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Displacement along extensive deformation zones at the two SKB sites: Forsmark and Laxemar

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SSM Perspective

This report concerns a study which has been conducted for the Swedish Radiation Safety Authority, SSM. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the SSM.

Background

The Fennoscandian shield is distinguished by that the exposed bedrock is mainly composed of Precambrian metamorphic and igneous rocks older than a billion or one and a half billion years with few easily distinguished testimonies for the younger history. Large parts of the present ground surface closely coincides with a late Precambrian denudation surface; the sub-Cambrian peneplain. Palaeozoic and younger sediments were deposited on the peneplain, but these sediments have been removed from most areas that now form the mainland of Sweden and Finland and where there area just some few remnants. However, Palaeozoic sediments are abundant in the Baltic Sea.

The Palaeozoic sedimentary rocks may form a memory of the late Palaeozoic and younger tectonic events in the underlying basement rocks. Such data are used in this report to complement the structural observations made at sites located on the mainland, giving information on displacement along faults. For construction of a geological repository for disposal of nuclear waste and for its long term safety it is important to understand the late history of geological and seismic events to be able to estimate its influence and consequences for the repository.

Purpose

The purpose of the current project is to describe displacement along tectonic structures forming the boundary of the sites Forsmark and Laxemar where the Swedish Nuclear Waste Management Co (SKB) recently has finished site investigations for a repository for spent nuclear fuel. The description of displacement will be based on information gained from marine geological investigations performed in the Baltic Sea. General observations of late displacement along faults in the Baltic-Sea Basin are also made in order to compare these with structures of similar orientation in the site areas. Of special interest are structures with evident indications of late bedrock movements where future movements cannot be excluded.

Results

The present study of the displacement of faults considers information about structures that have been reactivated since the formation of the sub-Cambrian peneplain; the periods of reactivation and the accumulated vertical displacement. It is obvious that the accumulated displacement along fault sets in one area, e.g. in parts of the Baltic Sea, cannot be directly transformed to similar fault sets in other areas, e.g. in the sites. However, it indicates which sets of faults may have a potential to be reactivated. Earthquakes along faults express local stress release, which, in some cases, may indicate on-going propagating displacement. In some cases earthquakes line up in areas where no fault lines are found to match.

Effects on SSM supervisory and regulatory task

An understanding of behaviour and influence of the accumulated vertical displacement along faults in areas surrounding Forsmark and Laxemar will give SSM improved knowledge about possible future movements in the target areas.

Project information

SSM reference: SSM 2009/426 Project 1525
Responsible at SSM has been Öivind Toverud and Lena Sonnerfelt

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Abstrakt

Den Fennoskandiska skölden, en del av den östeuropeiska jordskorpan, kännetecknas av att den exponerade berggrunden huvudsakligen består av prekambriska metamorfa och magmatiska bergarter. Stora delar av markytan sammanfaller nära med en sent prekambrisk blottad bergyta, det subkambriska peneplanet. Paleozoiska och yngre sediment avsattes på peneplanet, men dessa sediment har eroderats bort från de flesta områden som idag utgör Sveriges fastland och Finland, och det är bara några få rester bevarade. I Östersjön, som ligger i stora sänkor på gränsen till den Fennoskandiska skölden/i den östeuropeiska jordskorpan, är den prekambriska berggrunden fortfarande till stora delar täckt av palaeozoiska sediment.

De palaeozoiska sedimentära bergarterna, där de är väl bevarade, kan utgöra en kvarleva av palaeozoiska och yngre tektoniska händelser i den underliggande berggrunden. Sådana data används här för att komplettera de strukturella observationer på platser som är belägna på fastlandet, och som ger information om förskjutningar längs förkastningar.

Betydande för Östersjön är förkastningar orienterade i N-S som uppträder som segment och som är förskjutna i förhållande till varandra. Andra strukturer är orienterade i E-W, NE-SW och NW-SE.

Undersökningsområdet i Forsmark är beläget i ett relativt flackt kustområde inom det subkambriska peneplanet. Havsområdet vid Forsmark ”sajten” har en mera framträdande relief än vad som finns på fastlandet. Det finns t ex. en fåra längs den västra sidan av den nord-sydligt orienterade ön Gräsö nordost om Forsmark (<30 m under vattenytan och lokalt mer än 50 meter lägre än Gräsö). En fåra utgör även djupet mellan Åland och Sverige (301 m under vattenytan) ca 100 km ost-sydost om Forsmark. I Forsmarksområdet interfererar två uppsättningar strukturer: en WNW-ESE liknande struktur med relativt raka förkastningar längs nordkusten i Uppland och en NNW-ESE till N-S liknande uppsättning, som är något böjda, längs Upplands (nord) ostkust. Forsmark ligger i ett förhöjt WNW liknande ribbformat bergblock omgivet av WNW-ESE och NE-SW liknande förkastningar.

I Forsmarksområdet kan, en ackumulerad vertikal relativ förskjutning längs en struktur under slutet av prekambrium (från 1 600 till ca 1 000 miljoner år sedan), tillsammans med en brant stupande förkastning, t.ex. WNW-ESE liknande förkastningar, ha varit i kilometer skala. En fanerozoisk ackumulerad relativ förskjutning (från cirka 540 miljoner år sedan till nutid) är av storleksordningen ett tiotal meter eller mindre. Den fanerozoiska förskjutningen är relaterad till blockförkastningar och ofta i kombination med lutning på blocken.

Jordbävningar är små och relativt få i närheten av Forsmarks undersökningsområde. Men jordbävningar förekommer relativt ofta längs kusten norr om Gävle (ca 65 km nordväst om Forsmark). I närheten av Forsmark sker jordbävningar företrädesvis längs WNW-ESE och N-S liknande förkastningar.

Delområde Laxemar (”site”) är också beläget i ett kustnära område med låg relief där markytan i regional skala sluttar mot öster. Reliefen i havet öster

om Laxemarområdet liknar den inom Laxemarområdet, även om lutningen på havsbotten/ subkambriska peneplanet i regional skala ökar något österut. En senprekambrisk förskjutning (mellan 1 450 och 900 miljoner år sedan), med en vertikal relativ förskjutning i storleksordningen 500 meter, är indikerad för en ungefär nord-sydlig förkastning längs den västra gränsen av Laxemarområdet. Regionen utgör ett relativt komplext mönster av bergblock. Bergblock förekommer i olika skalor och blocken har i allmänhet en låg symmetri. Förkastningar av bergblock förekommer i olika skalor. Relativ vertikal förskjutning mellan blocken i regionen som omger Laxemar undersökningsområde är mindre än några tiotals meter sedan bildandet av det subkambriska peneplanet. Några sådana förskjutningar har dock inte observerats inom undersökningsområdet.

Postglacial påverkan finns längs två förkastningar i havet öster om Laxemar: en längs en NNE-lig förkastning öster om Öland och en annan längs en uppsättning NW-SE-liga förkastningar sydost om Gotland. Jordbävningar är små och få i sydöstra Sverige. De uppträder företrädesvis längs det NNE-liga sundet mellan Öland och fastlandet (Kalmarsund) och längs NW-SE-liga strukturer norr om Laxemar. Vissa jordbävningar radas upp längs NS och EW-liga förkastningar.

Mindre jordbävningar noteras för den regionala EW-liga Mederhultzonen, som utgör den norra gränsen för Laxemar undersökningsområde och sträcker sig österut, långt ut i havsområdet. Mederhultzonen verkar inte ha identifierats i den marina geofysiska undersökningen av havsområden öster om sydöstra Sveriges fastland trots att strukturen har en topografisk signatur.

Abstract

The Fennoscandian shield, a part of the East European Craton, is distinguished by the exposed bedrock which is mainly composed of Precambrian metamorphic and igneous rocks. Large parts of the ground surface closely coincides with a late Precambrian denudation surface; the sub-Cambrian peneplain. Palaeozoic and younger sediments were deposited on the peneplain but these sediments have been removed from most areas that now form the mainland of Sweden and Finland and there are just a few remnants left. In the Baltic Sea, located in large-scale depressions on the boundary of in the Fennoscandian Shield/ in the East European Craton/, the Precambrian bedrock is still in large parts covered by Palaeozoic sediments.

The Palaeozoic sedimentary rocks, as they are well bedded, may form a memory of the late Palaeozoic and younger tectonic events in the underlying basement rocks. Such data are used here to complement the structural observations made at sites located on the mainland, giving information on displacement along faults.

Significant for the Baltic Sea are faults oriented in N-S that appear as segments, displaced relative to each other. Other structures are oriented in E-W, NE-SW and NW-SE.

The SKB Forsmark site is located in a relatively flat coastal area within the sub-Cambrian peneplain. The sea area at the Forsmark site has a more accentuated relief than what is found on the mainland, for example, a furrow along the western side of the N-S oriented island Gräsö northeast of Forsmark (below 30m b.s.l. and locally more than 50m lower than Gräsö) and the deep between Åland and Sweden (301m b.s.l.) about 100km east-southeast of Forsmark. In the Forsmark-site area two sets of structures interfere: a WNW-ESE trending set with relatively straight faults along the north coast of Uppland and a NNW-SSE to N-S trending set, slightly curved, along the (north)east coast of Uppland. The Forsmark site is located in an elevated WNW trending lath-shaped rock block outlined by WNW-ESE and NE-SW trending faults.

In the Forsmark area, accumulated vertical, relative displacement on a structure during the late Precambrian (from 1 600 to about 1 000Ma), along steeply dipping faults, e.g. WNW-ESE trending faults, may have been on kilometre scale, while Phanerozoic accumulated relative displacement (about 540Ma to present) is of the scale of a few tens of metres or less. The Phanerozoic displacement is related to block-faulting and often combined with tilting of the blocks.

Earthquakes are minor and relatively few in the surroundings of the Forsmark site. However, earthquakes are relatively frequent along the coast north of Gävle (about 65km to the northwest). In the surroundings of Forsmark earthquakes occur preferentially along WNW-ESE and N-S trending faults.

The Laxemar site is also located in a coastal area with low relief; on a regional scale, the ground surface is tilted eastwards. The relief in the sea area

east of the Laxemar area is similar to that inside the Laxemar area, though on a regional scale the inclination of the sea bottom/sub-Cambrian peneplain increases slightly eastwards. Late Precambrian displacement (between 1 450 to 900Ma ago) with a vertical relative offset in the order of 500m is indicated for a N-S trending fault along the western boundary of the Laxemar area. The region displays a relatively complex rock block pattern. Rock blocks appear on different scales and the blocks have, in general, a low symmetry. Block faulting occurs on various scales. Relative vertical displacement between blocks in the region surrounding the Laxemar site, since the formation of the sub-Cambrian peneplain, is less than a few tens of metres. However, such displacement is not found in the Laxemar site.

Post-glacial distortions are found along two faults in the sea area east of Laxemar: along a NNE trending fault east of Öland and along a set of NW-SE trending faults southeast of Gotland. Earthquakes are minor and few in south-eastern Sweden. They occur preferentially along the NNE trending strait between Öland and the main land (Kalmarsund) and along NW-SE trending structures north of Laxemar. Some earthquakes line up along N-S and E-W trending faults.

Minor earthquakes are recorded for the regional E-W trending Mederhult zone, which forms the northern boundary of the Laxemar site and extends eastwards, far into the sea area. However, the Mederhult zone appears not to have been recognized in the marine geophysical survey covering the sea areas east of south-eastern Sweden despite that the structure has a topographical expression.

1. Introduction

The Swedish Nuclear Fuel and Waste Management Co (SKB) has, during the last 20 years, conducted site investigations and selection studies for the location of a deep geological repository for spent nuclear fuel. In the beginning of the present century, two sites were selected and within these comprehensive surface-based site-investigation programmes (SI) were performed. The two sites, both located on the east-coast of Sweden, were the Forsmark site on the north-eastern coast of Uppland (120km north of Stockholm) and the Laxemar site in the north-eastern part of Småland, (c. 245km south of Stockholm), Figure 1-1.

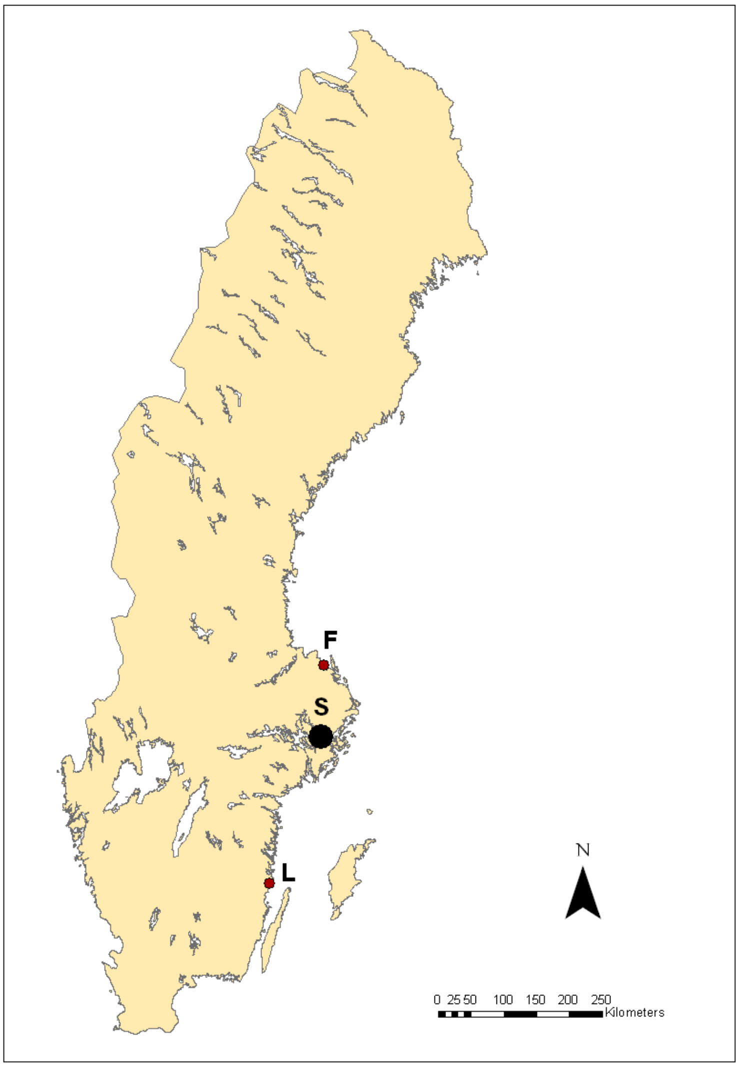

Figure 1-1. Location of the SKB sites marked as red dots: Forsmark (F) and Laxemar (L). Stockholm is the larger black dot.

Both sites are located within flat land, the ground surface of which approximately coincides with the sub-Cambrian peneplain.Both sites have natural harbours, which indicate that the local coastline is controlled by bedrock structures i.e. faults. These escarpments may either be formed by vertical displacements or be the result of erosion of the deformed rock along the faults, or a combination of both. At both sites there are extensive brittle deformation zones that may be traced seawards into the Baltic Sea/Östersjön (for definition of different parts of Östersjön see Section 2 and Figure 2-1. From Section 2, Swedish names are used for the different parts of Östersjön).

The investigations of sea-covered areas, which constitute parts of the regional areas for both the Forsmark and Laxemar sites, start from a lower level of general knowledge than of the land areas.This is due to the fact that ordinary geological maps do not generally include water-covered areas. The Baltic Sea (Figure 1-2), is a large-scale basin formed in the western part of the East European Craton (EEC). Unlike the land areas in the Fennoscandian Shield (the westernmost part of EEC), the Baltic-Sea Basin contains a relatively high proportion of sedimentary rocks but along the coasts of Sweden and Finland, the sea is mainly floored by Precambrian rocks. The sedimentary rocks are stratified and, where tectonically disturbed, they contain a record of these disturbances, e.g. faults. The morphology of the sea floor may also indicate late displacements. Together such information present the later structural history of the cratonic area that is hard to recognize when studying the bedrock on land, that in the two SKB Sites at Forsmark and Laxemar consists of metamorphic and igneous Precambrian rocks (older than approximately 1.8Ga[1]). The record of faulting in the Baltic Sea, from late Precambrian events up to post-glacial once, is mainly gained from marine geological surveys that cover large parts of the Baltic Sea.

1.1. Aim of the study

The main aim of the present study, SSM 2009/426 Project 1525, is to describe displacement along tectonic structures forming the boundary of the SKB Forsmark and Laxemar sites, based on information gained from marine geological investigations performed in the Baltic Sea. General observations of late displacement along faults in the Baltic-Sea Basin are also made in order to compare these with structures of similar orientation in the site areas.

1.2. Approach and base data

The general approach in this study is that the geomorphology of the ground surface, i.e. the landform, reflects the structural character of the underlying bedrock, even though it may be covered by soil or other unconsolidated materials. The study is based on structural interpretation of digital elevation models, i.e. lineament interpretations, to reveal structures that have been eroded (have an increased porosity, i.e. open structures) and structures that form landform brakes or both.

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[1] G= giga, a= year

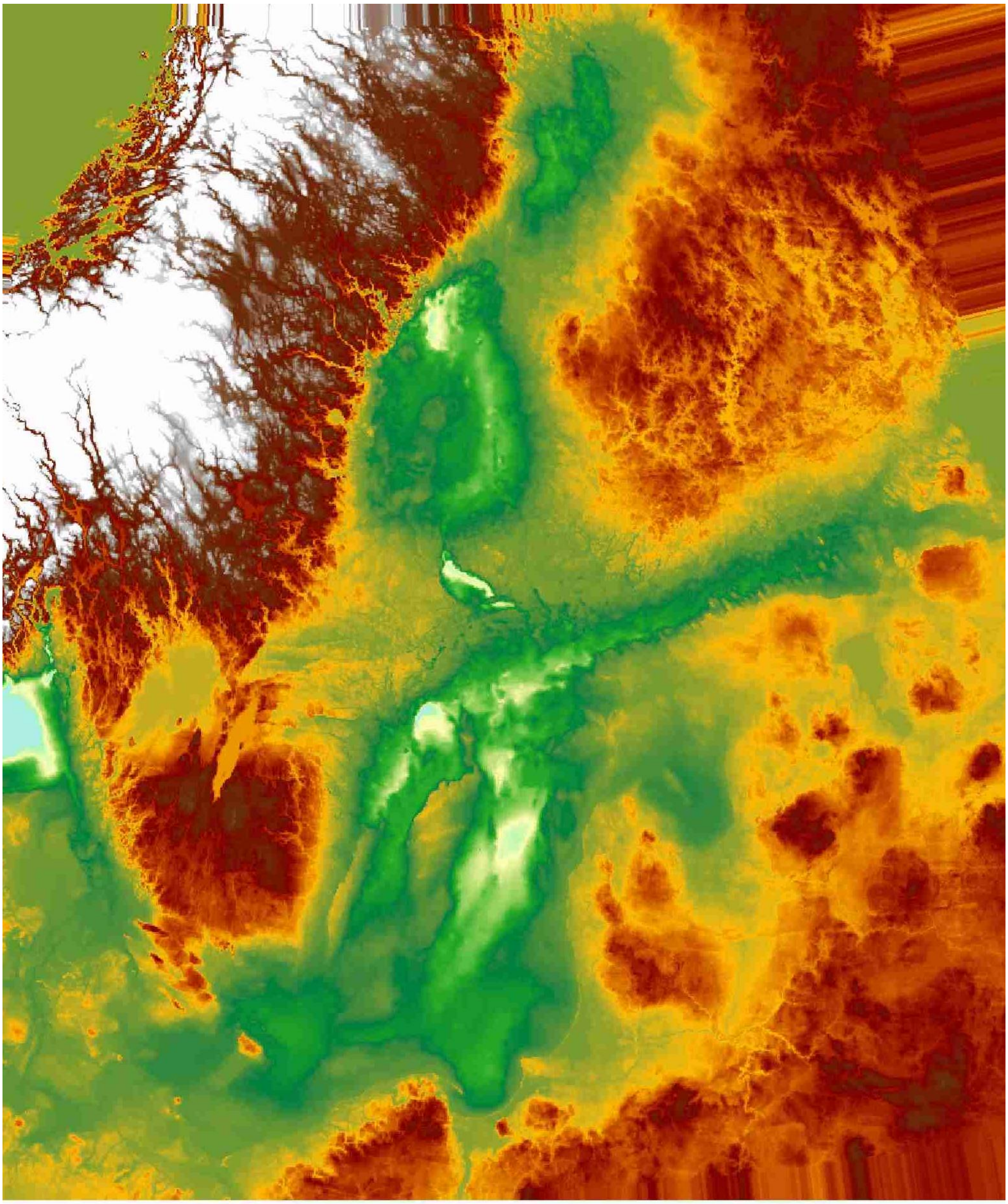


Figure 1-2. Topography of northwestern Europe with the Baltic-Sea Basin. (Seifert, T., Tauber, F. & Kayser. B., 2001). Light blue colours depict the lowest (deepest) and white the highest parts (mainly the Scandinavian mountain range).

A regional structural map covering the Baltic Sea based on topographical data has been compared with marine geological maps, which are mainly based in shallow reflection seismic measurements or other instrumental investigations. The used elevation/bathymetrical data covering the Baltic Sea are:

Topography of northwestern Europe with the Baltic. (Seifert, T., Tauber, F. & Kayser. B., 2001).

The main references are:

- For the overview of the Baltic-Sea Basin is Winterhalter et al. (1981).
- For the Bothnian Sea is Axberg (1980).
- For the Åland Sea is Söderberg (1993).
- For the Baltic Proper is Flodén (1980).

Other references, mainly regarding the eastern part of the Baltic Proper, i.e. along the coast of the Baltic States, are given in the text. Information about orientation of structures, vertical displacement along structures and length of structures are compiled and displayed in figures (rose- diagram) and tables.

Structural maps, covering the regional surroundings of the Forsmark and Laxemar sites, have been produced based on digital elevation data (20m gridded elevation data, coordinate system RT90 and height system RH 70). The base map input data are:

- Forsmark: 30x30km (Strömgren & Brydsten 2008a).
- Laxemar: 35x20km (Strömgren & Brydsten 2008b).

The structural maps have been produced to trace extensive structures in order to correlate these with structures found in sea-covered areas.

The present Baltic-Sea Basin represents a relatively late structure in the East European Craton and the major uncertainties in this study are: a) a “structure” traceable from a site into the sea area is generally not a single structure and b) the displacement along a structure will not be of the same order along all of its trace. The reason for the latter can be that some of the deformation has been taken up by crossing structures (linkage), the fault has been partially reactivated, and the elastic behaviour of the rock. However, a study of the structural pattern in the Baltic Sea gives information about families of structures that are prone to reactivate. Important reference surfaces, when giving reference to relative displacement, are the sub-Cambrian peneplain and the present ground surface.

1.3. Content of the report

The following section of the report (Section 2), first gives a general overview of the geography to present the names of different parts of the Baltic Sea and the structural setting, followed by a geomorphological description of its different parts and their coastal areas. The third section presents a lineament map of the Baltic Sea, faults indicated by marine seismic surveys and a review of neotectonics. In the fourth section, the regional settings of the two SKB sites, Forsmark and Laxemar are presented together with indications of local faulting. The results of this study is presented and discussed in the fifth section. The conclusions are presented the last section (Section 6). In an appendix (Appendix 1) additional sets of structural maps of the Baltic Sea produced during this study are presented.

2. Östersjön (the Baltic Sea)

2.1. Geography and geological setting

Östersjön (the Baltic Sea, Figure 2-1 and 1-2) constitutes a sequence of water-filled basins within the western part of the East European Craton (Figure 2-2). The outlets of the Baltic Sea via Kattegat and Skagerrak into the North Sea are Öresund and the Danish Belts. The Baltic Sea comprises the following main sea areas (from north to south): Bottenviken (Bothnian Bay), Bottenhavet (Bothnian Sea), Finska viken (Gulf of Finland), Rigabukten (Gulf of Riga), and Egentliga Östersjön (Baltic Proper). The sea areas between Bottenhavet and Egentliga Östersjön are Ålands hav (Åland Sea), located west of Åland, and Skärgårdshavet (Archipelago Sea), located east of Åland.

