limmaren is different. First, the sedimentation rate over the last 1,000 years has been considerably higher than that in Lake Erken, with an accumulation of some 1.4 m of sediment in the deepest part of the lake /Bergström 2001/. Secondly, Lake

Limmaren is much shallower than Lake Erken. Taken together, it seems reasonable to conclude that the Lake Limmaren basin will be completely filled with sediments in 5,000 to 10,000 years from now. A first transition to reed-marsh seems very likely, but whether this state will be a mire or a wetland forest (dominated by alders) is highly uncertain.

6.3.3 Long-term development of terrestrial areas

The Forsmark area is characterised by a high content of calcium-rich deposits, which is appearent in the field and bottom layer vegetation of most vegetation types /Jonsell and Jonsell 1995/. This also explains the high pH found in most wetlands. Most wetlands in the area lack the dominance of *Sphagnum* species in the bottom layer, and are instead dominated by brown mosses, e.g. *Scorpidium scorpioides*. Based on the wetland vegetation, /Göthberg and Wahlman 2006/ classified most of 19 investigated wetlands as rich to extremely rich fens, and this is typical for the region /Jonsell and Jonsell 1995/. There are also bogs in the area, mainly located in the inland, but these bogs seem to have had an earlier stage as rich fen. For example, /Fredriksson 2004/ found brown moss peat overlain by *Spaghnum* peat in the stratigraphy of wetlands that today are classified as Pine bogs. Consequently, in a longer time perspective rich fens seem to develop into a stage where *Spagnum* species dominate, even though some rich fen species seem to endure the more bog-like conditions /Göthberg and Wahlman 2006/. The whethering and leaching of carbonates will occur under all carbonate-rich vegetation types /Ingmar and Moreborg 1976/, leading to gradual change to a flora adapted to environments with a lower pH. Accordingly, there will be a zone of vegetation favoured by high pH along the coast, and this zone will continuosly move as new land areas emerge from the sea.

6.4 Ecosystem development at Laxemar-Simpevarp

The latest deglaciation in the Laxemar-Simpevarp area took place c 14,000 years ago, and the highest shoreline in the region is located c 100 m above the present sea level (cf. section 3.5.4). Thus, the whole Laxemar-Simpevarp regional model area is situated below the highest shoreline, since the highest point in the area is situated c 50 m above the present sea level. As described in section 3.5.4, the sea level dropped fast during the end of the Baltic Ice Lake, from c 66 meters above present sea level (m.a.s.l.) around 10,000 BC to less than 20 m.a.s.l. just over 1,000 years later. Accordingly, the first islands in the area emerged from the sea around 9400 BC.

The Yoldia Sea stage (9500–8800 BC) was characterised by regressive shoreline displacement, whereas the onset of the Ancylus Lake stage around 8700 BC was characterised by a transgression with total amplitude of c 11 m. Figure 3-25 shows the former shoreline in the Laxemar-Simpevarp regional model area at three different occasions during the Holocene. At around 8000 BC, i.e. in the middle of the lacustrine Ancylus Lake stage, the shoreline was situated just over 20 m.a.s.l., which means that the western part of the Laxemar-Simpevarp regional model area was free of water. Between 8000 BC and 5000 BC, i.e. the first part of the Littorina Sea stage, the shoreline displacement was mostly regressive, although there are indications of several minor transgressions during that period (cf. section 3.5). At 5000 BC, when the shoreline was situated c 15 m.a.s.l., the central parts of the regional model area were free of water, but the fissure valleys still constituted long and narrow coastal bays which intersected the area. At 2000 BC, most of today's terrestrial areas had emerged from the sea and the coastal bays had been considerably reduced in size. Since 0 BC, the sea level has dropped c 3 m, but this has resulted in only minor changes in the distribution of land and sea in the regional model area.

Similarly to the Forsmark area, the post-glacial development of ecosystems in the Laxemar-Simpevarp area is principally determined by the climate, the development of the Baltic basin and the shoreline displacement, as described above and in Chapter 3. The first terrestrial ecosystems appeared around 9000 BC, and the succession of both the terrestrial and aquatic ecosystems has in all essentials followed the general patterns outlined above. Site-specific information that can be added to the general successional trajectories is the regional vegetation development, the local and regional lake ontogeny and the development of areas used as arable land.

6.4.1 Regional vegetation development

Stratigraphical investigations of pollen from Blekinge show the succession of terrestrial plants in south-eastern Sweden from the latest deglaciation to the present /Berglund 1966/. Shortly after the Laxemar-Simpevarp area was deglaciated c 12,000 BC, it was characterised by tundra vegetation dominated by herbs and bushes and a low coverage of trees. During the following Alleröd chronozone (cf. Figure 3-1) a sparse Birch and Scots pine forest dominated the vegetation. In southern Sweden, the following cold Younger Dryas chronozone was characterised by tundra vegetation, which is reflected in a high proportion of Wormwood (*Artemisia*) pollen. In stratigraphical studies in the Laxemar-Simpevarp area, /Lagerbäck et al. 2004b/ found evidence of tundra conditions during the Younger Dryas.

At the beginning of the Holocene c 9500 years BC, the temperature increased and south-eastern Sweden was first covered by forests dominated by Birch and later by forests dominated by Scots Pine and Hazel. During the period 7000–4000 years BC, forests consisting of Lime, Oak and Elm covered south-eastern Sweden /e.g. Berglund 1966, Küttel 1985/. The spread and establishment of Beech (*Fagus sylvatica*) and Norway Spruce in southern Sweden has been investigated in several studies /Björkman 1996, Bradshaw and Lindbladh 2005/. The Norway spruce spread from the north and reached the Laxemar-Simpevarp area less than 1,000 years ago /Lindbladh 2004/. It is possible that domestic animals were involved in the spread of spruce, since grazing animals avoid spruce /Björkman 1996/. Beech has spread over southern Sweden during the last 4,000 years. The species was common in eastern Småland two thousand years ago, but has later disappeared from that area /Bradshaw and Lindbladh 2005/. The decline of Beech was probably caused by human activities.

A pollen investigation, covering the last c 1,500 years, has been carried out on sediments from two lakes situated 20 and 25 kilometres west of Fårbo (Aronsson and Persson, Dept of Quaternary Geology, Lund University, unpublished data). The results show an increase of Juniper and Corn (*Cerealea*) c 800 years AD, which indicates that areas used for pasture and as arable land increased at that time.

6.4.2 Long-term development of lakes in the region

Only five lakes are situated completely within the Laxemar-Simpevarp regional model area today. All of these lakes are relatively small, shallow, and characterised by more or less dystrophic conditions /cf. Tröjbom and Söderbäck 2006/. The ontogeny of these lakes has not been examined explicitly, but there are no reasons to suggest any major differences from the general ontogeny of dystrophic lakes outlined in section 6.2.5 above. The higher located lakes, e.g. Lake Jämsen and Lake Plittorpsgöl, were isolated from the Yoldia Sea stage of the Baltic early during the Holocene. According to the shoreline displacement model /Påsse 2001/, both these lakes may after a first isolation around year 9000 BC have been affected by the Ancylus transgression c 8500 BC, and then isolated again around 8200 BC (cf. Figure 3-24). The near-shore Lake Frisksjön is today situated at 1.3 m.a.s.l., indicating that the lake was isolated from the Baltic around 1200 AD. However, the lake threshold has been lowered by man during the last few centuries, and the lowering may be 1 m, or even more. This means that Lake Frisksjön was isolated from the Baltic Sea much earlier, possibly already before year 0 BC/AD. Moreover, there is at least one previously shallow lake in the area (Gäster) which has been totally drained during the last few centuries in order to gain new agriculture land (Appendix 1 in /Nyborg et al. 2004/).

The considerably larger and deeper Lake Götemar (surface area 3.0 km^2, max depth 18 m) is situated just north of, and partly within, the regional model area, at 1 m altitude above the present sea level. According to the shoreline displacement model /Påsse 2001/ it was isolated from the Baltic Sea around year 1200 AD. Lake Götemar is characterised by oligotrophic, clear-water conditions /cf. Tröjbom and Söderbäck 2006/. There are no investigations on sediment accumulation from Lake Götemar, but considering the relative nutrient-poor conditions and large depth it seems reasonable to suggest that the lake will remain large and deep for many millenia from now (cf. Lake Erken in the Forsmark region, section 6.3.2). The today relatively deep coastal basins north of Äspö (Granholmsfjärden and Kalvholmsfjärden) are expected to be isolated from the sea around 4000 AD (cf. section 4.1.6 in /SKB 2006a/). When they in the future develop into freshwater lakes, they will probably be more similar to the oligotrophic clear-water Lake Götemar than to the small dystrophic lakes in the area.

6.4.3 Long-term development of terrestrial areas

The agricultural land in Laxemar-Simpevarp today is characterised by clay-silt as the dominant Quaternary deposit, closely followed by clayey gyttja (and gyttja clay). However, the clay-silt category includes clay gyttja, gyttja clay and clay, because of differences in the classification between different parts of the area. The clay originates from the earlier stages of the Baltic Sea and has low organic content, whereas clay gyttja and gyttja clay originate from more recent sea bay or lake phases, in which organic matter was deposited as sediment. Sohlenius (cf. section 3.3.5 in /Lindborg 2006/) showed that present areas covered with gyttja clay coincide with areas once being sheltered bays. Gyttja as a dominant Quaternary deposit in agriculture land is scarce in this area, which suggests that the present agriculture areas seldom developed from a longer lake phase with organic sediment deposition.

A large part of today's agricultural land is characterised by a peat layer which was built up during a previous wetland phase. The peat layer is often thin, suggesting either a fast succession where the wetland stage was rather short, or else that the peat has been oxidised during a long period of cultivation. Due to different mapping techniques, the peat classification has not been uniform. In areas where detailed mapping has been performed, the more nutrient-rich fen peat and nutrient-poor bog peat were separated /Rudmark et al. 2005/. In these areas, all agricultural land which was situated on peat soils was located on fen peat and not on bog peat (cf. Figure 7-6). In the western part of the area, peat was mapped as unclassified peat. However, the peat type associated with arable land is probably fen peat also in this area. Another category of agricultural land with regard to Quaternary deposits is characterised by more coarse-grained non-organic materials and was deposited during the sea phase, such as wave-washed sand, gravel and till.

6.5 Summary

Long-term ecosystem development in near-coastal areas of Fennoscandia is driven mainly by two different factors; climate change and shoreline displacement. In addition, human activities have also strongly influenced the development of both terrestrial and aquatic ecosystems, especially during the last few millennia.

Shortly after the latest ice retreat, which started in southernmost Sweden c 15,000 BC, the landscape was free of vegetation and can be characterised as polar desert. Relatively soon after the deglaciation, the ice-free areas were colonised and in southern Sweden the landscape was covered by a sparse Birch forest. Thereafter, the climate has oscillated between colder and warmer periods. During the cold period called the Younger Dryas (c 11,000–9500 BC), large areas of the deglaciated parts of Sweden were again affected by permafrost and much of the previously established flora and fauna disappeared. From the onset of the Holocene (c 9500 BC) and thereafter, southern Sweden has been more or less covered by forests, although the species composition has varied due to climatic changes. Most of the present mammal fauna was established in southern Sweden during the early Holocene. During the last few thousand years, the composition of the vegetation has changed not only to due to climatic changes, but also due to human activities which have decreased the areas covered by forest. In southern Sweden, the introduction of agriculture and the subsequent opening of the landscape started c 3000 BC.

In coastal areas like Forsmark and Laxemar-Simpevarp, shoreline displacement has strongly affected ecosystem development and still causes continuing changes in the abiotic environment. Both areas are situated below the highest coastline, and, when the latest deglaciation took place, Forsmark was covered by 150 m and Laxemar-Simpevarp by 50–100 m of water. The first parts of the Laxemar-Simpevarp area emerged from the sea around year 9400 BC, and the corresponding time for Forsmark is c 500 BC. Thus, the post-glacial development, especially for Forsmark, is determined mainly by the development of the Baltic basin and by the shoreline displacement.

As a result of an overall regressive shoreline displacement, the sea bottom is uplifted and transformed into new terrestrial areas or to freshwater lakes. The starting conditions for ecosystem succession from the original near-shore sea bottom are strongly dependent on the topographical conditions. Sheltered bays accumulate organic and fine-grained inorganic material, whereas the finer fractions are washed out from more wave-exposed shorelines with a large fetch. During the process of shoreline displacement, a sea bay may either be isolated from the sea at an early stage, and thereafter gradually turn into a lake as the water becomes fresh, or it may remain as a bay until shoreline displacement turns it into a wetland.

After isolation from the sea, the lake ecosystem gradually matures in an ontogenetic process which includes subsequent sedimentation and deposition of substances originating from the surrounding catchment or produced within the lake. Hence, the long-term ultimate fate for all lakes is an inevitable fill-up and conversion to either a wetland or a drier land area, the final result depending on local hydrological and climatic conditions. In Forsmark, all present-day lakes have developed into oligotrophic hardwater lakes, characteristic for the area, whereas most lakes in the Laxemar-Simpevarp area follow another ontogenetic trajectory and show dystrophic (brownwater) conditions.

Mires are formed basically through three different processes; terrestrialisation, paludification and primary mire formation. Terrestrialisation is the filling-in of shallow lakes by sedimentation and establishment of vegetation. Paludification, which is the predominant way of mire formation in Sweden, is an ongoing water logging of more or less water-permeable soils, mainly by expanding mires. Primary mire formation is when peat is developed directly on fresh soils after emergence from water or ice. All three types of processes are likely to occur in the Forsmark and the Laxemar-Simpevarp areas, but peatland filling in lakes (terrestrialisation) is probably the most common type of peatland development in the investigation areas. The richer types of mires which are typical of the Forsmark area will undergo a natural long-term acidification when turning into more bog-like mires. Historically, mires have often been drained for forestry or to gain new agricultural areas, and in Sweden such activities peaked in the 1930s. In the Laxemar-Simpevarp area, a large part of today's agricultural land is characterised by a peat layer which was built up during a previous wetland phase.

7 Human population and land use

7.1 Human colonization of Scandinavia after the latest deglaciation

When the latest glaciation reached its maximum extent about 18,000 years BC, the ice cap covered Northern Europe. Any traces of humans in Scandinavia before this time, would in most cases have been erased by the ice. However, human remains that potentially may be older than the last glacial maximum have been found in a cave in Finland /Schulz 1998/. More than 13,000 years BC, the southernmost parts of Sweden were free of ice (cf. section 3.3.3), which gave the fauna and flora an opportunity to spread further north. The humans that were settled south of the ice cap in the present northern Germany moved north while hunting reindeer, which was the most important game at the time /Forsberg and Larsson 1994/.

The oldest known ancient remains of humans in Sweden are approximately 11,500 years old. The remains were discovered near Lake Finjasjön in the north of Skåne, and tools that were found looked like tools found in Germany. At that time, the sea surface was much lower than today and there was a land connection between Sweden, Denmark and Great Britain. This is one possible explanation of why the tools were similar over the whole of continental Northern Europe /Forsberg and Larsson 1994/.

With time, more land areas became free of ice, but the climate varied during the almost 3,000 year long deglaciation period. Approximately 11,000 years ago, the traces of human activities are scattered up to the south border of the southern Swedish highland and along the west coast. The settlements were camps with tents, where small groups of family size lived for shorter periods. Since the shoreline in southern Sweden was lower than today, there is no knowledge about any settlements in the coastal area, but fishing and hunting along the coast was likely of great importance /Forsberg and Larsson 1994/.

Around 7000 BC, after a period of temperature increase, the final ice cap disappeared from the north of Sweden (cf. Chapter 4). However, the traces of humans are scarce. What today is higher terrain was at that time smaller islands or land stripes, and on these, coast-settlements were established /Forsberg and Larsson 1994/. The coast zone is considered to have been very productive during this period, and the pre-historic settlement pattern indicates that the settlements were close to the shore /Åkerlund 1996/. Over time, the settlements likely followed the moving shoreline.

7.1.1 Prehistorical settlements and development

Human social systems and their development show an interplay with the surrounding physical settings of nature. The historical development of the human settlements can generally be described in six stages; the Older Stone Age, the Younger Stone Age, the Bronze Age, the Iron Age, the medieval period and the modern period /Hyenstrand 1994/ (Table 7-1).

The history of human settlement in Sweden covers more than 10,000 years. During the period following the deglaciation, the Older Stone Age (9000–4000 BC), the weather was favourable and the land was covered with deciduous forests. All parts of Scandinavia, from the south up to the northern parts, were exploited by humans during this period, mainly by hunting, fishing and gathering /Hyenstrand 1994/.

During the Younger Stone Age (4000–1800 BC), the settlements and the way of living started to differentiate between different parts of Sweden. In the southern parts, humans started to cultivate land and raise livestock /Hyenstrand 1994/. This was a new way of living that had spread from the Nile Valley /Stenberger 1964/, which gradually caused a more open landscape.

Table 7-1. Timing of prehistoric and historic periods /Lundqvist 2006/ and corresponding sea levels at Forsmark and Laxemar-Simpevarp. The sea level is estimated from the shoreline displacement model by /Påsse 2001/. The unit m.a.s.l. (metres above sea level) refers to the present sea level. Note that the Forsmark regional model area was situated below the sea level until c 500 BC.

Period	Start	End	Forsmark (m.a.s.l.)	Laxemar-Simpevarp (m.a.s.l.)
Older Stone Age (Mesolithic)	9000 BC	4000 BC	148–49	28–12
Younger Stone Age (Neolithic)	4000 BC	1800 BC	49–28	12–6
Bronze Age	1800 BC	300 BC	28–15	6–3
Older Iron Age	300 BC	400 AD	15–10	3–2.2
Younger Iron Age	400 AD	1100 AD	10–5.3	2.2–1.2
Old Middle Ages	1100 AD	1200 AD	5.3–4.7	1.2–1.0
High Middle Ages	1200 AD	1400 AD	4.7–3.4	1.0–0.8
Late Middle Ages	1400 AD	1530 AD	3.4–2.6	0.8–0.6

The first differentiated social groupings occurred. This was manifested by the construction of monumental graves in southern and western Sweden /Hyenstrand 1994/.

Livestock-raising and cultivation became even more common during the Bronze Age (1800–300 BC). The grave piles in the open landscape in Skåne and Halland, and cairns in the inner parts of Götaland, the middle of Sweden and along the coastline, show the expansion of agriculture. Extensive clearance of land took place, mainly in the inner parts of southern Sweden, for agricultural purposes. However, along the coastline, resources from the sea still had a great impact on the way of living /Hyenstrand 1994/.

The Iron Age (300 BC–1100 AD) was an intense agricultural period with livestock keeping, gathering of winter fodder, and development of the use of fertilizers. Many settlements became permanent during this period, and the settlers started to protect their crops and meadows from the grazing livestock with stone fences. An administrative organisation of the land took place, at the beginning as chief-quarters (Sw. *hövdingadömen*), later on as hundreds (Sw. *härader*). In the surroundings of Lake Mälaren, there was an increase in population and settlements during the Younger Iron Age. The significance of trading increased and trading centres were localized at places with advantageous geographic positions. As a consequence, population centres appeared at the end of this period /Hyenstrand 1994/.

The first towns were founded during the medieval period. Churches were constructed as a result of the christianization that took place in Sweden during this period. Parishes were founded at the same rate as the colonization of the land took place. The mining areas were colonized and the mining industry became organized at the beginning of the period. In the previous marginal areas, agrarian colonisation took place during the Early Middle Ages. In some areas agricultural estates developed, gradually with large-scale farming /Hyenstrand 1994/.

7.1.2 Historical settlements and development

Crofts and crofters were not very numerous in Sweden during the 16th century, but during the following centuries the number of crofters increased enormously. The crofters provided working force for the farms up until the 20th century, and crofters were also involved in industrial production and worked in the forests, e.g. by making charcoal and by providing transport /Berg et al. 2006/.

Before urbanisation and the land reforms in the 20th century, the majority of the settlements in Sweden consisted of small villages or hamlets. In many of the forested regions, which comprise most of Sweden, single farms dispersed in the landscape was the most common way of living during the late medieval and early modern period. In some parts of Sweden there were villages with more than eight to ten farms. This was true for Skåne in southern Sweden, for parts of Västergötland and along the rivers in northern Sweden /Berg et al. 2006/.

The agriculture became gradually more modernised, partly as an effect of land reforms, and the traditional village communities dispersed during the modern period (1750–1950). Moreover, the cultural landscapes as well as the settlements were both strongly affected by extensive land reclamation. There was a demand for increased food production since the population had grown. This resulted in extensive ditching of wetlands and lowering of lake surfaces which considerably changed the landscape. The towns started to expand due to increased industrialization. Also the ironworks expanded, as well as their surrounding communities. When the supply of wood declined, forestry developed. In 1950, only one fifth of the Swedish population lived in the countryside. All these changes affected the landscape, which went from a varied landscape towards monoculture and large-scale cultivation /Hyenstrand 1994/.