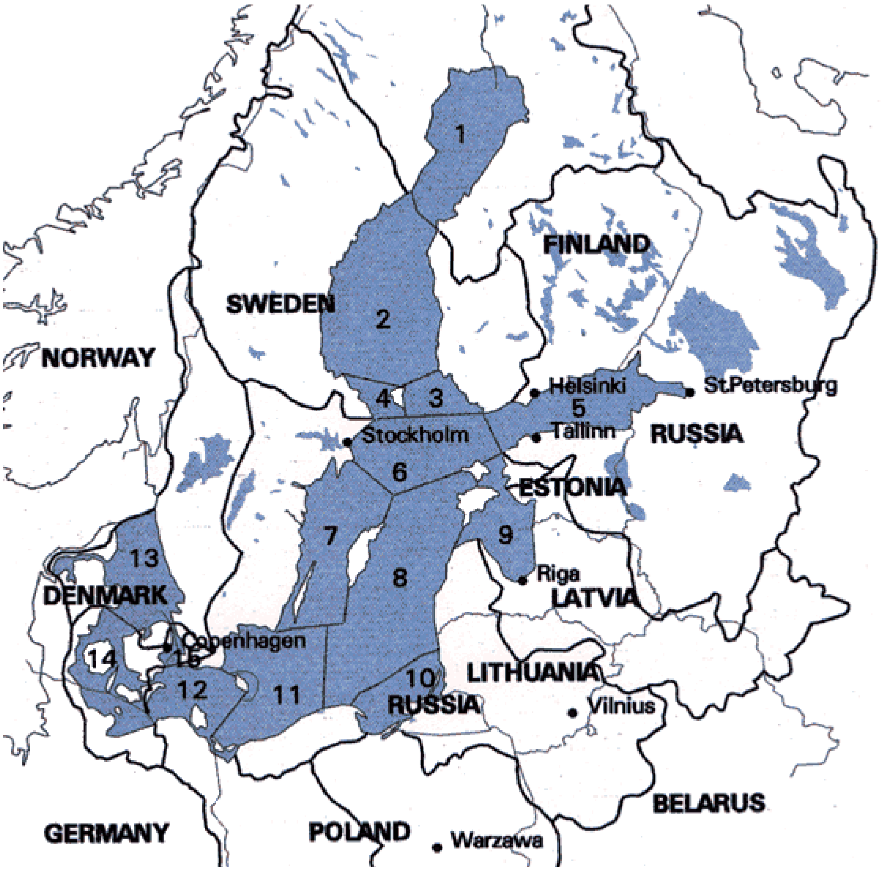


Figure 2-1. Östersjön and its main parts (http://www.baltic.vtt.fi/demo/baltmap.htm): 1. Bottenviken, 2. Bottenhavet, the border between 1 and 2 is Norra Kvarken, 3. Skärgårdshavet 4. Ålands hav, the border between 2

and 4 is Södra Kvarken, 5. Finska viken (Gulf of Finland), 6. Norra Östersjön (Northern Baltic Proper), 7. Västra gotlandsbassängen (Western Gotland Basin), 8. Östra gotlandsbassängen (Eastern Gotland Basin), 9. Rigabukten (Gulf of Riga), 10. Gdanskbukten (Gulf of Gdansk), 11. Bornholmsbassängen (Bornholm Basin), 12. Arkonabassängen (Arkona Basin), 14. Bälthavet (Stora and Lilla Bält, Belt Sea) and 15. Öresund (the Sound). 6-7 together with 8-12 comprise Egentliga Östersjön (Baltic Proper), and 11-12 is Södra Östersjön (Southern Baltic Proper). Note that sub-area 13, Kattegat, does not belong to Östersjön according to the Swedish Maritime Administration.

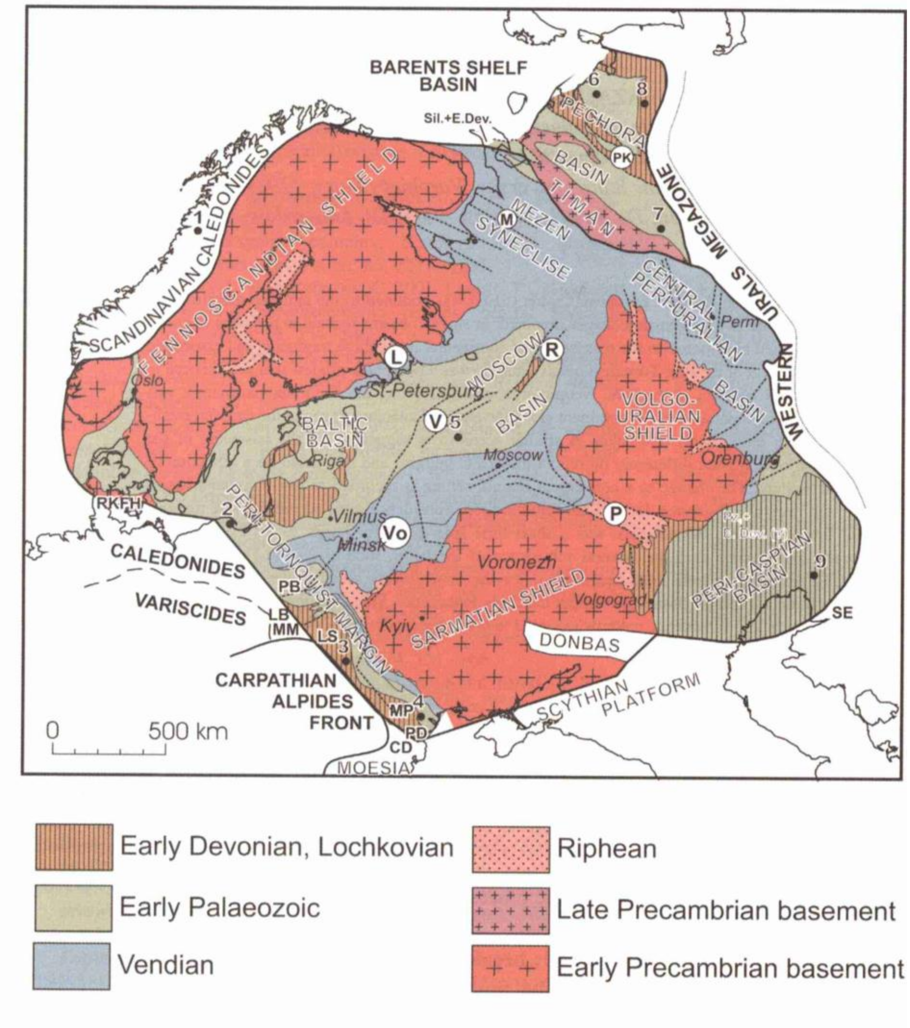


Figure 2-2. East European Craton and the location of Vendian-Early Palaeozoic basins (Riphean). Palaeorifts are indicated by dashed lines with names in white circles: L, Ladoga; M, Mezen; P, Pachelma; PK, Pechora-Kolva; R, Roslyatino; V, Valday; Vo, Volhyn (From Šliaupa et al. 2006)

The Fennoscandian Shield was formed 3 to 1Ga back. Most of it has been covered by Palaeozoic rocks and the crystalline basement is covered by Palaeozoic up to Quaternary cover in the southeast. The shield is framed by the younger orogens, the Timanides in the northeast and the Caledonides in the northwest, and is cut by the Tornquist–Teisseyre Zone (TTZ; also called the Trans-European Suture Zone) in the southwest. It has been repeatedly covered by glaciations during the last millions of years.

Bottenhavet–Bottenviken (Figures 2-1 to 2-3) are depressions in the shield separating micro-continental nuclei amalgamated around 1.9Ga and largely underlain by rapakivi granitoids (1.6-1.5Ga) and Jotnian sediments (1.5-1.3Ga), cut by mafic dykes (prior to 1.2Ga).

The Bottenhavet and Egentliga Östersjön depressions are separated by the Åland islands mainly built by the Åland Rapakivi Massif (Figures 1-2 and 2-3). Egentliga Östersjön and the Gulf of Finland are also partly underlain and bordered by large rapakivi plutons. The deepest depressions, (west of Åland and southeast of Stockholm) are floored by Jotnian sandstones (Figures 2-3 and 1-2).

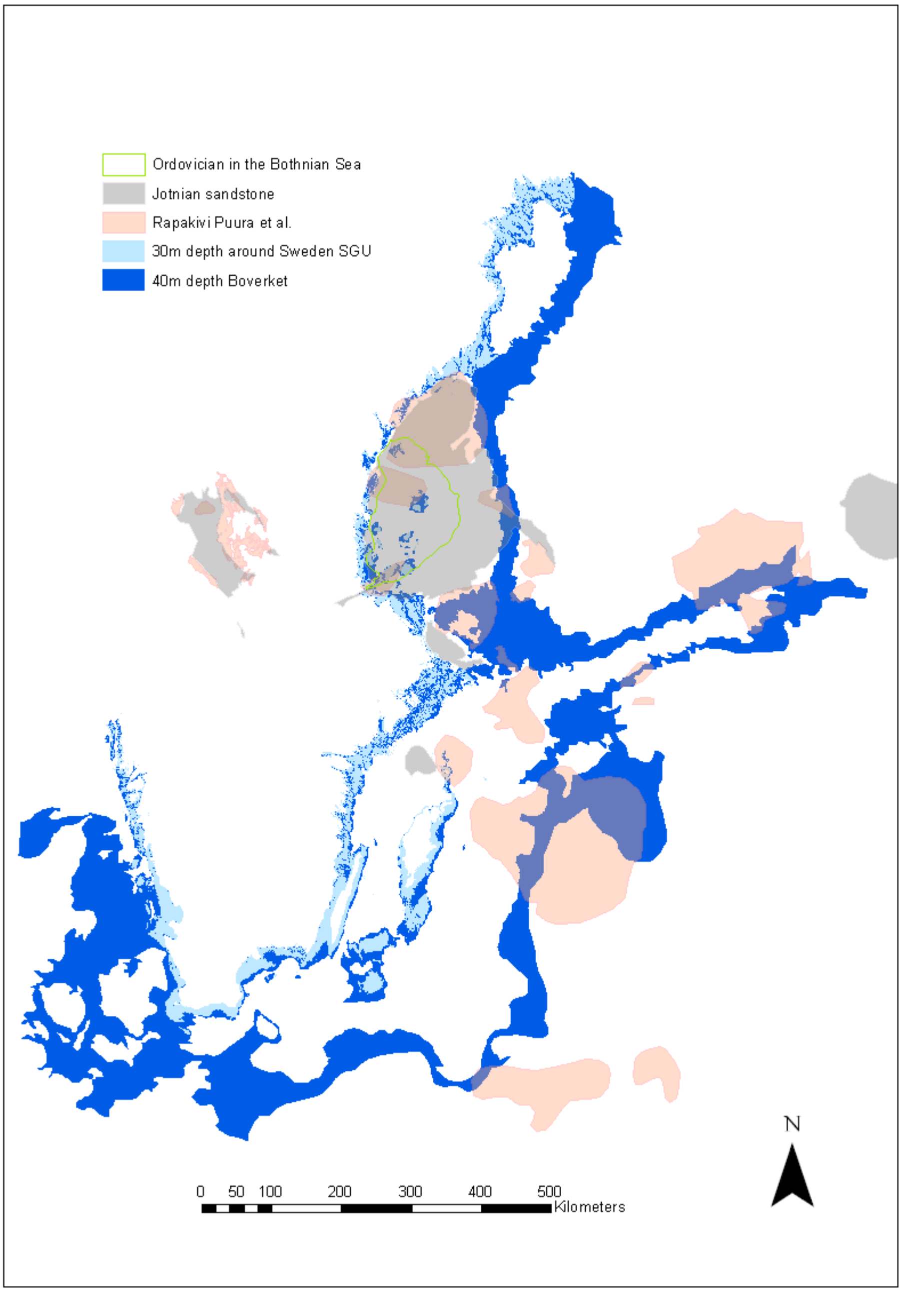


Figure 2-3. The distribution of Rapakivi granites and associated Jotnian sandstones in Östersjön. Ordovician sediments in the Bothnian Sea are marked with a green line. Light and deeper blue give the <30m and <40m depths.

Figure 2-2 gives the general framework of large-scale basins in the East European Craton and faults controlling the locations of Jotnian sandstones

(Riphean). However, Figure 2-2 does not display the extent of the Palaeozoic platform sediments once deposited on large parts of the Fennoscandian

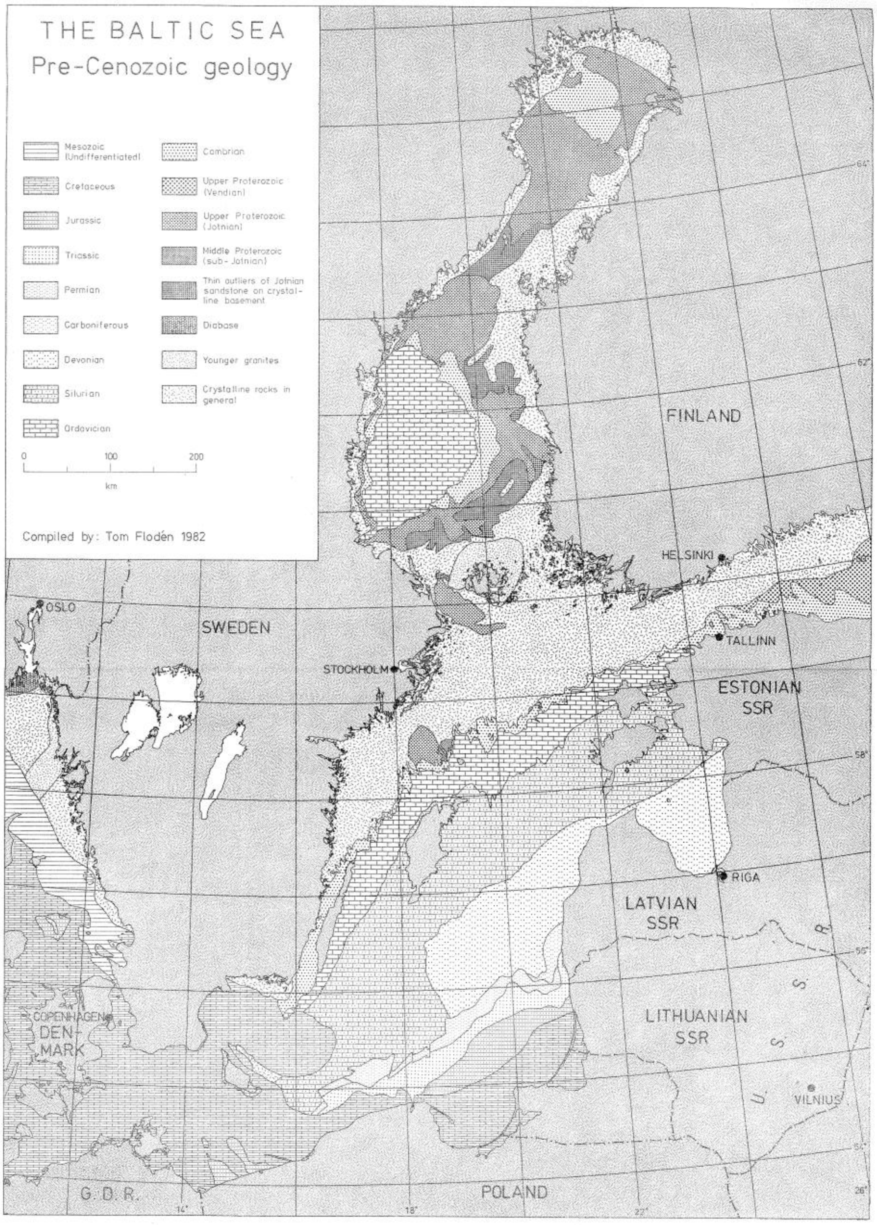


Figure 2-4. Geology of the Baltic Sea (Flodén 1984).

Shield, which are now removed except for in, e.g. Bottenhavet and Bottenviken (Figure 2-4, cf. Beckholmen and Tirén 2009 for further description and references).

3. Geomorphological description – Östersjön (the Baltic Sea)

In this section a brief geomorphologic description of Östersjön is given starting from its northern part going southwards.
Bottenviken and Bottenhavet constitute two fault basins/depressions, trending NNE-SSW and N-S, respectively, and formed within Precambrian rocks (>1.8Ga). These are in large parts floored with Precambrian/Jotnian sandstones (1.5-1.3Ga) partly covered by Cambro-Ordovician sediments. The sub-Cambrian peneplain comprises the top of the Jotnian sandstones and the surrounding bedrock.

A NW-SE trending culmination, Norra Kvarken (Umeå-Wasa), separates Bottenviken from Bottenhavet. To the south Bottenhavet is separated from Egentliga Östersjön by another, much wider, basement culmination across Åland, incorporating the local depression Ålands hav and the shallow sea area Skärgårdshavet. The name of the threshold between Ålands hav and Bottenhavet is Södra Kvarken. Egentliga Östersjön is located along the western side of a larger-scale basin, the Baltic Basin, filled with Palaeozoic and younger sedimentary rocks (Figure 2-2).

3.1. Bottenviken

Bottenviken trends NNE-SSW and is relatively shallow; depths below 100m occur mainly in its south-western part and shallow depths are usual along the Finnish coast. The deepest parts of Bottenviken are within a NNW-SSE trending narrow depression east of Skellefteå; having a greatest depth of 146m. A similar and parallel depression, but shallower, is located further to the northeast, east of Luleå (Figure 1-2).

However, the bottom relief of Bottenviken has a pronounced NW-trending grain formed by palaeo-river valleys along deformation zones (cf. Nenonen 1995). The water in these rivers was conducted southwards to Bottenhavet across the western part of the Norra Kvarken culmination along a NNE-SSW trending furrow (Figures 1-2 and 2-1).

3.2. Bottenhavet

The Bottenhavet Basin is bounded by the seismic Swedish, southern Norrland, the elevated ENE-WSW trending bridge of the Åland islands and Södra Kvarken, the shallow N-S trending east-coast of Finland, and the NW-SE trending bridge of Norra Kvarken.

Bathymetrically, the greatest depths (below100m) form a huge S-shape east of the Ordovician limestone and located mainly on the Finnish side, while an elevated NNNE stretch of “submerged islands” reaching above 30m b. s. l. is located on the Swedish side. The deepest part of Bottenhavet is located outside Höga Kusten, and reaches 293m (Ulvö djupet). The continuation of

Östersjön south of Bottenhavet is Ålandshav and Skärgårdshavet (Figure 2-1).

3.3. Ålands hav and Skärgårdshavet

Bottenhavet ends at the northernmost part of the large-scale basement culmination comprising Södra Kvarken, the larger island Åland and the Åland archipelago (cf. Figure 1-2). This culmination has an ENE-WSW orientation and also forms the northern boundary of Egentliga Östersjön (Baltic Proper). However, the Åland culmination is complex. East of Åland the sea is shallow, Skärgårdshavet (the Archipelago Sea), but the sea west of Åland is a fault-controlled deep-water basin, Ålands hav (Åland Sea). West to southwest of Åland there are two deeps separated by a narrow ENE-WSW trending ridge passing the island Långskär: The Åland Deep (Ålandsdjupet, 301m) to the north constitutes the central part of Ålands hav while the Långskär Deep (Långskärsdjupet, 220m) to the south belongs to Egentliga Östersjön (Figures 1-2 and 2-1).

A deep and narrow N-S trending incision transects Södra Kvarken, in the northern threshold into Ålands hav and represents a part of a palaeo-flow system transporting water southwards from the Bottenhavet Basin. A network of NNW-SSE trending palaeo-rivers is interpreted to be located between Åland and the Finnish mainland (cf. Nenonen 1995).

3.4. Egentliga Östersjön

The character of Egentliga Östersjön, and also the Gulf of Finland, differs from that of Bottenhavet and Bottenviken in the sense that the bedrocks on the eastern and southern side of these waters are composed of Phanerozoic sedimentary rocks. The western to northern sides of Egentliga Östersjön are controlled by the sub-Cambrian peneplain, which is gently inclined eastwards (Winterhalter et al. 1981). Egentliga Östersjön and the Gulf of Finland are situated along the western to northwestern flank of the early NE-trending Palaeozoic basin formed in the East European Craton (Figure 2-2). This basin comprises the Baltic Basin and its eastward continuation in the Moscow Basin (Šliaupa et al. 2006).

The topography in Östersjön is related to the distribution of sedimentary rock types, location of faults and erosion (cf. Flodén 1980, Ludwig 2001, Puura et al. 2003). A description of the morphology of the Gulf of Finland (does not belong to Egentliga Östersjön, Figure 2-1) and the south-western part of the Baltic Proper is not within the scope of this study. However, it is worth mentioning that the south-western tectonic boundary of the East European Craton (TTZ) crosses the south-western part of Östersjön.

The Egentliga Östersjön Basin, south of the Åland Archipelago, is characterized by an ENE-WSW trending deep furrow from the inner parts of the Gulf of Finland. It is complicated in the west by the fault-controlled Landsort Depression and Landsort Deep (494m b.s.l, deepest part of Egentliga

Östersjön, located about 90km north of Gotland), where it swings southwards through the Norrköping Depression towards Öland.

East of the Landsort Deep there is a narrow winding ridge from the previous mentioned furrow southwards across Gotska Sandön to Fårö and Gotland (the Kopparstenarna Ridge, the Sandö Bank). The higher ground of the island of Gotland can be followed, submerged, southwards where it connects with Midsjöbankarna (the Northern and Southern Middle Banks).

Major N-S tectonic structures occur associated with Klints Bank and the Fårö Depression along the Latvian coast and west of Gotland from Södertörn to Poland. The deep central part of Egentliga Östersjön is dominated by N-S and NE basins (the Gotland Deep, 205m b.s.l., and the western and eastern Gotland Depressions).

4. Geomorphological description – Coastal areas of eastern Sweden

The term “Landform” is defined as any physical, recognizable form of feature of the Earth´s surfaces, having a characteristic shape and produced by natural causes (Jackson 1997). Notable is, that the term landform does not only apply to features on land but also to features under water.

The following description is a general overview of the geological features that control the present coastline of eastern Sweden and especially at the two SKB sites, Forsmark and Laxemar. The description starts from Haparanda, at the border to Finland in northern part of Bottenviken, and goes southwards and is generally based on Lidmar-Bergströms description of the morphology of the bedrock surface in Sweden (1994, cf. Figure 2-5). Skåne, the southernmost part of Sweden, is located at the south-western boundary zone of the East European Craton and is not treated here.

Haparanda–Örnsköldsvik: The sub-Cambrian peneplain is traceable along the coast. It is recognized on Holmöarna in Norra Kvarken, the basement culmination forming the southern boundary of Bottenviken.

Örnsköldsvik–Sundsvall (Höga Kusten): The area is elevated and has a strong relief of presumably sub-Mesozoic age. The area is located in the centre of the post-glacial uplift, the highest coast line occur at about 285m, and it may still rise about 100 to 125m. However, the present centre of the highest uplift, 9mm/year, is now located further north.

Sundsvall–Gävle: The coastal zone between the higher Norrland inland terrain and Bottenhavet forms a relatively narrow strip, up to 25km wide, demarcated both on the western land-side and the eastern sea-side by N-S trending faults (eastern side down). Within this strip the sub-Cambrian peneplain is preserved, uplifted and/or eroded. In the sea-covered area the sub-Cambrian peneplain was formed in the top surface of the metamorphic Precambrian rocks as well as the Jotnian sandstones; it dips eastward and is down-faulted. The seismic activity along the coastal section from Gävle to north of Örnsköldsvik is strongly enhanced and this is the most pronounced seismic region in Sweden.

Gävle– Norrtälje: The morphology of eastern Uppland is controlled by a set of slightly curved faults (concave eastwards) that tilt blocks very gently south-eastwards. These faults also form the island Gräsö, just northeast of Forsmark, and affect the morphology in the archipelago and sea bottom east of Gräsö and the northeast coast of Uppland. NW-SE to WNW-ESE trending deformation zones along the northern coast of Uppland have minor affect on the coast line on a regional scale but may control it on a minor scale. On the northern side of the large-scale gentle basement culmination between Uppland and Finland, Södra Kvarken and northern part of Skärgårdshavet, the sub-Cambrian peneplain has a gentle northward dip.

Norrtälje–Bråviken: The ground surface in the southern part of the large scale “bulb” in the coast line around Stockholm represents the uplifted and eroded sub-Cambrian peneplain. The E-W trending Sörmland horst is located between Bråviken and Mälaren. The form of Lake Mälaren is controlled by a large scale shear pattern. The Mälaren structure is bounded to the north by an extensive E-W trending structure that reaches Ålands hav south of Norrtälje. The southeast part of the coast is governed by internal structures (banding) in the Sörmland gneiss and NE-trending deformation zones. In the sea southeast of Sörmland, the sub-Cambrian peneplain swings eastwards and dips very gently towards SSE.

Bråviken–Oskarshamn: At Oskarshamn the orientation of the coastline shifts by approximately 15° degrees towards north, having a roughly N-S trend, and the coast line becomes more irregular. The coastline at Laxemar is controlled by N-S and NE-SW trending faults. North of Laxemar the irregularities in the coastline are controlled by NW-SE trending valleys (deformation zones). Notable is that the shift in orientation of the coast line is not reflected in the form of the sub-Cambrian peneplain in the sea area. However, the distance between the coast line and, e.g. the -200m-contour line of depth to basement increases northwards, a deflection that may be structurally controlled (e.g. displacement along NS-trending faults).

Oskarshamn–Blekinge: In the easternmost part of Blekinge the orientation of the coast shifts to a NNE trend where the sub-Cretaceous etch surface intersects with the sub-Cambrian peneplain. The latter is found along the main part of the Swedish east-coast, though locally uplifted and/or eroded. From Blekinge to Oskarshamn the coastline is smooth and the sub-Cambrian surface is sloping gently (south-) eastwards (Winterhalter et al. 1981).

Blekinge: The main part of the coast of Blekinge trends E-W and has a sub-Cretaceous hilly relief (Jepsen et al. 2002) with dominance of NNE-SSW to NNW-SSE trending valleys forming a regular intersection pattern (cf. conjugate sets). This pattern continues into the Hanö Bay Slope (Wassnäs & Flodén, 1994), which dips very gently southwards.

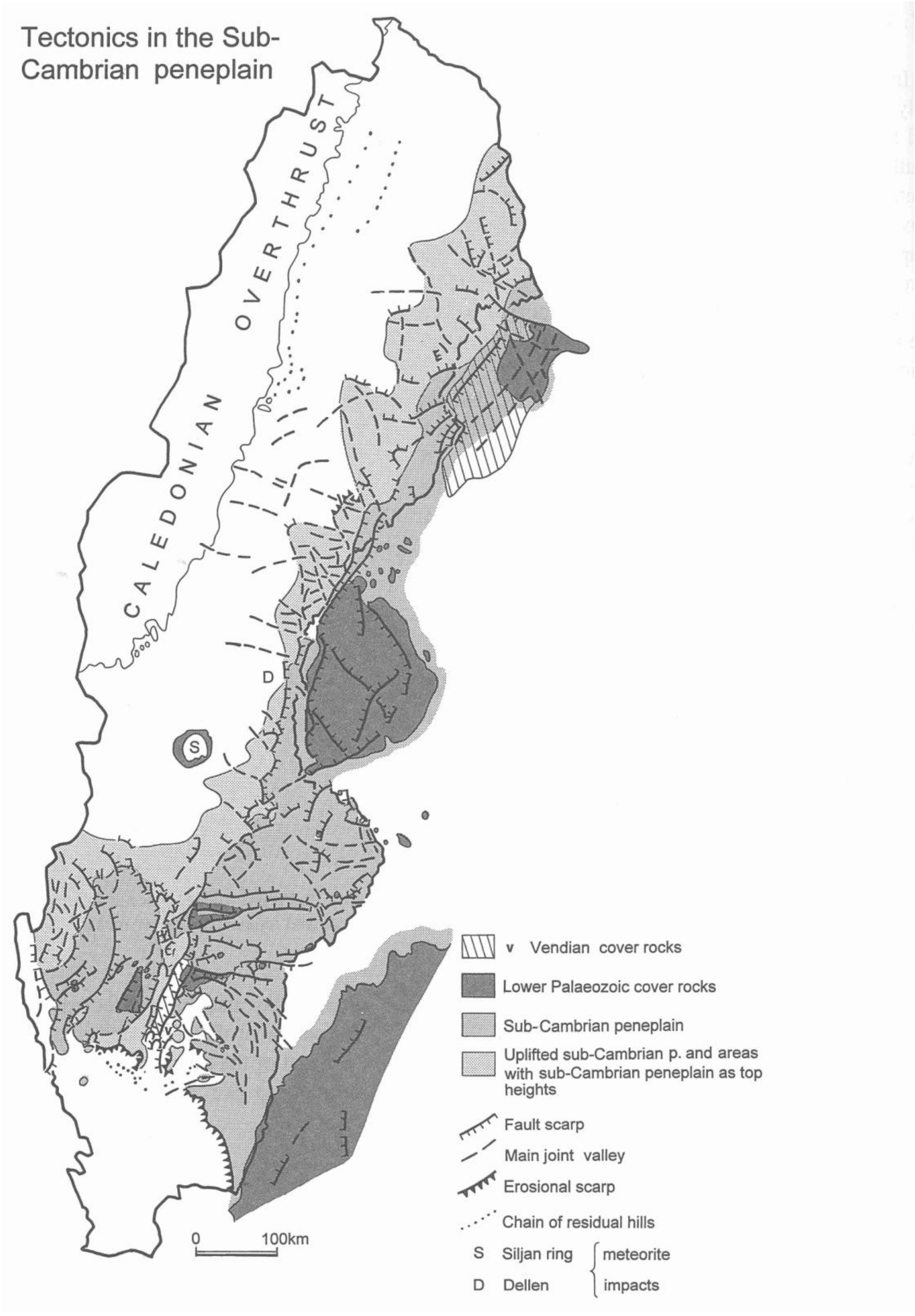


Figure 2-5. Long term morpho-tectonic evolution in Sweden (from Lidmar-Bergström 1996, Cf. Lidmar-Bergström 1994)

5. Structural map(s) – Östersjön/Baltic Sea

5.1. What does a lineament represent?

When observing, e.g. air or satellite photos, topographical, geophysical or geological maps, the eye always finds linear features. These reveal changes or breaks in the Earth's crust, a zone of crustal weakness or the scar of such a zone. The detailed appearance of such a structure varies with the scale at which the interpretation has been performed. What, at large scales, may be apprehended as a single line may at a closer look be dissolved into two or more components of different strike to the overall common strike direction.

A lineament may represent a zone of crustal weakness or the single branch in a zone of crustal weakness; it may represent the centre of a zone, the boundary to a zone; it may be a detail of a larger structural complex.

The underlying structure giving rise to a line in a lineament interpretation may be a deformation zone, and this is often considered to be the only just cause for drawing a line in a lineament interpretation. Different capacity to resist erosion, i.e. a lithological boundary, may give rise to linear features which are not always tectonic lineaments, but still, they sometimes are. Sorting out such structures takes time and may require specific field investigation. Linear structures should not be considered as non-tectonic just because they coincide with lithological boundaries.

5.1.1. The same structural pattern from microscopic to global scale

The self similarity of structures is amazing. When producing line-drawings from specimens at all scale, from thin sections of bedrock some tenths of µm thick, to satellite interpretations of global features, the same kind of pattern appears – the configuration seen in microlithons; a cleaved piece of rock with an internal cleavage at high angle to an enveloping cleavage.

5.1.2. Length of a structure depends on the scale of observation

When the Earth's crust is deformed it is stretched, compressed, dragged and twisted. Rupture depends on strength, strain rate and scale of observation. The deformation of the crust may appear as a deformed "marshmallow", a large structure may consist of the grouping of several, apparently individual elements. Segments of a structure are displaced relative to each other within the enveloping surface of the entire structure, from global (mid-ocean ridges) to microscopic scales. These segments are connected in three dimensions and the connection is not always seen in a two-dimensional section (a map or a profile). The length of a structure is thus dependent on at what scale it is observed, in microscope or from space. As the calculating of the amount of displacement is scale-dependent; what is the cut-off limit? Large displacement may be recorded on major structures. But if the deformation is taken out also in minor amounts on small-scale structures with distortion of the rock body, how is this accounted for?

5.2. What lies behind a topographic lineament?

A structure giving rise to a lineament may have various physical expressions. Mathematically it can be expressed as inflection points. It may be a step in the topography, a change in gradient, or a change in the roughness of the ground surface. The latter may be due to differences in lithological competence. A straight lithological contact as such does not qualify for a lineament. However, deformation often takes place at lithological contacts, especially if the competence difference between the involved lithologies is great. The rock pattern may change across a lineament. A major structure can thus be revealed by the lack of mapped structures across an imagined line.

If the lineament represents a shear zone it may be a composite structure, lensoidal network or composed of minor constituents with mutual divergent ‘internal’ strike directions. It may be bordered by, or encompass, elevated or descended rock blocks along its strike. A deformation zone, depending on the lithologies involved may comprise a low, or a high, due to the competence of the rocks and may vary along strike. Thus you are allowed to ‘mix apples and pears’.

The intensity of a feature as revealed in topographic signature is dependent on its direction in relation to foliations, fracture systems, ice-transport directions, and the slope of the surface that it occurs in, i.e. the palaeo- and present drainage pattern.

5.3. Methodological comments

As structures are complex with multiple characteristics, interpretations also vary due to the scale at which it has been performed and the intension with which it has been carried out (e.g. one line or its smaller components). The lines drawn for rock-block boundaries may differ from the lines that are drawn for other purposes. A zone may sometimes be revealed by a series of structures in a line with an angle to their internal strike direction. The time available for verification of the reproducibility of a study influences the appearance and completeness of the presented result. The reproducibility of the interpretation of a structure testifies to the dignity of the structure. The accuracy of a line is connected with the scale at which it was interpreted. A line interpreted and drawn at 1:2 000 000 looks the same on a map at 1:20 000 as does one drawn at this scale, although their characters are totally different. Still the position of the line is easily, wrongly judged, as precise as the line drawn at 1:20 000 in spite of the fact that the 1:2 000 000 line represents a zone of several hundred metres width.

To test interpretations for the most important structures more than one data set may be used. These, most commonly, do not carry information covering identical areas. This interpretation has its focus on the sea areas and is less dense in structures as the distance from the seas increases.

Working on the edge of resolution always invokes fears that N-S and E-W structures are overrepresented, to a lesser degree also NW and NE structures, due to the form of the pixels as the eye easily connects along straight lines and diagonals. However, investigations at smaller scale of larger areas and with other methods still give these four directions as the main directions of fracture pattern in south-eastern Sweden. And in detail the N-S structures range from NNNE to NNNW. Digitally drawn interpretations have a tendency to be straighter and less "organic" than hand-drawn lineaments for technical reasons. A digital lineament is perceived and clicked at reference points while a hand-drawn line continuously follows an outline. This may give a digital interpretation a more rigid appearance, as a net lying on top of its base map rather than being an "integrated" part of the map.

6. Major lineaments

According to their orientations interpreted lineaments form four groups of structures trending approximately N-S, E-W, NE-SW and NE-SE, Figures 3-1 and 3-2.

N-S group
On a multi-interpretation map of the Baltic-Fennoscandian area, lineaments in the N-S direction appear in major groups. These are regularly spaced; the southern part of the Protogine zone – the eastern boundary of the Dala group volcanics and their associated magnetic anomaly; the centre of the Baltic and Bothnian Seas; the eastern parts of the Baltic Republics and Finland. These lineaments are not expressed as one solid thick line along the interpreted length, but appear as segments, displaced relative to each other in the east-west direction.

These structures are imaged at smaller scales with structures of less dignity separated regularly at fairly even distances down to the local scale.

E-W group
E-W lineaments occur regularly spaced over the entire area and are well visible in eastern Sweden and the sea areas. In Bottenhavet, they often occur in doubles and link with EENE (azimuth 80°) and occasionally WWNW (azimuth 280°) traces.

The structures in both these groups appear in rather straight lines.

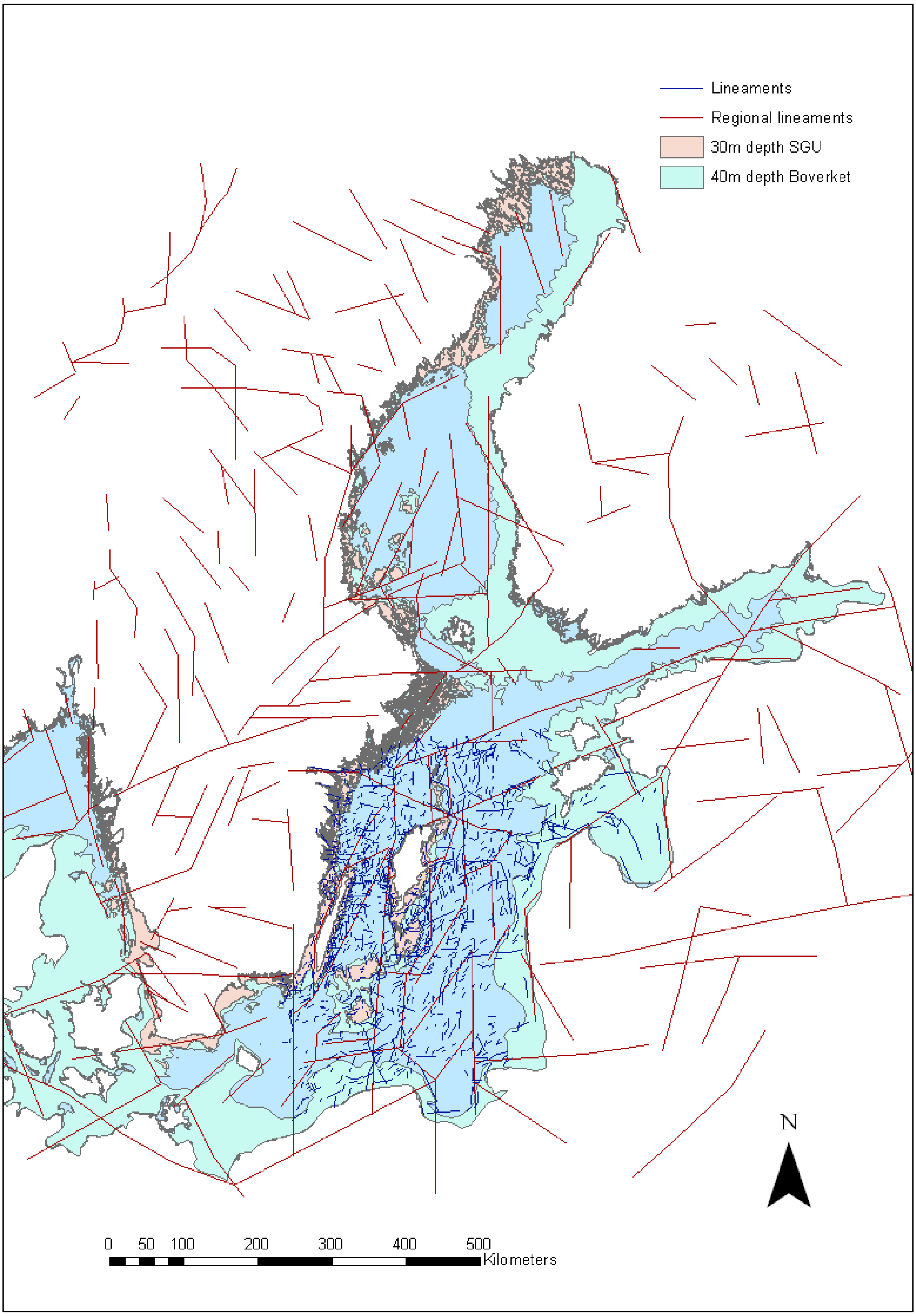
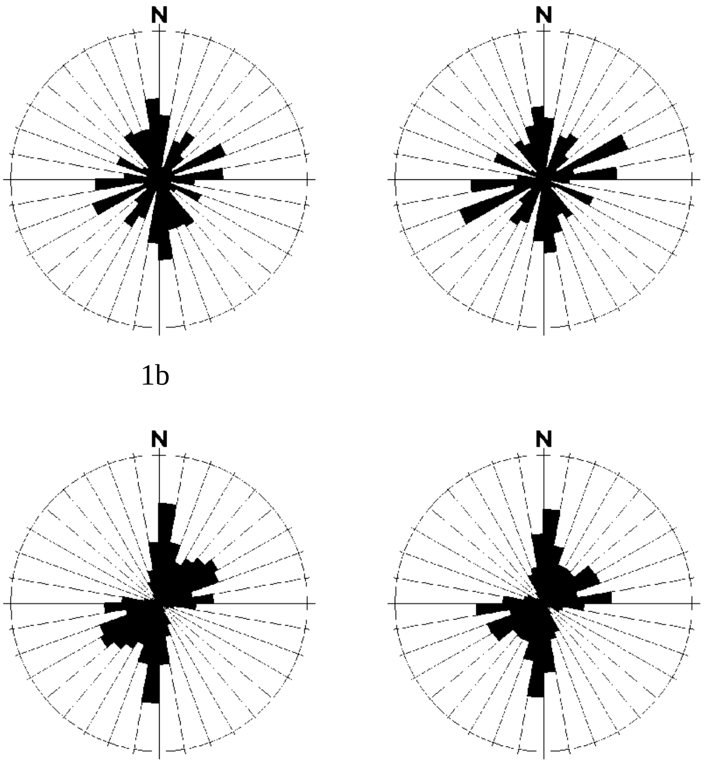


Figure 3-1: Lineament map, Östersjön area, based on topographical data. Data on lineaments are given in Figure 3-2. (The detailed lineament interpretation of Egentliga Östersjön is presented in Appendix 1, Figure A1-1.)

NW and NE groups

NW and NE structures are more varied in their appearance and lengths. At the Swedish coast along Egentliga Östersjön, NNE traces gradually swing into a more easterly strike as you go northwards, e.g. east of Ävrö and Stockholm.



1a 1b

2a 2b

Figure 3-2. Orientations of lineaments (rose diagrams) in Figure 3-1:
1). Large scale interpretation of lineaments (regional lineaments);
1a. according to number N= 229 and
1b. according to length per 10°-sector in relation to the total length of mapped tectonic structures, Lengthtot= 27 260km ,and
2) Local scale interpretation of lineaments in Egentliga Östersjön (local scale interpretation);
2.a. according to number N= 1427 (2a) and
2b. according to length per 10°-sector in relation to the total length of mapped tectonic structures, Lengthtot= 12 832km.

6.1. Regularly spaced structures

Looking at the map of northern Europe a few linear peculiarities stand out. The Gulf of Gdansk, Riga Bay, Peipus Lake, Ladoga and Onega mark depressions at fairly evenly separated distances, 250-300km apart on a NE axis. Also the large islands Öland and Gotland comprise a ribbon (NE-ENE) across Egentliga Östersjön.

6.2. Mirror images

Like South America mirrors Africa the Polish-Lithuanian-Latvian coast roughly mirrors the outline of the coast around Skåne up to Bråviken and a comparison of a lineament interpretation map of the southern Swedish mainland and Egentliga Östersjön have great similarities: a) The overall shape of the areas, and b) white spots for large areas of divergent character – large lakes on the mainland (Vänern and Vättern) and islands in the sea area (Öland and Gotland); their shapes even resembling each other (cf. Appendix 1).

Another peculiar resemblance is displayed in the fracture pattern when comparing a lineament interpretation from a local area in south-western Sweden and the major lineament outline of Gotland. The entire Egentliga Östersjön Basin has a smoother, lensoidal, version of the same outline while Bottenhavet is a half structure. The higher ground in the south-western part of Bottenhavet has a different pattern from the trace of low areas in the eastern to northern parts of Bottenhavet having an S-shape.

The swinging east of east-of-northerly striking traces into an almost east-westerly direction occurs at different scales: East of the Sörmland coast and east of Ävrö near the Laxemar site.

7. Faults - displacements

This section of the report is mainly a literature review and is focused on areas close to the two SKB sites Forsmark and Laxemar (i.e. Bottenhavet, Ålands hav and the northwestern and central parts of Egentliga Östersjön – areas in which marine reflection seismic surveys have been performed). A general presentation of the occurrence of post-glacial faults is given. Faults and related lineaments described in this section are based on reflection seismic measurements.

7.1. Bottenviken

Bottenviken is an open NE-SW trending basin and the grain of regional structures trend NW-SE. NNE-SSW faults (eastern side down), parallel to the Swedish coastline at Norra Kvarken, are also common. On land, north of Bottenviken N-S trending faults are common cf. Figure 3-12. Jotnian sandstones cover the major part of Bottenviken and the thickness of these sediments varies considerably. In the central part of the bay, Lower to Middle Cambrian sediments (Wannäs 1989) occur on top of the Jotnian sandstones.

7.2. Bottenhavet

Bottenhavet is an asymmetrical basin with a pronounced N-S trending fault-escarpment along its western part (southern part of Norrlandskusten). Faults are reactivated and have, e.g. both down-faulted the Jotnian sandstones (eastern side down; thickness of the sandstone c. 1 000m) and, with the same sense of movement, offset the sub-Cambrian peneplain formed on top of the sandstones. A sequence of Lower Palaeozoic sediments was deposited on the Jotnian sandstones. The remnants of the latter, down-faulted in Bottenhavet Basin, indicate that the Cambro-Ordovician sediments here had a thickness of 200 to 300m (Axberg 1980).

The tectonic map of the Bottenhavet part of Östersjön (Floden 1984 and Winterhalter et al. 1981) is mainly based on the work by Axberg (1980) and shows that faults are generally detected in areas with Ordovician limestones; either bounding the extension of the limestones or located in areas with limestones. In surveyed areas with only few outliers/remnants of Palaeozoic rocks, as in the northern parts of Bottenhavet, no faults are inferred.

The Cambrian-Ordovician sediments are assumed to have been deposited on the sub-Cambrian peneplain which had a very low relief (some tens of metres, Rudberg 1954). However, the contact between the Cambrian sediments and the peneplain is irregular and may indicate that the peneplain has been faulted. Similar irregular contacts between the lower Palaeozoic sediments and the underlying Jotnian sediments are found in the northern parts of Egentliga Östersjön and this pattern is caused by faulting (Flodén 1980). In the latter case the orientation of faults is mainly N-S. However, the southerly extension of Ordovician limestones in Bottenhavet is mainly controlled by NE-SW (NW side down) and NNE trending faults.

In Bottenhavet the most prominent structures are three extensive NW-SE trending faults (trace length >100km) with a separation of about 70km. The most northerly of these faults (the southern side down-faulted) is filled with glacio-fluvial sediments, an esker. The esker is traceable across Bottenhavet. The “Aranda Rift” (cf. Figure 3-3) is up to 100m deep and also forms the northern boundary of the remnants of Ordovician limestone in Bottenhavet and also in Östersjön.

The largest displacement of the sub-Cambrian peneplain has occurred along faults with a northerly trend along the Swedish coast. The accumulated down-faulting of the sub-Cambrian peneplain along the Swedish coast is in the order of 170m. In the coastal blocks the peneplain is inclined (dips about 5°to the east), while the in the sea area the tilting is much less (max dip about 2°, both to the east and west). The displacement along mapped faults is generally less than 10-15m, in extreme cases up to about 30m. Largest indicated vertical displacement is about 150m. However, the throw indicated on the tectonic map are not always identical to the displayed movements in the seismic profiles.

Of special interest is the occurrence of late dolerite dykes in the area, especially post-Ordovician dykes. Such dykes are found just east of Sundsvall and they are possibly related to the Alnön alkaline complex (Snäll 1977).

In the central parts of the investigated area (from Söderhamn to Sundsvall) seismic reflection profiles are mainly oriented E-W which may cause a bias

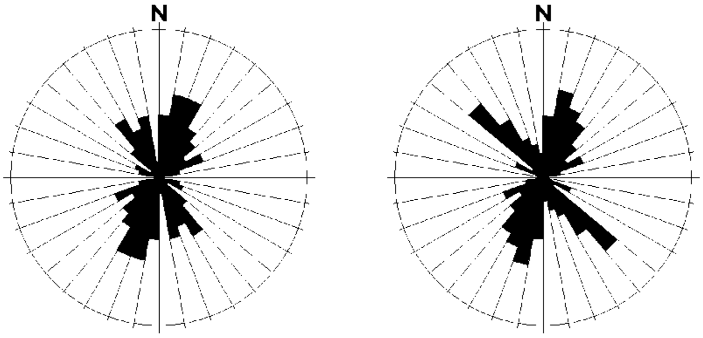
Figure 3-3: Faults in Bottenhavet (Axberg 1980, Figure 30); down-faulted side is hatched (cf. Figures 3-4 and Table 3-1).

in the detection of structures sub-parallel to the profiles. The main purpose of the study appears to be the mapping of the sediments in Bottenhavet and all displayed faults in profiles are close to vertical.