Around the 1850s there was a surplus of workers in Sweden and generally hard times with severe suffering. Many people chose to emigrate. During the late 19th century, Sweden lost between 20–25% of its inhabitants. About 1.1 million people emigrated in the period between 1850 and the beginning of the Great War /Hofsten 1986/ (Figure 7-1). The emigration rate varied from region to region, but generally the forested areas in southern and western Sweden, including the investigated region of Laxemar-Simpevarp, accounted for a substantial part of the emigration. After the 1920s, the emigration from Sweden slowed down and around 1930 there was an immigration trend instead /Berg et al. 2006/.

Figure 7-1. Rates of emigration and immigration for Sweden in 5-year intervals during the period 1851–1985 /Hofsten 1986/.

7.1.3 Historical land use

Before the Younger Stone Age, the impact of human activities on the natural landscape was small. As described above, almost all parts of Scandinavia were exploited during the Older Stone Age, but human activities were restricted to hunting, fishing and gathering. At around 4000 years BC, the knowledge of how to cultivate soils and keep livestock spread over Scandinavia, and this resulted successively in a change from a nomadic lifestyle to more permanent settlements. With this change, the transformation of the natural landscape to an agricultural landscape started, especially in the southern parts of Scandinavia /Andreasson 2006/.

During the first phase of the Younger Stone Age, the dense forests were cleared, often by the use of fire, and the open areas created were first cultivated for some years and than used as grazing land. When the available soil nutrients were consumed, the area was left and became overgrown. After 30–40 years it was possible to clear and use the area again. The extensive farming, in combination with a growing population, means that large areas were made use of. Within c 1,000 years, human land use had brought about large changes of the landscape in southern Sweden.

The opening of the landscape continued during the Bronze Age. In southern Sweden also the forests were used as grazing land, and they were thereby kept more open than before. Until the end of the Bronze Age, stock keeping was the base of the economy, but from the beginning of the Iron Age around year 0 BC, agriculture increased in importance and became gradually more important than stock keeping /Andreasson 2006/. The land surrounding the villages was divided into inland and outlying land. Generally, the inland was individually owned and was cultivated, lay in fallow, and was used for haymaking or pasture, whereas the commonly owned outlying land was used as grazing land and for collecting winter fodder. A static, but well functioning, rustic society developed and remained until it was abruptly broken down by the land reforms in the early 19th century. After the land reforms, individual landowners could develop their own land by land reclamation, ditching, forest clearance and later also by afforestation. The open landscape showed its largest extension in the late 18th century. Thereafter, afforestation together with reduced utilisation of less valuable land has resulted in considerably reduced open areas in the landscape /Andreasson 2006/.

Historically, wetland areas were often seen as trouble areas that contained too much water to serve as good agricultural or forestry land, and that some bred mosquitoes and disease. Swampy pits", "mosquito hells and "water sick areas" are all names to describe wetlands. In Sweden, from the end of the 19th century until the middle of the 20th century wetlands were mainly considered land of no use. Little was then known of the important ecological services that wetlands provide, and large efforts were made to dry out wetlands in order to use the land for agriculture to feed the growing population and for forest industry. Draining was accomplished by digging ditches and lowering lake levels to result in new agricultural land. In some areas in the south of Sweden as much as 90% of the wetlands have been drained /Svanberg and Vilborg 2001/.

Mires can be drained for forestry and such activities peaked in the 1930s in Sweden /Eliasson 1992/. Mires have also been used for haymaking and, in this context the rich fens were more important than the poor fens. Haymaking slows down or stops the succession of the rich fen, resulting in poorer fen-like stages due to the inhibition of peat formation. Mires have also been used for agricultural purposes and such use was, during the 1850s and subsequently, often preceded by ditching activities to ensure the best possible conditions for the crops cultivated. This resulted in lowering of the water table, inducing a switch from anaerobic to aerobic conditions, and initiating decomposition and erosion of peat-dominated soil.

Peat cutting has a long tradition in Sweden. Peat was often used as soil improvement material, as bedding in animal barns, and, during difficult times, for heat production /Svanberg and Vilborg 2001/. Peat cutting for energy production in Sweden ended during the 1960s but was taken up again in the 1980s.

7.1.4 Sources of site specific historical information

The knowledge of the prehistoric epochs (Stone-, Bronze- and Iron Ages) in the Laxemar-Simpevarp region is to a great extent based on the results from two inventories of ancient monuments, performed at the end of the 1970s /Berg et al. 2006/. Since most parts of the Forsmark area were covered by sea water during the Stone and Bronze Ages, no prehistoric remains are to be found there. The information about the later historical settlements in the two regions are drawn from a variety of sources: cadastral books, tithe registers on harvests (Sw. *tiondelängder*), livestock registers (Sw. *boskapslängder*), and other written documentation /Berg et al. 2006/. For reconstruction of the development of populations in the Forsmark and Laxemar regions over time, the main source is /Tabellverket 2007, www/.

7.2 Forsmark region

The *Forsmark region* refers in this chapter to six parishes in the surroundings of Forsmark, together covering approximately 1,000 km², which were investigated by /Berg et al. 2006/ (Figure 7-2). The Forsmark region should not be confused with the *Forsmark regional model area*, which is the area used in the SKB site modelling (see section 1.4, Figure 1-2).

7.2.1 Prehistoric settlements in the Forsmark region

The major part of the Forsmark region is today situated below 10 metres above sea level. In the inland parts, there are a few places situated more than 20 metres above the present sea level. Around year 1000 AD the sea level was approximately six metres above the present level, and during the Older Iron Age it was approximately 10–15 metres higher than today (cf. Figure 3-15, Table 7-1). Even further back in time there were only smaller islands, islets and skerries in the region, which means that there are no prehistoric remains from the Stone and Bronze Ages to be found in the region /Bondesson 2006/.

***Figure 7-2.** The area investigated for human population and land use in the Forsmark region, including six parishes which together cover c 1,000 km² /Berg et al. 2006/.*

In the register of prehistoric remains made by the National Heritage Board (Sw. *Riksantikvarie-ämbetet*), there are about 30 places with one or several prehistoric- or cultural remains registered in the investigated region. The oldest remains are graves from the Iron Age, today situated 10–15 metres above sea level, but when built they were situated at the coastline. An area with clearance cairns after agricultural activities might well be from the Iron Age, which is indicated by its location by a group of graves /RAÄ 2007, www/. However, it has to be remembered that there are many gaps in the knowledge of the prehistory in the investigated region. /Landin and Rönnby 2002/ assumed that there might have been settlements in the higher terrain, not yet discovered, in the investigated area. Further inland, extensive archaeological excavations during to the construction of a new highway (E4) in Uppland have revealed many new settlements /Syse 2005/, which supports the statement made by /Landin and Rönnby 2002/.

On the Hållnäs peninsula, permanent settlements were established during the early part of the Younger Iron Age /Welinder 1974/, and there are indications that a wave of colonization took place within the area during the 9th century (/Ranheden 1989/ and references therein).

7.2.2 Historical settlements in the Forsmark region

The Medieval period

The tax register from 1312 includes the parishes of Hållnäs, Valö and Österlövsta. It is unique in its kind, and it makes it possible to evaluate settlement changes in the Forsmark region between 1312 and 1550 /Berg et al. 2006/. It is uncertain whether the 1312 tax register really mentions all settlement units in the parishes at this time; farms belonging to the church and the nobility were probably not included /Dahlbäck et al. 1972/. At around 1550, the majority of the farms belonged to freeholders, and only a few farms belonged to the church or the nobility. Between 1312 and 1550 there seems to have been a substantial decrease in the number of settlement units in the region /Berg et al. 2006/. However, at the same time as the number of taxpaying settlement units decreased, the number of settlement names in the area increased. This can probably be explained by the emancipation of the settlement units that had been colonised during the Older Middle Ages /Dahlbäck 1974, Windelhed 1995/. These units were built in the forest of the existing settlement units and were recorded under the names of the existing units in 1312. In the mid-16th century the colonised units were emancipated and were recorded under their own names in the land registers.

Later on a population decline, probably as an effect of the recurrent plague epidemics after 1349, caused a decrease in the number of farms. In a regional perspective, the abandonment of farms was probably most pronounced in marginal areas and in areas characterised by early medieval colonisation /Gissel 1981/. According to the figures in Table 7-2, the population decrease in the Forsmark region suggests that at least one third of the farms in the area were abandoned in the Later Middle Ages /Berg et al. 2006/.

The early modern period until today

Similarly to other parts of Sweden, the number of crofters in the Forsmark region increased between 1750 and 1850, which is confirmed by the cadastral books. In Uppland there was a general increase in crofter's holdings during the 18th and 19th centuries. However, this increase was rather modest in the Forsmark region /Berg et al. 2006/.

The towns

The port town of Östhammar was founded in 1368. The harbour in Östhammar soon became too shallow, due to land rise in the region. In 1491, the town Öregrund was established, but the town was burned down by the Danes in 1509 and many townspeople moved back to Östhammar. Öregrund was given new town privileges in 1554. In the 17th century, the harbour in Öregrund carried most of the transportation of iron from the ironworks in Uppland to Stockholm. The major source of livelihood for the people in Öregrund was, however, the sea /Sandelin 1992/.

Table 7-2. Estimated population in three parishes in the Forsmark region (from /Berg et al. 2006/, cf. Table 7-1).

Village	Estimated population 1312	Approximated population 1571	Population 1620
Österlövsta	996–1,328	604	953
Hållnäs	810–1,080	513	628
Valö	732–976	264	455

Landed estates

Around the end of the 16th century and the beginning of the 17th century, a landed estate was created around the Forsmark ironworks. The crown owned both the estate and the ironworks until 1624 and thereafter it was left in private hands /Almquist 1931/. The Forsmark ironworks was built on the site of the former village of Bolunda /Dahlbäck et al. 1972/. At the end of the 17th century, the whole area north of the Forsmark ironworks, including several farms, belonged to the Forsmark estate /Berg et al. 2006/.

7.2.3 Development of human population in the Forsmark region

Population change

Population growth in the Forsmark region from the Later Middle Ages to the beginning of the 20th century was significant, especially between the 18th and 19th century. The figures in Table 7-3 show that there were two periods of intensive population growth. The first period was between 1620 and 1699, and the second period was between 1800 and 1850. In the second half of the 20th century (1952–1990), there has been a negative population trend in the area. Since there are no comprehensive sources on the Swedish population size before c 1750, the early figures in Table 7-3 must be regarded as approximations. A possible explanation for the drastic population increase between 1571 and 1750 is that the population was underestimated at the beginning of the period /Berg et al. 2006/.

Household population size

During the 19th century, there was an increase in the number of crofter's holdings and other new establishments in the Forsmark region, as well as an increase in population size. However, the average household size in the region decreased from almost 10 persons per household in 1751–62 to c 6 persons per household in 1891–95 /Berg et al. 2006/.

Table 7-3. Estimated population density in the investigated region of Forsmark for some years between 1571 and 1990 (modified from Table 9-1 in /Berg et al. 2006/).

Year	Inhabitants per km^2
1571	2.9
1620	3.8
1699	8.8
1750	10.5
1800	11.4
1850	14.3
1900	15.9
1990	10.3

7.2.4 Historical land use

The landscape in the Forsmark region

The landscape in the Forsmark region is characterised by its flat terrain. The more elevated parts are characterised by bare rocks or wave-washed till. The cultivable land is situated in the lower parts of the terrain, often in small irregular pockets in the surrounding boulder-rich land. This means that the arable fields are generally small, with irregular geometric forms. It is only on Storskäret in the candidate area, in the area around the central part of Valö, and in the immediate proximity of the Forsmark ironworks that there are larger open areas dominated by arable land. Until the middle of the 19th century there were large wetland areas in the woodlands. Many of these were later drained and cultivated. Some of them are still cultivated today, whereas others are deserted or even have turned into woodlands /Berg et al. 2006/.

The flat landscape in the Forsmark region in combination with the fast land uplift caused dramatic effects in the form of shoreline displacement, which in turn affected the settlement structure and land use /Berg et al. 2006/. The land uplift facilitated the colonisation of former wetlands and woodlands, which contributed to sustentaning an increasing population /Dahlbäck 1974/. Moreover, the shoreline displacement led to dramatic effects on the economy, which in turn led to changes in the landscape /Broberg 1990/. Farms, that in the Older Iron Age were situated on the coast and had drawn a large part of their incomes from the sea, had just some hundred years later lost the contact with the sea. This, in turn, forced farms to change from an economy based on incomes from the sea to an economy based on agriculture. The major part of the newly elevated land was initially wetland and therefore not suitable for agriculture. This, combined with an increasing population and the establishment of new settlements on the new land, caused a crisis in the region during the 13th and 14th centuries. This crisis is apparent in archaeological material, which shows that the health of people who died during this period was poor in comparison with earlier periods /Broberg 1990/.

Land use over time

The extent of arable land in the region increased continuously from the colonisation of the area until around 1950. From the beginning of the 18th century and onwards, much of this new agricultural land was gained from ditching of wetlands. Between 1709 and 1829, the proportion of arable land and meadows in Valö increased and the proportion of wetland and water decreased (see Table 7-4).

To increase the amount of hay that was fed to the farm animals, small farms and individual families carried out hay-making with the reeds and grasses on wetland areas. These areas were often distant and hard to reach and were thus mainly used by poor families that needed to feed their animals. Until the middle of the 19th century there were large wetland areas in the woodlands. These areas were subsequently drained and then cultivated as arable land. Some of these areas are still cultivated, whereas others are now deserted and, in some cases, have been turned into woodlands.

Table 7-4. The area extent of arable land in the mapped areas in Valö in square metres at 1709 and 1829. Note that the older map covers a larger area (modified from Table 12-3 in /Berg et al. 2006/.

	1709		1829	
Arable	891,000	(2%)	1,400,000	(5%)
Meadow	5,920,000	(14%)	8,031,000	(27%)
Wetlands	5,232,000	(13%)	990,000	(3%)
Water	1,652,000	(4%)	51,000	(0.2%)
Total	41,388,000		29,489,000	

From the early 1900s until the 1950s, most of the arable land in the Forsmark region was unchanged (/Berg et al. 2006/, cf. section 12.2). Some of the fields, comprising about 26 million square metres (which correspond to c 18% of the total amount of arable land) were abandoned. However, during the same period almost 65 million new square metres of arable fields were created. The total amount of arable land in the Forsmark region in 1950 was 148 million square meters. Similar to the general pattern in Sweden, a significant part of the former open land has been abandoned during recent decades. Figure 7-3 shows changes in the areal extent of arable land in the Forsmark area between 1950 and 1998. The reduction in the area covered by meadows during the period was probably even larger (cf. /Berg et al. 2006/, section 12.1).

The Forsmark ironworks, land and settlements

A typical feature in the northern part of Uppland is the ironworks. Many of the ironworks were founded during the 16th and 17th centuries, and a large number remained in operation until the beginning of the 20th century. Two ironworks were located in the investigated area; Valö and Forsmark /Berg et al. 2006/.

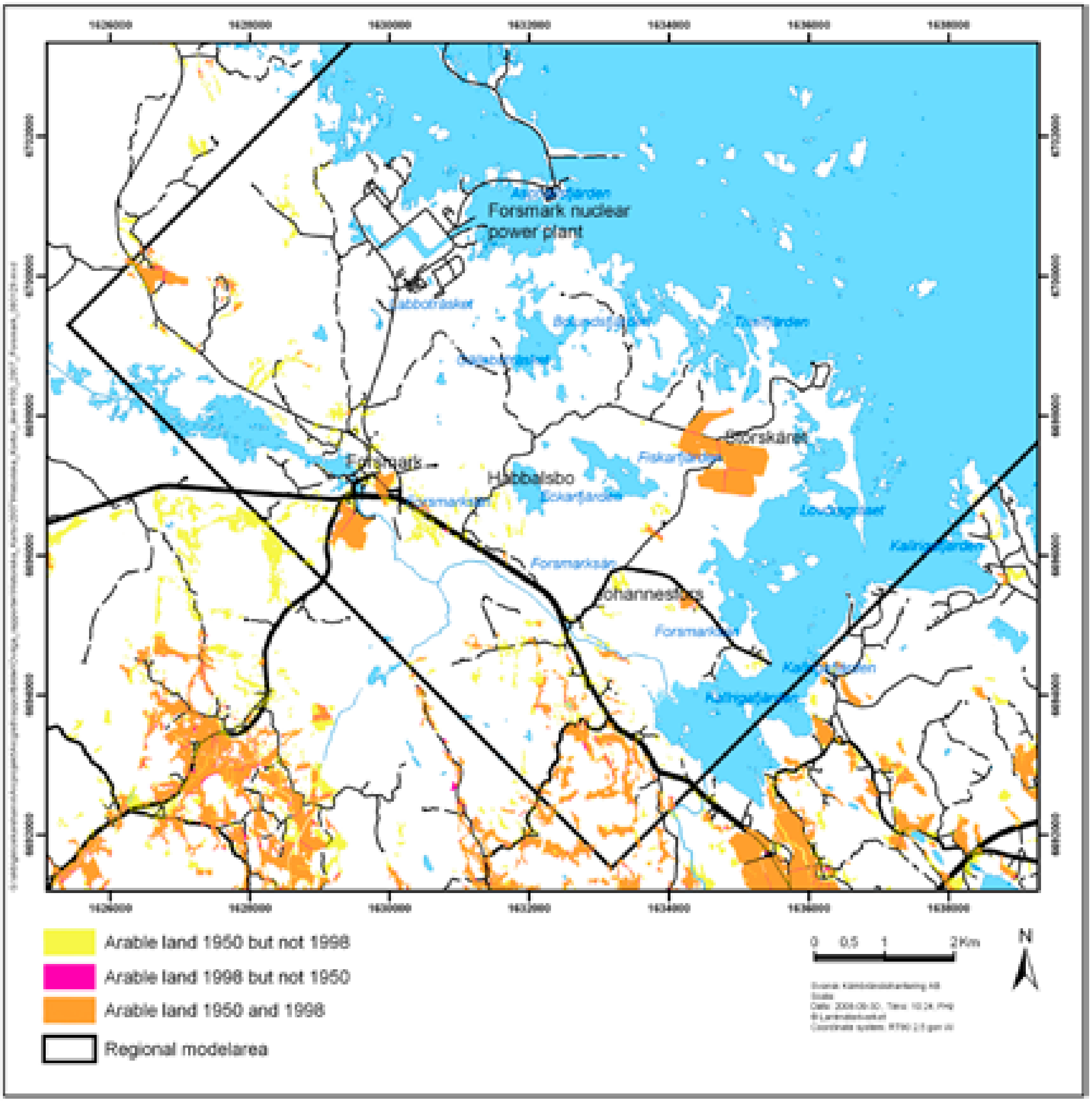


Figure 7-3. *Areal exent of arable land in the Forsmark area at 1950 and 1998 (the map is based on information from the Economic Map (1950) and the Property Map (1998)).*

The name Forsmark was mentioned in a written source for the first time in 1558. At that time Forsmark was a fishery in a lake at Simundö, situated immediately south of the later Forsmark ironworks. The ironworks was probably founded around 1583. At the beginning, Forsmark ironworks was owned by the crown, but in 1624 it was leased to a privately owned company /Berg et al. 2006/. Storskäret, situated to the east of Forsmark, was purchased by the Forsmark ironworks in the 1640s from the village of Simundö. Subsequently, the place was used as meadow land, where people living at the ironworks could get hay for their livestock /Berg et al. 2006/. In 1699 a major part of the northern woodland area belonged to the ironworks as well, and before the end of the 17th century all of the freeholders' farms in the area were purchased by the ironworks /Berg et al. 2006/.

In the early 18th century, there were a large number of crofters (19) in the forest situated to the north of the Forsmark ironworks. The crofters had small areas of arable land with meadows close to their houses. Judging from the tax register from 1749, Forsmark ironworks was not only an ironwork, but also an agricultural enterprise /Essemyr 1988/. During the 19th century, agricultural land was established at Storskäret. At the beginning of the 20th century, the number of crofters in the forests of the Forsmark ironworks had increased to 120. The crofts represented a new wave of colonisation in the area, which took place from the 17th century onwards. The crofts also represented the physical manifestation of the labour requirements of the Forsmark ironworks. Many of these crofters' places are still in use, but not for agricultural purposes. Instead they are used as summerhouses or as permanent residences, and others are abandoned /Berg et al. 2006/.

Other examples of historical features in the present landscape are old roads (Figure 7-4), which were at the time more adjusted to the topography and land use. Many of the small roads connected the crofts and wet-meadows in the woodlands with the ironworks. In today's woodlands there are the remains of several 19th century small roads, which are difficult to identify today /Berg et al. 2006/.