A component of vertical displacement has been recorded for 73 percent of all mapped faults, corresponding to 77 percent of the total length of faults in the area (Table 3-1). Most frequent are structures trending NNE and NNW (Figure 3-4) and the mean lengths of these faults are pronounced compared to most other fault sets. NW trending faults are also frequent and include the most extensive faults (mean length of 35km; the Aranda rift is the longest

Table 3-1: Faults in Bottenhavet compiled from Axberg (1980; Figure 30) described by the orientation (22.25° sectors symmetric across north):
Ntotal= 141 and Lengthtotal= 3028km (cf. Figures 3-3 and 3.4).
The uncertainty in measured length for each fault is less than 1km for shorter structures and 5km for extensive structures. Down-faulted side along faults, number of faults and length of faults per orientation sector, are presented.

Sector	Down-faulted side	Number	Length (km)
EW		3	15
	no indication	0	0
	N side down	2	11
	S side down	1	4
WNW		8	150
	no indication	4	73
	N side down	3	42
	S side down	1	35
NW		19	691
	no indication	1	90
	E side down	13	326
	W side down	5	275
NNW		25	350
	no indication	4	52
	E side down	12	155
	W side down	9	143
NS		19	421
	no indication	2	36
	E side down	9	189
	W side down	8	196
NNE		32	698
	no indication	8	93
	E side down	15	332
	W side down	9	273
NE		22	456
	no indication	3	50
	E side down	13	284
	W side down	6	122
ENE		13	247
	no indication	2	16
	N side down	9	195
	S side down	2	36



a. b.

Figure 3-4: Orientation of tectonic structures in Bottenhavet (Axberg 1980):
a) orientation according to number, N=141, and
b) orientation according to length per 10°-sector in relation to the total length of mapped tectonic structures, total length = 3 028km (rose diagram, outer circle is 10%).

with a length of more than 145km, cf. Figure 3-3). Mapped faults with an E-W orientation are very few and these are short.

7.3. Ålands hav

Ålands hav is a fault graben formed in the western part of an ENE-WSW trending basement culmination representing a late Cretaceous high (Lidmar-Bergström 1996) with a central part, Åland, consisting of Rapakivi granites (c. 1.6Ga old). Flodén (1980) interpreted the main part of the lower Palaeozoic sedimentary cover to have been eroded before the faults, outlining major rock blocks with Jotnian sandstones, were reactivated in the Tertiary and large-scale rock-blocks were down-faulted and the Ålands-hav depression was formed.

The main part of the Jotnian sandstones in Ålands hav is located in an open asymmetrical NW-SE trending basin; the south-western side slightly steeper then the north-eastern side and presumably fault controlled. The top surface of the Jotnian sediments was denudated during the formation of the sub-Cambrian peneplain. This surface is in large parts preserved in the down-faulted blocks with Jotnian sandstones in Ålands hav and it is locally covered by remnants of Lower Palaeozoic sediments (Cambrian sandstones and Ordovician limestones; the thickness of the Lower Palaeozoic sediments is less than 350m; Söderberg 1993).

In the western part of Ålands hav the down-faulted sub-Cambrian peneplain forms a nearly sub-horizontal surface, slightly eastward-dipping, at a depth of about 90m b.s.l. (Söderberg 1993). The deeper parts of Ålands hav coincide with the location of the older part/lower unit of the Jotnian sandstones. In the neighbouring Swedish mainland, with the SKB-site at Forsmark, the sub-Cambrian peneplain closely represents the ground surface.

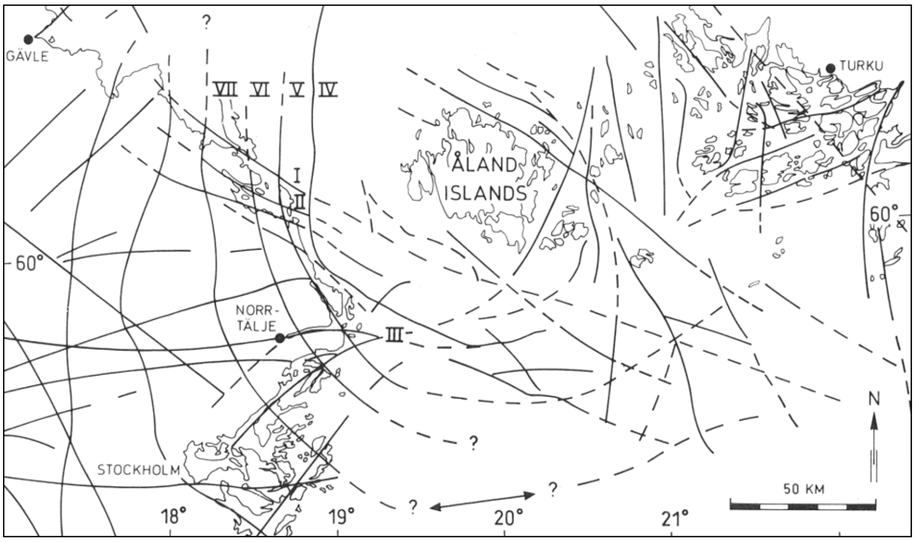


Figure 3-5: Faults at the basement culmination from Sweden to Finland across Åland; Ålands hav is located west of Åland and Skärgårdshavet east of Åland (Söderberg 1993, Figure 30 – here reduced in size, the southern part of Bottehavet is here excluded), cf. Figures 3-3 and 3-7.

Dolerite dykes (c. 1.3Ga, Suominen 1987) are found in two localities in the Jotnian sandstones:
West of Åland and
East of the island Väddö, on the northeast coast of Uppland.

The system of deformation zones in the Åland culmination and in north-eastern Uppland and south-western Finland (Figure 3-5) contains structures oriented in: WNW-ESE, N-S, NE-SW and ENE-WSW. Extensive deformation zones are generally oriented N-S and WNW. ENE-WSW trending deformation zones are mainly found in the mainland of Finland and Sweden but are rare in the Ålands-hav area.

As previously mentioned, the boundaries of the Jotnian sediments are controlled by faults and the Ålands-hav Basin is controlled by at least 3 sets of tectonic zones (Söderberg 1993):

The WNW-ESE tectonic zones along the north-eastern coast of Uppland.
The NE-SW fault system.
The Åland Gross Structure (cf. zones IV to VII in Figure 3-5).

Statistics on faults according to their main trends are given in Table 3-2 and Figure 3-6. Observe that many of the faults displayed in Figure 3-5 are extensive and many are curved, e.g. Set 3 faults, and some apparently change their direction by linkage. Most frequent are WNW-ESE, N-S and ENE-WSW trending faults having mean trace lengths of 68, 82 and 53km respectively. Faults trending E-W are also extensive, mean length 83km.

Table 3-2: Faults in the basement culmination between Sweden and Finland at Åland including the sea areas Ålands hav and Skärgårdshavet compiled by Söderberg (1993: Figure 17, the southern part of Bottenhavet in the original figure is not included here) described by the orientation (22.25° sectors symmetric across N): Ntotal= 62 and Lengthtotal=>> 4 357km (cf. Figures 3-5 and 3-6; the full extent of 24 faults are not presented in the Figure 3-5).

Displacements of faults are not systematically presented by Söderberg. The uncertainty in the measured length for each fault is less than 1km for shorter structures and 5km for extensive structures).

Sector	Down-faulted side	Number	Length (km)
EW	n.a.	6	495
WNW	n.a.	12	810
NW	n.a.	6	439
NNW	n.a.	9	669
NS	n.a.	11	904
NNE	n.a.	2	78
NE	n.a.	6	435
ENE	n.a.	10	527

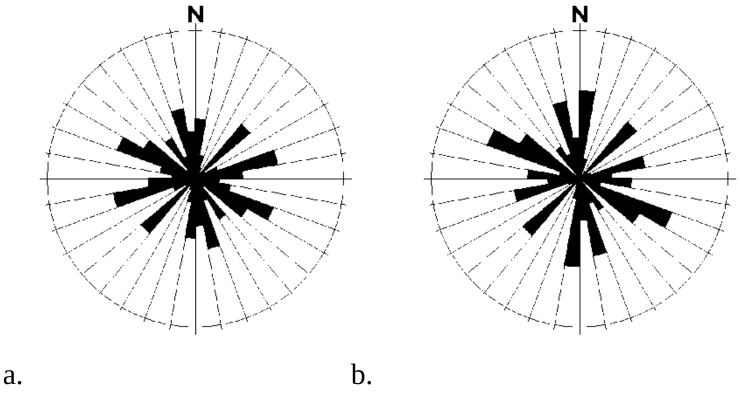


Figure 3-6: Orientation of tectonic structures in the Åland culmination and adjacent areas in Sweden and Finland (Söderberg 1993):
a. orientation according to number, N=62, and
b. orientation according to length per 10°-sector in relation to the total length of mapped tectonic structures, total length = 4 357km (rose diagram, outer circle is 10%).

The Set 1 fault zones are both morphologically expressed in the sea beds and detected in the marine seismic survey. Three major faults belonging to Set 1 are mapped by Söderberg (1993) and they are:

1. The Öregrund–Singö fault zone (denoted the Singö deformation zone by SKB, cf. SKB 2008).
2. The Forsmark–Granfjärden fault zone (denoted the Forsmark deformation zone by SKB, cf. SKB 2008).
3. A zone some kilometres south of the Forsmark–Granfjärden fault zone.

Descriptions of the main faults belonging to Set 1 are given below and thereafter follow descriptions of Set 2 and Set 3 faults.

Set 1, the Öregrund–Singö fault: The zone is located north of Singö. The SE extension of the Öregrund–Singö fault zone forms a morphological escarpment in the sea bottom. The Åland deep (>250m b.s.l.) is located north of and sub-parallel to the Öregrund–Singö fault zone, apparently steered by the Öregrund–Singö fault zone and a north-westerly trending branch from this zone. The fault zone transects the Jotnian blocks apparently without any lateral displacement of the sandstones. East of Singö, the zone intersects a semi-circular fault zone (belonging to the Åland Gross Structure). In the reflection seismic measurements there is an offset (eastern side down about 60m) at an intersection point with a crossing fault. However, it is not clear along which fault the displacement has occurred.

Set 1, the Forsmark–Granfjärden fault zone: The zone is sub-parallel to the Öregrund–Singö fault zone and located less than 10km to the south. It passes south of Singö, and forms a valley in the sedimentary rocks in Ålands hav. It partly follows the contact between the younger and older units of the Jotnian sandstones and apparently affects the lateral distribution of the two sandstone units just east of Singö, indicating a left-lateral separation. Söderberg (1993) presents a NE-SE trending reflection seismic profile cutting across the Forsmark–Granfjärden fault zone. At this locality, the fault zone coincides with the lithological contact between the lower unit (to the north) and upper unit (to the south) of the Jotnian sandstone. The top surface of the Jotnian sediments south of the Forsmark–Granfjärden fault is elevated about 20m compared to the area north of the fault. In the same profile the Öregrund–Singö fault is indicated (northern side is about 20m lower).

Set 1, a third fault zone south of the Forsmark–Granfjärden fault zone, passing through Hargshamn and Grisslehamn (unlabeled by Söderberg 1993): This zone is herein denoted the Hargshamn–Herräng–Grisslehamn fault zone and forms a sharp escarpment west of Väddö, northern side down; east of Väddö it has a NW-SE orientation in Ålands hav. The fault is traceable about 30km in the sea area.

Other WNW-ESE trending faults occur between Åland and the Finnish mainland and faults of this set continue eastwards to south of the Gulf of Finland and westwards into the Swedish mainland. On a regional scale the WNW-ESE set of fault zones formed a part of a regional Precambrian right lateral shear zone, formed at c. 1.82Ga ago (Lahtinen et al. 2008), that is assumed to have crossed a former continental plate and presumably had an extension in the order of 1 000km.

The Set 2 is represented by an extensive and winding fault with a main NE-SW trend, the Vaxholm–Långskär–Kummlinge fault. The fault is traceable northwards from north of Stockholm, forms a channel between the Swedish mainland and the archipelago and reaches open sea east of Norrtälje at the shoal of Söderarm. From there, it passes across Ålands hav north of the islet Långskär and swings northwards east of Åland and west of the island Kumminge in Skärgårdshavet. The fault divides the area with Jotnian sandstones into a larger northwestern part and a minor south-eastern part. The larger sandstone area has a NW-SE extension and the sandstones are partly covered by Palaeozoic sediments, while the minor sandstone basin trends E-W and contains only the older Jotnian sandstone unit. The fault crosses a semi-circular Set 3 fault at the islet Långskär, where a tilted basement block has developed.

The set 3 faults consist of a group of “semi-circular”, concentric regional faults located on the western and southern side of the mainland of Åland. The origin of this pattern is located in Åland and the radius is at least about 100km. The separation between the faults ranges from 5km to more than 10km. In northern Uppland the terrain between these faults is gently tilted eastwards. The continuation south of Åland is uncertain. Noteworthy is that the trace of the faults appears to become N-S in the southernmost parts of Bottenhavet. Four semi-circular fault zones are considered in the work by Söderberg (1993) and only the easternmost (inner) structure, which is located just outside the Swedish coast, is covered by marine physical investigations. However, it is located in the peripheral western and southern parts of the investigated area. The trace of the inner semi-circular fault starts in the southernmost part of Bottenhavet (Södra Kvarken) as a N-S trending canyon-like incision (a former river valley, still seismically active). East of Singö it crosses three Set 1 faults and further to the south, east of Väddö, there is a shift to a WNW-ESE orientation i.e. parallel to the Set 1 structures and the fault trace crosses the ESE-WSW trending Vaxholm–Långskär–Kummlinge fault and, still further to the south, joins an E-W-trending fault passing through Norrtälje. What is here described is a linkage of structures. However, it is noteworthy that faults such as the regional and significant E-W trending faults in the Norrtälje area are not recognized by Söderberg (1993) as a separate set of structures in Ålands hav.

Söderberg (1993) has not presented any seismic profile displaying late deformation along structures belonging to the Åland Gross Structure. However, the “inner” structure is indeed a major structure and demarcates the western and southern extension of the sedimentary rocks in Ålands hav. The accumulated vertical throw along the “inner” structure can be in the order of 1000m (south of Långskär) and is about 900m or more just east of Väddö. In the surroundings of Forsmark, the most pronounced landform related to semi-circular faults is Gräsö and the furrow just west of Gräsö. Across the N-S trending incision/canyon at Södra Kvarken the offset of the bottom topography is somewhat irregular although with the eastern side down.

The bottom of Ålands hav rises fast at the coast of Åland along a combination of vertical and horizontal fractures reflecting the internal structural pattern in the rapakivi granite (Winterhalter 1986). The bottom topography of Ålands hav (Söderberg 1993) indicates the existence of N-S trending structures in its south central parts (structures not displayed by Söderberg).

The Åland Gross Structure is interpreted as inherited sub-Jotnian ring faults (Söderberg 1993, Puura and Flodén 2000) associated with the intrusion of the Åland rapakivi granites about 1.6Ga ago. The association of down-faulted blocks with coarse sediments and rapakivi granite is common in the

Baltic Sea region. However, the formation of concentric ring structures of diameters greatly exceeding the diameter of the rapakivi granite intrusion is very uncertain, cf. Selonen et al. (2005) and Cruden (2008). The prominent structure (Fault IV in Figure 3-5; the “inner fault”) is a very dominating fault located in the fringe zone of the investigated area. An alternative interpretation for this zone is that it represents a distortion in the basement linked through an existing system of intersecting deformation zones; by activations of linked segments of existing zones.

7.4. Central and northwestern part of Egentliga Östersjön

The western part of Egentliga Östersjön is described first in this section and is followed by a description of a sub-area east of Laxemar (northern Öland – Gotland area). The general reference for this section is Flodén (1980).

The crystalline Precambrian bedrock is exposed in large parts along the west coast of Egentliga Östersjön: Along the E-W trending southern coast of Blekinge and from just south of Oskarshamn all the way northwards along the south-eastern coast of Sweden via the Åland culmination and along the northern coast of the Gulf of Finland. The surface of the crystalline basement in the western and northern part of Egentliga Östersjön generally occurs as a relatively smooth surface on a regional scale that generally coincides with the sub-Cambrian peneplain. However, on a detailed scale the bedrock surface may be uneven (normal relief within the undeformed sub-Cambrian peneplain was 10 to 20m, Rudberg 1954).

Along the south-eastern coast of Sweden the bedrock surface dips very gently ESE whereas in the northern part of Egentliga Östersjön it slopes gently towards SSE (Winterhalter et al. 1981). The major shift in orientation of the bedrock surface occurs north of Gotland. This is the location where the bedrock surface is most intensely disturbed and faulted. It is also the location of the deepest part of Egentliga Östersjön, the Landsort Deep (459m deep), Figures 3-7a and 1-2.

The Landsort Deep is actually a half-circular trench/graben, locally 5km wide, located at the northern boundary of a down-faulted NNW-SSE trending block segment of a larger scale fault-controlled basin, which extends south-eastwards in under the Palaeozoic sedimentary rocks in the northern part of Gotland. A concentric system of half-circular fault is located to the northwest of the fault-graben at the Landsort Deep. The segment with Jotnian sandstones to the south, within the sub-Cambrian peneplain forming the top surface, is down-faulted more than 100m (120-140m). The thickness or the sandstones in the basin ranges from 500 to 1 500m and the geometry of the fault-controlled basin is asymmetrical, deepest along its south-western side (All et al. 2005). The slopes that control the Jotnian basin are inclined about 20° at its south-western and northwestern sides and about 10° at its north-eastern side (cf. sandstones in Ålands hav above).

East of the reactivated bedrock block segment there is another sandstone basin without indications of reactivation and its eastern boundary is controlled by a NS-trending fault. Most of the Jotnian sandstones in the area are covered by Palaeozoic sedimentary rocks. As in Ålands hav the down-faulted sandstones are deposited close to a rapakivi granite intrusion (cf. All et al. 2005).

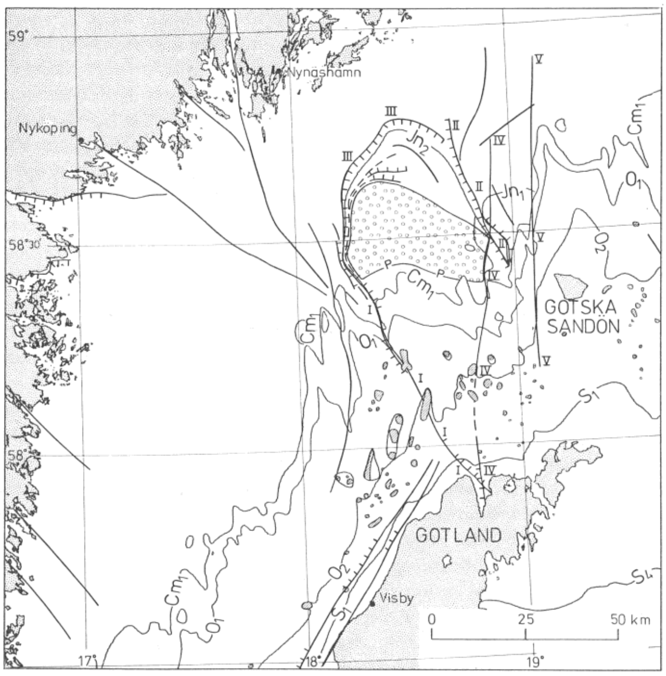
Southeast of southern Gotland there is prominent NW-trending structure, the Neman zone (cf. Figure 3-7d), which also represents a reactivated Precambrian zone. The vertical accumulated displacement as displayed in the sedimentary sequence along structures within the Neman zone does not exceed 20 to 30m. The deformation is Post-Silurian close to Gotland and Post-Devonian further to the southeast. However, there are several structures along the zone that do not show any displacement.

The reactivation of the faults at Landsort Deep was initiated during Lower Cambrian. In the northwestern part of the Egentliga Östersjön region, large areas were inundated during Ordovician, indicating low relief and the strata were deposited during a relatively stable period. However, the sedimentary sequence indicates a slight change in the tilt of the basement during the Middle Ordovician. Distortions occurred along NNE-SSW trending faults along the southeast-coast of Sweden and ENE-WSW trending faults south of the Åland culmination (Figure 3-7a and 3-7b), though the relative movements along the faults were small (less than 20m, down-faulted sides are always the western/ northwestern side).

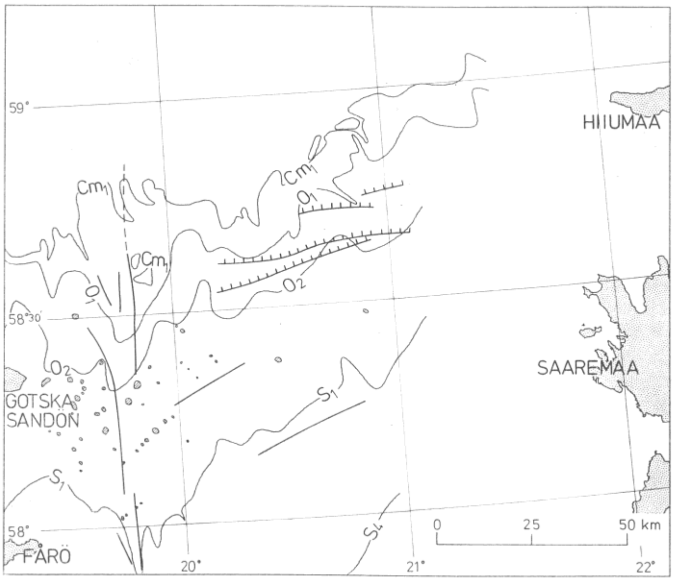
In lower Silurian the rate of sedimentation increased reflecting a period of uplift to the west and faults (oriented in, e.g. ENE-SSW, N-S and E-W; Figure 3-7a to 3-7d) were reactivated. The vertical displacements along the faults were small. At Visby the thickness of the Palaeozoic sediments is about 500m (about 150m of Silurian sediments). NW-SE trending faults were reactivated during the Devonian period (Figure 3-7d and 3-7e).

Indication of later movements, Caledonian reactivation (Figure 3-8), in the eastern part of Egentliga Östersjön, preferentially took place along ENE- to E-W-trending faults. Displacement along some N-S trending faults in the central southern part of Egentliga Östersjön is also found (Šliaupa et al. 2006). Tensional distortion is associated with the Tertiary uplift of Scandinavia (Flodén 1980).

The direction of the marine survey lines vary within the surveyed central and northwestern parts of Egentliga Östersjön. The performed marine survey was focused on mapping the sedimentary rocks and the surface of the basement. In the subarea east of Öland and south of Gotland the survey lines are relatively sparsely spaced and mainly oriented in E-W. Northwest of Gotland the survey lines have a dominant NNW-trend and far NE of Gotland the survey lines are also sparsely spaced with a N-S orientation. North and east of Gotland the density of survey lines is larger and there are several sets of survey lines. This implies for example that there is a bias in the sampling of E-W trending deformation zone east of Öland and south of Gotland.

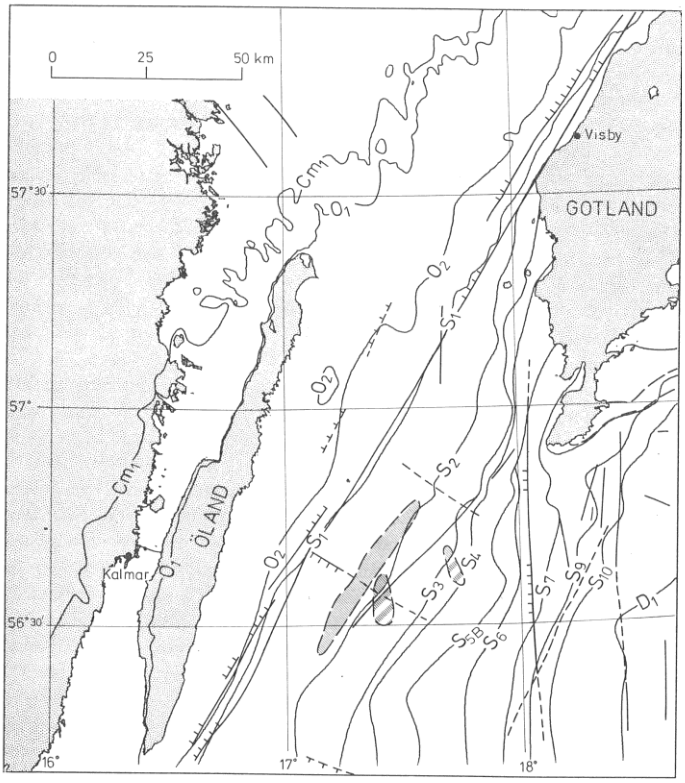


a.