Figure 7-4. *The old road from Lövsta ironworks to Öregrund and Stockholm. The photograph is taken just south of Forsmark ironworks where an impressive stone wall lines the road /from Berg et al. 2006/.*

Charcoal production

A prerequisite for iron production was a large and reliable supply of charcoal. The forest was therefore the single most important resource in the Forsmark region as a source of charcoal production, but the wood was also needed for building material and for fuel. Lövsta ironworks was permitted to yearly forge c 1,105 tons of bar iron that required c 20,000 m^3 of charcoal. Producing this amount of charcoal required an estimated 30,000 days of work /Renting 1996/. Most of the charcoal had to be produced close to the production site /Karlsson 1990/. These figures indicate that the supply of charcoal was as crucial as the ore for production to continue on a regular basis. The preservation of the forests and maintaining production meant that forestry in the modern sense was introduced relatively early in these areas. Since iron was an important product for the country, the crown tried to restrict the use of the forests by spatially separating the mines, the blast furnaces and the hammers from one another, i.e. that certain areas were dedicated solely to one of the activities /Kardell 2003/.

The owners of iron production facilities in Sweden organised the supply of charcoal in two ways. One was to recruit workers and locate them on the premises, i.e. in the forests where they produced charcoal for the ironworks. The other way was to use the right to buy all charcoal from the surrounding farming communities. This was granted to a specific ironworks so that no other competing company could intrude /Renting 1996/.

The present landscape in a historical perspective

The Forsmark region is today a landscape with working farms and an active agricultural society. There are parts of the area where arable land has been reduced in size or abandoned, most notably close to the power plant. Like most areas in Sweden, there has been a reduction in the number of farms over the years. The most striking feature concerns the large-scale demesnes, e.g. Forsmark ironworks that dominated the central region. One landowner controlled a large estate and was able to influence the settlement and the economy. This has led to large-scale impacts imposed by only a few decision makers. This can be contrasted with the history of the large villages in the region. There, land partition and the buying and selling of land resulted in the restructuring of both the settlement system and land use over the past 150 years. Without understanding the effects of the iron industry and the landowners, the landscape cannot be fully understood. Even the landscape in the archipelago and the surrounding areas should be viewed in the context that the mines, the blast furnaces, and the hammers were central places of employment in the region /Berg et al. 2006/.

7.3 Laxemar-Simpevarp region

The *Laxemar-Simpevarp region* refers in this chapter to three parishes in the surrounding of Oskarshamn that together constitute approximately 1,000 km^2, and which were investigated by /Berg et al. 2006/ (Figure 7-5). The Laxemar-Simpevarp region should not be confused with the Laxemar-Simpevarp *regional model area* (see section 1.4, Figure 1-3).

Since the first humans arrived, the Laxemar-Simpevarp region has been characterised by its forest- and archipelago settlements. The main occupation in the region has been a combination of agriculture, forestry and fishing activities /Lundqvist 2006/.

7.3.1 Prehistoric settlements in the Laxemar-Simpevarp region

With archaeological methods it is possible to identify traces of the 300–400 generations that have lived in the Laxemar-Simpevarp region since the latest deglaciation. Generally, the prehistoric human is often revealed by insignificant stone items and by potsherds found in the topsoil in arable land, whereas it is almost impossible to find prehistoric settlements in uncultivated land areas. In the Laxemar-Simpevarp region, however, prehistoric remains, often in the form of visible graves, are unusually common /Lundqvist 2006/.

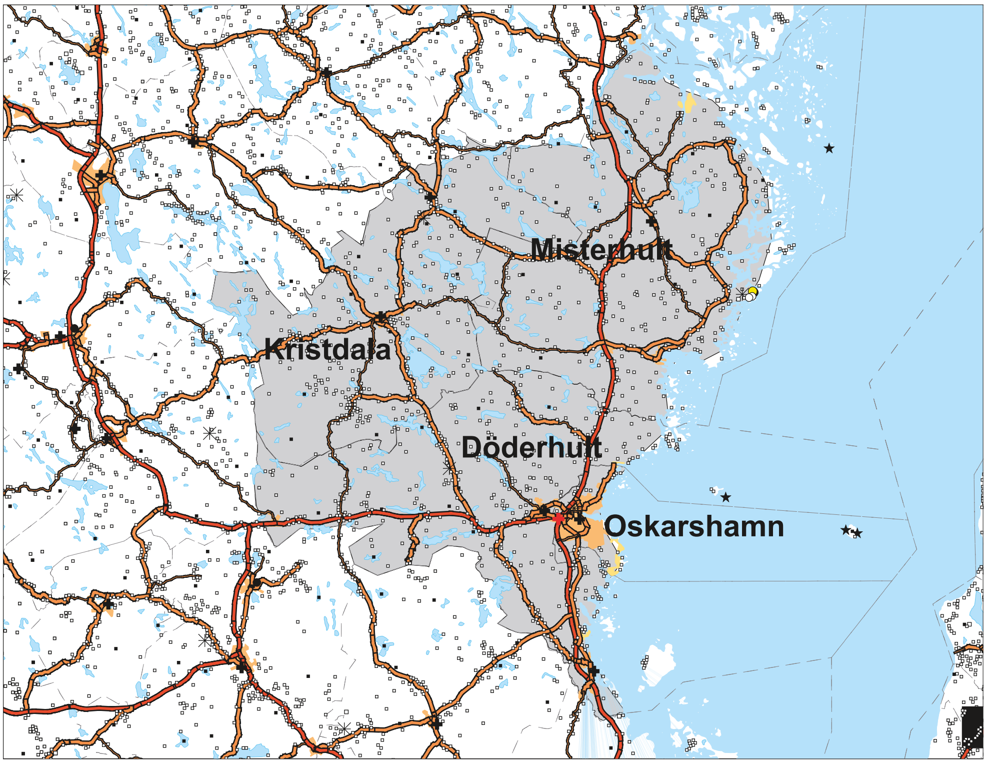


Figure 7-5. *The area of historical investigations in the Laxemar-Simpevarp region. The three investigated parishes cover c 1,000 km² /Berg et al. 2006/.*

The coast in Småland became ice-free around 12,000 BC (cf. Figure 3-8). When searching for signs of prehistoric inhabitants, this is generally done along previous shoreline levels. The coastline was at its highest around 100 metres above the present sea level, which is some 30 km from today's coast. At the time of the deglaciation, the whole Laxemar-Simpevarp region was situated beneath sea level. The oldest human remains in the region are found in the highest situated terrain, which is located in the western parts of the region 25–40 metres above sea level (which corresponds to emergence from the sea around 9400–8300 BC) /Lundqvist 2006/.

A complication in the search of prehistoric settlements is the periods of shoreline transgression that occurred in the Laxemar-Simpevarp regin a couple of times during the Stone Age. Old settlements were flooded and new settlements were located higher up in the terrain. This means that the flooded settlements may have been covered with sand and gravel, which today are overgrown by vegetation /Lundqvist 2006/.

Stone Age (9000–1800 BC)

Previously, few remains in the Laxemar-Simpevarp region from the Older Stone Age (9000–4000 BC) were known. However, recent investigations have shown that the region was highly exploited during this period /Lundqvist 2006/. None of the newly found settlements have been excavated though. Ancient monuments have been found further south in the area of Oskarshamn, where a settlement was situated at the mouth of a bay (at present the valley of Döderhult) of the Littorina Sea. The settlement was dated to 6000–4000 BC, a period when humans intensively used settlements situated in the river mouths and lagoons by the coast. These settlements were more or less permanently inhabited. The inhabitants had extensive contact nets, comprising the whole Kalmarsund area and parts of Öland and Gotland. The contact between these groups is indicated through raw materials for tool production. Flint, which is not found naturally in the area, is one example of long distance transport of such goods /Lundqvist 2006/.

During the Younger Stone Age (4000–1800 BC), the practise of agriculture and livestock-raising increased, in addition to hunting, gathering and catching. There are several known settlements, both large and small, from this period in the northern part of Kalmar County, and they were all associated with surface water bodies /Lundqvist 2006/.

Bronze Age (1800–300 BC)

The Bronze Age is represented in the region by many graves, cairns, circles of stones and piles with stone sherds (Sw. *skärvstenshögar*). The general opinion is that most of the graves in the region were built during the Younger Bronze Age (1200–300 BC), at the shoreline of the prehistoric Baltic proper /Lundqvist 2006/. One Bronze Age relic, Snäckedal, differs from other remains by its great extent; it consists of c 30 cairns and over a hundred circles of stone, and is regarded as a centre for a larger area /Lundqvist 2006/.

The economics of the Younger Stone Age and the Bronze Age were probably quite similar, even if the importance of the various systems of sustenance may have differed. Likely, the Bronze Age humans in the region got their main income from the sea since the land was not suitable for extensive agriculture or livestock-raising /Lundqvist 2006/.

The settlements of the Bronze Age probably consisted of solitary estates. Due to the shoreline displacement, new areas for settlements were created continuously. These “colonisation zones” are recognised by circles of stone, whereas the previously settled areas are distinguished by cairns /Lundqvist 2006/.

Iron Age (300 BC–1100 AD)

If the Bronze Age in the region can be described as rich, the Iron Age gives an opposite picture. There is an almost complete lack of typical graves and characteristic site-names from this period, and based on this the region has been described as almost deserted during the period /Lundqvist 2006/. However, as discussed below there was a population in the region, both in the coastal environment and in the inland. The typical grave formation for the Bronze Age was apparently used during the Iron Age as well, and also at the beginning of the medieval period. Near the present coastline so called “Bronze Age graves” occur, and by their localization at low altitudes the graves can not be older then from the Iron Age. In one case this has been verified by an investigation and archaeological dating (1000–1100 AD). The conclusion is that the Laxemar-Simpevarp region was populated also during the Iron Age, but the characteristics of the settlement and its extent remains to be described /Lundqvist 2006/.

7.3.2 Historical settlements in the Laxemar-Simpevarp region

Medieval period

There are no reliable sources to enable a reconstruction of the number of farms in the Laxemar-Simpevarp region before the 16th century. In the central parts of the province of Småland, however, a population decline during the medieval period has been established /Bååth 1983/, coinciding with a similar decline in the Forsmark region /Berg et al. 2006/. It seems reasonable that a medieval population decline occurred also in the Laxemar-Simpevarp region.

Early modern period until today

According to the cadastral books, the number of crofters’ holdings in the Laxemar-Simpevarp region was generally low during the early modern period, and this appears to have been the situation also during the 18th and 19th centuries. However, all crofters’ holdings were not registered in the cadastral books since these settlements were not taxed. Hence, the number of crofters’ holdings during the 18th and 19th centuries was likely higher than the noted number in the cadastral book /Berg et al. 2006/. The number of abandoned settlements in the Laxemar-Simpevarp region was in general low during this period /Berg et al. 2006/.

In 1646, the small market town of Döderhultsvik was established. Döderhultsvik was granted town rights in 1856 and at the same time the name was changed to Oskarshamn /Nilsson 1992/.

Throughout the Middle Ages until the end of the 17th century, several farms in the Laxemar-Simpevarp region belonged to an aristocratic landed estate. One of the estates was probably established already in the mid-14th century /Rahmqvist 1999/. In the mid-16th century, King Gustav Vasa confiscated a number of manors and estates in the Laxemar-Simpevarp region. During the 17th century, several new manors were founded. The farms, which were under the manors during the 17th century, belonged to the crown from the end of the 17th century /Almquist 1976/. Many of these farms were thereafter bought free and became freeholder farms /Berg et al. 2006/.

7.3.3 Development of human population

Population change

Population growth in the Laxemar-Simpevarp region was relatively steady during most of the investigated period (1571–1990), and almost doubled every 50 years (Table 7-5). After c 1800, there was strong population growth until the late 19th century. At the turn of the century the increase ceased and during the latter part of the 20th century the rural population decreased. The number of people involved in agriculture decreased, and the number of people employed in industry and crafts was greater than before /Morell 2001/. After 1960, there was a positive population trend in parts of the investigated region, i.e. in Döderhult and Misterhult /Berg et al. 2006/.

Household population size

The average household size decreased between the years of 1851–1899 from almost 7 persons per household to c 5.5 persons per household. Separating farms from crofters' holdings reveals some differences. In 1851–60, the average farm household comprised approximately 8 persons, whereas the average crofter household comprised just over 5 persons. At the end of the 19th century, however, the average farm household size had decreased to 6 persons, whereas the average crofter household remained stable at c 5 persons per household /Berg et al. 2006/.

7.3.4 Historical land use

The landscape in the Laxemar-Simpevarp region

The agricultural landscape in the region is shaped by the physical setting, i.e. the topography and the soils. The areas that are possible to cultivate are limited to the valleys (see Chapter 3). These areas often have a thin peat cover, suggesting that they have been wetlands during some time period (Figure 7-6). The overlap between arable land and areas with a peat cover is also a strong indication of the extensive earlier ditching activities, performed in order to lower the water table and make cultivation more productive. The change of the water table depth induces oxidation and disappearance of the peat, which suggests that the earlier distribution of the peat/wetlands, and its coincidence with the arable land, is underestimated in Figure 7-6.

Woodland was and is dominant in the region. A characteristic feature in the landscape was the occurrence of single farms, which were subdivided into several smaller farms when the population increased. The substantial population increase during the 19th century, combined with the limited availability of resources, resulted in considerable pressure on the landscape. With the population decline at the turn of the 19th century, this pressure diminished /Berg et al. 2006/.

Detailed historical maps of the investigated region indicate that most farms were in fact small, and that the arable fields principally consisted of patches of land, which were often filled with clearance cairns. In maps from the 17th and 18th centuries, many meadows can be observed.

Table 7-5. The total population of the Laxemar-Simpevarp region for some years between 1571 and 1990 (modified from Table 9-2 in /Berg et al. 2006/).

Year	Inhabitants per km^2
1571	1.3
1620	1.3
1699	3.6
1750	4.9
1800	8.5
1850	15.3
1900	21.9*
1990	10.6**

* Including the town of Oskarshamn.

** Excluding the town of Oskarshamn.

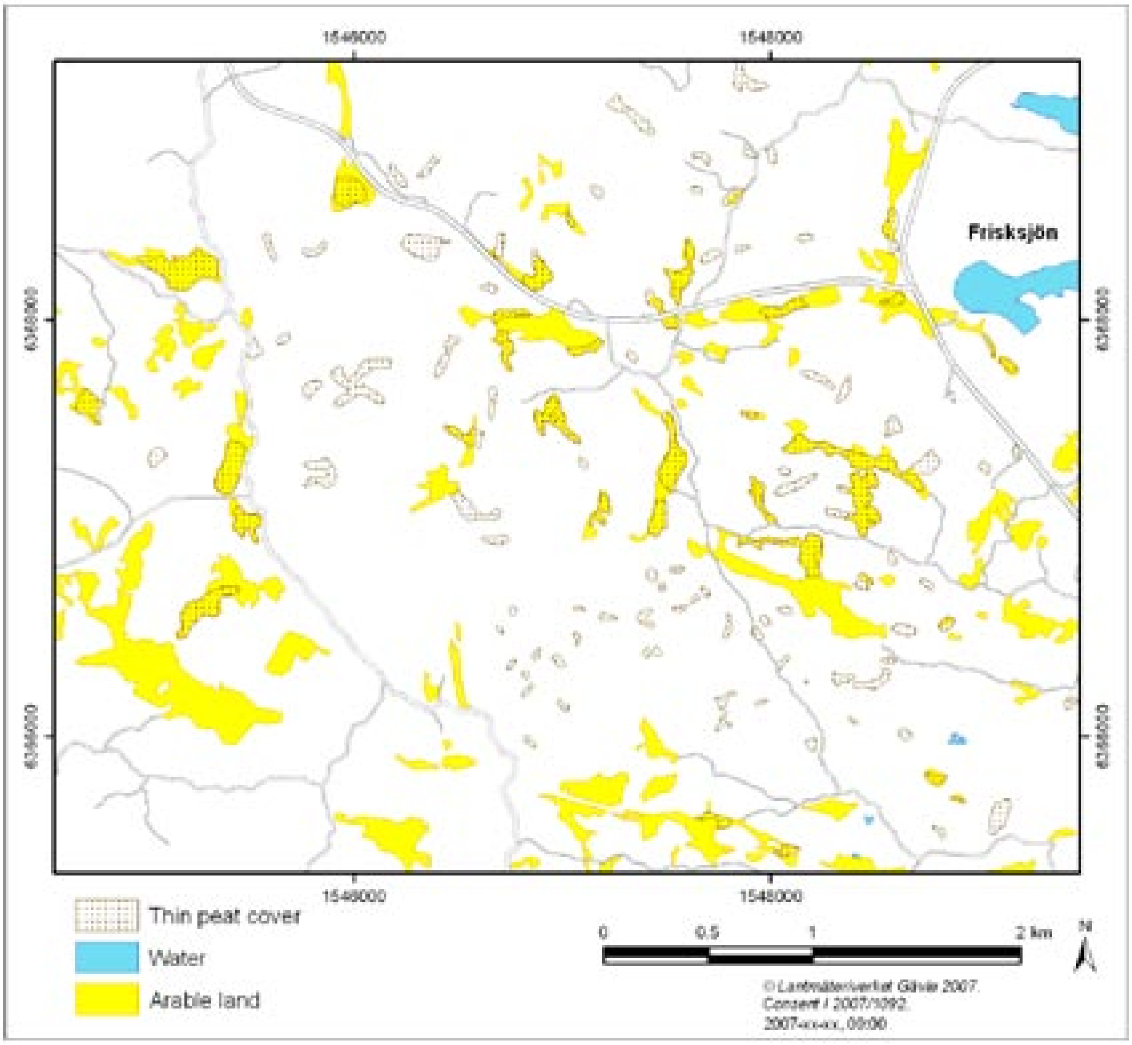


Figure 7-6. *The location of the arable land in the Laxemar-Simpevarp area coincides strongly with areas covered with a thin peat layer, here exemplified in the central parts of the regional model area. This indicates that much of the arable land is located on former wetlands.*

The meadows were often located next to the cultivated fields. Small wooded areas or single trees could grow in the meadows without preventing the production of winter fodder. The leaves and twigs from the trees were probably used as fodder for smaller animals such as goats or sheep /Berg et al. 2006/.

Another important characteristic of the region is the location of farms by the coast or in the archipelago, sometimes relatively far away from the arable land. The location of these farms was closely connected to the importance of fishing, and it shows that arable production was not always the most important form of livelihood in the local economy /Berg et al. 2006/.

The areal extent of arable land, and even more so of meadows, increased throughout the 18th and 19th centuries. The wetlands in the wooded areas were then also being used as meadows. At the same time, the old meadows located near the settlements were transformed into arable land. The increase in population and the increasing number of farms during the period may partly explain this situation. Another possible explanation is that fishing and fishing-related incomes decreased in relation to other incomes, and that agriculture increased in importance as a source of income at the same time. This does not mean that incomes related to fishing disappeared, but that agriculture became relatively more important.

One of the clear changes that can be observed in maps spanning the period from 1689 to 1872, is an increase in the amount of meadowland located in the central part of the village. In the 17th century, the meadows were concentrated in the eastern part, close to the settlement. Most of the meadows were in the same fenced-in area as the arable land. The picture had changed dramatically one hundred years later, and many of the former wetlands and peatlands were now being used as meadows. This can be interpreted as a result of the increase in population and hence a greater pressure on the landscape, but may also reflect a change in production with larger numbers of animals requiring winter fodder /Berg et al. 2006/.

The agrarian revolution and the changes that took place during the 19th century also affected the farms and people in the Laxemar-Simpevarp region. New roads were created and new ownership structures became apparent in the landscape. Stone walls were built in straight lines and divided the landscape into separate domains. The meadows were to some degree abandoned and wetlands were reclaimed as arable land in many areas of the region /Berg et al. 2006/ (Figure 7-6). Landscape change in the Laxemar-Simpevarp region was dramatic in the middle of the 20th century (Figure 7-7). From 114 million square metres of arable land in 1940, only 41 million were still in production in 1980, i.e. approximately 36% of the former arable land. The forms of the arable fields can also be analysed in relation to the changes. It is common that field configurations have become simplified over time, i.e. that the irregular shapes and forms have been changed into simple rectangular forms /Berg et al. 2006/.

Land use over time

As noted above, fishing has always been an important activity for sustenance in the Laxemar-Simpevarp region. There are notes from the 11th century describing several places along the east coast that are assumed to have been seasonal fishing sites or harbours. Some of the mentioned places have for a long time played a significant roll in shipping, and several of these sites have been permanently settled since the 11th century, e.g. Fittjehammar, Uthammar, and Vinö in the Misterhult parish /Lundqvist 2006/.

The households in the archipelago were very imprinted by strong traditions and a high degree of self-sufficiency, where fishing and livestock-raising constituted the main occupation. The many islands in the region provided excellent pastures for the livestock. Cultivated products such as cereal were exchanged with farmers from the inland. During the 18th and 19th centuries, the number of households increased drastically in the region and the reclamation of land was intense /Lundqvist 2006/. Despite this, the region has since the 17th century been one of the weakest agricultural areas in the Kalmar County, especially with regard to cereal production. During the post-war era this is the region that has lost most arable land and agricultural units in the Kalmar County /Lundqvist 2006/.

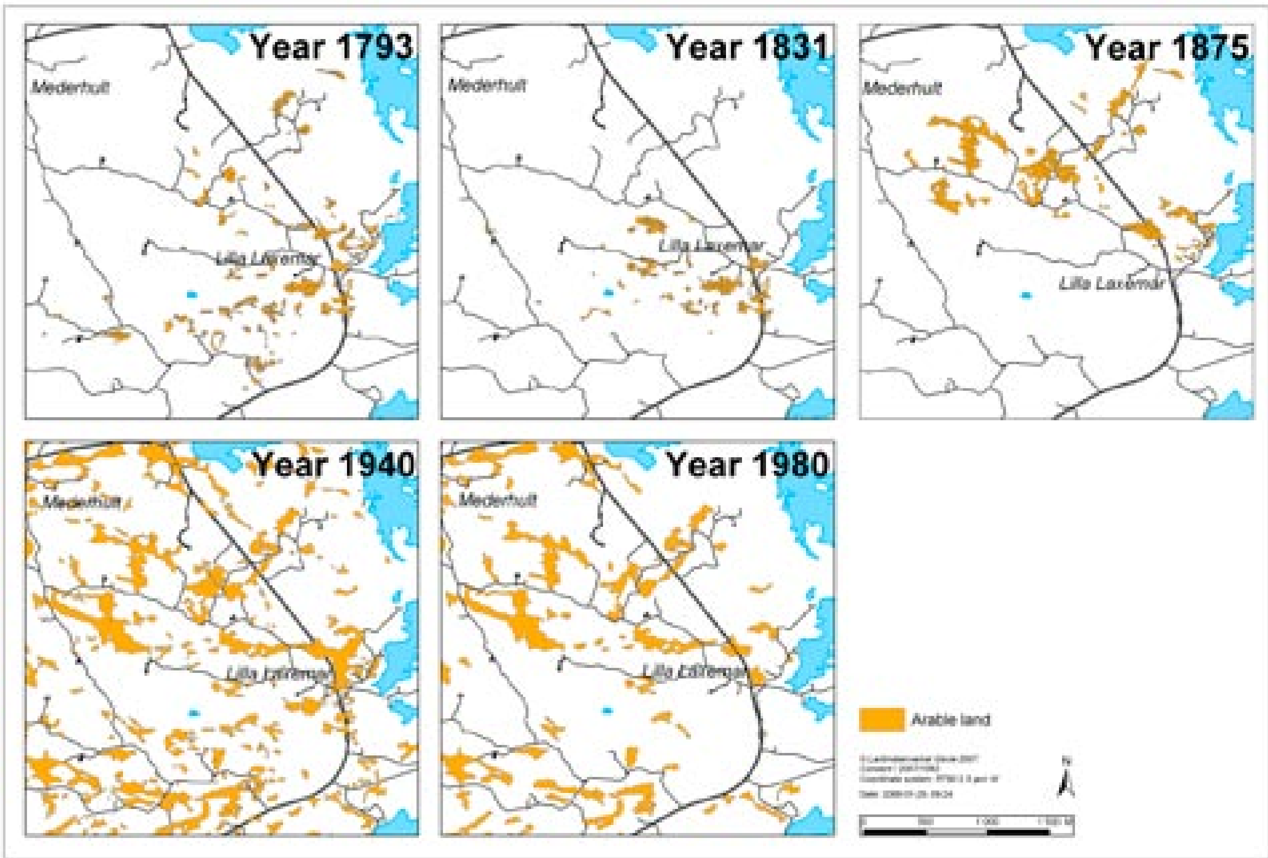


Figure 7-7. *Spatial distribution of arable land in the Laxemar landscape at 5 occasions during 200 years. The first three maps do not cover the whole regional model area and are only partially overlapping. Despite this is it possible to see an increase in arable land area between 1831 and 1875, and the extent of arable land reaches a maximum around the middle of the 20th century. Thereafter, the arable land area has drastically declined, mainly due to the abandonment of smaller (the first three maps are based on maps of hundreds whereas the two last maps are based on the Economic Map (1940) and the Property Map (1980)).*

The forests in the Laxemar-Simpevarp region were used for many different purposes; pastures, firewood, fencing material, subsistence needs, burn-beating, as well as production of charcoal, tar and potash. In addition to sawmill activities, the production of charcoal, tar and potash, were in many cases an important part of the household economy. Trading in timber was advantageous since the timber was easily transported in the coastal areas. In the Laxemar-Simpevarp region there was also a boat-building tradition, which grew during the 19th century to a minor shipbuilding industry /Lundqvist 2006/.

Before the 17th century, large parts of the region were owned by the crown, but during the 19th century this changed. When the nobles took over, several industry investments were made. The nobles brought new inventions to the region during the 19th and 20th centuries. Bogs and wet-meadows became arable land through ditching and stone fences were built to protect the forest from the livestock /Lundqvist 2006/.

In the archipelago there was no agriculture worth mentioning before the middle of the 18th century. Instead people practised livestock-raising, which was so intense that many areas in the archipelago were overgrazed. However, when the population increased after the middle of the 18th century, the agriculture in the archipelago became more extensive. The agriculture was limited though, due to the lack of suitable land /Lundqvist 2006/.

7.4 Recent changes in land use – a comparison between the Forsmark and Laxemar-Simpevarp regions

The land reforms that took place in Sweden in the 18th and the 19th centuries caused profound changes in the spatial organisation of settlements and land use. In some cases, settlements were forced to move away from the old villages and to relocate to previously uncultivated areas. However, this was not the general pattern in the two investigated regions. Instead, the changes that occurred in the Laxemar-Simpevarp region were small; many of the farms were not moved at all and the farms that actually moved were located to areas where the land was already tilled. Generally, this was also the case in the Forsmark region, and many of the larger villages there are still visible today.

As the technology changed, the old agricultural system of arable land and meadows, where the meadows were used to produce winter fodder, was abandoned. The local agro-ecological cycle was broken, which means that the fodder instead was grown in the arable fields, creating a rotation of crops involving cereal production, fodder production and fallow in the same field. This new crop rotation improved not only the amount of fodder, but also the yields of barley and other crops. These changes in technology coincided more or less with the land reforms. Accordingly, in the earlier part of the period there were hamlets and villages that cooperated in the use of arable land, forests and meadows, whereas at the end of the period, most farmers had direct control of their holdings and used them without the involvement of the neighbours. The forests were divided, and the pattern of the land reforms can easily be seen in today's landscape (Figure 7-8). Many new fences were built to separate the different parts of the arable land and also to separate land belonging to different landowners /Berg et al. 2006/.

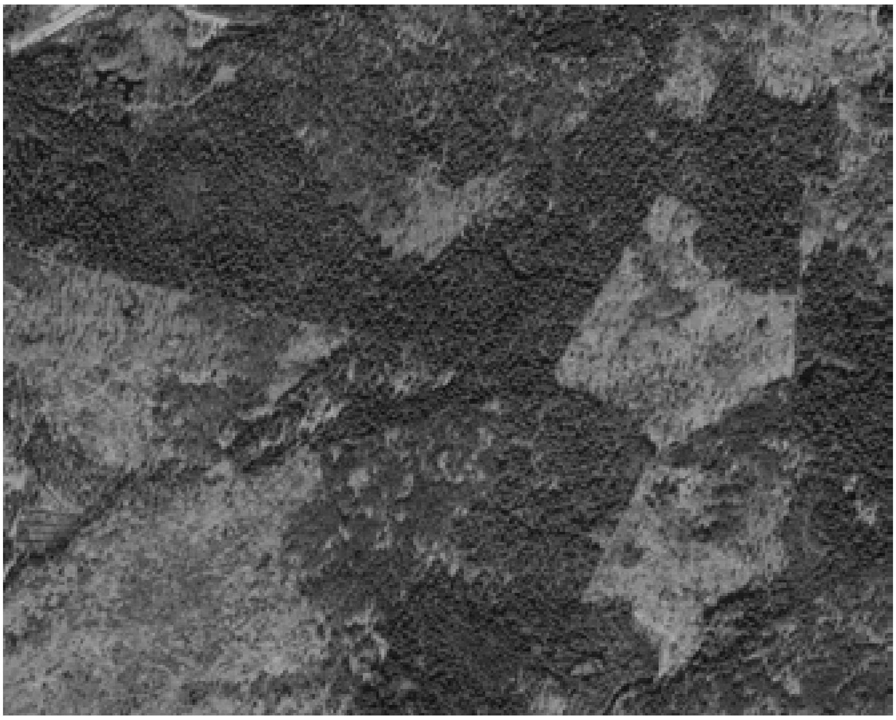


Figure 7-8. *The rectangular pattern in the forests can be observed in many parts of the investigated region. This pattern is often attributed to the new division of the forests that took place as a result of the land reforms during the 17th and the 18th centuries. This aerial photograph from 2001 of the forests between Finnshult and Fallegärde, north-west of Oskarshamn, exemplifies this well /Berg et al. 2006/.*

After the Second World War, the aim of Swedish agriculture policy was to rationalise the sector. Before the war, cultivation was carried out either by relatively small family farms, or by large estates with employees. Three different goals were formulated by the state; the income goal, the efficiency goal, and the self-sufficiency goal in case of war. The income goal meant that farmers' standard of living should be comparable/equal to an employed industrial worker. The efficiency goal aimed at rationalised and efficient production. Today the goals have changed and the agricultural politics is a part of the EU policy. The EU gives subsidies to farmers for different types of land use /Flygare and Isacson 2003/. This means that non-agricultural values have come into focus to a much larger extent than previously. Today, the preservation of old meadows and grazing land can provide better returns than agricultural production /Berg et al. 2006/.

The policies and the changes in economy after the war have substantially altered the landscape and the conditions for farming in all parts of Sweden. These changes were especially visible in the areas where conditions for cultivation are good. As a consequence of rationalisation and mechanisation, a smaller number of farmers are now able to cultivate larger areas, which was also a necessity for the urbanisation and industrialisation of society /Berg et al. 2006/.

Current land use in the investigated areas is in some aspects typical of the forested rural areas in Sweden; small-scale family-based farming with grazing animals dominates in both areas. However, there are some subtle but important differences between the two regions. Firstly, a difference in the traditional land use can be recognised. It seems that there has been a more diverse land use in the Laxemar-Simpevarp region, focusing more on fishing, hunting and collecting berries, whereas in the Forsmark region land use has been more focused on the traditional practice of growing seeds. Secondly, the re-organisation of properties to build sufficiently sized farms has gone one step further in the Forsmark region than in the Laxemar-Simpevarp region. In the Laxemar-Simpevarp region, most farms are still intact from the time of the land reforms, and the current land users are instead lease-holding many tracts of land from other farms, up to 25 contracts in some cases. In the Forsmark region, large forest companies bought whole farms in the post-war period and sold off the arable land to family farmers. In the Laxemar-Simpevarp region most farms are still owned by the same families as in the early twenties. Thirdly, the spatial dimensions are different in terms of field size and distribution. Today, it is necessary to have somewhere in the region of 50 to 60 cows in order to have a solid economic base for milk production. In the Forsmark region, the field size and distribution is favourable for keeping the necessary livestock numbers, which has resulted in modernisation and investments in milking machines and new stables. In the Laxemar-Simpevarp region, however, there is not enough grazing land close to the hamlets and not enough fodder producing land in the proximity of farms, which makes the establishment of a dairy farm in the region increasingly difficult /Berg et al. 2006/.

In conclusion, the land use in the two investigated regions can, in a larger context, be seen as that of agriculturally marginal areas. In both regions, land use is to some extent dependent on subsidies. In the Laxemar-Simpevarp region many landowners do not see much future in farming. For the inhabitants in the Forsmark region, however, the idea of farming as a source of revenue and a livelihood is still alive and thus incorporated in the perception of everyday life /Berg et al. 2006/.

7.5 Summary

The two studied regions surrounding Forsmark and Laxemar-Simpevarp are both located along the coast to the Baltic Sea. Despite this similarity, they exhibit many differences in the development of human population and land use. This is partly due to their different physical settings, but also to the fact that their societies and economies have developed differently.

Prehistory–1100 AD

The prehistoric period is considerably shorter in the Forsmark region than in Laxemar-Simpevarp, since Forsmark was covered with water for a longer time period. In the Laxemar-Simpevarp region, there is a rich occurrence of prehistoric remains, some of them indicating that the area was highly exploited already during the Older Stone Age. In contrast, the Forsmark region was not permanently settled until the end of the prehistoric period.

Medieval period 1100–1550 AD

The medieval period illustrates the differences between the regions in more detail. One difference is that the Forsmark region during this period was characterised by small villages, whereas single farms dominated the settlement structure in the Laxemar-Simpevarp region. Another difference concerns the phase of expansion in the Forsmark region, whereby new settlements were created in the peripheral areas of the older ones. This expansion cannot be easily observed in the Laxemar-Simpevarp region. The recession during the middle of the medieval period in the Forsmark region, which is often attributed to the plague, has not been confirmed in the Laxemar-Simpevarp region, even though there are indications from the general trend in Småland that it also occurred in the Laxemar-Simpevarp region.

The investigated parishes in the Forsmark region showed a dominance of freeholders at the end of the medieval period and the share of farms belonging to the nobility was small. The Laxemar-Simpevarp region showed instead an unusually large share of farms belonging to the crown, and the share of freeholders was correspondingly very small.

Early modern period 1550–1750 AD

During the early modern period, the establishment of the iron industry in the Forsmark region dramatically affected the surrounding landscape. Production was geared towards the needs of the industry; charcoal production, mining, and the production of fodder for animals used in the industry. The ownership structure also changed abruptly with the establishment of large estates. Similar to many other places in Sweden, there was a strong population expansion in both regions. In the Forsmark region, many crofts were established in the forested areas, inhabited by people involved in charcoal production. The increase in number of crofts was more moderate in the Laxemar-Simpevarp region, even though the settlements in the region increased, partly due to partitioning of farms. The population in both regions doubled or increased at an even faster rate between the 1570s and the 1750s.

Era of modernisation 1750–1950 AD

The number of freehold farmers increased in the Laxemar-Simpevarp region during the 18^{th} century, both due to the partitioning of farms and to the fact that farmers purchased farms previously belonging to the nobility. The trend in the Forsmark region was the opposite; the large estates expanded and, accordingly, the number of freehold farms decreased.

In both regions, the population increased dramatically from the 1780s up to the late 19^{th} century. At the turn of the century the increase ceased and during the latter part of the 20^{th} century the rural population decreased. The number of people involved in agriculture decreased, and instead, the number of people employed in industry and crafts was greater than before. A common pattern for the two investigated regions during recent centuries was the decrease in the average household size. The Forsmark region had in general larger households than the investigated region in Laxemar-Simpevarp, but from the 1890s and onwards the household sizes were almost the same for both regions.

References

Aggeryd I, Aquilonius K, Landström O, Sundblad B, Tullborg E-L, 1995. Long-term transfer of elements across the interface of the biosphere and geosphere – The natural analogue at the Island of Äspö. SKB Project report U-96-24, Svensk Kärnbränslehantering AB.

Agrell H, 1976. The highest coastline in south-eastern Sweden. Boreas 5, 143–154.

Agrell H, Friberg N, Oppgården R, 1976. The Vimmerby Line – An ice-margin zone in north-eastern Småland. Svensk geografisk årsbok 52, 71–91.

Agrell H, Björnbom S, 1978. Blå morän vid Forsmarks kärnkraftverk. SGU centralarkiv F8 ID: C3 ME: paper (in Swedish).

Albrecht J, 2005. Forsmark site investigation. Study of Quaternary sediments in connection with investigations of bedrock lineaments. SKB P-05-138, Svensk Kärnbränslehantering AB.

Alexanderson H, Murray A S, 2007. Was southern Sweden ice free at 19–25 ka, or were the post LGM glaciofluvial sediments incompletely bleached? Quaternary Geochronology 2, 229–236.

Allen R L, Lundström I, Ripa M, Simeonov A, Christofferson H, 1996. Facies Analysis of a 1.9 Ga, Continental Margin, Back-Arc, Felsic Caldera Province with Diverse Zn-Pb-Ag-(Cu-Au) Sulfide and Fe Oxide Deposits, Bergslagen Region, Sweden. Economic Geology 91, 979–1008.

Alley R B, Mayewski P A, Sowers T, Stuiver M, Taylor K C, Clark P U, 1997. Holocene climatic instability. A prominent widespread event 8,200 years ago. Geology 25, 483–486.

Almquist J A, 1931. Frälsegodsen i Sverige under storhetstiden: med särskild hänsyn till proveniens och säteribildning, D. 1, Stockholms och Uppsala län, Bd 1, Inledning och tabeller, LiberFörlag/Allmänna förl., Stockholm. (In Swedish).

Almquist J A, 1976. Frälsegodsen i Sverige under storhetstiden : med särskild hänsyn till proveniens och säteribildning, D. 4, Småland, Bd 3, LiberFörlag/Allmänna förl., Stockholm. (In Swedish).

Andersen B, Borns H W, 1997. The Ice Age World. Scandinavian University Press. 208 pp.

Anderson E M, 1951. The dynamics of faulting. Oliver & Boyd, Edinburgh.

Andersson U B, 1997. The sub-Jotnian Strömsbro granite complex at Gävle, Sweden. GFF 119, 159–167.

Andersson U B, Högdahl K, Sjöström H, Bergman S, 2006. Multistage growth and reworking of the Palaeoproterozoic crust in the Bergslagen area, southern Sweden: evidence from U-Pb geochronology. Geological Magazine 143, 679–697.

Andreasson P-G (ed), 2006. Geobiosfären – en introduktion. Studentlitteratur. (In Swedish).

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

Andrén E, Andrén T, Sohlenius G, 2000. The Holocene history of the southwestern Baltic Sea as reflected in a sediment core from the Bornholm Basin. Boreas 29, 233–250.

Angelstam P, 1992. Conservation of communities. The importance of edges, surroundings and landscape mosaic structure. p. 4–6 In: Hansson L (ed), Ecological principles of nature conservation. Elsevier Science Publishers Ltd, Essex, England.

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

Antal I, Bergman T, Gierup J, Johansson R, Lindén A, Stephens M, Thunholm B, 1998b. Översiktsstudie av Östergötlands län: Geologiska förutsättningar. SKB R-98-26, Svensk Kärnbränslehantering AB.

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

Antal I, Bergman T, Johansson R, Persson C, Stephens M, Thunholm B, Åsman M, 1998d. Översiktsstudie av Stockholms län: Geologiska förutsättningar. SKB R-98-30, Svensk Kärnbränslehantering AB.

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

Antal I, Bergman S, Fredèn C, Gierup J, Johansson R, Stephens M, Thunholm B, 1998f. Översiktsstudie av Gävleborgs län: Geologiska förutsättningar. SKB R-98-34, Svensk Kärnbränslehantering AB.

Antonsson K, Seppä H, 2007. Holocene temperatures in Bohuslän, southwest Sweden: a quantitative reconstruction from fossil pollen data. Boreas 36, 400–410.

Arvidsson R, 1996. Fennoscandian earthquakes: Whole crustal rupturing related to postglacial rebound. Science 274, 744–746.

BABEL Working Group, 1990. Evidence for Early Proterozoic plate tectonics from seismic reflection profiles in the Baltic Shield. Nature 348, 34–38.

Berg J, Jansson U, Wästfelt A, 2006. Landscape history and people in a geographical perspective. Studies of land-use, settlement and livehood in Oskarshamn and Forsmark. SKB R-06-37, Svensk Kärnbränslehantering AB.

Berger A, Loutre M F, 1997. Palaeoclimate sensitivity to CO_2 and insolation. Ambio 26, 32–37.

Berger A, Loutre M F, 2002. An Exceptionally Long Interglacial Ahead? Science 297, 1287-1288.

Bergkvist M, Ekström L, Eriksson K, Hammarlund E, Hollsten M, Lind A-L, Lundholm K, 2003. Kallrigafjärden, NO Uppland. Områdets historia, nuläge samt framtida landskapsutveckling. SKB R-03-26, Svensk Kärnbränslehantering AB.

Berglund B, 1966. Late-Quaternary vegetation in southeastern Sweden. A pollen-analytical study. II. Post-Glacial time. Opera Botanica 12:1, 190 pp.

Berglund B, 1971. Littorina transgressions in Blekinge, South Sweden. A preliminary survey. Geologiska Föreningens i Stockholm Förhandlingar 93, 625–652.

Berglund B E, Digerfeldt G, Engelmark R, Gaillard M-J, Karlsson S, Miller U, Risberg J, 1996a. Palaeoecological events during the last 15,000 years, Regional syntheses of palaeoecological studies of lakes and mires in Europe – Sweden. In Berglund B E, Birks H J B, Ralska-Jasiewiczowa M and Wright H E (eds): IGCP Project 158B 233–280.