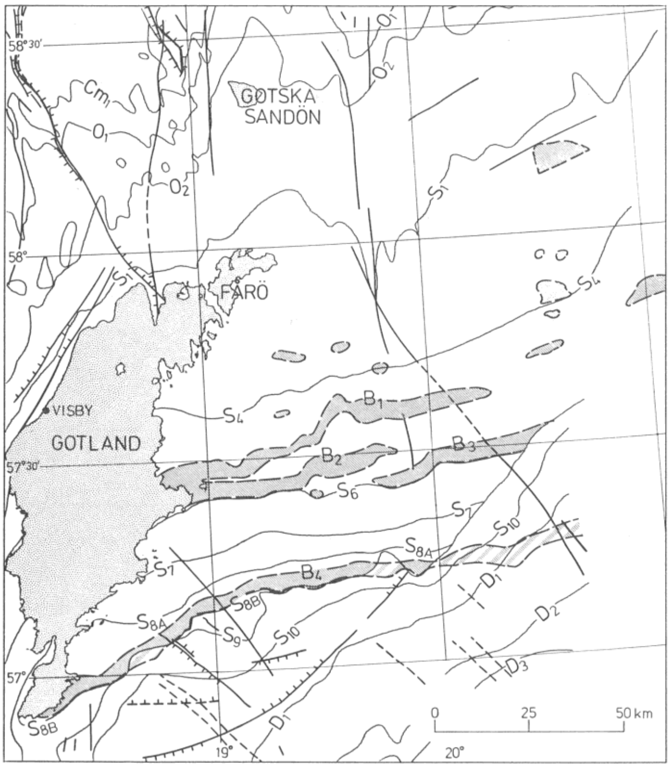


b. (to be continued)

Figure 3-7. Tectonic structures in the central and northwestern parts of Egentliga Östersjön (Flodén 1980):
a. Landsort-Fårö area,
b. NE of Gotland, SW of Gotland,
c. SW of Gotland (next page)
d. E and NE of Gotland (next page), and
e. SE of Gotland (following page).
C The down-faulted side of faults is hatched, cf. Table 3-3. Contours are isopach curves; Jotnian /Jn, rings/ , Cambrian (Cm) , Ordovician (O), Silurian, and Devonian (D). The down-faulted side of faults is hatched.

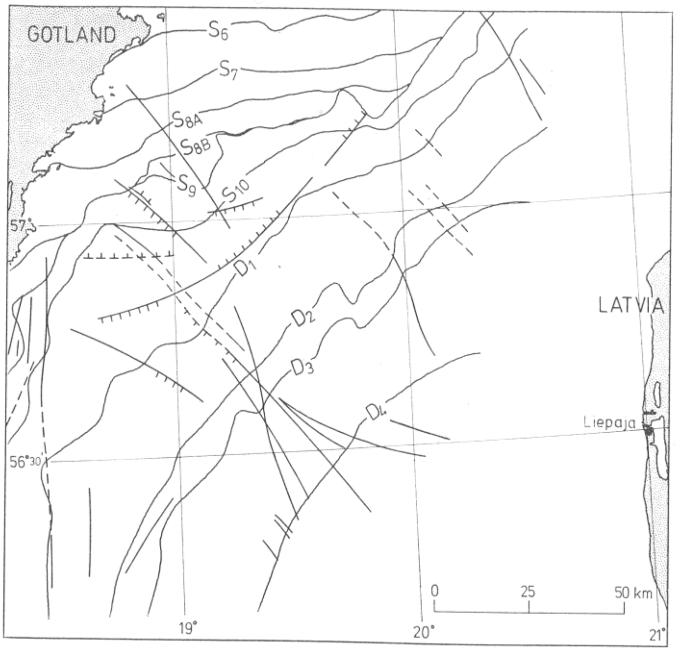


c.



d. (to be continued)

Figure 3-7 (continued). Tectonic structures in the central and northwestern parts of Egentliga Östersjön (Flodén 1980):
c. SW of Gotland,
d. E and NE of Gotland and
e. SE of Gotland (next page).



e.

Figure 3-7 (continued). Tectonic structures in the central and northwestern parts of Egentliga Östersjön (Flodén 1980):
e. SE of Gotland.

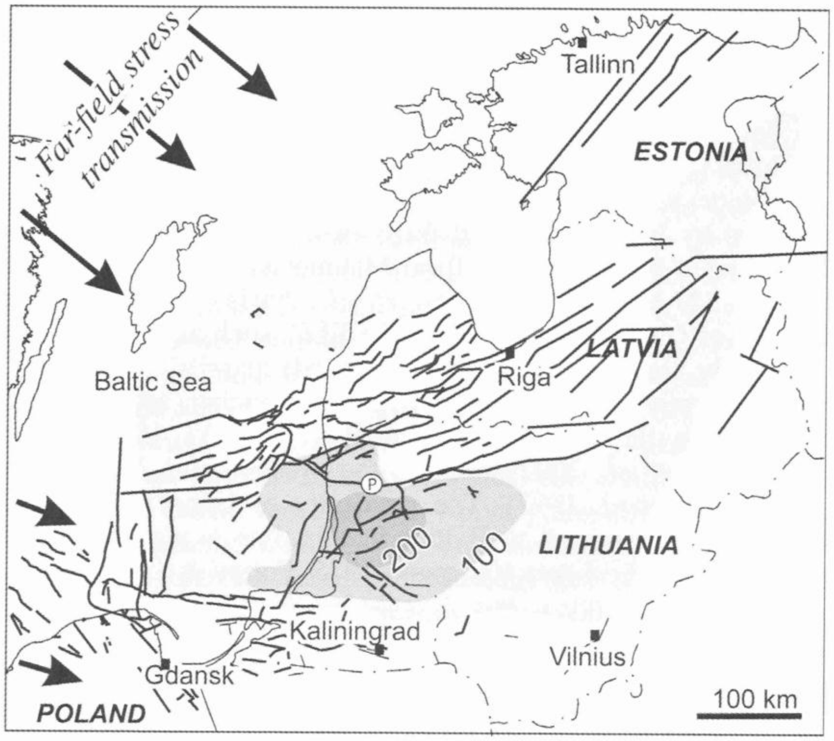


Figure 3-8: Late Caledonian faults in the south-eastern part of Egentliga Östersjön. Arrows indicates the direction of compression during Late Silurian-Early Devonian times (Šliaupa et al. 2006).

Table 3-3: Faults in the central and northwestern part of Egentliga Östersjön (Flodén 1980; Figures 11, 18, 50, 60 and 66) described by the orientation (22.25° sectors symmetric across N):
Ntotal= 88 and Lengthtotal= 2 811km (cf. Figures 3-7 and 3-9).
Uncertainty in measured length for each fault is less than 1km for shorter structures and 5km for extensive structures. Down-faulted side along faults, number of faults and length of faults per orientation sector, are presented.

Sector	Down-faulted side	Number	Length (km)
EW		9	186
	no indication	2	27
	N side down	5	100
	S side down	2	59
WNW		6	158
	no indication	3	70
	N side down	0	0
	S side down	3	88
NW		21	418
	no indication	17	329
	E side down	2	14
	W side down	2	75
NNW		15	505
	no indication	9	312
	E side down	2	84
	W side down	4	109
NS		16	691
	no indication	13	504
	E side down	1	6
	W side down	2	181
NNE		8	445
	no indication	2	75
	E side down	0	0
	W side down	6	370
NE		7	197
	no indication	4	93
	E side down	2	44
	W side down	1	60
ENE		6	211
	no indication	4	99
	N side down	2	112
	S side down	0	

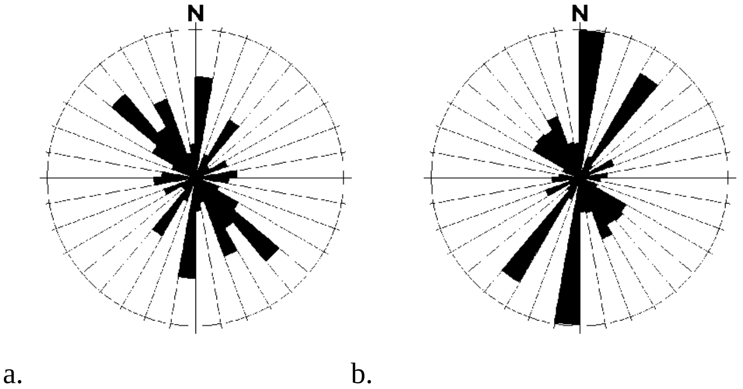


Figure: 3-9 Orientation of tectonic structures in the central and northwestern part of Egentliga Östersjön (Figure 3-7):

a. orientation according to number, N=88, and

b. orientation according to length per 10°-sector in relation to the total length of mapped tectonic structures, total length = 2 811km (rose diagram, outer circle is 10%).

The statistics of the faults in Egentliga Östersjön, Table 3-3 and Figure 3-9, show that faults trending N-S and NW-SE are the most frequent and that the NW-SE trending faults are relatively short while N-S and NNE-SSW trending faults are extensive. This picture is interesting as NW-SE trending valleys are pronounced along the Swedish coast and mainland, from north of Simpevarp to Norrköping/Bråviken. The highest mean length is found for NNE-SSW trending faults (about 55km) but these are relatively few. The mean length of mapped traces of N-S trending faults is about 43km, while the corresponding value for NW-SE and E-W trending faults is about 20km. The orientation of the seismic survey lines may introduce some bias in the sampling of faults oriented in NW-SE and E-W. Still, the N-S faults form an important tectonic component in Egentliga Östersjön.

7.5. Egentliga Östersjön: Northern Öland – Gotland area, Western Gotland Basin

The sub-Cambrian peneplain dips very gently towards ESE (about 0.2°) and is developed in Precambrian crystalline rocks. The crystalline Precambrian basement is divided into rock blocks. The relief inside the rock blocks is 10-20m, which is of the same order as the relief within the sub-Cambrian peneplain when it was formed (Rudberg 1954). Fracture valleys are formed in the crystalline rocks and these are commonly not more than 30-40m deep, in exceptional cases almost 100m deep. The vertical displacements along the boundaries of larger scale rock blocks are normally minor in the western part of Egentliga Östersjön. Generally, the eastern side of the faults is elevated some 5 to 20m across a block boundary. The tilt of the top surface of the bedrock block generally increases eastwards i.e. towards the central parts of Egentliga Östersjön. However, local fluctuations in the tilt attitude may occur.

The fracture valleys are generally deeper and wider just offshore along the Swedish coast than close to the Palaeozoic boundary. This is to some extent due to partial filling of the fracture valleys with Cambrian sandstone along the Palaeozoic boundary. The main reason for enhanced depth of valleys, especially those oriented NW-SE, is presumably the glacial erosion. However, an alternative interpretation is, that areas away from the Palaeozoic boundary i.e. west of it have been exposed to erosion during a longer period than areas close to the boundary. This can be compared to the relief inside regional bedrock blocks in the inland. For example, there are rock blocks about 30km west of Laxemar that have an extremely low relief compared to the surrounding rock blocks. One explanation can be that the cover of Lower Palaeozoic rocks were removed relatively late, cf. the remnants of Palaeozoic rocks further to the west in Västergötland.

In an E-W trending profile from Ankarsrum, at the coast of the Swedish mainland, to Visby, there are 7 incisions (noted blocks, eastern side up, c. 10m) west of the boundary of the Cambrian sediments (Flodén 1980). Notable is that the tilt angle of the blocks is not uniform. West of Visby there is a major fault system with eastern side up c. 30m. On the tectonic map (Figure 3-7c) there are two NNE trending faults along the western side of Gotland and there is also a N-S-trending fault, eastern side up, along the southwestern side of Gotland.

In Kalmarsund (Kalmar Strait), parallel to the trend of the bedding in the Lower Palaeozoic sedimentary rocks and the peneplain, there are monadnocks of Precambrian Västervik Quartzites forming NW-trending ridges elevated up to 40m above the peneplain (Flodén 1980). A conspicuous upstanding rock, the island of Blå Jungfrun in Kalmarsund east of Oskarshamn, reaches about 170m above the peneplain and is composed of rapakivi granite. Other rapakivi granites, e.g. Götemar and Uthammar granites (about 1.4Ga old), in the region are not elevated above the peneplain why a tectonic component of uplift for Blå Jungfrun cannot be excluded. The area in the northern part of Kalmarsund, between the northern part of Öland and the mainland is investigated along E-W, NNE-SSW and N-S trending survey lines. However, no indications of structures are presented by Flodén (1980) for this area.

8. Late tectonics – Östersjön/Baltic Sea region

Neotectonics comprises the study of the post-Miocene structures (<5 Ma2) and structural history of the Earth (Jackson 1997). The northern parts of Europe have been subjected to repeated glaciations since the end of Miocene. In the Nordic countries the last glaciation ended about ten thousand years ago and most of the deformation in soft sediments that predates the last deglaciation has been obliterated. Late faults formed during the deglaciation or post-dating the deglaciation are generally denoted post-glacial faults. Many of these structures are found to be of early Holocene age i.e. from a time related to the deglaciation. Mapping of distortion in soft sediments may give indications of the existence of post-glacial faulting, but to connect such indications to a certain fault can be difficult.

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[2] M=mega, a= year

8.1. General description

Ludvig in 2001 presented a map of the most important areas of neotectonic subsidence and uplift in northwestern Europe (Figure 3-10). In the East European Craton, such areas are located in Östersjön. Nikulin in 2007 presented a similar map for Egentliga Östersjön (Figure 3-11). Notable is his interpretation that the depressions east and west of Gotland may have a neotectonic vertical component. However, Puura et al. (2003) mapped the same area and found that the depressions coincide with areas that have the highest post-Palaeozoic magnitudes of erosion, more than 280m northwest and southeast of Gotland.

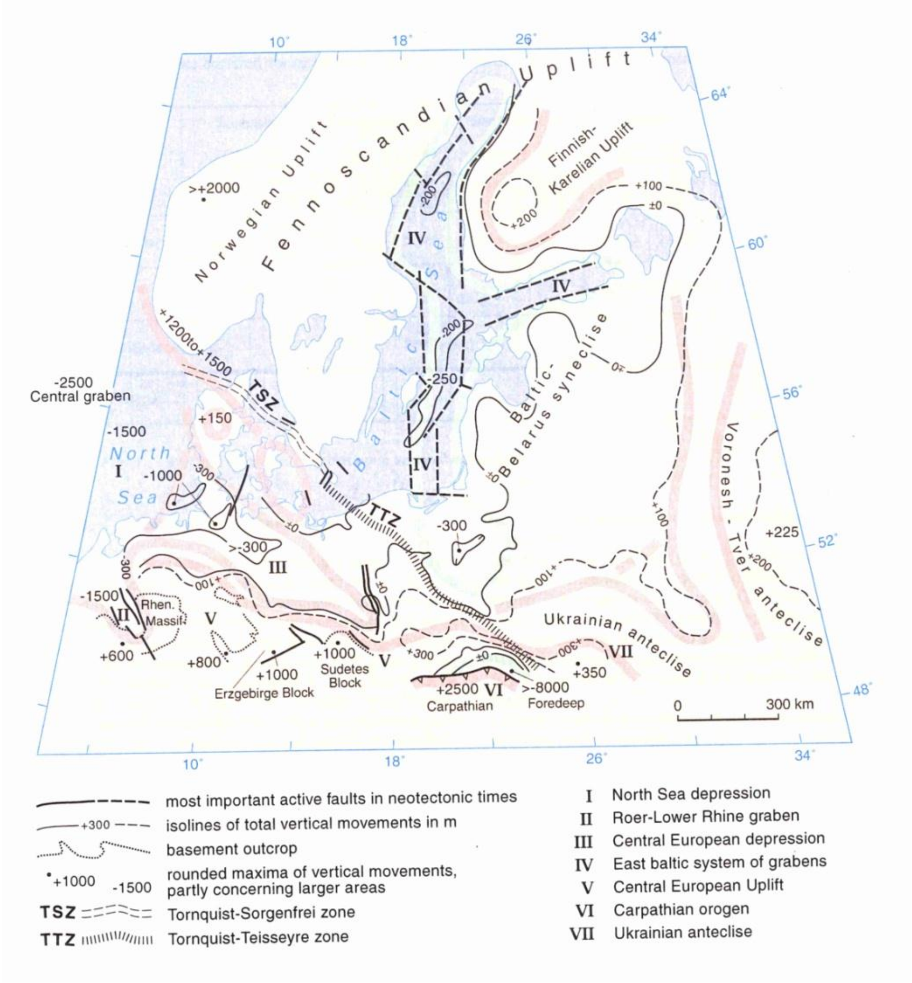


Figure 3-10: Most important areas of neotectonic subsidence/uplift (from Ludwig 2001)

The crust is relatively thinner under the main Baltic Basin in the bathymetric deeps of the Gotland Deep and the Gotland, Fårö and Landsort Depressions; the depth to Moho is less than 45km (Puura, et al. 2003, Hjelth et al. 2006, Artemieva 2007). The relatively lesser crustal thickness east of Gotland and in Bottenviken and Finland have been suggested to be due to embryonic rifts

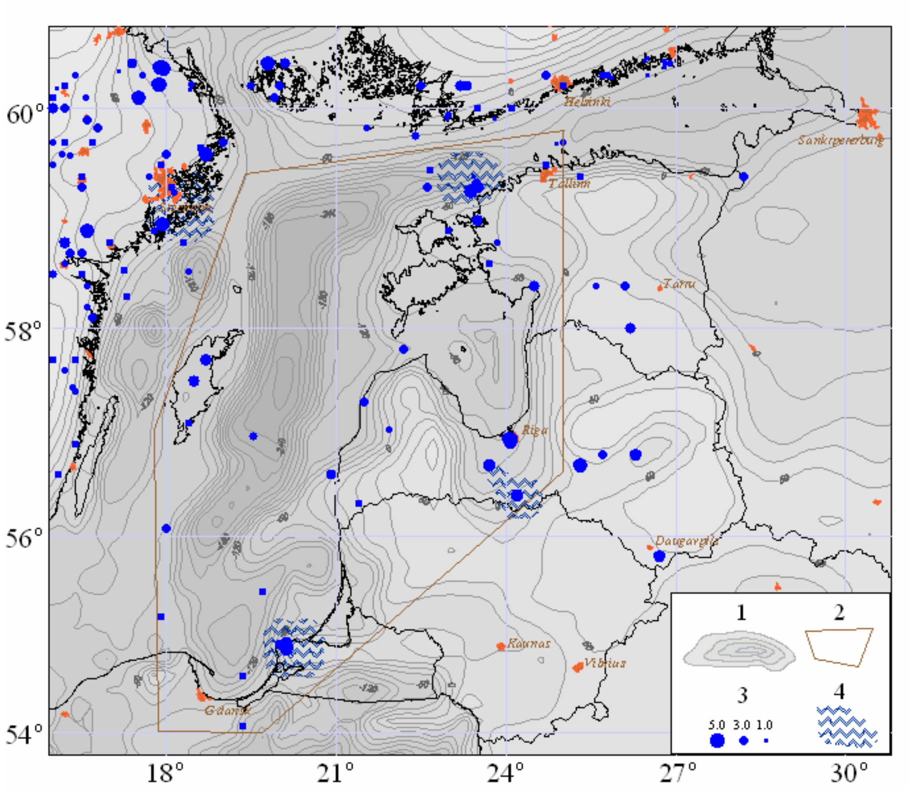


Figure 3-11: Total amplitudes of neotectonic motions of the earth's crust and epicentres of earthquakes of the Baltic region during the period from 1375 to 2006 (From Nikulin 2007):

1 – lines of equal values of total neotectonic amplitudes in meters, 2 – area of neotectonic depressions of the Baltic Sea and coast of Baltic countries, 3 – epicentres of earthquakes (the diameter of circumference corresponds the size of moment magnitude Mw), 4 – areas of the maximal accumulated seismic moment M0.

in a triple-arm system (Karabanov et al. 2003). The Central Gotland Uplift was by them interpreted as a horst while Puura et al. (2003) distinguished the N-S trending, normal Gotland–Leba faults to mark the site for the post-Devonian uplift of southern Sweden. An assessment of the isostatic data for parts of Scandinavia, Finland and the land masses south and east of Östersjön (Meyer 2003) revealed a marked roughly N-S trending structure through the Egentliga Östersjön east of Gotland, separating areas that rise or sink in relation to the present sea level. The northernmost tip of Estonia is also subsiding.

Earthquakes recorded by the SNSN-net for the years 2000-2008 have been compared to the lineament interpretations for the Egentliga Östersjön and Bottenhavet Basins. Many earthquakes can be associated with lineaments and in some cases a "missing" line is depicted by a row of earthquake-epicentre dots (Figure 3-14, see also Appendix 1 and Beckholmen Tirén 2008 and 2009). A general description of indicated occurrence of neotectonics in Östersjön is given below, starting from north going southwards.

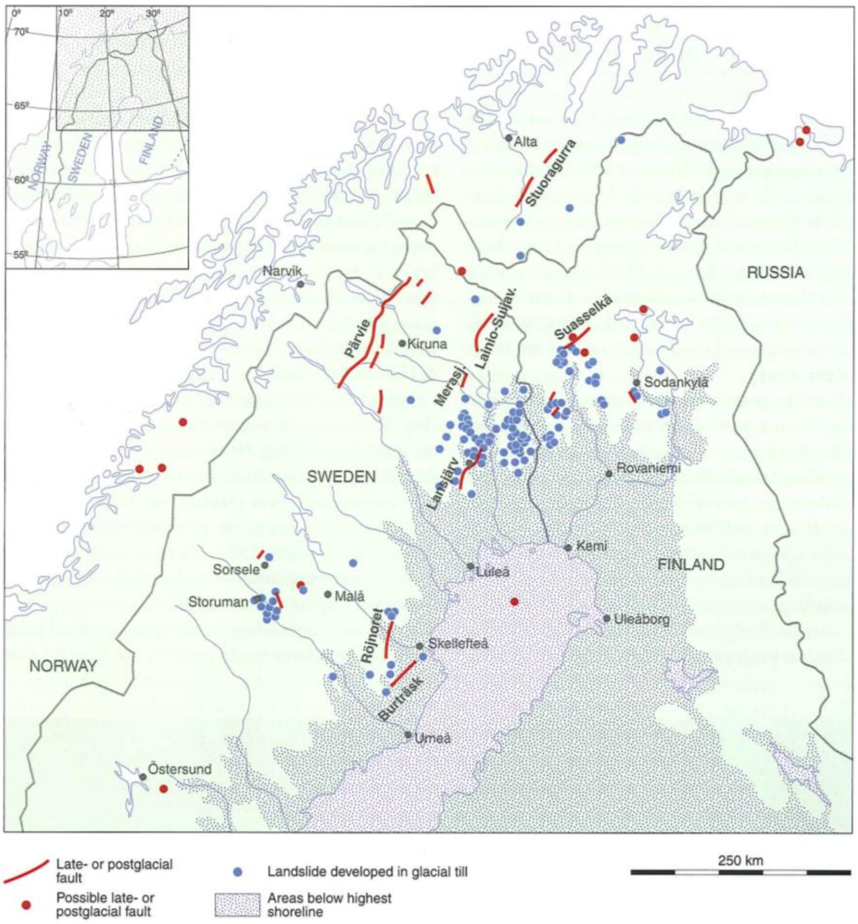


Figure 3-12: Location of late- or post glacial faults and landslide scars in northern Fennoscandia (Lagerbäck and Sundh 2008, Swedish Geological Survey ©).

8.2. Bottenviken and surrounding areas

Largerbäck and Sundh (2008), Figure 3-12, have presented a summary of post-glacial faults in northern Sweden and Finland and they also examined indications on late faulting found in other parts of Sweden. It is notable that most of the faults trend NNE-SSE and a subdominant orientation is N-S. Earthquakes are recorded at NNE-SSE-trending faults and these faults occur at a large angle to the structural grain of regional deformation zones and the main stress direction in the area, oriented approximately NW-SE.

One indicated late- or postglacial fault has been recorded (Andrén 1990) in Bottenviken (Figure 3-12). The analysis of seismic reflection and refraction measurements performed by Wannäs (1989) in Bottenviken did not consider minor faults.

8.3. Bottenhavet

In Bottenhavet the “Aranda Rift” trending NW-SE (Figure 3-3) is one of the most prominent bottom structures. It is up to 100m deep and more than 150km long (Axberg 1980). It is formed as an incision along a fault that forms the northwestern boundary of the present extension of the Ordovician sediments in the Baltic Sea. The Aranda Rift is filled by glacifluvial sediments, an esker, that can be traced across Bottenhavet i.e. about 200km. However, no late faulting along this zone was described by Axberg (1980).

Mörner (2003) described a number of localities along the southern part of the east-coast of Bottenhavet where sedimentary features and displaced blocks at the head of the bedrock could indicate post-glacial faulting. The seismicity in the area is increased as in the areas with the post-glacial faults in northern Sweden, Norway and Finland. However, the location of faults that may have caused the disturbances is not yet found. Notable is, that even in the area of maximum post-glacial uplift at Höga Kusten, late relative displacement along faults outlining deep fracture valleys have not yet been established. However, the on-going tectonic distortion along the west-coast of Bottenhavet is well indicated by the seismic activity. In Bottenhavet, SNSN-recorded earthquakes are relatively rare and mainly located in a few areas:

1. Bottenhavet is framed with earthquake epicentres along its west coast and the earthquakes are clustered (Figure 4-1 and Appendix 1 Figure A1-3).
2. East of Gävle, a cluster of earthquakes is located (at a distance of 75km from Forsmark) in the northeast sector between two crossing regional structures; N-S structure, along the coast and an ENE-WSW trending structure along the southern boundary of the Palaeozoic sediments in Bottenhavet (Figures 2-3 and 4-1 and Appendix 1).
3. Many earthquakes can be associated with lineaments and in some cases a “missing” line is depicted by a row of earthquake-epicentre dots, e.g. along a WNW-ESE trending virtual line (not yet detected as a fault) in the south central part of the sea (Figure 4-1); earthquakes are located where this line intersects N-S trending lineaments (Cf. Figure 4-1 and Appendix 1). Many epicentres line up along E-W lines (Appendix 1 Figure A1-3).
4. In central Bottenhavet about 90km ENE of Sundsvall and in close connection to the intersection between extensive E-W and NW-SE trending lineaments/faults (Appendix 1 Figure A1-3).
5. Along an extensive ENE-WSW trending lineament passing through Sundsvall (Appendix 1 Figure A1-3).
6. Along NNE-SSW trending faults in the sea area just outside the coastline between Sundsvall and Örnsköldsvik (Appendix 1 Figure A1-3)
7. Along a N-S trending deep incision, a former river valley located between Åland and Uppland, in Södra Kvarken (Figure 4-1).

In summary: The eastern half of Bottenhavet is essentially an area devoid of seismic events while earthquakes are frequent along its western coast line but otherwise relatively sparse in western parts of the sea.

8.4. Egentliga Östersjön

There are relatively few earthquakes recorded in Egentliga Östersjön as compared to Bottenhavet. The SNSN net may not fully cover the area occupied by Egentliga Östersjön. Much of the recorded earthquake data come from Kalmarsund, Figure 4-4 and Appendix 1.

In Egentliga Östersjön and Ålands hav, Flodén (1984) investigated four areas for neotectonic structures:

- Ålands hav – no late faults found.
- Landsort Deep/Trench – no late faults found
- The NW-trending Neman zone southeast of Gotland – “a very limited number of possible structures found”
- The easternmost part of Hanö Bay - “a very limited number of possible structures found”.

Söderberg (1993) found that pockmarks, formed by gas venting, are common in Ålands hav. The pattern of pockmarks is found to line up with the bedding in the underlying Jotnian sandstones and deformation zones. Earthquakes are relatively few in Ålands hav–north-eastern Uppland coastal areas (Roslagen). Those recorded are located along faults trending WNW-ESE and N-S and at lineament intersections (Figure 4-1 and Tirén and Beckholmen 2007).

In the central part of the Baltic Proper, the NW-SE trending structures in the Neman zone southeast of central Gotland are indistinct while structures found south of Öland are distinct with a NNE-SSW trend. In both areas, the structures found are located in close connection to faults in the sedimentary rock successions. However, other origins than neotectonics cannot be ruled out for the structures in the area south of Öland. In this area there is also a “recent fault” with an offset in the order of one metre (eastern side down; Flodén 1984). There is no information about the sea area west of central Gotland, where the extension of the Neman zone crosses the NNE-SSW trending Öland zone.

Minor distortions recorded one year in the sea bed may not be found the following year (Flodén, personal communication about 1995). The reason for this may be the on-going sea floor erosion and deposition of bottom sediments.

Flodén (1984) concluded that:

- “Neotectonic lineaments occur in the Baltic, but they are restricted to areas with older fractures. They are all related to reactivation of older structures.
- Only occasionally neotectonic movements have occurred since the deglaciation period.

- The majority of the pre-Quaternary fractures in the Baltic show no evidence of neotectonic activity”.

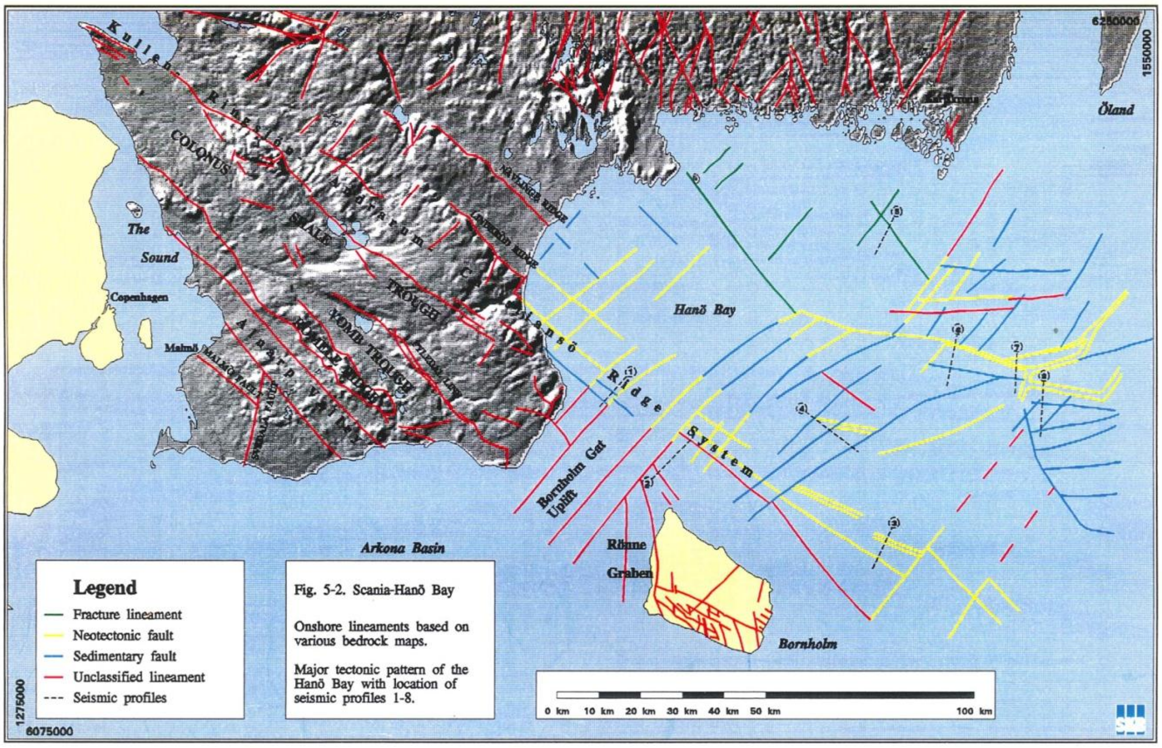


Figure 3-13.Faults in the Hanöbukten and Bornholmsgattet (Wannäs and Flodén 1994).

Hanöbukten was re-investigated by Wannäs and Flodén (1994) and neotectonic structures were found to be preferentially oriented in NE-SW and NW-SE, Figure 3-13. The latter is subparallel to the border zone of the craton, the Tornquist-Teisseyre Zone (TTZ). Late deformation is also inferred for the southern part of NNE-SSW trending faults located east of Öland and west of Gotland.

In summary: Late to post-glacial faulting is indicated in the sea beds of Egentliga Östersjön. However, the performed marine-geological surveys have generally not been focused on detecting late deformation. In many cases where late deformation is indicated by distortion of the sea beds, it may alternatively be interpreted as deformation related to sedimentary compaction. Indications of late to post-glacial displacements are found to occur along old structures.

9. Site maps

9.1. General

9.1.1. Structural maps

Construction of structural maps

The construction of structural maps of the two site areas and their surroundings (Figures 4-2 and 4-5) performed in the present study was made in several steps:

1. High resolution lineament interpretation based on 20m gridded elevation data was first performed – interpretation of lineaments regardless of the scale of the lineaments and mapped only where observed.
2. The next step in the lineament interpretation was simplification; sorting out minor solitary structures and checking possibilities to connect lineaments that line up (using additional complimentary elevation models).
3. The last step was the production of a thematic model showing structures that have an extension of more than 5km and structures that are essential in the description/communication of interpreted structural pattern of the area.

The last step is the weakest part in the structural interpretation process, but in this case it does not contribute to any uncertainties regarding the trace of extensive structures. On the other hand, it provides an expression of the interpreted dynamics of the formation of the structures. It is worth noting that the full resolution interpretations of the two sites show a higher density of lineaments in the Laxemar area than in the Forsmark area. This is also displayed in the thematical structural maps; cf. Figures 4-2and 4-5.

To connect the structures in the site areas with structures in sea areas thematic regional maps based on 20 and 50m gridded elevation data for land areas and nautical charts for sea covered areas (Figures 4-1 and 4-4).

The SKB mapping of structures at the sites (especially in the target/focus areas of the sites) is strongly based on geophysical measurements, e.g. detailed magnetic measurements. Low-magnetic lineaments are generally interpreted as deformation zones while high-magnetic lineaments are interpreted as dykes, e.g. dolerites. Electro-magnetic measurements may reveal whether a structure is open, water conductive, or sealed. Detailed geophysical measurements are restricted to minor parts of the target/focus area and do not cover the surroundings of the sites. The elevation data of fairly good resolution (20m grid), on the other hand, cover relatively large areas surrounding of both sites and constitute uniform base data for structural interpretation and give information about variations in altitude across structures. As already pointed out in the text above, such variations may be due to differences in erosion resistance across a structure, displacement along a structure or the combination of both.

9.1.2. Recognition of structures and structural relationships

The present study is based on structural maps and topographical data. Information gained regarding the character of structures is dependent on the resolution in the base data and, of course, the character of the mapped structures. In this study, three types of characteristics of deformation zones are of interest:

1. Trace length of structures.
2. Termination of structures.
3. Late displacement along structures.

These features reflect the character of structures. However, on lineament maps these features are not based on direct observations of the actual structures but rather reflect how the structures appear in the base data, e.g. in digital elevation models (and airborne/detailed ground magnetic measurements in the SKB interpretation). To clarify this the three listed charters of structures are discussed below.

Structures in the bedrock are formed, reactivated and deformed during the geological evolution of an area. Existing structures may, for example be deformed (e.g. bent, rotated), displaced (shortened, e.g. faulted) and prolonged (e.g. by reactivation). Displacement along an extensive fault can ever be uniform along the entire length of the fault and reactivation may affect only a part of a structure (partial reactivation).

9.1.3. Trace length of structures

To understand what the trace length of a remotely sensed deformation zone represents, a synthesis based on observations, although in many cases fragmentary, may help. Essential information comprise terminations of deformation zones belonging to a fracture family and also how structures are related to deformation zones belonging to other fracture families. Two extreme cases may occur:

The structure appears as a solitary discrete feature, or
it forms a part of a connected braided network of structures.

Blindly terminating brittle shears generally have horse tails, while brittle structures formed by tensile deformation just have a tip.

If structures intersect each other at small angles and terminate against each other at small angles, forming a more or less uniform network, it may not be possible to determine where a structure starts or ends. Similar problems defining length of structure may appear if structures bifurcate, forming branches. On the other hand, in a geological terrain showing pseudo-orthogonal

structural patterns, the termination of deformation zones may stand out more clearly.
The resolution in the base data in relation to the size of studied structures is of great importance. Structures that on larger scales are identified as single structures may at smaller scales appear as a cluster of minor structures.

9.1.4. Termination of brittle structures

Structures on a structural map may either have blind terminations or terminate against another structure. To determine the three-dimensional relations between structures, additional information, e.g. borehole investigation and seismic investigations, is needed. Regarding structures that “terminate” against other structures three possibilities occur:

1. Branching,
2. one structure stops against another structure, i.e. is arrested/stranded, and
3. the structure is transected and displaced by the structure it appears to stop against.

The width of faulted deformation zones in relation to their length may vary considerably. In rock block maps all deformation zones (block boundaries) terminates against other zones.

9.1.5. Late displacement along faults

Reference structures (markers) are needed to recognize the relative age of displacement along faults. In general, moderate displacement along a late fault is easier to detect if the displacement has a vertical component. This holds true especially for, e.g. post-glacial faulting. In remote sensing, the ground surface can be used as datum surface.

In general, the offset along a fault should, if possible, distinguish between slip (true measure of the direction, the relative displacement of previously adjacent points on opposite sides of a fault, measured in the fault surface) and separation (the separation of a recognizable plane surface displacement at a translational fault is the distance between two parts, measured in any specific direction, i.e. distance between displaced markers). In the later case the separation can give the impression of a relative movement that is opposite to the true slip/displacement. However, in a lineament study it is only the separation that can be given for displaced structures.

10. Site structures

In this section the pattern and occurrence of extensive structures (generally longer than 5km) in the Forsmark area and the Laxemar area are described according to their terrain expression and the general structural pattern. Each described structure has an identification code (a number or a letter) given in figures.

10.1. Forsmark

10.1.1. Regional structures outlining the Forsmark site.

Large scale structures that control the geomorphology of north-eastern and eastern coastal areas of Uppland trend preferentially NNW-SSE (structures 8 to 11 in Figure 4-1, cf. Appendix 1 Figures A1-2 and A1-5a) and WNW-ESE (12 to 14) and they interfere at Forsmark. Other large scale structures in the northern part of Uppland and the adjacent sea area and in the central parts of Uppland are trending E-W (4 to 7).

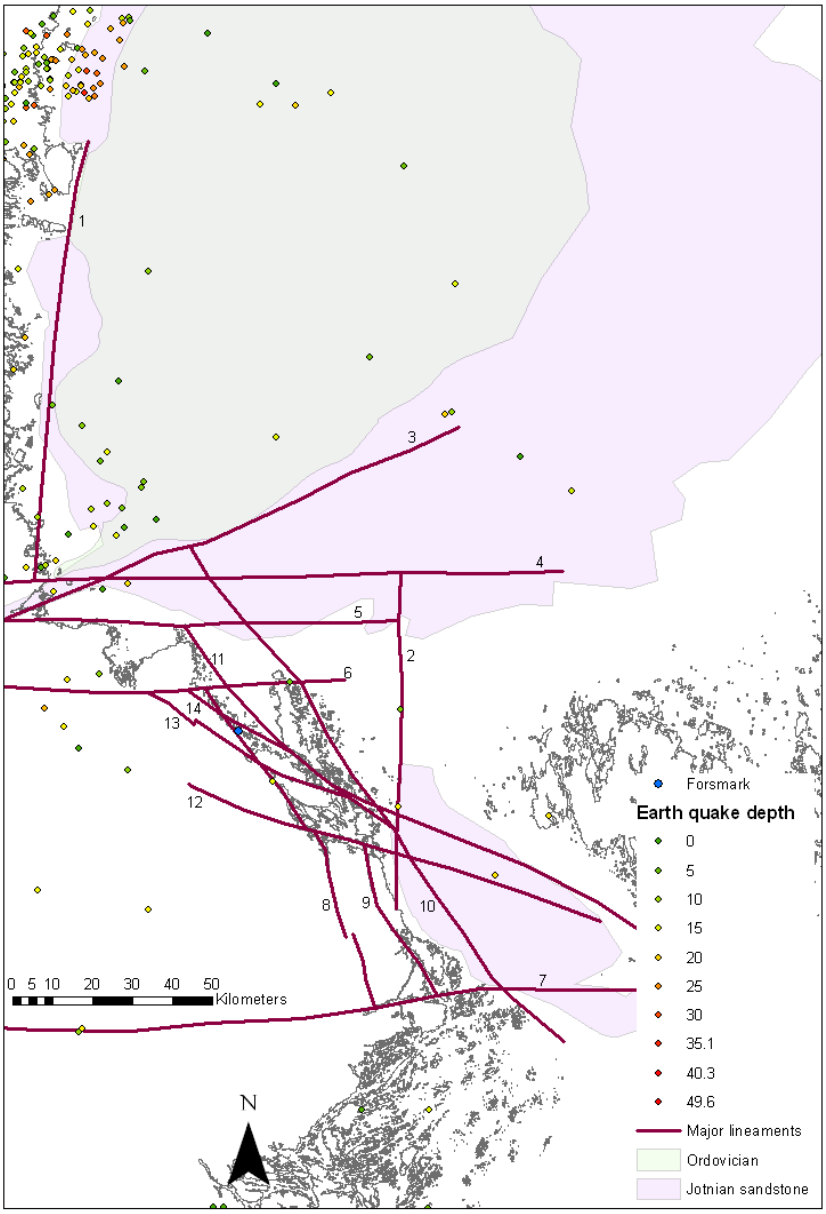


Figure 4-1. Regional scale lineaments in the regional surroundings of the Forsmark candidate area. The Forsmark site marked with a blue dot. Light blue is Palaeozoic sediments and purple is Jotnian sandstones. Earthquakes (SNSN Uppsala) are displayed as circles. Described faults are given identification codes 1 to 15.

The coast north of Gävle follows an N-S trending fault line (1) and there is another N-S fault along a pronounced incision in the basement culmination south of Bottenhavet at Södra Kvarken (2). An ENE-WSW trending fault (3) passes through Gävle and follows the southern boundary of the Palaeozoic sedimentary rocks in Bottenhavet.

Block-faulting along NNW-SSE trending faults (8 to 11) along the north-eastern coast of Uppland outline lath-shaped blocks gently tilted eastwards, e.g. Väddö and Gräsö. The blocks east of these islands are descended; slightly for the block east of Gräsö and strongly for the block east of Väddö (cf. Section 3; Ålandshav). The area west of Gräsö, i.e. north of the Forsmark site, is a low area and along the western side of Gräsö there is a deep furrow (see text below). On the other hand there is no distinct landform brake along the approximately NW-SE trending fault located in the western part of the Forsmark site (8; northern part of a regional NNW-SSE trending fault).

A WNW-ESE fault (14), the Singö deformation zone, demarcates the north-eastern side of the Forsmark candidate area. Most part of the Singö deformation zone is at Forsmark covered by sea water and it forms a furrow. The lower side of WNW-ESE trending zones may vary; northern side down (12, 14) and southern side down (13). The Forsmark candidate area is located at the intersection of the Singö deformation zone (14) and a NW-SE trending deformation zone (8, the northerly extension).

10.2. Extensive structures at the Forsmark site

10.2.1. Description of structures

The pattern of extensive lineaments in the Forsmark area is dominated by structures oriented WNW-ESE, N-S, NE-SW and E-W, Figures 4-2 and 4-3. The topographically most pronounced structures in the close vicinity of the Forsmark candidate area are two WNW-ESE trending structures, the Singö deformation zone (C) to the northeast and the Forsmark deformation zone (F) to the southwest, and a NE-SE trending zone (K) along the bay Kallrigafjärden southeast of the candidate area, Figures 4-2. The latter (K) appears to intersect the former two (C, F) and its landform expression is less distinct compared to WNW-ESE trending structures. Although, all three structures are eroded (generally less than 8 m below their surroundings). An esker is crossing Kallrigafjärden at its mouth.

However, the most pronounced landform brake in the regional surroundings of the Forsmark candidate area is a NNW-SSE trending deep furrow (B; locally more than 30m b.s.l.), covered by sea water and located northeast of the Forsmark candidate area. Together with a N-S trending structure (A) it forms the western boundary of the northerly trending Gräsö rock block. The maximum difference in altitude, along the western border of the lath-shaped Gräsö rock block and the furrow to the west, is more than 60m across a distance of 2.25km. The Gräsö block is a high, compared to the rock block to the west; it is in the order 30m higher, while relative to the blocks to the east

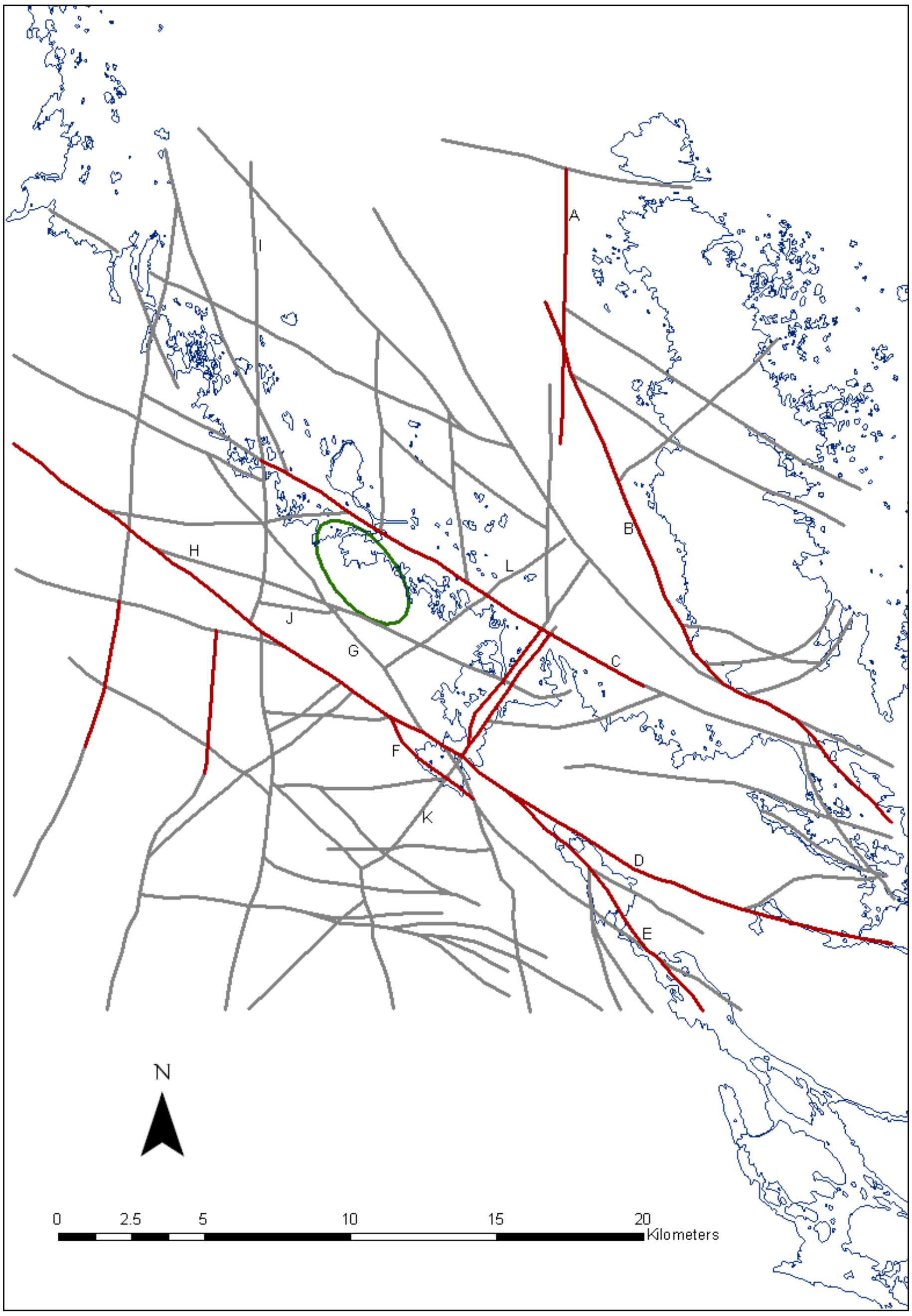
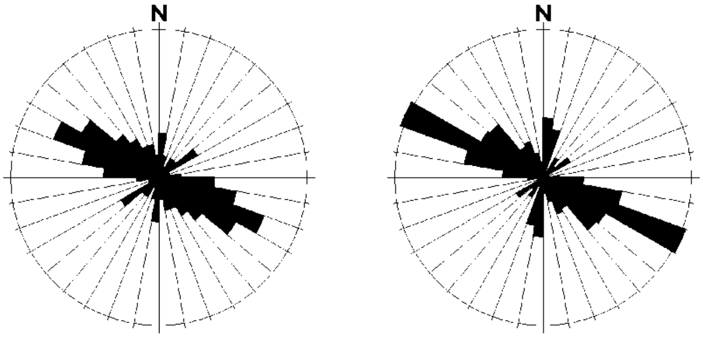


Figure 4-2. Extensive tectonic structures at the Forsmark candidate area (marked as green ellipse), structures longer than 5km and most presumably representing brittle deformation zones. Morphologically well expressed structures are drawn in red. Structures discussed in the text are given identification codes A to L.

it is c. 10m higher. The landforms across other structures in the vicinity or the candidate area are modest.