Berglund B E, Björse G, Liljegren R, 1996b. Från istid till nutid. pp. 14–24. In Gustafsson L and Ahlén I (eds): Sveriges Nationalatlas, Växter och djur. Bokförlaget Bra Böcker, Höganäs (in Swedish).

Berglund J, 1997. Compressional and extensional ductile shearing along a terrane boundary in south-western Sweden. In J. Berglund, Mid-Proterozoic evolution in south-western Sweden. Thesis A15 1997, Earth Sciences Centre, Göteborg University.

Berglund B, Sandgren P, Barnekow L, Hannon G, Jiang H, Skog G, Yu S-Y, 2005. Early Holocene history of the Baltic Sea, as reflected in coastal sediments in Blekinge, southeastern Sweden. Quaternary International 130, 111–139.

Bergman L, 1982. Clastic dykes in the Åland islands, SW Finland and their origin. Geological Survey of Finland Bulletin 317, 7–27.

Bergman T, Isaksson H, Johansson R, Lindén A H, Lindgren J, Lindroos H, Rudmark L, Wahlgren C-H, 1998. Förstudie Oskarshamn. Jordarter, bergarter och deformationszoner. SKB R-98-56, Svensk Kärnbränslehantering AB.

Bergman T, Fredén C, Gierup J, Johansson R, Kübler L, Stephens M, Stølen L K, Thunholm B, 1999a. Översiktsstudie av Örebro län: Geologiska förutsättningar. SKB R-99-23, Svensk Kärnbränslehantering AB.

Bergman T, Gierup J, Johansson R, Kübler L, Lindén A, Stephens M, Stølen L K, Thunholm B, 1999b. Översiktsstudie av Västmanlands län: Geologiska förutsättningar. SKB R-99-31, Svensk Kärnbränslehantering AB.

Bergman T, Isaksson H, Johansson R, Lindèn A H, Lindroos H, Rudmark L, Stephens M, 1999c. Förstudie Tierp. Jordarter, bergarter och deformationszoner. SKB R-99-53, Svensk Kärnbränslehantering AB.

Bergman T, Isaksson H, Rudmark L, Stanfors R, Wahlgren C-H, Johansson R, 2000. Förstudie Oskarshamn. Kompletterande geologiska studier. SKB R-00-45, Svensk Kärnbränslehantering AB.

Bergman S, Delin H, Karis L, Kübler L, Ripa M, Söderman J, 2002. Projekt Svealand. In H Delin (edit.), Regional berggrundsgeologisk undersökning. Sammanfattning av pågående undersökningar 2001. SGU Rapporter och meddelanden 110, Sveriges geologiska undersökning, 10–39.

Bergman T, Andersson J, Hermansson T, Zetterström Evins L, Albrecht L, Stephens M, Petersson J, Nordman C, 2004. Forsmark site investigation. Bedrock mapping. Stage 2 (2003) – bedrock data from outcrops and the basal parts of trenches and shallow boreholes through the Quaternary cover. SKB P-04-91, Svensk Kärnbränslehantering AB.

Bergman S, Karis L, Söderman J, 2005. Bedrock map 13H Gävle NO, scale 1:50 000. Sveriges geologiska undersökning K33.

Bergman T, Hedenström A, 2006. Forsmark site investigation. Petrographic analysis of gravel and boulders in the Forsmark candidate area. SKB P-06-87, Svensk Kärnbränslehantering AB.

Bergman S, Sjöström H, Högdahl, K, 2006. Transpressive shear related to arc magmatism: The Paleoproterozoic Storsjön-Edsbyn Deformation Zone, central Sweden. Tectonics 25, TC1004, doi:10.1029/2005TC001815.

Bergman T, Sohlenius G, 2007. Oskarshamn site investigation. Petrographic analysis of gravel and boulders in till from the Laxemar area. SKB P-07-30, Svensk Kärnbränslehantering AB.

Bergström, E, 2001. Late Holocene distribution of lake sediment and peat in NE Uppland, Sweden. SKB R-01-12, Svensk Kärnbränslehantering AB.

Berthelsen A, 1980. Towards a palinspastic tectonic analysis of the Baltic shield. In J Cogné and M Slansky (eds), Geology of Europe from Precambrian to Post-Hercynian sedimentary basins. International Geological Congress Colloquium C6, Paris, 5–21.

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

Bianchi T S, Westman P, Rolff C, Engelhaupt E, Andrén T, Elmgren R, 2000. Cyanobacterial blooms in the Baltic Sea: natural or human induced Limnology and Oceanography 45, 716–726.

Birkeland P W, Shroba R R, Burns S F, Price A B, Tonkin P J, 1999. Integrating soils and geomorphology in mountains – an example from the Front Range of Colorado. Geomorphology Vol. 55(1–4):329–344.

Björck S, 1995. A review of the history of the Baltic Sea, 13.0–8.0 ka BP. Quaternary International 27, 19–40.

Björck S, Kromer B, Johnsen S, Bennike O, Hammarlund D, Lemdahl G, Possnert G, Lander Rasmussen T, Wohlfarth B, Hammer C H, Spurk M, 1996. Synchronized terrestrial-atmospheric deglacial records around the North Atlantic. Science 274, 1155–1160.

Björck J, 1999. The Alleröd-Younger Dryas pollen zone in an 800-years varve chronology from southeastern Sweden. GFF 121, 287–292.

Björkman H, Trägårdh J, 1982. Differential uplift in Blekinge indicating late-glacial neotectonics. GFF 104, 75–79.

Björkman L, 1996. The Late Holocene history of beech *Fagus sylvatica* and Norway spruce *Picea abies* at stand-scale in southern Sweden. Lundqa Thesis 39, Lund University, Department of Quaternary Geology, 44 pp.

Björnbom S, 1979. Clayey basal till in central and northern Sweden. A deposit from an old phase of the Würm glaciation. Sveriges Geologiska Undersökning, Ser. C 753, 62 pp.

Bondesson W, 2006. Arkeologisk utredning (etapp 1) Forsmark. SKB P-05-256, Svensk Kärnbränslehantering AB. (In Swedish).

Borg G Ch, Paabo K, 1984. Area description and sediment investigation of the coastal area between Karlskrona and Oskarshamn S.E. Sweden. Striolae, Uppsala University. 85 pp.

Boulton G S, Kautsky U, Morén L, 1999. Impact of long-term climate change on a deep geological repository of spent nuclear fuel. SKB TR-99-05, Svensk Kärnbränslehantering AB.

Bradshaw R H W, Lindbladh M, 2005. Regional spread and stand-scale establishment of *Fagus Sylvatica* and *Picea abies* in Scandinavia. Ecology 86, 1679–1686.

Broberg A, 1990. Bönder och samhälle i statsbildningstid: en bebyggelsearkeologisk studie av agrarsamhället i Norra Roden 700–1350, Upplands fornminnesförening. Uppsala. (In Swedish).

Brown G H, 2002. Glacier meltwater hydrochemistry. Appl. Geochem., 17, 855–883.

Brunberg A-K, Blomqvist P, 1998. Vatten i Uppsala län 1997. Beskrivning, utvärdering, åtgärdsförslag. Rapport nr 8/1998. Upplandsstiftelsen. 944 pp. (In Swedish).

Brunberg A-K, Blomqvist P, 1999. Characteristics and ontogeny of oligotrophic hardwater lakes in the Forsmark area, central Sweden. SKB R-99-68, Svensk Kärnbränslehantering AB.

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

Brunberg A-K, Blomqvist P, Rydin E, 2002. Contrasting ontogeny among ephemeral hardwater lakes as revealed by sediment P-fractionation. Arch. Hydrobiol. 153(3), 491–502.

Brunberg A-K, Blomqvist P, 2003. Ontogeny of lake ecosystems in the Forsmark area – chemical analyses of deep sediment cores. SKB R-03-28, Svensk Kärnbränslehantering AB.

Brunberg A-K, Carlsson T, Blomqvist P, Brydsten L, Strömgren M, 2004. Identification of catchments, lake-related drainage parameters and lake habitats. Forsmark site investigation. SKB P-04-25, Svensk Kärnbränslehantering AB.

Brunnberg L, 1995. Clay-varve chronology and deglaciation during the Younger Dryas and Preboreal in the easternmost part of the Middle Swedish Ice Marginal Zone. Department of Quaternary Research, Stockholm University. Quaternaria 2. 94 pp.

Brydsten L, 2006. A model for landscape development in terms of shoreline displacement, sediment dynamics, lake formation, and lake choke-up processes. SKB TR-06-40, Svensk Kärnbränslehantering AB.

Bååth K, 1983. Öde sedan stora döden var – bebyggelse och befolkning i Norra Vedbo under senmedeltid och 1500-tal, Det nordiske ødegårdsprosjekt 12, Bibliotheca historica Lundensis 51, Liber/Gleerup, Lund. (In Swedish).

Bödvarsson R, Lund B, Roberts R, Slunga S, 2006. Earthquake activity in Sweden. Study in connection with a proposed nuclear waste repository in Forsmark or Oskarshamn. SKB R-06-67, Svensk Kärnbränslehantering AB.

Bödvarsson R, 2007. Swedish National Seismic network (SNSN). A short report on recorded earthquakes during the third quarter of the year 2007. SKB P-07-201, Svensk Kärnbränslehantering AB.

Carlsson A, 1979. Characteristic features of a superficial rock mass in southern central Sweden – Horizontal and subhorizontal fractures and filling material. Striae 11, 1–79.

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

Cederbom C, 2001. Phanerozoic, pre-Cretaceous thermotectonic events in southern Sweden revealed by fission track thermochronology. Earth and Planetary Science Letters 188, 199–209.

Cederbom C, 2002. The thermotectonic development of southern Sweden during Mesozoic and Cenozoic time. In A G Doré, J A Cartwright, M S Stoker, J P Turner and N White (eds), Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. Geological Society Special Publication 196, 169–182.

Christoffel C A, Connelly J N, Åhäll K-I, 1999. Timing and characterization of recurrent pre-Sveconorwegian metamorphism and deformation in the Varberg-Halmstad region of SW Sweden. Precambrian Research 98, 173–195.

Claesson S, Kresten P, 1997. The anorogenic Nora intrusion – a Mesoproterozoic rapakivi massif in south-central Sweden. GFF 119, 115–122.

Collins W J, 2002. Hot orogens, tectonic switching, and creation of continental crust. Geology 30, 535–538.

Connelly J N, Åhäll K-I, 1996. The mid-Proterozoic cratonisation of Laurentia-Baltica; new age constraints from SW Sweden. In T S Brewer (edit.), Precambrian Crustal Evolution in the North Atlantic Region. Geological Society of London Special Publication 112, 261–273.

Cousins S A O, 2001. Analysis of land cover transitions based on 17^{th} and 18^{th} century cadastral maps and aerial photographs. Landscape Ecology 16, 41–54.

Cronquist T, Forssberg O, Hansen L, Jonsson A, Koyi S, Leiner P, Sävås J, Vestgård J, 2004. Oskarshamn site investigation. Detailed fracture mapping of two outcrops at Laxemar. SKB P-04-274, Svensk Kärnbränslehantering AB.

Cronquist T, Forssberg O, Maersk Hansen L, Jonsson A, Leiner P, Vestgård J, Petersson J, 2005. Forsmark site investigation. Detailed fracture mapping of two trenches at Forsmark. SKB P-04-88, Svensk Kärnbränslehantering AB.

Cronquist T, Forssberg O, Hansen L, Koyi S, Vestgård J, Wikholm M, 2006. Oskarshamn site investigation. Detailed outcrop mapping on drillsite KLX11. SKB P-06-06, Svensk Kärnbränslehantering AB.

Dahlbäck G, Jansson B, Westin G T, 1972. Det Medeltida Sverige, Uppland, Norra Roden: Älvkarleby, Västlands, Österlövsta, Hållnäs, Valö, Börstils, Hargs, Hökhuvuds, Ekeby och Edebo socknar, 1:1. Riksantikvarieämbetet, Stockholm. (In Swedish).

Dahlbäck G, 1974. ”Landhöjning och bebyggelse i nordligaste Uppland” p 121–131 in Fornvännen 1974/3. (In Swedish).

Daniel E, 1989. Beskrivning till jordartskartan Växjö SV. SGU Ae 101, 77 pp

Davis B A S, Brewer S, Stevenson A C, Guiot J, Data Contributors, 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews 22, 1701–1716.

De Geer G, 1912. A Geochronology of the last 12,000 years. Compte Rendu du XI:e Congrès Géologique International, 241–253.

De Geer G, 1940. Geochronologia Suecia Principles. Kungliga vetenskapsakademiens Handlingar, Ser 111, 18 (6). 367 pp.

Drake H, Tullborg E-L, 2004. Oskarshamn site investigation. Fracture mineralogy and wall rock alteration, results from drill core KSH01A+B. SKB P-04-250, Svensk Kärnbränslehantering AB.

Drake H, Tullborg E-L, 2005. Oskarshamn site investigation. Fracture mineralogy and wall rock alteration, results from drill cores KAS04, KA1755A and KLX02. SKB P-05-174, Svensk Kärnbränslehantering AB.

Drake H, Tullborg E-L, 2006a. Oskarshamn site investigation. Fracture mineralogy, Results from drill core KSH03A+B. SKB P-06-03, Svensk Kärnbränslehantering AB.

Drake H, Tullborg E-L, 2006b. Oskarshamn site investigation. Fracture mineralogy of the Götemar granite, Results from drill cores KKR01, KKR02 and KKR03. SKB P-06-04, Svensk Kärnbränslehantering AB.

Drake H, Tullborg E-L, 2006c. Oskarshamn site investigation. Mineralogical, chemical and redox features of red-staining adjacent to fractures, Results from drill cores KSH01A+B and KSH03A+B. SKB P-06-01, Svensk Kärnbränslehantering AB.

Drake H, Tullborg E-L, 2006d. Oskarshamn site investigation. Mineralogical, chemical and redox features of red-staining adjacent to fractures, Results from drill core KLX04. SKB P-06-02, Svensk Kärnbränslehantering AB.

Drake H, Tullborg E-L, 2007. Oskarshamn site investigation. Fracture mineralogy. Results from drill cores KLX03, KLX04, KLX06, KLX07A, KLX08 and KLX10. SKB P-07-74, Svensk Kärnbränslehantering AB.

Drake H, Page L, Tullborg E-L, 2007. Oskarshamn site investigation. $^{40}Ar/^{39}Ar$ dating of fracture minerals. SKB P-07-27, Svensk Kärnbränslehantering AB.

Drake H, Tullborg E-L, Smellie J, MacKenzie A B, Suksi J, 2008. Fracture mineralogy Laxemar. Site descriptive modelling. SDM-Site Laxemar. SKB R-08-99, Svensk Kärnbränslehantering AB.

Droxler A W, Farrell J W, 2000. Marine Isotope Stage 11 (MIS 11): new insights for a warm future. Global and Planetary Change 24, 1–5.

Ekman M, 1996. A consistent map of the postglacial uplift of Fennoscandia. Terra Nova 8/2, 158–165.

El-Daoushy F, 1986. Scandinavian limnochronology of sediment and heavy metals. Hydrobiologia 143, 267–276.

Elhammer A, Sandkvist Å, 2005a. Forsmark site investigation: Detailed marine geological mapping. SKB P-03-111, Svensk Kärnbränslehantering AB.

Elhammer A, Sandkvist Å, 2005b. Oskarshamn site investigation: Detailed marine geological survey of the sea bottom outside Simpevarp. SKB P-05-35, Svensk Kärnbränslehantering AB.

Eliasson P, 1992. Genom helvetes port, men... Skogsdikning som mål och medel. Aktuellt om historia 3–4, 46–60. (In Swedish).

Elveland J, 1978. Skötsel av Norrländska rikkärr. Studier av vegetationsförändringar vid olika skötselåtgärder och annan påverkan. SNV PM 1007.

Emeis K C, Struck U, Leipe T, Pollehne F Kunzendorf H, Christiansen C, 2000. Changes in the C, N, P burial rates in some Baltic Sea sediments over the last 150 years-relevance to P regeneration rates and the phosphorus cycle. Marine Geology 167, 43–59.

Emeis K C, Struck U, Blanz T, Kohly A, Voss M, 2003. Salinity changes in the central Baltic Sea (NW Europe) over the last 10,000 years. The Holocene 13, 411–421.

Engelmark O, Hytteborn H, 1999. Coniferous forests. p. 2–8 In: Rydin H, (ed). Swedish plantgeography. Acta Phytogeographica Suecica 84, Opulus Press AB, Uppsala.

Engstrom D R, Fritz C S, Almendinger J E, Juggins S, 2000. Chemical and biological trends during lake evolution in recently deglaciated terrain. Nature 408, 161–166.

Erlström M, Sivhed U, 2001. Intra-cratonic dextral transtension and inversion of the southern Kattegat on the southwest margin of Baltica – Seismostratigraphy and structural development. SGU C 832, Sveriges geologiska undersökning.

Eronen M, 1983. Late Weichselian and Holocene shore displacement in Finland. In D.E. Smith and Dawson (eds): Shorelines and Isostacy. Institute of British Geographers, Special Publication 16, Academic Press, 183–207.

Eronen M, 1989. Eemian sea levels and crustal deformation in eastern Fennoscandia. GFF 111, 295–296.

Essemyr M, 1988. Bruksarbetarnas livsmedelskonsumtion: Forsmarks bruk 1730–1880, Uppsala. (In Swedish).

Fairbanks R, 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342, 637–642.

Farley K A, 2000. Helium diffusion from apatite: general behaviour as illustrated by Durango fluorapatite. Journal of Geophysical Research 105, 2903–2914.

Fitzgerald P G, Baldwin S L, Webb L E, O'Sullivan P B, 2006. Interpretation of (U-Th)/He single grain ages from slowly cooled crustal terranes: A case study from the Transantarctic Mountains of southern Victoria Land. Chemical Geology 225, 91–120.

Flodén T, 1977. Tectonic lineaments in the Baltic from Gävle to Simrishamn. KBS Teknisk Rapport 59.

Flodén T, 1980. Seismic stratigraphy and bedrock geology of the central Baltic. Stockholm contributions in geology 35. Doctoral Thesis, Stockholm University.

Flodén T, 1984. Der strukturbau im Seegebiet von Schweden. Zeitschrift für angewandte geologie 30, 2–16.

Flygare I, Isacson M, 2003. ”Jordbruket i välfärdssamhället 1945–2000.” I: Det svenska jordbrukets historia, band 5. Natur och kultur/LTs förlag. Örebro. (In Swedish).

Follin S, Stephens M B, Laaksoharju M, Nilsson A-C, Smellie J A T, Tullborg E-L, 2008. Modelling the evolution of hydrochemical conditions in the Fennoscandian Shield during Holocene time using mulidisciplinary information. Appl. Geochem. 23, 2004–2020.

Forsberg L, Larsson L, 1994. Tidiga fångstkulturer. In: K-G Selinge (ed): Kulturminnen och kulturmiljövård. Sveriges Nationalatlas, 10–15. ISBN 91-87760-25-8, Bra Böcker, Höganäs. (In Swedish).

Forssberg O, Cronquist T, Hansen L, Vestgård J, 2005. Oskarshamn site investigation. Detailed outcrop mapping at the drill site of KLX09 in Laxemar. SKB P-05-260, Svensk Kärnbränslehantering AB.

Forssberg O, Hansen L M, Koyi S, Vestgård J, Öhman J, Petersson J, Albrecht J, Hedenström A, Gustavsson J, 2007a. Forsmark site investigation. Detailed fracture and bedrock mapping, Quaternary investigations and GPR measurements at excavated outcrop AFM001264. SKB P-05-269, Svensk Kärnbränslehantering AB.

Forssberg O, Cronquist T, Vestgård J, Bergkvist L, Hermanson J, Öhman J, Pettersson A, Koyi S, Bergman T, 2007b. Oskarshamn site investigation. Detailed outcrop mapping in trenches. SKB P-07-29, Svensk Kärnbränslehantering AB.

Fredén C (ed), 1994. Geology. National Atlas of Sweden, 1st edition.

Fredén C (ed), 2002. Berg och jord. Sveriges Nationalatlas. Third edition. 208 pp. (In Swedish).

Fredriksson D, 2004. Peatland investigation Forsmark. Forsmark site investigation. SKB P-04-127, Svensk Kärnbränslehantering AB.

Funder S, 2000. The Baltic in the Eemian, evidence from mollusc faunas. Nordiske Geologiske Vintermøte. Abstract 24, 66–68.

Funder S, Demidov I, Yelovicheva Y, 2002. Hydrography and mollusc faunas of the Baltic and the White Sea-North Sea seaway in the Eemian. Palaoegeography, Palaeoclimatology, Palaeoclimatology 184, 275–304.

Gaál G, 1982. Proterozoic tectonic evolution and late Svecokarelian plate deformation of the Central Baltic Shield. Geologisch Rundschau 71, 158–170.