The Singö and Forsmark deformation zones (C, D) outline an elevated lath-shaped rock block containing the Forsmark candidate area. This block is here denoted the Forsmark rock block and is bounded to the southeast by the NE trending Kallrigafjärden deformation zone (K). Its northwestern block boundary is not defined. The highest altitudes in the Forsmark rock block are found along its south-western and northwestern parts, locally above 20m a.s.l. However, the Forsmark candidate area is located in a lower part of the rock block, where altitude is generally less than 5m a.s.l. The elevation of the bedrock head along the south-western, descended side of the Forsmark deformation zone (D) varies markedly. Low areas are bounded by tectonic structures (e.g. E, F). The geometry of the low areas, their relation to the Forsmark deformation zone and the ice-transport direction during the latest glaciation make them (C to F), less probable to be solely caused by selective erosion. The relative difference in altitude of the bedrock head along the Forsmark deformation zone, western side down, may exceed 10m, for example at Bruksdammen at Forsmark, which is located within a wedge shaped lake and wetland area (a down-faulted block).



a. b.

Figure 4-3. Orientation of extensive structures in the surroundings of the Forsmark candidate area:
a. orientation according to number Ntot=66, and
b. orientation according to length per 10°-sector in relation to the total length of mapped tectonic structures, total length = 576 053m (rose diagram, outer circle is 10%).

The area northeast of the Singö deformation zone (C) is lower than the candidate area and it is a shallow sea area containing minor islands and shoals with a general elevation less than 3m a.s.l. The area has the same type of relief as the Forsmark candidate area.

Across the NW-trending structure (G) located along the south-western boundary of the Forsmark candidate area there does not appear any shift in the altitude. This structure is a part of the NNW-SSE fault system located along the north-eastern coast of Uppland (cf. Figure 4-1 structure 8). Another structure trending more E-W (H) crosses the southern corner of the candidate area and there is no obvious change in altitude across the structure. It (H) is partly located along a lithological boundary.

The NE-SW structure along Kallrigafjärden southeast of the candidate area differs from all other structures in the area regarding the size of the low area connected to this structure. The land area southeast of Kallrigafjärden is somewhat elevated (less than 5m) in relation to the southernmost parts of the Forsmark rock block. Another NE-SW trending structure crosses the southern part of the Forsmark candidate area. This structure line up with two structures, one located southwest of the Forsmark deformation zone and the other is crossing Gräsö. No change in altitude is indicated across this zone inside the Forsmark rock block.

There are however, changes in the altitude inside the Forsmark rock block across two structures (I, J), trending N-S and E-W, respectively. The eastern side of the N-S trending structure is about 5 to 10m lower, and the northern side of the E-W trending structure up to about 10m lower. Other low rock blocks outlined by N-S and E-W block boundaries occur south of the Forsmark deformation zone (D). The lowering of the bedrock head within rock blocks outlined by N-S and E-W trending rock block boundaries may be caused by block faulting or selective erosion of the fractured upper part of the bedrock in the Forsmark region.

10.2.2. Relationships between site structures on land and structures in sea covered areas

Two structures in the Forsmark area can be traced into sea areas investigated by marine seismics. These structures are the WNW-ESE trending deformation zones located southwest and northwest of the Forsmark candidate area, i.e. the Singö deformation zone and the Forsmark deformation zone. However, these structures do not form single continuous lines from the candidate area into the sea area.

The WNW-ESE trending faults are of Precambrian age and fault belonging to the same set of structures may have controlled the location of basins of the late Precambrian, Jotnian sandstones. By relative late, Tertiary faulting, the Ålands-hav depression/deep was formed in the western part of the ENE-WSW trending Jurassic basement culmination between Sweden and Finland (cf. Flodén 1989 and Lidmar-Bergstöm 1996)

The western side of the Ålands-hav depression is formed along a complex fault system. This block faulting appears to have taken place along linked fault segments of N-S, NNW-SSE and E-W trending structures, i.e. a chain formed by reactivated parts of faults belonging to different fracture families. This involves differential and partial reactivation of existing structures. The down-faulted rocks appear to in large parts to have been kept as intact blocks with the top surface, the sub-Cambrian peneplain, preserved and descended (90m) and tilted eastwards.

The interpretation of the location of the eastward continuation of the WNW-ESE trending Forsmark structures into the Ålands-hav depression is indistinct. Bathometric data of the Ålands-hav area show that the deepest parts of Ålands hav are located north of the eastward extension of the Singö deformation zone. It appears as a trench having the same orientation as the Singö deformation zone. The marine geological investigation indicates however, that the accumulated vertical fault component along WNW-ESE faults can be larger than 1 400m in geological time (Söderberg 1993). The offset of the ground surface along similar structures at the Forsmark candidate area is about 10m and this is in agreement with displacements found along faults with similar orientations in Palaeozoic rocks in Bottenhavet (Axberg 1980).

The alteration of the fault escarpments indicate that the ground surface was offset prior to the last glaciation (Largerbäck and Sundh 2008).

A correlation between NE-SW trending Forsmark structures with structures in Ålands hav is not made mainly due to spatial (distance) and geometrical reasons (extension of structures) together with unknown age relationships. Similar structures are found the southern part of Bottenhavet (Figure 3-3), where the northwestern side most commonly is the down-thrown side (cf. the fault along Kallrigafjärden southeast of the Forsmark site).

E-W trending structures are uncommon in the interpretation made from marine seismics performed in Bottenhavet (Figure 3-3), probably due to sampling bias. In the Ålands-hav investigation, only extensive E-W trending structures are included, , e.g. a deformation zone passing through Norrtälje (Figure 3-5). Marine seismic information on E-W zones is generally missing though. No extensive E-W trending zones are found to transect the Forsmark candidate area.

N-S trending zones are relatively frequent in the surroundings of the Forsmark candidate area and they are common in Bottenhavet and Ålands hav according to marine seismics (Figures 3-3 and 3-5). In Bottenhavet pairs of N-S zones form both minor grabens and horsts (Figure 3-3). The vertical displacement appears to have been moderate, less than some tens of metres. In the northern part of Ålands hav the change in altitude of the sea bottom across an N-S trending structure could be considerable. In the most prominent case the eastern side is more the hundreds of metres lower, for example at the western termination of the Åland deep. In the Forsmark regional area some of the N-S trending zones appear to cross the Forsmark rock block in its western parts, outside the candidate area. Change in altitude, eastern side low, is indicated for an N-S trending structure (Figure 4-2, structure I) west of the Forsmark candidate area.

10.3. Laxemar

10.3.1. Regional structures in south-eastern Sweden

Regional structures in south-eastern Sweden display preudo-orthogonal pattern, the structures are mainly oriented E-W, N-S, NNE-SSW to NE-SW and NW-SE (Figure 4-4, cf. Appendix 1 Figures A1-2 and A1-5b). The basal contact of the Lower Palaeozoic sedimentary rocks is parallel to the coast line and located on land from eastern Blekinge to just south of Oskarhamn. From Oskarshamn to the Landsort Deep the trend of the contact steps eastwards at N-S trending structures in the Baltic Sea. As the coast-line north of Oskarshamn has a dominant north southerly trend, it implies the distance between the mainland and the location of Palaeozoic sediments increases northwards along the coast. At the Landsort Deep there is another breaking point for the orientation of the contact to the sedimentary rocks where it shifts more towards the east (Figure 2-4).

Prominent faults at the Laxemar site are oriented in N-S, NNE-SSW, E-W and NW-SE, Figure cf. 4-5. The only structure, amongst those demarcating the Laxemar area, that is traceable into Egentliga Östersjön is the E-W structure that outlines the northern boundary of the site (cf. Figures 4-4 and 4-5; the Mederhult zone/ zone III, cf. Appendix 1 Figure A1-5b). None of the other structures demarcating the Laxemar area have such dignity that they appear as large scale regional structures traceable into the sea.

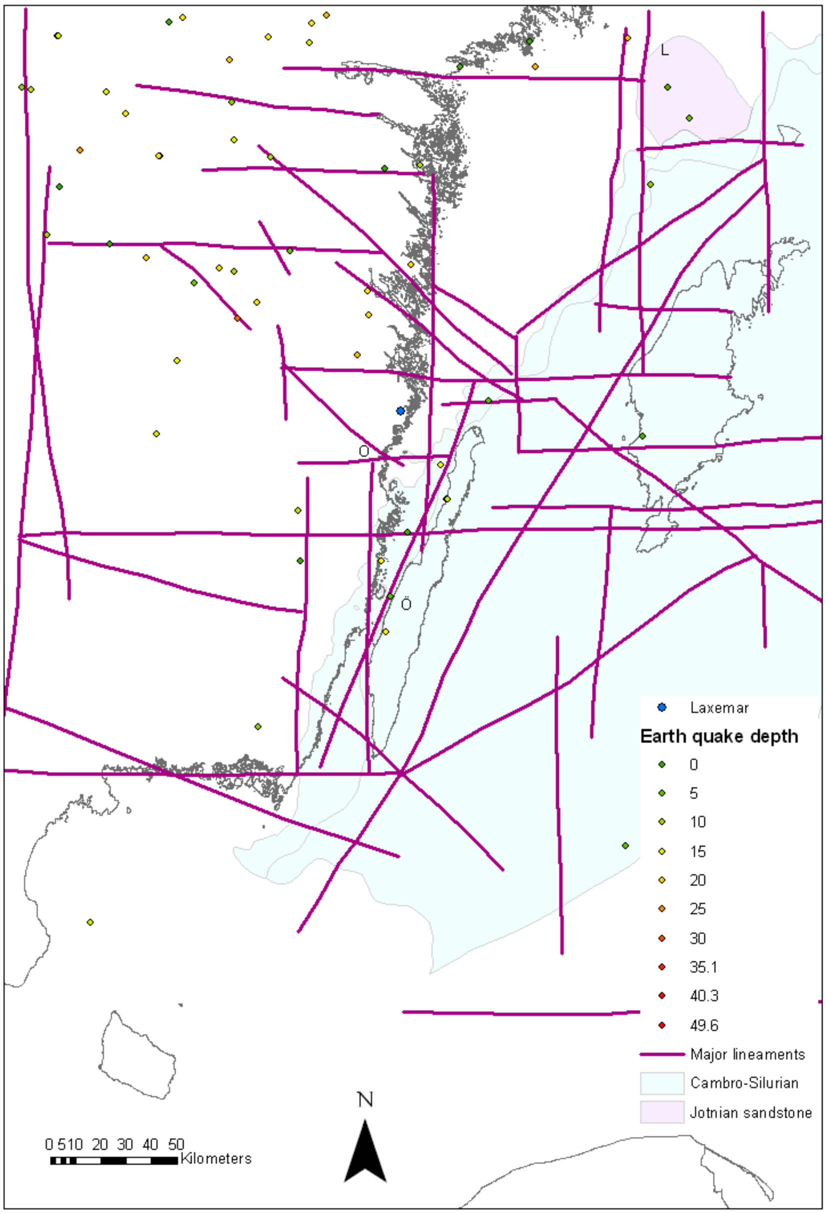


Figure 4-4. Regional scale faults around the Laxemar site. Light blue is Palaeozoic sediments and purple is Jotnian sandstones. Earthquakes (SNSN) are displayed as circles. Note the E-W trending structure in the sea area east of Laxemar. This structure appears to be the eastern extension of the structure forming the northern boundary of the Laxemar area (the Mederhult zone, cf. Figure 4-5 zone III). The locating of the Laxemar area is indicated with a blue dot, and to the southwest is O = Oskarshamn and the elongated island is Ö = Öland.

The number of earthquakes is low in south-eastern Sweden and they are most common along Kalmarsund, representing a structure that has a trend at right angle to the dip of the sub-Cambrian peneplain. In the south-eastern Sweden recent ? the frequency of earthquakes are 3 to 4 times higher north of Laxemar as compared to south of Laxemar (SNSN).

10.3.2. Extensive structures at the Laxemar site

Description of structures

The pattern of extensive lineaments in the Laxemar area is dominantly outlined by structures oriented in WNW-ESE, N-S, NE-SW and E-W, Figures 4-5 and 4-6. The topographically most pronounced structures in the regional surroundings (Figure 4-4) are oriented in N-S, WNW-ESE, E-W and NE-SW.

Common for all structures is that their topographical expressions may, in general, change along their traces, i.e. change in width, depth and/or the relative elevation across structures. Outlined rock blocks, on local scales, in general have low symmetry. The relative shifts in elevation of blocks along a major fault may indicate that the zone is partially reactivated. Shifts in altitude along a structure or a trace of a structure may occur on all scales.

The most extensive of all pronounced structures is trending E-W and located along the northern boundary of the Laxemar site (the Mederhult zone, structure III in Figure 4-5). The floor of the valley along the Mederhult zone is up to 20m lower than the surrounding hills. In the Laxemar area the elevation of the ground is a few metres higher south of the zone than north of it. The Mederhult zone bifurcates eastwards and a southeast trending branch (IV), having a marked topographical expression, follows the southern boundary of the site. It demarcates slightly lower land to the south. This implies that the Laxemar area forms a minor ridge sloping eastwards.

The western boundary of the site is a straight and well expressed N-S trending fault (I) intruded by dolerite. The dolerite is not exposed (eroded). It appears as an up to 10m deep valley. The eastern boundary (II) of the Laxemar area is also a topographically well-expressed N-S trending structure, although it appears to be relatively short. The rock block to the east of it is lower (about 5 to 10m lower) and includes the island of Äspö. The N-S deformation zones are relatively evenly distributed in the Laxemar regional area. The level of the bedrock head inside the Laxemar area does not indicate any significant shifts across N-S structures.

N-S deformation zones do either appear as straight lines (I, II, VIII) or are irregular (VI, VII and IX). However, in contrast to the local N-S structures in the Laxemar area, some of the more extensive regional N-S trending faults outline steps in topography; generally stepping up westwards (e.g. zone IX locally displays a vertical shift of about 30m).

Along the coast east of the Laxemar area (Figure 4-5) there is a furrow formed along a domain of NE-SW trending structures (the Ävrö fault zone) and its depth is up to 25m b.s.l. The Ävrö fault zone is also the location of a

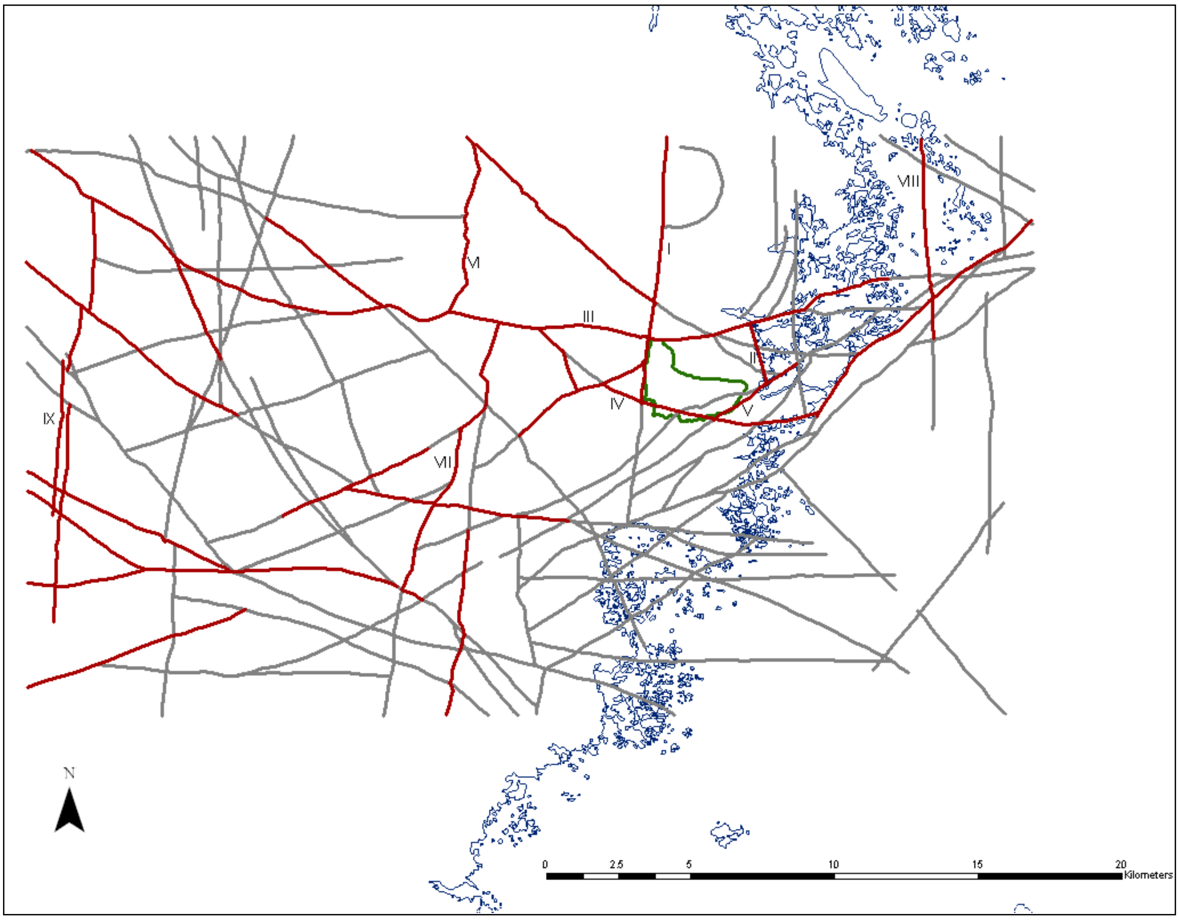
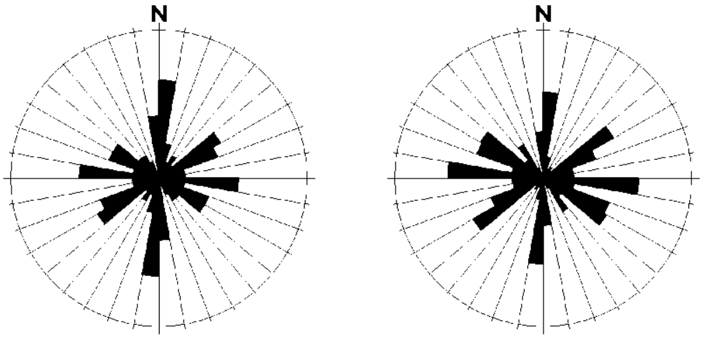


Figure 4-5. Extensive tectonic structures in the Laxemar regional area (the Laxemar sub-area is circumscribed by a green line), structures longer than 5km and most presumably representing brittle deformation zones. Morphologically well expressed structures are drawn in red. Structures discussed in the text are given ID I to IX. The Laxemar focused area is circumscribed by a green line.



a. b.

Figure 4-6. Orientation of extensive structures in the surroundings of the Forsmark candidate area:

a. orientation according to number Ntot=83, and

b. orientation according to length per 20°-sector in relation to the total length of mapped tectonic structures, total length = 106 291m (rose diagram, outer circle is 20%).

larger scale landform break; east of the fault zone the sea bottom is located about 10m b.s.l. and the water depth increases gently eastwards and to the west there is a minor archipelago (the elevation is generally less than 10m a.s.l.), i.e. the topographical vertical offset along the Ävrö fault zone is in the order of 10 to 15m.

The intersection between a topographically well expressed N-S trending deformation zone (VIII) and the Ävrö fault line, in the north-eastern part of Figure 4-5, is the location of a local deep, about 45m b.s.l. This indicates that the intersection between the two zones has an increased porosity and is easily eroded.

In the north-eastern part of the map (Figure 4-5) there is also a junction between NE-SW and NW-SE trending structures and the E-W trending deformation zone III, the Mederhult zone. The Mederhult zone is traceable into Egentliga Östersjön.

Outside the NE-SE domain of deformation zones along the coast, the rock block pattern on the map can roughly be described as an overprint (interference) of two sets of rock blocks outlined either by N-S and E-W deformation zones or by NE-SE and NW-SE zones. N-S/E-W blocks are most distinct in the central and north-eastern part of the map, while NW-SE/NE-SW blocks are more pronounced in the western part of the map.

10.3.3. Relation between site structures on land and structures in sea covered areas

The E-W structure demarcating the northern side of the Laxemar site, the Mederhult zone, is the only structure that can be traced from the site into an area included by the marine seismic investigations of the Egentliga Östersjön. Minor earthquakes are recorded along this zone and it is topographically indicated in the sea area. However, this structure is not recognized by the marine seismic survey in spite of the number of N-S trending survey lines that crosses this structure near the coast. The few E-W structures detected by the marine survey are relatively short (9 structures, the summary of their lengths is less the 7% of the total length of all mapped structures) and located in the central and western part of Egentliga Östersjön. E-W trending faults are, however, relatively frequent in, e.g. Lithuania (Šliaupa et al. 2006) and on the Swedish main land, e.g. the Oskarshamn zone.

The NE-SW trending Ävrö deformation zone forms a furrow in the sea just east of Ävrö and Simpevarp and it appears to obliterate the eastward continuation of site structures south of the Mederhult zone. It is not fully clear if the Ävrö zone joins the Mederhult zone or crosses it.

Even though the marine seismic investigations that are performed north of Öland do not indicate any fault along Kalmarsund (the strait between Öland and the mainland) it is well indicated by the SNSN record of earthquakes. A similar fault line is located along the eastern side of Öland and touches the western side of Gotland (Figure 4-4, cf. Figures 3-1 and 3-7) and is well established. Disturbances in the bottom sediments along the fault may indicate late, neotectonic, reactivation of the fault, but the SNSN catalogue has no data related to this structure.

11. Discussion and results

In the present study mainly four sets of information have been used to elucidate relatively late deformation:

- Geological maps
- Elevation data
- Marine seismic surveys
- Earthquake data

11.1. Geological maps

The different data sets reflect different time scales. The geological maps used in this study represent background data. It is generally considered that late structures are, in some way or the other, related to old structures, i.e. old structures control late deformation as these act as precursors. The reason for this can be that the accumulated pattern of structures in the bedrock is mature, i.e. the existing structures can accommodate most types of natural tectonic stress changes.

The published structural maps may differ in content and style and also the cartographical projection may vary. However, it is not in the scope of this study to make a compilation of a structural map of Östersjön or relate whether or not late displacement occurred along pre-existing faults.

On the other hand, this study is focused on displacement along faults, especially late faults, and the distribution of sedimentary rocks is therefore, for general reasons, of interest due to:

1. The contacts between low-metamorphic sedimentary rocks (Palaeozoic and Jotnian) and the underlying Precambrian metamorphic and igneous rocks are a well defined reference structure, and
2. the Palaeozoic rocks are well layered and distortions may be detected by marine seismics.

Large scale blocks-faulting associated with Rapakivi granites, down-faulting Jotnian sandstones, is well documented and the occurrence of the late granites is relatively common in the Östersjön area. That is the reason why these granites are of interest in this study. However, large-scale structures related to the intrusions of Rapakivi granites are very few due to the intrusion mechanism (cf. Selonen et al. 2005; Cruden 2008). Late granites can be used as markers to give the lower possible age of fault or reactivation of faults. Kresten and Chyssler (1976) found indication of vertical displacement (possibly 500m, western side up) along a N-S trending fault cutting through the Götemar granite before the formation of the sub-Cambrian peneplain and occurrence of minor reverse movement in post-Cambrian time (based on the distribution of clastic dykes). This zone forms the western boundary of the Laxemar area. Munier (1993) described the bedrock in the Baltic Shield (based on data from Äspö) as “segmented into blocks by ductile shear zones that fragmented as brittle fracture zones and have jostled by fault reactivation ever since”.

The block faulting associated with the Rapakivi granites displaces the sub-Jotnian denudation surface and down-faulted bocks are recognized when they contain Jotnian sandstones (Figure 2-3). Jotnian sandstones are common in Bottenhavet–Bottenhavet–Ålands hav, while in Egentliga Östersjön Jotnian sandstones are only found exposed in some down-faulted blocks north of Gotland. However, these sandstones continues southwards in under the cover of Palaeozoic rocks.