Garcia Ambrosiani K, 1990. Macrofossils from the till-covered sediments at Öje, central Sweden. In: Late Quaternary Stratigraphy in the Nordic Countries 150,000–15,000 B.P. (Andersen B G & Königsson L-K. Eds). Striae 34, 1–10

Gee D G, 1975. A tectonic model for the central part of the Scandinavian Caledonides. American Journal of Science 275A, 468–515.

Gierup J, Johansson R, Persson M, Stølen L K, Stephens M, Thunholm B, Wahlgren C-H, Wikman H, 1999a. Översiktsstudie av Kronobergs län: Geologiska förutsättningar. SKB R-99-19, Svensk Kärnbränslehantering AB.

Gierup J, Kübler L, Lindén A, Ripa M, Stephens M, Stølen L K, Thunholm B, 1999b. Översiktsstudie av Dalarnas län (urbergsdelen): Geologiska förutsättningar. SKB R-99-29, Svensk Kärnbränslehantering AB.

Gierup J, Johansson R, Pamnert P, Persson M, Stephens M, Thunholm B, Wahlgren C-H, Wikman H, 1999c. Översiktsstudie av Jönköpings län: Geologiska förutsättningar. SKB R-99-35, Svensk Kärnbränslehantering AB.

Gissel S, 1981. Desertion and land colonization in the Nordic countries ca 1300–1600. Comparative report from the Scandinavian research project on deserted farms and villages, Almqvist & Wiksell International, Stockholm.

Gorbatschev R, 1980. The Precambrian development of southern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 102, 129–136.

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

Guggisberg B C, 1986. Eine Zweidimenensionale Refraktionsseismische Interpretation der Geschwindigkeits-Tiefen-Struktur des Oberen Erdmantels unter dem Fennoskandischen Schild (Projekt Fennolora). Diss. ETH 7945, Zurich.

Gunnarsson U, Malmer N, Rydin H, 2002. Dynamics or constancy in Sphagnum dominated mire ecosystems? A 40-year study. Ecography 25, 685–704.

Gustafsson B, 2004a. Millennial changes of the Baltic Sea salinity. Studies of the sensitivity of the salinity to climate change. SKB TR-04-12, Svensk Kärnbränslehantering AB.

Gustafsson B, 2004b. Sensitivity of the Baltic Sea salinity to large perturbations in climate. Climate Research, 27, 237–251.

Gustafson L, Ljungberg A, 2006. Forsmark site investigation. GPS deformation measurements in Forsmark. Annual report 2006. SKB P-07-89, Svensk Kärnbränslehantering AB.

Göthberg A, Wahlman H, 2006. Inventory of vascular plants and classification of calcareous wetlands in the Forsmark area. Forsmark site investigation. SKB P-06-115, Svensk Kärnbränslehantering AB.

Hedenström A, Risberg J, 1999. Early Holocene shore-displacement in southern central Sweden based on as recorded in elevated isolated basins. Boreas 28, 490–504.

Hedenström A, 2001. Early Holocene shore displacement in eastern Svealand, Sweden, based on diatom stratigraphy, radiocarbon chronology and geochemical parameters. Doctoral thesis. Stockholm University. Department of Physical Geography and Quaternary Geology. Quaternaria Ser A, No 10. 36 pp.

Hedenström A, 2003. Forsmark site investigation. Investigation of marine and lacustrine sediments in lakes. SKB P-03-24, Svensk Kärnbränslehantering AB.

Hedenström A, Risberg J, 2003. Shore displacement in northern Uppland during the last 6,500 calendar years. SKB TR-03-17, Svensk Kärnbränslehantering AB.

Hedenström A, 2004. Forsmark site investigation. Investigation of marine and lacustrine sediments in lakes. Stratigraphical and analytical data. SKB P-04-86, Svensk Kärnbränslehantering AB.

Hedenström A, Sohlenius G, Albrecht J, 2004. Forsmark site investigation. Stratigraphical and analytical data from auger drillings and pits. SKB P-04-111, Svensk Kärnbränslehantering AB.

Hedenström A, Sohlenius G, 2008. Description of the regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-04, Svensk Kärnbränslehantering AB.

Hedenström A, Sohlenius G, Strömgren M, Brydsten L, Nyman H, 2008. Depth and stratigraphy of regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-07, Svensk Kärnbränslehantering AB.

Hegardt E A, Cornell D, Claesson L, Simakov S, Stein H, Hannah J, 2005. Eclogites in the central part of the Sveconorwegian Eastern Segment of the Baltic Shield: Support for an extensive eclogite terrane. GFF 127, 221–232.

Helmens K F, Bos J A A, Engels S, van Meerbeeck C J, Bohncke S, Renssen H, Heiri O, Brooks S J, Seppä H, Birks H J B, Wohlfarth B, 2007. Present-day temperatures in northern Scandinavia during the last glaciation. Geology 35, 987–990.

Henkel H, Pesonen L J, 1992. Impact craters and craterform structures in Fennoscandia. Tectonophysics 216, 31–40.

Hermanson J, Hansen L, Olofsson J, Sävås J, Vestgård J, 2003a. Forsmark site investigation. Detailed fracture mapping at the KFM02 and KFM03 drill sites. SKB P-03-12, Svensk Kärnbränslehantering AB.

Hermanson J, Hansen L, Vestgård J, Leiner P, 2003b. Forsmark site investigation. Detailed fracture mapping of the outcrops Klubbudden, AFM001098 and drill site 4, AFM001097. SKB P-03-115, Svensk Kärnbränslehantering AB.

Hermanson J, Hansen L, Vestgård J, Leiner P, 2004a. Forsmark site investigation. Detailed fracture mapping of excavated rock outcrop at drilling site 5, AFM100201. SKB P-04-90, Svensk Kärnbränslehantering AB.

Hermanson J, Hansen L, Wikholm M, Cronquist T, Leiner P, Vestgård J, Sandahl K-A, 2004b. Detailed fracture mapping of four outcrops at the Simpevarp peninsula and Ävrö. SKB P-04-35, Svensk Kärnbränslehantering AB.

Hermansson T, Stephens M B, Corfu F, Andersson J, Page L, 2007. Penetrative ductile deformation and amphibolite-facies metamorphism prior to 1851 Ma in the western part of the Svecofennian orogen, Fennoscandian Shield. Precambrian Research 153, 29–45.

Hermansson T, Stephens M B, Corfu F, Page L M, Andersson J, 2008. Migratory tectonic switching, western Svecofennian orogen, central Sweden: Constraints from U/Pb zircon and titanite geochronology. Precambrian Research 161, 250–278.

Hermansson T, Stephens M B, Page L M, in press. $^{40}Ar/^{39}Ar$ hornblende geochronology from the Forsmark area in central Sweden – constraints on late Svecofennian cooling, ductile deformation and exhumation. Precambrian Research.

Hietanen A, 1975. Generation of potassium-poor magmas in the northern Sierra Nevada and the Svecofennian in Finland. Journal of Research U.S. Geological Survey 3, 631–645.

Hofsten E, 1986. Svensk befolkningshistoria. Några grunddrag i utveckligen från 1750, Prisma, Göteborg. (In Swedish).

Hohl V, 2005. Northern European long term climate archives. SKB TR-05-01, Svensk Kärnbränslehantering AB.

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

Houmark-Nielsen M, Kjær K, 2003. Southwest Scandinavia, 40–15 kyr BP: paleogeography and environmental change. Journal of Quaternary Science 18, 769–786.

Hubbard F H, 1975. The Precambrian crystalline complex of south-western Sweden; the geology and petrogenetic development of the Varberg region. Geologiska Föreningens i Stockholm Förhandlingar 97, 223–236.

Huntley B, Birks H J B, 1983. An atlas of past and present pollen maps for Europe: 0–13,000 years ago. Cambridge University Press. 667 pp.

Hutchinson G E, 1975. A treatise on limnology. Wiley.

Hyenstrand Å, 1994. Kulturminnen och kulturmiljövård. In: K-G Selinge (ed): Kulturminnen och kulturmiljövård. Sveriges Nationalatlas, 8–9. ISBN 91-87760-25-8, Bra Böcker, Höganäs. (In Swedish).

Hättestrand C, 1994. Boulder depressions in central Sweden-remnants of a pre-Late Weichselian landscape? Geografiska Annaler 76, 153–160.

Hättestrand C, Stroeven A, 2002. A preglacial landscape in the centre of Fennoscandian glaciation: geomorphological evidence of minimal Quaternary glacial erosion. Geomorphology 44, 127–143.

Högdahl K, Andersson A, Eklund O (eds), 2004. The Transscandinavian Igneous belt (TIB) in Sweden: a review of its character and evolution. Geological Survey of Finland Special Paper 37.

Ingmar T, 1963. Från havsvik till mosse – något om Florornas utveckling. Sveriges Natur, Årsbok 1963, 120–132. (In Swedish).

Ingmar T, Moreborg K, 1976. The leaching and original content of calcium carbonate in till in northern Uppland, Sweden. Geologiska Föreningens i Stockholm Förhandlingar 98, 120–132.

Ingvarson N H, Palmeby A S L F, Svensson L O, Nilsson K O, Ekfeldt T C I, 2004. Oskarshamn site investigation – Marine survey in shallow coastal waters, Bathymetric and geophysical investigation 2004. SKB P-04-254, Svensk Kärnbränslehantering AB.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K B, Tignor M, Miller H L (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Jakobsson M, Björck S, Alm G, Lindeberg G, Svensson N-O, 2007. Reconstructing the Younger Dryas ice dammed lake in the Baltic Basin: Bathymetry, area and volume. Global and Planetary Change 57, 355–370.

Japsen P, Bidstrup T, Lidmar-Bergström K, 2002. Neogene uplift and erosion of southern Scandinavia induced by the rise of the South Swedish Dome. In A G Doré, J A Cartwright, M S Stoker, J P Turner and N White (eds), Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. Geological Society Special Publication 196, 183–207.

Johansson L, Johansson Å, 1990. Isotope geochemistry and age relationships of mafic intrusions along the Protogine Zone, southern Sweden. Precambrian Research 48, 395–414.

Johansson J M, et al. 2002. Continuous GPS measurements of postglacial adjustment in Fennoscandia: 1. Geodetic results. Journal of Geophysical Research 107, doi: 10.1029/2001JB000400.

Johansson P-O, 2003. Forsmark site investigation. Drilling and sampling in soil. Installation of groundwater monitoring wells and surface water level gauges. SKB P-03-64, Svensk Kärnbränslehantering AB.

Johansson T, Adestam L, 2004. Oskarshamn site investigation, Drilling and sampling in soil – Installation of groundwater monitoring wells in the Laxemar area. SKB P-04-317, Svensk Kärnbränslehantering AB.

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

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

Jonsell B, Jonsell L, 1995. Floran i Hållnäs socken: Svensk Botanisk Tidskrift, 89: 257. (In Swedish).

Jönsson L O, 1979. Studier av deglaciationen inom Växsjö – Alvestaområdet. In Projektgruppen för deglaciationsundersökningar på Sydsvenska höglandet: Problem och undersökningsmetodik rörande deglaciationsmönstret i Sydsverige. University of Lund, Department of Quaternary Geology, 29–46.

Kaislahti Tillman P, Risberg J, 2006. Oskarshamn site investigation. Holocene sedimentary environmental changes at sites PSM002118 and PSM002123 offshore Simpevarp. SKB P-06-250, Svensk Kärnbränslehantering AB.

Kardell L, 2003. Svenskarna och skogen. D. 1, Från ved till linjeskepp, Skogsstyrelsens förlag, Jönköping. (In Swedish).

Karlén W, Bodin A, Kuylenstierna J, Näslund J-O, 1995. Climate of Northern Sweden during the Holocene. Journal of Coastal Research, Special Issue 17, 49–54.

Karlén W, 1998. Climate variations and the enhanced greenhouse effect. Ambio 27, 270–274.

Karlsson P-A, 1990. Järnbruken och ståndssamhället. Institutionell och attitydmässig konflikt under Sveriges tidiga industrialisering. Jernkontorets bergshistoriska skriftserie 25. Stockholm. (In Swedish).

Karlsson S, 2007. Stone age vegetation in Uppland, Southeastern Svealand, Sweden. GFF 129, 295–305.

Kautsky U (ed), 2001. The biosphere today and tomorrow in the SFR area. SKB R-01-27, Svensk Kärnbränslehantering AB.

Kellner E, 2007. Effects of variations in hydraulic conductivity and flow conditions on groundwater flow and solute transport in peatlands. SKB P-07-41, Svensk Kärnbränslehantering AB.

Kijko A, Skordas E, Wahlström R, Mäntyniemi P, 1993. Maximum likelihood estimation of seismic hazard for Sweden. Natural Hazards 7, 41–57.

Kinck J J, Husebye E S, Larsson F R, 1993. The Moho depth distribution in Fennoscandia and the regional tectonic evolution from Archean to Permian times. Precambrian Research 64, 23–51.

Kleman J, Hättestrand C, Borgström I, Stroeven A, 1997. Fennoscandian palaeoglaciology reconstructed using a glacial geological inversion model. Journal of Glaciology 43, 283–299.

Koistinen T, Stephens M B, Bogatchev V, Nordgulen O, Wennerström M, Korhonen J, 2001. Geological map of the Fennoscandian Shield, scale 1:2 000 000. Geological Surveys of Finland, Norway and Sweden and the North-West Department of Natural Resources of Russia.

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

Kortekaas M, Murray A S, Sandgren P, Björck S, in press. OSL chronology for a sediment core from the southern Baltic Sea: A continuous sedimentation record since deglaciation. Accepted for publication in Quaternary Geochronology.

Kresten P, Chyssler J, 1976. The Götemar massif in south-eastern Sweden: A reconnaissance survey. Geologiska Föreningens i Stockholm Förhandlingar 98, 155–161.

Kristiansson J, 1986. The ice recession in the south-easten part of Sweden. University of Stockholm. Department of Quaternary Research 7, 132 pp.

Kuivamäki A, Vuorela P, Paananen M, 1998. Indications of postglacial and recent bedrock movements in Finland and Russian Karelia. Geological Survey of Finland, Report YST-99.

Kulling O, 1972. The Swedish Caledonides. In T Strand and O Kulling (eds), Scandinavian Caledonides. John Wiley and Sons, London.

Küttel M, 1985. Biostratigraphische und paläoökologische untersuchungen in SE-Småland, Schweden. Striae 21, 34 pp.

Laaksoharju M, Smellie J, Tullborg E-L, Gimeno M, 2008. Hydrogeochemistry Forsmark, Site descriptive modelling, SDM-Site Forsmark. SKB R-08-47, Svensk Kärnbränslehantering AB.

Lagerbäck, 1979. Neotectonic structures in northern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 100, 263–269.

Lagerbäck R, 1986. Weichselistiden i norra Sverige. 17 Nordiska Geologmötet 1986, Helsingfors Universitet. Abstracts 92.

Lagerbäck R, 1988. Periglacial phenomena in the wooded areas of northern Sweden – relicts from the Tärendö interstadial. Boreas 17, 487–499.

Lagerbäck R, Robertsson A-M, 1988. Kettle holes – stratigraphical archives for Weichselian geology and palaeoenvironment in northernmost Sweden. Boreas 17, 439–468

Lagerbäck R, 1990. Late Quaternary faulting and paleoseismicity in northern Fennoscandia, with particular reference to the Lansjärv area, northern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 112, 333–354.

Lagerbäck R, Sundh M, 2003. Forsmark site investigation. Searching for evidence of late- or post-glacial faulting in the Forsmark region. Results from 2002. SKB P-03-76, Svensk Kärnbränslehantering AB.

Lagerbäck R, Sundh M, Johansson H, 2004a. Forsmark site investigation. Searching for evidence of late- or post-glacial faulting in the Forsmark region. SKB P-04-123, Svensk Kärnbränslehantering AB.

Lagerbäck R, **Sundh M, Svedlund J-O, 2004b.** Oskarshamn site investigation. Searching for evidence of late- or postglacial faulting in the Oskarshamn region. SKB P-04-192, Svensk Kärnbränslehantering AB.

Lagerbäck R, Sundh M, Svedlund J-O, Johansson H, 2005a. Forsmark site investigation. Searching for evidence of late- and postglacial faulting in the Forsmark region. Results from 2002–2004. SKB R-05-51, Svensk Kärnbränslehantering AB.

Lagerbäck R, **Sundh M, Svantesson S-I, Svedlund J-O, 2005b.** Oskarshamn site investigation. Searching for evidence of late- or postglacial faulting in the Oskarshamn region. SKB P-05-232, Svensk Kärnbränslehantering AB.

Lagerbäck R, **Sundh M, Svantesson S-I, 2006.** Oskarshamn site investigation. Searching for evidence of late- or postglacial faulting in the Oskarshamn region. Results from 2005. SKB P-06-160, Svensk Kärnbränslehantering AB.

Lagerbäck R, 2007a. Ventifacts – means to reconstruct glacial development and palaeo-environment in northern and central Sweden. GFF 129, 315–324.

Lagerbäck R, 2007b. Vilken ålder har den periglaciala vindslipningen I södra Sverige? Uppföljning 2007. SGU-report 2007:37. Utförd inom programmet för geologisk dokumentation.

Lagerlund E, 1987. An alternative Weichselian glaciation model, with special reference to the glacial history of Skåne, South Sweden. Boreas 16, 433–459.

Lahdenperä A M, 2006. Literature Review on Future Development of the Baltic Sea and Recommendations for Safety Modelling. POSIVA Working Report 2006-111, POSIVA Oy.

Lahtinen R, Korja A, Nironen M, 2005. Paleoproterozoic tectonic evolution. In Lehtinen M, Nurmi P A, Rämö O T (eds), Precambrian Geology of Finland – Key to the Evolution of the Fennoscandian Shield. Elsevier B.V., Amsterdam, 481–532.

Lambeck K, 2006. Hyperbolic tangents are no substitute for simple classical physics. GFF 128, 349–350.

Landin M, Rönnby J, 2002. Tomtningar i utskärgården från yngre järnåldern. Arkeologiska undersökningar på Landsort, Torö socken, Södermanland. Research Reports 6: 2002. Södertörns Högskola. (In Swedish).

Landström O, Aggeryd I, Mathiasson L, Sundblad B, 1994. Chemical composition of sediments from the Äspö area and interaction between biosphere and geosphere. SKB Arbetsrapport forskning och utveckling 94-13, Svensk Kärnbränslehantering AB.

Larson S Å, Tullborg E-L, 1993. Tectonic regimes in the Baltic Shield during the last 1200 Ma – A review. SKB TR-94-05, Svensk Kärnbränslehantering AB.

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

Larson S Å, Cederbom C, Tullborg E-L, Stiberg J-P, 2006. Comment on ”Apatite fission track and (U-Th)/He data from Fennoscandia: An example of underestimation of fission track annealing in apatite” by Hendriks and Redfield (Earth Planet. Sci. Lett. 236, 443–458). Earth and Planetary Science Letters 248, 561–568.

Lay T, Wallace T C, 1995. Modern Global Seismology. Academic Press, San Diego.

Leijon B (ed), 2005. Forsmark site investigation. Investigations of superficial fracturing and block displacements at drill site 5. SKB P-05-199, Svensk Kärnbränslehantering AB.

Lidmar-Bergström K, 1991. Phanerozoic tectonics in southern Sweden. Zeitschrift für Geomorphologie N.F. 82, 1–16.

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

Lidmar-Bergström K, 1994. Morphology of the bedrock surface. In C Fredén (edit.), Geology. National Atlas of Sweden, 1st edition, 44–54.

Lidmar-Bergström K, 1995. Relief and saprolites through time on the Baltic Shield. Geomorphology 12, 45–61.

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

Lidmar-Bergström K, Olsson S, Olvmo M, 1997. Paleosurfaces and associated saprolites in southern Sweden. Geological Society 120, 95–124.

Lidmar-Bergström K, Näslund J O, 2002. Landforms and uplift in Scandinavia. In A G Doré, J A Cartwright, M S Stoker, J P Turner and N White (eds), Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. Geological Society Special Publication 196, 103–116.

Lindbladh M, Niklasson M, Nilsson S G, 2003. Long-time record of fire and open canopy in a high biodiversity forest in southeast Sweden. Biological Conservation 114, 231–243.

Lindbladh M, 2004. När granen kom till byn – några tankar kring granens invandring i södra Sverige. Svensk botanisk tidskrift 98, 249–262.

Lindborg T, 2006. Description of surface systems. Preliminary site description Laxemar subarea – Version 1.2. SKB R-06-11, Svensk Kärnbränslehantering AB.

Lindén A, 1984. Some ice-marginal deposits in the east-central part of the South Swedish Upland. Sveriges Geologiska Undersöknig C 805, 35 pp.

Lindroos H, 2004. Oskarshamn site investigation. The potential for ore, industrial minerals and commercial stones in the Simpevarp area. SKB R-04-72, Svensk Kärnbränslehantering AB.

Liski J, Ilvesniemi H, Mäkelä A, Starr M, 1998. Model analysis of the effects of soil age, fires and harvesting on the carbon storage of boreal forests. European J. Soil Sci. 49(3):407–416.

Lokrantz H, Sohlenius G, 2006. Ice marginal fluctuations during the Weichselian glaciation in Fennoscandia, a literature review. SKB TR-06-36, Svensk Kärnbränslehantering AB.

Lund B, 2005. Effects of deglaciation on the crustal stress field and implications for endglacial faulting: A parametric study of simple Earth and ice models. SKB TR-05-04, Svensk Kärnbränslehantering AB.

Lund B, 2006. Stress variations during a glacial cycle at 500 m depth in Forsmark and Oskarshamn: Earth model effects. SKB R-06-95, Svensk Kärnbränslehantering AB.

Lundberg E, Sjöström H, 2006. Oskarshamn site investigation. Kinematic analysis of ductile and brittle/ductile shear zones in Simpevarp and Laxemar subareas. SKB P-06-118**,** Svensk Kärnbränslehantering AB.

Lundin L, Lode E, Stendahl J, Melkerud P A, Björkvald L, Thorstensson A, 2004. Soils and site types in the Forsmark area. R-04-08, Svensk Kärnbränslehantering AB.

Lundin L, Lode E, Stendahl J, Björkvald L, Hansson J, 2005. Soils and site types in the Oskarshamn area. SKB R-05-15, Svensk Kärnbränslehantering AB.

Lundqvist J, Lagerbäck R, 1976. The Pärve Fault: A late-glacial fault in the Precambrian of Swedish Lapland. Geologiska Föreningens i Stockholm Förhandlingar 98, 45–51.

Lundqvist T, 1968. Precambrian geology of the Los-Hamra region, central Sweden. SGU Ba 23, Sveriges geologiska undersökning.

Lundqvist J, 1985. Deep-weathering in Sweden. Fennia 163, 287–292.

Lundqvist J, 1992. Glacial stratigraphy in Sweden. Geological Survey of Finland Special Paper 15. 43–59.

Lundqvist J, Wohlfarth B, 2001. Timing and east-west correlation of south Swedish ice marginal lines during the Late Weichselian. Quaternary Science Reviews 20, 1127–1148.

Lundqvist J, 2002. Weichsel-istidens huvudfas. In C Fredén (edit.), Berg och jord. Sveriges nationalatlas, tredje utgåvan, 124–136.

Lundqvist L, 2006. Inledande kulturhistoriska studier i Simpevarpsområdet: Småland, Misterhults socken, Oskarshamn kommun. SKB R-06-65, Svensk Kärnbränslehantering AB. (In Swedish).

Lundström I, Persson P-O, Ahl M, 2002. Ages of post-tectonic dyke porphyries and breccias in Bergslagen, south-central Sweden. In S Bergman (edit.), Radiometric dating results 5. SGU C 834, 43–49.

Luosto U, 1997. Structure of the Earth's crust in Fennoscandia as revealed from refraction and wide-angle reflection studies. In L J Pesonen (edit.), The Lithosphere in Finland – a geophysical perspective. Geophysica 33, 3–16.

Löfgren A, Jerling L, 2002. Species richness, extinction and immigration rates of vascular plants on islands in the Stockholm archipelago, Sweden, during a century of ceasing management. Folia Geobotanica 37:3, 297–308.

Löfgren A (ed), 2008. The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp. Site descriptive modelling, SDM-Site. SKB R-08-01, Svensk Kärnbränslehantering AB.

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

Malmberg Persson K, Persson M Lindén A, 2007. Israndstråket Vimmerbymoränen mellan Knivshult och Vanstad i nordöstra Småland. SGU-rapport 2007:7. Geological Survey of Sweden.

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

Mansfeld J, Beunk F F, Barling J, 2005. 1.83–1.82 Ga formation of a juvenile volcanic arc – implications from U-Pb and Sm-Nd analyses of the Oskarshamn-Jönköping Belt, southeastern Sweden. GFF 127, 149–157.

Martin C D, Christiansson R, 2007. Interpreting in situ stress measurements using geological models, Sweden. In L R Sousa, C Olalla and N Grossmann (edit.), Proceedings 11th Congress of the International Society for Rock Mechanics, Lisbon, Taylor & Francis Group, London, 935–938

Milankovitch M, 1941. Canon of insolation and the Ice-Age problem. K. serb. akad. georg., special Publications No 132. (Translation into English by Israel Programme for Scientific Translations, Jerusalem 1969, US Dept. of Commerce).

Milne G A, Mitrovica J X, Scherneck H-G, Davis J L, Johansson J M, Koivula H, Vermeer M, 2004. Continuous GPS measurements of postglacial adjustment in Fennoscandia: 2. Modeling results. Journal of Geophysical Research 109, doi: 10.1029/2003JB002619.

Milnes A G, Gee D G, 1992. Bedrock stability in southeastern Sweden. Evidence from fracturing in the ordovician limestones of northern Öland. SKB TR 92-23, Svensk Kärnbränslehantering AB.

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

Ministry of the Environment, 2007. Klimat och sårbarhetsutredningens slutbetänkande. The Swedish Ministry of the Environment. SOU 2007:60

Mitsch W J, Gosselink J G, 2000. Wetlands. John Wiley & Sons, New York, US.

Morell M, 2001. ”Jordbruket i industrisamhället:1870–1945”. I: Det svenska jordbrukets historia, Band 4, Natur och kultur/LT i samarbete med Nordiska museet och Stift. Lagersberg, Stockholm. (In Swedish).

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

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

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

Munier R, 1995. Studies of geological structures at Äspö. Comprehensive summary of results. SKB PR 25-95-21, Svensk Kärnbränslehantering AB.

Munier R, Hökmark H, 2004. Respect distances. Rationale and means of computation. SKB R-04-17, Svensk Kärnbränslehantering AB.

Munthe H, 1892. Baltiska hafvets qvartära historia. Bihang till Kungliga svenska vetenskaps akademiens handlingar 18. 120 pp. (In Swedish).

Munthe H, 1894. Preliminary report on the physical geography of the Litorina Sea. Bulletin of the Geological Institution of the University of Upsala 2, 1–38.

Munthe H, 1910. Studier over Gotlands senkvatära historia. Sveriges Geologiska Undersökning Ca 4, 213 p.

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

Möller C, 1998. Decompressed eclogites in the Sveconorwegian (-Grenvillian) orogen of SW Sweden: petrology and tectonic implications. Journal of Metamorphic Petrology 16, 641–656.

Möller C, Andersson J, Lundqvist I, Hellström F, 2007. Linking deformation, migmatite formation and zircon U-Pb geochronology in polymetamorphic orthogneisses, Sveconorwegian Province, Sweden. Journal of Metamorphic Petrology 25, 727–750.

Mörner N-A, 1990. The failure in defining an acceptable bedrock repository for nuclear waste deposition. Geologiska Föreningen i Stockholm Förhandlingar 112, 375–380.

Mörner N A, 2003. Paleoseismicity of Sweden a novel paradigm. Paleogeophysics & Geodynamics, Stockholm.

Niering W A, 1989. Wetland vegetation development. In Majumdar S K, Brooks R P, Brenner F J, Tiner J R W (eds) Wetlands Ecology Conservation: Emphasis in Pennsylvania. Pennsylvania Academy of Science, Easton, 103–113.

Nilsson L, 1992. Historisk tätortsstatistik. Del 1: Folkmängden i administrativa tätorter 1800–1970, Stads- och kommunhistoriska institutet, Stockhom. (In Swedish).

Nilsson G, 2004. Oskarshamn site investigation – Investigation of sediments, peat lands and wetlands. Stratigraphical and analytical data. SKB P-04-273, Svensk Kärnbränslehantering AB.

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

Nyborg M, Vesti E, Wilén P, 2004. Oskarshamns site investigation – Hydrogeological inventory in the Oskarshamn area. SKB P-04-277, Svensk Kärnbränslehantering AB.

Nyström J-O, 2004. Dala volcanism, sedimentation and structural setting. In K Högdahl, A Andersson and O Eklund (eds), The Transscandinavian Igneous belt (TIB) in Sweden: a review of its character and evolution. Geological Survey of Finland Special Paper 37, 58–70.

Näslund J O, Rodhe L, Fastook J L, Holmlund P, 2003. New ways of studying ice sheet flow directions and glacial erosion by computer modelling-examples from Fennoscandia. Quaternary Sciences Reviews 22, 245–258.

Ojala V J, Kuivamäki A, Vuorela P, 2004. Postglacial deformation of bedrock in Finland. Report YST-120, Geological Survey of Finland, Nuclear Waste Disposal Research.

Olesen O, Blikra L H, Braaten A, Dehls J F, Olsen L, Rise L, Roberts D, Riis F, Faleide J I, Anda E, 2004. Neotectonic deformation in Norway and its implications: a review. Norwegian Journal of Geology 84.

Olofsson I, Simeonov A, Stigsson M, Stephens M, Follin S, Nilsson A-C, Röshoff K, Lindberg U, Lanaro F, Fredriksson A, Persson L, 2007. Site descriptive modelling Forsmark, stage 2.2. A fracture domain concept as a basis for the statistical modelling of fractures and minor deformation zones, and interdisciplinary coordination. SKB R-07-15, Svensk Kärnbränslehantering AB.

Olsen L, Mejdahl V, Selvik S, 1996. Middle and Late Pleistocene stratigraphy, Finnmak, north Norway. NGU Bulletin 429, 111p.

Olsson M, Melkerud P A, 1989. Chemical and mineralogical changes during genesis of a podzol from till in southern Sweden. Geoderma 45, 267–287.

Page L, Hermansson T, Söderlund P, Andersson J, Stephens M B, 2004. Forsmark site investigation. Bedrock mapping. U/Pb, $^{40}Ar/^{39}Ar$ and (U-Th)/He geochronology. SKB P-04-126, Svensk Kärnbränslehantering AB.

Page L, Hermansson T, Söderlund P, Stephens M B, 2007a. Forsmark site investigation. $^{40}Ar/^{39}Ar$ and U-Th/He geochronology: Phase 2. SKB P-06-211, Svensk Kärnbränslehantering AB.

Page L, Söderlund P, Wahlgren C-H, 2007b. Oskarshamn site investigation. $^{40}Ar/^{39}Ar$ and (U-Th)/He geochronology of samples from the cored boreholes KSH03A, KSH03B, KLX01, KLX02 and the access tunnel to the Äspö Hard Rock Laboratory. SKB P-07-160, Svensk Kärnbränslehantering AB.

Pan M, Sjöberg L E, 1999. Estimating present day post-glacial rebound and horizontal movements in Fennoscandia by repeated GPS campaigns in 1993 and 1997. Geophysical Research Letters 26, 771–774.

Pan M, Sjöberg L E, Talbot C J, Asenjo E, 1999. GPS measurements of crustal deformation in Skåne, Sweden, between 1989 and 1996. GFF 121, 67–72.

Park A F, 1985, Accretion tectonism in the Proterozoic Svecokarelides of the Baltic Shield. Geology 13, 725–729.

Patchett P J, Gorbatschev R, Todt W, 1987. Origin of continental crust of 1.9–1.7 Ga age: Nd isotopes in the Svecofennian orogenic terrains of Sweden. Precambrian Research 35, 145–160.

Persson C, 1985. Jordartskarta 12I Östhammar NO med beskrivning. Sveriges geologiska undersökning Ae 73. (In Swedish with English summary).

Persson C, 1986. Jordartskarta 13I Österlövsta SO/13J Grundkallen SV med beskrivning. Sveriges geologiska undersökning Ae 76. (In Swedish with English summary).

Persson C, 1992. The latest ice recession and till deposits in northern Uppland, eastern central Sweden. Sveriges Geologiska Undersökning, Ser. Ca 81, pp 217–224.

Persson K S, Sjöström H, 2003. Late-orogenic progressive shearing in eastern Bergslagen, central Sweden. GFF 125, 23–36.

Persson Nilsson K, Bergman T, Eliasson T, 2004. Oskarshamn site investigation. Bedrock mapping 2004 – Laxemar subarea and regional model area. Outcrop data and description of rock types. SKB P-04-221, Svensk Kärnbränslehantering AB.

Petersson J, Skogsmo G, Vestgård J, Albrecht J, Hedenström A, Gustavsson J, 2007. Forsmark site investigation. Bedrock mapping and magnetic susceptibility measurements, Quaternary investigations and GPR measurements in trench AFM001265. SKB P-06-136, Svensk Kärnbränslehantering AB.

Punning J-M, Martma T, Kessel H, Vaikmäe R, 1988. The isotopic composition of oxygen and carbon in the subfossil mollusc shells of the Baltic Sea as an indicator of palaeosalinity. Boreas 17, 27–31.

Pusch R, Börgesson L, Knutsson S, 1990. Origin of silty fracture fillings in crystlline bedrock. Geologiska Föreningens i Stockolm Förhandlingar 112, 209–213.

Påsse T, Robertsson A-M, Miller U, Klingberg F, 1988. A late Pleistocene sequence at Margreteberg, southwestern Sweden. Boreas 17, 141–163.

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

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

Påsse T, 2004. The amount of glacial erosion of the bedrock. SKB TR-04-25, Svensk Kärnbränslehantering AB.

Påsse T, Andersson L, 2005. Shore-level displacement in Fennoscandia calculated from empirical data. Geologiska Föreningens i Stockholm Förhandlingar 127, 253–268.

Påsse T, 2006. Never forget the highest coastline! – Reply to "Hyperbolic tangents are not substitute for simple classical physics". GFF 128, 350–351.

Rahmqvist S (ed), 1999. Det Medeltida Sverige, Småland, Aspeland, Sevede, Tuna län, 4:4, Riksantikvarieämbetet, Stockholm. (In Swedish).

Ranheden, 1989. Barknåre och Lingnåre, human impact and vegetational development in an area of subrecent landuplift. Striae 33.

Renting A, 1996. I skuggan av Lövsta bruk. Järnbruksrörelsens inverkan på agrarsamhället i norra Uppland 1630–1930, Rapporter från Barknåreprojektet nr 6, Meddelanden nr 96, Kulturgeografiska institutionen, Stockholms universitet. (In Swedish).

Ringberg B, Hang T, Kristiansson J, 2002. Local clay-varve chronology in the Karlskrona-Hultsfred region, southeast Sweden. GFF 124, 79–86

Risberg J, 1991. Palaeoenvironment and sea level changes during the early Holocene on the Södertörn peninsula, Södermanland, eastern Sweden. Department of Quaternary Research, Stockholm University, Report 20, 1–27.

Risberg J, Miller U, Brunnberg L, 1991. Deglaciation, Holocene shore displacement and coastal settlements in eastern Svealand, Sweden. Quaternary International 9, 33–39.

Risberg J, Sandgren P, Andrén E, 1996. Early Holocene shore displacement and evidence of irregular isostatic uplift nothwest of Lake Vanern, western Sweden. Journal of Paleolimnology 15, 47-63.

Risberg J, 2002. Holocene sediment accumulation in the Äspö area. SKB R-02-47, Svensk Kärnbränslehantering AB.

Risberg J, 2005. Bio- and lithostratigraphy in off shore sediment core PFM004396. Salinity variations in the Bothnian Sea off-shore Forsmark. Forsmark site investigation. SKB P-05-139, Svensk Kärnbränslehantering AB.

Risberg J, Alm G, Goslar T, 2005. Variable isostatic uplift patterns during the Holocene in southeast Sweden, based on high-resolution AMS radiocarbon datings of lake isolations. The Holocene, 15, 847–857.

Roberts D, Stephens M B, 2000. Caledonian orogenic belt. In Lundqvist T and Autio S, Description to the Bedrock Map of Central Scandinavia (Mid-Norden). Geological Survey of Finland Special Paper 28, 79–104.

Robertsson A-M, Persson Ch, 1989. Biostratigraphical studies of three mires in northern Uppland, Sweden. Sveriges Geologiska Undersökning, Ser C 821, 19 pp.

Robertsson A-M, Garcia Ambrosiani K, 1992. The Pleistocene in Sweden – a review of research, 1960–1990. Sveriges Geologiska Undersökning Ca 81. 299–306.

Robertsson A-M, 1997. Shore displacement in north-eastern Småland c. 9000–2500 BP. Sveriges Geologiska Undersökning Ca 86, 145–152.

Robertsson A-M, Svedlund J-O, Andrén Th, Sundh M, 1997. Pleistocene stratigraphy in the Dellen region, central Sweden. Boreas 26, 237–260.

Robertsson A-M, 2000. The Eemian interglacial in Sweden, and comparison with Finland. Geologie en Mijnbouw/Netherlands Journal of Geosciences 79, 325–333.

Robertsson A-M, 2004. Forsmark site investigation. Microfossil analyses of till and sediment samples from Forsmark, northern Uppland. SKB P-04-110, Svensk Kärnbränslehantering AB.

Robertsson A-M, Lundqvist J, Brunnberg L, 2005. Dark clayey till in central and northern Sweden – microfossil content and stratigraphical importance. GFF, vol 127, pp. 169–178.

Rosén E, Borgegård S-O, 1999. The open cultural landscape. In: Rydin H, Snoeijs P and Diekmann M (eds), Swedish plant geography. Acta Phytogeographica.

Rudmark L, 2000. Beskrivning till jordartskartan 5G Oskarshamn NO. SGU Ae 94. 64 pp.

Rudmark L, Malmberg-Persson K, Mikko H, 2005. Oskarshamn site investigation – Investigation of Quaternary deposits 2003–2004. SKB P-05-49, Svensk Kärnbränslehantering AB.

Rydin H, Borgegård S-O, 1991. Plant characteristics over a centuary of primary succession on islands: Lake Hjälmaren. Ecology 72(3):1089–1101.

Rydin H, Sjörs H, Löfroth M, 1999. Mires. In: Rydin H, Snoeijs P and Diekmann M (eds). Swedish plant geography. Acta Phytogeogr. Suec. 84: 91–112.

Rydström S, 1971. The Värend district during the last glaciation. GFF 93, 537–552.

Röshoff K, Cosgrove J, 2002. Sedimentary dykes in the Oskarshamn-Västervik area. A study of the mechanism of formation. SKB R-02-37, Svensk Kärnbränslehantering AB.

Sandelin S, 1992. Öregrund, Roslagens pärla, Streiffert Stockholm. (In Swedish).

Sandström B, Savolainen M, Tullborg E-L, 2004. Forsmark site investigation. Fracture mineralogy. Results from fracture minerals and wall rock alteration in boreholes KFM01A, KFM02A, KFM03A and KFM03B. SKB P-04-149, Svensk Kärnbränslehantering AB.

Sandström B, Tullborg E-L, 2005. Forsmark site investigation. Fracture mineralogy. Results from fracture minerals and wall rock alteration in boreholes KFM01B, KFM04A, KFM05A and KFM06A. SKB P-05-197, Svensk Kärnbränslehantering AB.

Sandström B, Tullborg E-L, 2006. Forsmark site investigation. Fracture mineralogy. Results from KFM06B, KFM06C, KFM07A, KFM08A, KFM08B. SKB P-06-226, Svensk Kärnbränslehantering AB.

Sandström B, Tullborg E-L, de Torres T, Ortiz J E, 2006a. The occurrence and possible origin of asphaltite in bedrock fractures, Forsmark, central Sweden. GFF 128, 233–242.

Sandström B, Page L, Tullborg E-L, 2006b. Forsmark site investigation. $^{40}Ar/^{39}Ar$ (adularia) and Rb-Sr (adularia, prehnite, calcite) ages of fracture minerals. SKB P-06-213, Svensk Kärnbränslehantering AB.

Sandström B, Tullborg E-L, 2007. Paleohydrogeological events in Forsmark, central Sweden, recorded by stable isotopes in calcite and pyrite. In Water-Rock Interaction, Taylor and Francis Group, London, 773–776.

Sandström B, Tullborg E-L, Page L, 2007. Forsmark site investigation. Fracture mineralogy and $^{40}Ar/^{39}Ar$ ages of adularia in fracture filling and K-feldspar in breccia. Data from drill cores KFM01C, KFM01D, KFM02B, KFM04A, KFM06A, KFM06B, KFM07A, KFM08A, KFM08B, KFM08C, KFM08D, KFM09A, KFM09B, KFM10A and KFM11A. SKB P-08-14, Svensk Kärnbränslehantering AB.

Sandström B, Tullborg E-L, Smellie J, MacKenzie A B, Suksi J, 2008. Fracture mineralogy of the Forsmark site. SDM-Site Forsmark. SKB R-08-102, Svensk Kärnbränslehantering AB.

Sauramo M, 1958. Die Geschichte der Ostsee. Annales Academiae Scientarum Fennicae A3 51, 522 pp.

Schoning K, 2001. Marine conditions in middle Sweden during the Late Weichselian and Early Holocene as inferred from foraminifirea, Ostracoda and stable isotopes. Stockholm University, Department of Physical Geography and Quaternary Geology. Quaternaria Ser A, No 8. 26. pp. Doctoral thesis.

Schoning K, Klingberg F, Wastegård S, 2001. Marine conditions in central Sweden during the early Preboreal as inferred from a stable oxygen gradient. Journal of Quaternary Science 16, 785–784.

Schulz H-P, 1998. De tog skydd i Varggrottan. De första spåren av människor i Norden är mer än hundratusen år gamla. Populär Arkeologi. Årgång 16, Nr 3, 1998. s. 3–7 (in Swedish).

Shackleton N J, Berger A, Peltier W R, 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. Transactions of the Royal Society of Edinburgh: Earth Sciences 81, 251–261.

Shackleton N J, 1997. The deep-sea sediment record and the Pliocene-Pleistocene boundary. Quaternary International 40, 33–35.

Shotyk W, Goodsite E, Roos-Barraclough F, Givelet N, Le Roux G, Weiss, Cheburkin K, Knudsen K, Heinemeier J, Van der Knaap J O, Norton A, Lohse C, 2005. Accumulation rates and predominant atmospheric sources of natural and anthropogenic Hg and Pb on the Faroe Islands. Geochimica et Cosmochimica Acta 69, 1–17.

Sjöberg R, 1994. Bedrock caves and fractured rock surfaces in Sweden. Occurrence and origin. Doctoral Thesis, Paleogeophysics and Geodynamics, Stockholm University.

Sjöberg L E, Pan M, Asenjo E, 2004. Oskarshamn site investigation. A deformation analysis of the Äspö GPS monitoring network from 2000 to 2004. SKB P-04-196, Svensk Kärnbränslehantering AB.

Sjörs H, 1967. Nordisk växtgeografi. 2nd edition, Bonniers Stockholm. (In Swedish).

Sjörs H, 1983. Mires of Sweden, In: Gore A J P (ed), Ecosystems of the World 4B Mires: Swamp, Bog, Fen and Moor, Regional Studies, Elsevier Scientific Publishing Company, Amsterdam, pp. 69–94.

SKB, 2004. Preliminary site description. Simpevarp area – version 1.1. SKB R-04-25, Svensk Kärnbränslehantering AB.

SKB, 2005a. Preliminary site description. Forsmark area – version 1.2. SKB R-05-18, Svensk Kärnbränslehantering AB.

SKB, 2005b. Programme for further investigations of geosphere and biosphere. Forsmark site investigation. SKB R-05-14, Svensk Kärnbränslehantering AB.

SKB, 2005c. Platsundersökning Oskarshamn. Program för fortsatta undersökningar av berggrund, mark, vatten och miljö inom delområde Laxemar. SKB R-05-37, Svensk Kärnbränslehantering AB.

SKB, 2005a. Preliminary site description Forsmark area – version 1.2. SKB R-05-18, Svensk Kärnbränslehantering AB.

SKB, 2005d. Preliminary site description. Simpevarp subarea – version 1.2. SKB R-05-08, Svensk Kärnbränslehantering AB.

SKB, 2005e. Hydrochemical evaluation. Preliminary site description, Forsmark area – version 1.2. SKB R-05-17. Svensk Kärnbränslehantering AB.

SKB, 2006a. Preliminary site description. Laxemar subarea – version 1.2. SKB R-06-10, Svensk Kärnbränslehantering AB.

SKB, 2006b. The biosphere at Laxemar. Data, assumptions and models used in the SR-Can assessment. SKB R-06-83, Svensk Kärnbränslehantering AB.

SKB, 2006c. Climate and climate-related issues for the safety assessment SR-Can. SKB TR-06-23, Svensk Kärnbränslehantering AB.

SKB, 2006d. Hydrogeochemical evaluation. Preliminary site description Laxemar subarea – Version 2.1. SKB R-06-70, Svensk Kärnbränslehantering AB.

Slunga R, Norrmann P, Glans A-C, 1984. Seismicity of southern Sweden, FOA Rapport C 20543-T1, ISSN 0347-3694, Stockholm, 1984.

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

Sohlenius G, Sternbeck J, Andrén E, Westman P, 1996. Holocene development of the Baltic Sea – as recorded in a sediment core from the Gotland Deep. Marine Geology 134, 186–201.

Sohlenius G, Westman P, 1998. Salinity and redox alternations in the northwestern Baltic proper during the late Holocene. Boreas 27, 101–114.

Sohlenius G, Hedenström A, Rudmark L, 2004. Mapping of unconsolidated Quaternary deposits 2002–2003. Map description. SKB R-04-39, Svensk Kärnbränslehantering AB.

Sohlenius G, Bergman T, Snäll S, Lundin L, Lode E, Stendahl J, Riise A, Nilsson J, Johansson T, Göransson M, 2006. Oskarshamn site investigation Soils, Quaternary deposits and bedrock in topographic lineaments situated in the Laxemar subarea. SKB P-06-121, Svensk Kärnbränslehantering AB.

Sohlenius G, Hedenström A, 2008. Description of regolith at Laxemar. SKB R-08-05, Svensk Kärnbränslehantering AB.

Sonesten L, 2005. Chemical characteristics of surface waters in the Forsmark area. Evaluation of data from lakes, streams, and coastal sites. SKB R-05-41, Svensk Kärnbränslehantering AB.

Sporrong U, Ekstam U, Samuelsson K, 1995. Swedish landscapes. Swedish Environmental Protection Agency. 184 pp.

Starr M R, 1991. Soil formation and fertility along a 5000 year chronosequence. In: Pulkkinen, E. (ed). Environmental geochemistry in northern Europe. Geological Survey of Finland, Special Paper 9: 99–104.

Stenberger M, 1964. Det forntida Sverige. ISBN 91-20-06035-1, Berlings, Lund. (In Swedish).

Stephansson O, Ericsson B, 1975. Pre-Holocene joint fillings at Forsmark, Uppland, Sweden. Geologiska Föreningens i Stockholm Förhandlingar 97, 91–95.

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

Stephens M B, 1988. The Scandinavian Caledonides: a complexity of collisions. Geology Today 4, 20–26.

Stephens M B, Beckholmen M, Zachrissson E, 1994. The Caledonides. In C Fredén (edit.), Geology. National Atlas of Sweden, 1st edition, 22–24.

Stephens M B, Wahlgren C-H, Weijermars R, Cruden A R, 1996. Left-lateral transpressive deformation and its tectonic implications, Sveconorwegian orogen, Baltic Shield, southwestern Sweden. Precambrian Research 79, 261–279.

Stephens M B, Wahlgren C-H, Weihed P, 1997. Sweden. In Moores E M and Fairbridge R W (eds), Encyclopedia of European and Asian Regional Geology. Encyclopedia of Earth Sciences Series, Chapman & Hall, London.

Stephens M B, Bergman T, Andersson J, Hermansson T, Wahlgren C-H, Albrecht L, Mikko H, 2003a. Forsmark site investigation. Bedrock mapping. Stage 1 (2002) – Outcrop data including fracture data. SKB P-03-09, Svensk Kärnbränslehantering AB.

Stephens M B, Lundqvist S, Ekström M, Bergman T, Andersson J, 2003b. Forsmark site investigation. Bedrock mapping. Rock types, their petrographic and geochemical characteristics, and a structural analysis of the bedrock based on stage 1 (2002) surface data. SKB P-03-75, Svensk Kärnbränslehantering AB.

Stephens M B, Fox A, La Pointe P, Simeonov A, Isaksson H, Hermanson J, Öhman J, 2007. Site descriptive modelling, Forsmark stage 2.2. Geology. SKB R-07-45, Svensk Kärnbränslehantering AB.

Sternbeck J, Sohlenius G, 1997. Authigenic sulfide and carbonate mineral formation in Holocene sediments of the Baltic. Chemical Geology 135, 55–73.

Sternbeck J, Land M, Nilsson Ö, 2006. Oskarshamn and Forsmark site investigations – ^{210}Pb and ^{14}C dating of sediments and peat. Accumulation rates of carbon, nitrogen and phosphorus. SKB P-06-301, Svensk Kärnbränslehantering AB.

Strömberg B, 1989. Late Weichselian deglaciation and clay varve chronology in east-central Sweden. Sveriges geologiska undersökning, Ca 73.

Sundblad K, Alm E, Huhma H, Vaasjoki M, Sollien D B, 2004. Early Devonian tectonic and hydrothermal activity in the Fennoscandian Shield; evidence from calcite-fluorite-galena mineralization, In Mertanen S (edit.), Extended abstracts, 5th Nordic Paleomagnetic Workshop. Supercontinents, remagnetizations and geomagnetic modelling. Geological Survey of Finland, 67–71.

Sundh M, Sohlenius G, Hedenström A, 2004. Stratigraphical investigation of till in machine cut trenches. SKB P-04-34, Svensk Kärnbränslehantering AB.

Svanberg O, Vilborg I, 2001. Från surkål och mygghelvete till myllrande våtmarker. Naturvårdsverket Rapport 5146. Naturvårdsverkets förlag. ISSN 0282-7298. (In Swedish).

Svantesson S, 1999. Beskrivning till jordartskartan 7G Västervik SO/ 7H Loftahammar SV. SGU Ae 124. 109 pp.

Svedmark E, 1904. Beskrifning till kartbladet Oskasrhamn. SGU Ac 5, 85 pp.

Svensson H, 1982. A low-lying polygon locality on the Laholm plain, Swedish west coast. Geologiska Föreningen i Stockholm Förhandlingar 104, 69–73.

Svensson N-O, 1989. Late Weichselian and early Holocene shore displacement in the central Baltic, based on stratigraphical and morphological records from eastern Småland and Gotland, Sweden. LUNDQUA 25, 181 pp.

Svensson J, Jeglum J K, 2000. Primary succession and dynamics of Norway spruce coastal forests on land-uplift ground moraine. Studia Forestalia Suecica 209, 2 pp.

Syse B, 2005. E4 – också en lång arkeologisk historia. pp. 7–10, In Syse B (ed): Uppland 2005. Upplands fornminnesförenings förlag (in Swedish).

Söderlund U, Möller C, Andersson J, Johansson L, Whitehouse M, 2002. Zircon geochronology in polymetamorphic gneisses in the Sveconorwegian orogen, SW Sweden: ion microprobe evidence for 1.46–1.42 and 0.98–0.96 Ga reworking. Precambrian Research 113, 193–225.

Söderlund U, Isachsen C, Bylund G, Heaman L, Patchett P J, Vervoort J D, Andersson U B, 2005a. U-Pb baddeleyite ages and Hf, Nd isotope chemistry constraining repeated mafic magmatism in the Fennoscandian Shield from 1.6 to 0.9 Ga. Contributions to Mineralogy and Petrology 150, 174–194.

Söderlund P, Juez-Larré J, Page L, Dunai T, 2005b. Extending the time range of apatite (U-Th/He) thermochronometry in slowly cooled terranes: Palaeozoic to Cenozoic exhumation history of southeast Sweden. Earth and Planetary Science Letters 239, 266–275.

Söderlund P, Juez-Larré J, Page L M, Stuart F M, Andriessen P M, 2008. Assessment of discrepant (U-Th)/He and apatite fission-track ages in slowly cooled Precambrian terrains: a case study from SE Sweden. In Söderlund P, ^{40}Ar-^{39}Ar, AFT and (U-Th)/He thermochronologic implications for the low-temperature geological evolution in SE Sweden. PhD Thesis, University of Lund, Sweden.

Söderlund P, Hermansson T, Page L M, Stephens M B, in press a. Biotite and muscovite ^{40}Ar-^{39}Ar geochronological constraints on the post-Svecofennian tectonothermal evolution, Forsmark site, central Sweden. International Journal of Earth Sciences.

Söderlund P, Page L, Söderlund U, in press b. ^{40}Ar/^{39}Ar biotite and hornblende geochronology from the Oskarshamn area, SE Sweden: Discerning multiple Proterozoic tectonothermal events. Geological Magazine.

Talbot C J, Sokoutis D, 1995. Strain ellipsoids from incompetent dykes: application to volume loss during mylonitization in the Singö gneiss zone, central Sweden. Journal of Structural Geology 17, 927–948.

Texier D, Degnan P, Loutre MF, Paillard D, Thorne M, 2003. Modelling BIOsphere systems under CLIMate change for radioactive waste disposal Proceedings of the International High-Level Waste Management Conference (March30–April 2, 2003, Las Vegas, USA).

Thomasson H, 1927. Baltiska tidsbestämningar och baltisk tidsindelning vid Kalmarsund. Geologiska Föreningens i Stockhom Förhandlingar 49, 7–26.

Triumf C-A, 2004. Oskarshamn site investigation. Gravity measurements in the Laxemar model area with surroundings. SKB P-04-128, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, 2006. Chemical characteristics of surface systems in the Forsmark area. Visualisation and statistical evaluation of data from shallow groundwater, precipitation, and regolith. SKB R-06-19, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, Johansson P-O, 2007. Hydrochemistry in surface water and shallow groundwater. Site descriptive modelling, SDM-Site Forsmark. SKB R-07-55, Svensk Kärnbränslehantering AB.

Turunen J, Tomppo E, Tolonen K, Reinikainen A, 2002. Estimating carbon accumulation rates of undrained mires in Finland-application to boreal and subarctic regions. The Holocene 12, 69–80.

Ukkonen P, Lunkka J P, Jungner H, Donner J, 1999. New radiocarbon dates from Finnish mammoths indicating large ice-free areas in Fennoscandia during the Middle Weichselian. Journal of Quaternary Science 14, 711–714.

Ukkonen P, Arppe L, Houmark-Nielsen M, Kjær K-H, Karhu J A, 2007. MIS 3 mammoth remains from Sweden – implications for faunal history, palaeoclimate and glaciation chronology. Quaternary Science Reviews.

Vera F W M, 2000. Grazing Ecology and Forest History. CABI Publishing, 506 pp.

Viola G, Venvik Ganerød G, 2007a. Oskarshamn site investigation. Structural analysis of brittle deformation zones in the Simpevarp-Laxemar area, Oskarshamn, southeast Sweden. SKB P-07-41, Svensk Kärnbränslehantering AB.

Viola G, Venvik Ganerød G, 2007b. Oskarshamn site investigation. Structural characterization of deformation zones (faults and ductile shear zones) from selected drill cores and outcrops from the Laxemar area – results from Phase 2. SKB P-07-227, Svensk Kärnbränslehantering AB.

von Post L, 1929. Vänernbassängens strandlinjer. GFF 51, 199–235.

von Post L, Granlund E, 1926. Södra sveriges torvtillgångar. Sveriges geologiska undersökning. Serie C, Avhandlingar och uppsatser 335, 127 pp.

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

Wahlgren C-H, Ahl M, Sandahl K-A, Berglund J, Petersson J, Ekström M, Persson P-O, 2004. Oskarshamn site investigation. Bedrock mapping 2003 – Simpevarp subarea. Outcrop data, fracture data, modal and geochemical classification of rock types, bedrock map, radiometric dating. SKB P-04-102, Svensk Kärnbränslehantering AB.

Wahlgren C-H, Bergman T, Persson Nilsson K, Eliasson T, Ahl M, Ekström M, 2005. Oskarshamn site investigation. Bedrock map of the Laxemar subarea and surroundings. Description of rock types, modal and geochemical analyses, including the cored boreholes KLX03, KSH03 and KAV01. SKB P-05-180, Svensk Kärnbränslehantering AB.

Wahlgren C-H, Hermanson J, Forssberg O, Curtis P, Triumf C-A, Drake H, Tullborg E-L, 2006. Geological description of rock domains and deformation zones in the Simpevarp and Laxemar subareas. Preliminary site description Laxemar subarea – version 1.2. SKB R-05-69, Svensk Kärnbränslehantering AB.

Wahlgren C-H, Bergman T, Ahl M, Ekström M, Page L, Söderlund U, 2007. Oskarshamn site investigation. Modal and geochemical analyses of drill core samples 2007 and $^{40}Ar/^{39}Ar$ dating of a dolerite. SKB P-07-191, Svensk Kärnbränslehantering AB.

Wahlström R, 1990. A catalogue of earthquakes in Sweden 1375–1890. GFF 112, 215–225.

Wastegård S, Andrén T, Sohlenius G, Sandgren P, 1995. Different phases of the Yoldia Sea in the north-western Baltic proper. Quaternary International 27, 121–129

Welin E, 1964. Uranium disseminations and vein fillings in iron ores of northern Uppland, Central Sweden. Geologiska Föreningens i Stockholm Förhandlingar 86, 51–82.

Welinder S, 1974. Kulturlandskapet i Mälarområdet. Univ. of Lund. Dep. Of Quarter. Geol., Reports, 5 & 6, 367 pp, Lund. (In Swedish).

Werner K, Lundholm L, Johansson P-O, 2004. Forsmark site investigation. Drilling and pumping test of wells at Börstilåsen. SKB P-04-138, Svensk Kärnbränslehantering AB.

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

Westman P, Borgendahl J, Bianchi T S, Chen N, 2003. Probable causes of cyanobacterial expansion in the Baltic Sea: Role of anoxia and phosphorus retention. Estuaries 26, 680–689.

Wetzel R G, 2001. Limnology: Lake and River Ecosystems. Third edition, Academic Press, San Diego, 1066 pp.

Wickman F E, Åberg G, Levi B, 1983. Rb-Sr dating of alteration events in granitoids. Contributions to Mineralogy and Petrology 83, 358–362.

Wickman F E, 1988. Possible impact structures in Sweden. In A. Boden and K.-G Eriksson, (eds), Deep Drilling in Crystalline Bedrock. Volume 1: The Deep Gas Drilling in the Siljan Impact Structure, Sweden and Astroblemes. Springer-Verlag, Berlin.

Widerlund A, Andersson P S, 2006. Strontium isotopic composition of modern and Holocene mollusc shells as a palaeosalinity indicator for the Baltic Sea. Chemical Geology 232, 54–66.

Wik N-G, Bergström U, Bruun Å, Claeson D, Jelinek C, Juhojuntti N, Kero L, Lundqvist L, Stephens M B, Sukotjo S, Wikman H, 2005. Beskrivning till regional berggrundskarta över Kalmar län. SGU Ba 66, Sveriges geologiska undersökning.

Wikman H, Kornfält K-A, 1995. Updating of a lithological model of the bedrock of the Äspö area. SKB PR 25-95-04, Svensk Kärnbränslehantering AB.

Wikström A, Sjöberg B, Kapicka A, 1997. A precursory study of magnetic fabrics in the transition zone between magmatic and metamorphic textures in the Askersund granitoid, Sweden. GFF 119, 285–290.

Windelhed B, 1995. Barknåre by. Markanvändning och bebyggelse i en uppländsk by under tusen år. Meddelanden serie B92. Kulturgeografiska institutionen Stockholms universitet. Stockholm. (In Swedish).

WRB, 1998. World Reference Base for Soil Resources World Soil Resources Reports 84. Food and Agriculture Organisation of the United Nations, Rome 1998. 88pp.

Wu P, Hasegawa H S, 1996a. Induced stresses and fault potential in eastern Canada due to a disc load: a preliminary analysis. Geophysical Journal International 125, 415–430.

Wu P, Hasegawa H S, 1996b. Induced stresses and fault potential in eastern Canada due to a realistic load: a preliminary analysis. Geophysical Journal International 127, 215–229.

Wu P, Johnston P, Lambeck K, 1999. Postglacial rebound and fault instability in Fennoscandia. Geophysical Journal International 139, 657–670.

Åhäll K-I, Gower, C F, 1997. The Gothian and Labradorian orogens: variations in accretionary tectonism along a late Paleoproterozoic Laurentia-Baltica margin. GFF 119, 181–191.

Åhäll K-I, Connelly J N, Brewer T S, 2000. Episodic rapakivi magmatism due to distal orogenesis? Correlation of 1.69–1.50 Ga orogenic and inboard "anorogenic" events in the Baltic Shield. Geology 28, 823–826.

Åhäll K-I, 2001. Åldersbestämning av svårdaterade bergarter i sydöstra Sverige. SKB R-01-60, Svensk Kärnbränslehantering AB.

Åhäll K-I, Connelly J N, Brewer T S, 2002. Transition from Svecofennian to Transscandinavian igneous Belt(TIB) magmatism in SE Sweden: Implications from the 1.82 Ga Eksjö tonalite. GFF 124, 217–224.

Åkerlund A, 1996. Human responses to shore displacement – living by the sea in Eastern Middle Sweden during the Stone Age. Grafiska Gruppen, Stockholm.

www-references

INQUA, 2008. www. International Union for Quaternary Research [Web]. http://www.inqua.tcd.ie [Accessed 2008-03-11]

Tabellverket, 2007. www. Tabellverket på nätet [Web]. http://www.ddb.umu.se/tabellverk/Atkomst/tabnet.htm [Accessed 2007-05-03]

RAÄ, 2007. www. Riksantikvareämbetets Fornsök (88:1–4, 89) [Web]. http://www.kms.raa.se/cocoon/fmis-public/index.info [Accessed 2007-05-03]