In the Bottenhavet–Bottenhavet–Ålands-hav area the Palaeozoic sediments are relatively flat laying. In Egentliga Östersjön the sedimentary pile comprises also late Phanerozoic rocks which occur in the eastern and southern part of Egentliga Östersjön. In other words, the fundamental difference between the Bottenhavet–Bottenhavet–Ålands-hav area and the Egentliga Östersjön area, is that the former, the northern part, is surrounded by Precambrian crystalline rocks, while Egentliga Östersjön on its eastern and southern shores expose Phanerozoic sedimentary rocks. The northern parts of Östersjön, Bottenhavet and Bottenviken, comprise fault-controlled depressions with the main faults along its western side, i.e. along the coast of northern Sweden. Egentliga Östersjön and Finska Viken (Gulf of Finland) are located along the northwestern limb of a large scale NE-SW trending sedimentary basin.

One additional component in the formation of the Egentliga-Östersjön basin, as compared to Bottenhavet–Bottenhavet, is inclination of the top surface of the underlying Precambrian rocks; a general east- to south-eastward inclination in Egentliga Östersjön while a westward inclination in Bottenhavet–Bottenhavet. The location of the Egentliga-Östersjön Basin is affected by the difference in resistance to erosion between the softer sedimentary Palaeozoic rocks and harder Precambrian rocks. In the Swedish and Finnish mainlands the occurrence of Palaeozoic and younger rocks is very sparse as compared to the Östersjön area; exceptions are in the Scandinavian mountain range and Skåne (the southernmost part of Sweden). Jotnian sandstones are also scarce in Sweden.

The Lower Palaeozoic deposits have had a much wider occurrence than seen today, yet their preservation and erosion bear witness of a fluctuating region. The Lower Palaeozoic rocks generally rest directly on the crystalline basement. The Palaeozoic Baltic Depression is considered the failed arm of the Tornquist Sea (Šliaupa 2002); it was founded on the weaker crust of the Polish-Lithuanian Terrane of Bogdanova et al. (2006). The Bottehavet–Bottenviken depression is another example of a failed palaeo-rift system (Korja et al. 2001); this of Precambrian age.

12. Elevation data

Elevation data are neutral data describing the three dimensional geometry of landforms on land and in water covered areas. The landform in its turn, is the shape that the Earth’s surface has achieved by natural processes. In areas with relatively thin soil cover it reflects the character of the bedrock, the tectonic distortions and the erosional forces it has been exposed to. In this study elevation data for Östersjön and the surrounding countries have been used as base data in structural interpretation of large scale landforms that reveals tectonic structures in the underlying bedrock, i.e. lineament studies.

For Egentliga Östersjön minor lineaments have also been mapped in order to get information about the scale relation between regional and minor lineaments (cf. Appendix 1, Figure A1-1). On a still smaller scale, detailed elevation data has been used to detect structures at the SKB sites Forsmark and Laxemar, respectively. This has been done to get control of structures (>5km) that could be traced into the sea area and also to get a multi-scale control of the structural setting of the sites.

Common for the whole of Östersjön, from the Gulf of Gdansk to Bottenviken, is the occurrence of N-S trending lineaments (cf. Appendix 1, Figures A1-2, A1-3 and A1-4). The N-S trending lineaments are common on all scales on the eastern Swedish mainland. In the coastal areas in south-eastern Sweden the coast line shifts its orientation from NNE-SSW to N-S from Oskarshamn northwards to Norrköping followed by a large-scale bulb, verging eastwards centred on Stockholm. North of Gävle, northwest of the Forsmark site, the coast line trends N-S again and at north of Sundsvall, in the area of greatest post-glacial uplift, it has a more easterly trend. The coastal areas in western Finland has a low relief and the coast line has a more regular form (N-S in its southern part and NNE in the northern part) as compared to the coast on the opposite side of Bottenhavet–Bottenviken, cf. Figure 3-1.

The location of the change in orientation of the coast-line of south-eastern Sweden is also the location of the change in trend of the contact between the Precambrian and the Cambrian/lower Palaeozoic sediments. While at Oskarshamn the coast shifts to a N-S direction, the contact of the sediments shifts towards east, which implies that the distance between the coastline and the location of the Lower Palaeozoic sediments increases when going north. The reason for this deviation is not clear. The shift in the orientation of the coastline may be related to differential displacements along N-S trending faults, which are common and extensive in the regional surroundings of Laxemar, while the shift in the trend and depth level of the contact to the Palaeozoic sediments may be due to erosion.

Other prominent lineament directions in the western part of East European Craton are NW-SE, NNE-SSW, ENE-WSW and E-W. NW-SE trending faults are common in northern Sweden, outlining the location of larger rivers. NW-SE trending faults are also common in central Finland. NNE-SSW trending lineaments form a slightly curved trace across southern and central Sweden through Gävlebukten, just northwest of Forsmark, and as ENE-WSW trending structures, enters the southern part of Bottenhavet (Figure 3.1). Further to the south, in the northern part of Egentliga Östersjön, ENE-WSW trending lineaments line up along Finska Viken (Gulf of Finland), i.e. they are sub-parallel to the northwestern limb of the regional-scale Baltic-Moscow Basin (cf. Figure 2-2 and 3-1).

E-W trending lineaments are common and are located along conspicuous topographical features such as, e.g. the southern coastline of Blekinge, the Oskarshamn shear zone and outline the Sörmland horst (southern boundary along Bråviken at Norrköping and northern boundary through Stockholm) and an extensive fault just north of the Mälaren depression, which passes into Ålands hav through Norrtälje (cf. Appendix 1, Figures A1-3 and A1-4).

The regional surroundings of the two SKB sites Forsmark and Laxemar have been studied on a more detailed scale.

12.1. Forsmark

It is indicated that the Forsmark site is located in the intersection between two domains of faults trending WNW-ESE and NNW-SSE. Faults are parallel to the extension of the domains. However, at Forsmark the NNW-SSE trending fault comprises also faults trending more NW-SE. More precisely, the Forsmark site is located inside an area the shape of a parallelogram outlined by faults intersecting each other at a small angle, i.e. resembling a lens (Figure 4-1).

On a somewhat larger scale however, it is found that the Forsmark site is located in an elevated WNW-ESE trending lath shaped rock block with the south-eastern side outlined by a NE-SW trending fault (not apparent on more regional scales) and the northwestern side is presumably outlined by a N-S trending fault. The south-western border of the Forsmark rock block is along the Forsmark deformation zone and the north-eastern boundary is along the Singö deformation zone. The elevation of the ground surface southwest of the Forsmark rock block is down about 10m and about 5m down on its north-eastern side, i.e. the Forsmark rock block appear as a slightly uplifted bedrock segment.

The trace of the NW-SE trending fault in the local Forsmark area, a part of the NNW-SSE fault system, has only a minor topographical signature and no apparent topographical offset. Furthermore, the relief of the sea covered areas is more accentuated around the coast of Uppland than on the main land in northern and north-eastern Uppland. Offset of the bedrock head in the order of 90m, associated with rotational block faulting along a curved trace of faults in Ålands hav, about 55km southeast of Forsmark. Along a similar fault, about 10km northeast of the Forsmark site, the displacement at the western side of the island of Gräsö is of opposite direction, the sea bottom is, in relative terms, about 30m lower. Mentioned relative movements are related to the accumulated displacement of the sub-Cambrian peneplain, i.e. they are younger than 550 Ma.

12.2. Laxemar

The Laxemar area is located in a wedge-shaped culmination sloping very gently eastwards. The wedge is controlled at its northern side by WNW-ESE trending faults and at its southern side by ENE-WSW trending faults. At the tip of the wedge, just east of the Laxemar area there is a low rectangular area including the island Äspö. The wedge has eroded traces of E-W trending faults both along the northern and southern sides of the local Laxemar area.

Marked landform brakes may occur along regional N-S trending faults, stepping up going westwards. However, on a more local scale it is apparent that displacements along the faults are not uniform (Tirén and Beckholmen 1989). Indications of displacement of the ground surface along N-S trending zones are not found in the Laxemar area.

The structural pattern in the Laxemar area and its surroundings, as outlined by lineaments, consists of irregular rock blocks on all scales. The E-W trending structure along the northern boundary of the Laxemar area can be traced into the sea, while other structures appear to be stopped/obliterated by the NE-SW trending Ävrö shear zone along the coast.

13. Marine geophysical data

The Palaeozoic rocks in Östersjön have been surveyed by marine seismic investigation and the main objectives were to study the arrangement and succession of strata and, where indicated, faults were also mapped. However, the track charts indicate that the planning of the survey lines did not consider the structural pattern in the mainland areas. This cause a bias in the sampling of faults as the survey lines in many cases are parallel to the structural grain in the mainland. Furthermore, the density and the orientation of survey lines are not uniform. The amplitude of faulting detected by seismic measurements is in general greater than 10m. However, minor displacement of the sea bottom is detected by echo-soundings.

13.1. Bottenhavet and Ålands hav – Forsmark

The Jotnian sandstones in Ålands hav are down-faulted troughs located inside large scale rock blocks. It is apparent that the faulting has occurred stepwise: early reactivation of faults, down-faulting of the sub-Jotnian erosion surface, followed by syn-sedimentary faulting during the deposition of the Jotnian sandstones and during late event postdating the formation of the sub-Cambrian peneplain. Söderberg (1993) presented a model, vertical cross-section, across the Jotnian sandstones in Ålands hav. It shows that the accumulated vertical displacements along the western fault, demarcating, the block with Jotnian sandstones, is greater than 900m. However, the structural cross-section and the geological and structural maps presented by Söderberg are not fully congruent/consistent. This makes the correlation between faults displayed in the model and in the maps uncertain.

Accumulated vertical displacements along WNW trending faults, demarcating the Forsmark, site is indicated to have been in the order of 1 400m during Precambrian time. This period of block faulting was followed by a stabile period during which the sub-Cambrian peneplain was formed. During the Tertiary (Flodén 1980), the Ålands-hav depression was formed in the western part of a Jurassic bedrock culmination (Lidmar-Bergström 1996). Large parts of the sub-Cambrian surface were kept intact with the down-faulted bedrock blocks.

The Tertiary age of the depression is based on the assumption that the most of the Palaeozoic rocks in Ålands hav must have been eroded before the depression was formed and Palaeozoic rocks are very rare in Sweden and Finland. The blocks with Jotnian sediments and the peneplain preserved were down-faulted at least 90m and the faulting had a minor rotational component, tilting eastwards (Söderberg 1993). It is of special interest that the western boundaries of the down-faulted blocks were outlined by a linkage of several faults, for example, a N-S fault (to the north) linked to a partially reactivated segment of a curved NNW-SSE fault which south of Åland via a WNW-ESE trending fault joins up with the eastern extension of an E-W trending fault (Winterhalter et al 1981). The WNW-ESE trending faults involved in the bock faulting belongs to the same family of structures as the Singö and Forsmark deformation zones (Figures 3-5 and 4-1, cf. Appendix 1 Figures A1-3 and A1-5a).

Jotnian sandstones are also found in the southern part of Bottenhavet north of Forsmark. The southern boundary of these sandstones is located south of the area investigated by marine seismics (Axberg 1980) and the contact may to a large extent be of primary nature and only locally fault controlled.

N-S faults mapped in Bottenhavet deform both Ordovician and older strata and faults with eastern or western sides down appear to have the same frequency. The location of the N-S structures indicates that they are related to a general descending movement, the formation of grabens. However, there are also minor N-S trending horsts which could indicate that the faults are listric, dipping booth east- and westwards and have been reactivated at least during a period of regional extension. The relative displacement within the Bottenhavet depression along N-S faults is up 10 to 15m, locally 30m and in an extreme case 150m. Along the western border of the Bottenhavet depression where relatively large vertical displacements are most common, displacement of the sub-Cambrian peneplain in the order of 170m has been found. An absolute uplift of about 285m has taken place after the last glaciation at the northern part of the west coast of Bottenhavet, at Höga Kusten.

Extensive NW-SE trending faults occur with regular spacing of 75km in Bottenhavet. The most northerly of these, the Aranda rift (with a relative depth up to 100m), is traceable across Bottenhavet and line up with a down-faulted block with up to 1800m thick Jotnian sandstones at Pori on the east-coast of Finland (Paulamäki et al. 2002, Elo 1982). The maximum depth to the sub-Jotnian denudation surface, i.e. the depth of the Bottenhavet sedimentary basin, is probably as much as three to four kilometres (Korja et al. 2001).

13.2. Egentliga Östersjön – Laxemar

In the sea to the east, outside the Laxemar area, there are only a few structures indicated by the marine survey. The extensive E-W trending structure along the northern boundary of the Laxemar area, the Mederhult zone, is the only Laxemar zone that reaches out into the sea area. Despite it is topographically expressed to Gotland, it is not recognised by the marine geophysical investigations performed by Flodén in 1980.

The most extensive structure indicated by marine seismics in the eastern part of Egentliga Östersjön is a fault zone oriented NNE-SSW from east of Öland to west of Gotland with the western side down. N-S trending faults are frequent north and south of Gotland and these have a dominance of western side down. The major N-S trending faults in south-eastern Sweden have an opposite throw, western side up. This opposite relative displacement of rock blocks and the regional-scale inclination of the ground surface indicate that there are major listric faults inclined eastwards (cf. Gibbs 1984).

The vertical displacement of the sub-Cambrian peneplain along the faults is, in general, less than some tens of metres, i.e. amplitude of the throw is of the same order as the natural variation in elevation within the sub-Cambrian. It is also of the same order as the present variation in altitude of the present ground surface, except for some regional N-S trending fault zones and some deeply eroded fault zones.

13.3. Neotectonics

In the central parts of Egentliga Östersjön and Ålands hav four localities were studied for neotectonics (Floden 1984). In two of these, neotectonic deformation could not be ruled out, but the observed structures could alternatively be interpreted as gravity collapse and escape of water from the sediments. One is localised east of the southern tip of Öland along an extensive NNE-SSW trending fault along the west side of Öland and passing just west of Gotland and the other is a system of zones trending NW-SE, the Neman zone, located in the sea southeast of central Gotland. However, north of the southern boundary of the Fennoscandian Shield, the Tornquist–Teisseyre Zone (TTZ), distortion along most of the E-W and NE-SW trending faults, are considered as neotectonic. There are indications that minor offsets or structures in soft bottom sediments can be erased, eroded, within a very short period of time (within a year; Flodén personal communication c. 1995). Side scanning sonar data from of the sea floor some 30km east of Gotland indicate that extensive linear NW-SE trending structures interfering with plough/drag marks created by icebergs in the bottom sediments (Elhammar et al. 1988). One explanation of the recorded pattern of bottom structures is that the NW-SE structures represent late displacements.

14. Earthquake data

The SNSN seismic data span a short period, from 2000 to the present day (Jan. 2009), but there are complimentary catalogues with older data and different coverage, e.g. one comprising known earthquakes in the Nordic region from 1375 to 2005 (cf. Bödvarsson et al. 2006). The record of earthquakes in the sea covered areas is far more sparse than for land areas. Of general interest is, that most earthquakes are spatially related to lineaments/faults and that some of the SNSN recorded earthquakes located outside lineaments /mapped faults line up along rows. This indicates that there are structures along which there is on-going minor distortion, which has no apparent, topographical or geophysical signature. All SNSN recorded earthquakes within a radius of 100km around the two sites are minor earthquakes (M<3) and there are fewer in the Laxemar regional area.

14.1. Forsmark

In the vicinity of Forsmark there is a cluster of earthquakes east of Gävle and others line up with a WNW structures located about 18km south of the site. Two small earthquakes occurred, with a very short time interval, along a N-S trending incision located between Åland and Forsmark, i.e. the northern fault arm of the curved, large scale fault that further south, west of Åland forms the southern boundary of Jotnian sandstones.

14.2. Laxemar

The number of SNSN earthquakes in the vicinity of the Laxemar area are few and their magnitudes are generally small (<2.5). Most common are earthquakes located along the NNE-SSW trending strait between Öland and the mainland, Kalmarsund. The marine seismic measurements did not indicate any structure along the strait. However, distortions of the sea beds along a similar, sub-parallel and extensive structure located just east of Öland and passing just west of Gotland, indicates postglacial deformation. There is no recorded earthquake along this structure.

Earthquakes indicate distortion along N-S, NW-SE and E-W trending zones in the regional surroundings of Laxemar site. One E-W trending zones has two minor seismic events and it forms the northern boundary of the Laxemar site, the Mederhult deformation zone. No earthquakes have been recorded for structures inside the Laxemar site. North of Laxemar earthquakes appear to cluster around the NW-SE trending lineaments/faults.

15. General remarks

15.1. Regarding Precambrian displacements – predating the sub-Cambrian peneplain

The peneplain in the Baltic Sea region is mainly a denudation surface forming the head of the Precambrian metamorphic and igneous rocks but also the head of Jotnian sandstones. The distribution and thickness of these sandstones give information of block faulting that occurred within the time span from the deposition of the Jotnian sediments which were deposited before to the rapakivi granites (intruded about 1 600Ma) were exposed to erosion, via the intrusions of olivine bearing dolerites dated at 1 270 to 1 250Ma (Suominen 1991) to the formation of the peneplain. Vertical displacement up to at least 1km is indicated, e.g. along WNW-ESE trending faults southwest of Åland and about the same amount along NNW-SSE tending faults north of Gotland. Vertical displacement of some hundreds of metres, predating the formation of the sub-Cambrian peneplain, is found along N-S trending faults north of Gotland (All et al. 2006).

15.2. Forsmark

In the Forsmark site there is an uncertainty regarding the structural relation between gently and steeply dipping faults (SKB 2008). If large displacements, postdating the formation of the gently dipping zones, have taken place along the major WNW-ESE zones, as indicated in Ålands hav, any continuation of the gently dipping zones across the WNW-ESE trending zones are not to be expected. However, the partial reactivation that is indicated to have occurred along WNW-ESE trending faults makes it uncertain to extrapolate any measured accumulated displacement in the Ålands-hav area to the Forsmark area. The vertical displacement related to the descended rock blocks with Jotnian sandstones and intrusion of post-Jotnian dolerites indicate extensional tectonics while the low-angle reverse faults, thrusts, dipping east, appears to predate the deposition of the Jotnian sediments and to be synchronous with displacement along NE-SW and ENE-WSW trending steep faults formed during bulk shortening (SKB 2008).

15.3. Laxemar

In the regional Laxemar area, the early vertical displacement of the Götemar granite (relative displacement of about 500m) has occurred along a N-S trending fault which constitutes the western boundary of the Laxemar area. Vertical displacements along N-S of the same order are found along faults north of Gotland. The amount of early, Precambrian, faulting for other structures in the Laxemar area is not known.

15.4. Complimentary notes

A general uncertainty in the extrapolation of displacement along a fault line regards the occurrence of partial reactivation and how the active parts of deformation zones are linked together in the total mosaic of structures in the bedrock. In other words, accommodation of stress takes place along sections of structures that are most easily displaced.

The Bottenhavet–Bottenviken depressions were initiated as a palaeorift with up to several kilometres of sandstones, which were partly denudated during a relatively stable period during which the sub-Cambrian peneplain was formed.

15.5. Regarding Cambrian - Tertiary displacements – postdating the sub-Cambrian peneplain

During the formation of the Baltic Basin (Šliaupa et al. 2006), which is in connection with the Moscow Basin, the sub-Cambrian peneplain was gently tilted (Winterhalter et al. 1981) and the basin was filled with Palaeozoic and Mesozoic sediments of considerable thickness. This large scale deformation was associated with orogenic processes in the border zones of the East European Craton. Faults offsetting the peneplain are dominated by faults that trend parallel to the contour lines of the depth to the peneplain and faults occurring at a high angle to these contour lines.

N-S structures are common along the centre of Egentliga Östersjön (see next section; neotectonics) and along some of these structures no indication of relative displacement is found. N-S trending faults form steps in the terrain in south-eastern Sweden, stepping up westwards into the south Swedish Highland. NW-SE faults are found east of Gotland and they are lining up with structures in the Swedish mainland. Along these scissor-type of faulting are found, indicating differential rotation of local rock blocks along the faults. An additional set of faults trends E-W.

In the Bottenhavet–Bottenviken depression the sub-Cambrian peneplain is relatively flat-lying. Block faulting on minor scales with relative offsets in the order of some tens of metres and rotation of block up to a few degrees deform the peneplain. The major line of displacement during formation of the depression is along the Sweden coast. The most extensive faults are trending NW-SE and have been reactivated in post- Ordovician time. They cross Bottenhavet. N-S structures are also common.

The ENE-WSW trending culmination of Precambrian rocks between Sweden and Finland across Åland is interpreted to be of Jurassic age (Lidmar-Bergström 1996) while the formation of the Ålands-hav depression, with the Åland Deep, in the western part of this culmination is Tertiary in age (Flodén 1980).

The deeps of the Baltic Sea are associated with rapakivi massifs, e.g. to the (north) east of the Riga Pluton, east of the Landsort Deep, and west of the Åland Massif. The deep in the northern Bottenhavet is connected to a rapakivi massif, but less well constrained in its position relative to the massif; it appears to occur in its western part. All of these deeps are steered by faults that displace the sub-Cambrian peneplain. Note that there occur also down-faulted blocks or basins with Jotnian sediments that are not disturbed after the formation of the peneplain, e.g. east of the Landsort Deep.

15.6. Regarding neotectonics – post glacial deformation

The neotectonic motions in Östersjön are in its southern parts, Egentliga Östersjön, mainly steered by N-S trending structure controlling basins east and west of Gotland. Just south of Gotland the eastern basin, the larger of the two, shifts eastwards, while a similar shift is found for the western basin northwest of Gotland (Ludvig 2001, Nikulin 2007), cf. Figures 3-10 and 3-11).
The number of earthquakes recorded in the sea-covered areas is relatively small. Notable are the seismic events along the NNE-SSW trending straight between the Swedish mainland and the elongated island Öland, Kalmarsund. Neotectonic distortions occur along a parallel fault located along the eastern side of Öland and passing just west of Gotland. This structure is however, apparently dormant at present, as no earthquakes along its extension has been recorded.

Indications of neotectonic motion are found along NW-SE trending faults east of Gotland. In Ålands hav and along the north-eastern coast along Uppland the most potential neotectonic faults trend about NW-SW (Ludwig 2001; cf. Figure 3-10) and in Bottenhavet the earthquake data indicate ongoing distortion along its fault controlled western coast. The SNSN earthquake data in many cases, despite that the recording time is short, allow to track propagation of distortion along faults and also indicate that successions of seismic events are located, forming rows in sea areas, where no structure is indicated, e.g. rows trending NW-SE.

16. Complimentary studies – future work

The present study is based on data that could either be further processed (e.g. marine geophysical data, earthquake data) or data that could be substituted by similar data with higher resolution. This is of cause a matter of cost but it will considerably contribute in the identification of structures and evaluate their significance.

The topographical data used in this study are free data having a relatively low resolution when focusing on regions close to the site of interest. SKB have published detailed topographic data for what they consider to be the regional surroundings of the sites. However, this study indicates that these areas are too small and larger areas need to be studied. For example, for the Forsmark site, the regional area that should be considered may constitute the land area of central and northern Uppland, and the sea area from Gävlebukten, Södra Kvarken and Ålands hav.

The marine geophysical survey performed in Ålands hav could be revaluated regarding location of structures, correlation of structures mapped on land and the offset of lithological units and the bottom topography. On-going marine geophysical investigations by the Swedish Geological Survey will contribute regarding the distribution of, for example, the Jotnian sandstones in the southern part of Bottenhavet and Södra Kvarken. Some complimentary investigation of the extension of WNW-ESE structures into Ålands hav at Singö should be of value.

The SNSN earthquake data give date, magnitude, depth and location. Calculation of fault plane solutions will contribute with the orientation along which the seismic events have occurred.

17. Conclusions

To evaluate the size of the regional surroundings that is needed to understand the geological setting of a site, a separate investigation is needed. Such a study should have a general geoscientific base as the outcome may not be expected. However, the reason for the study must be in focus, i.e. to understand the setting and character of the local site.

The present study of the displacement of faults considers information about structures that have been reactivated, the periods of reactivation, and the accumulated vertical displacement; mainly displacements taken place since the formation of the sub-Cambrian peneplain. Erosion of Precambrian basement rocks, post-dating the formation of the peneplain, is considered to be minor, i.e. to have a minor affect on the general level of the present ground surface. However, it is indicated that there is a variation in relief that may be related to the time of the removal of the sedimentary cover, i.e. the time that the bedrock has been exposed to erosion.

Furthermore, it is not obvious that the accumulated displacement along faults in Östersjön cannot be directly transformed to faults in the sites. The reason for this is partial reactivation of structures combined with linkage of deformation along intersecting structures. The latter may cause curved or winding traces although the majority of engaged sections belongs to more or less rectilinear faults. Earthquakes along faults express local stress release, which in some cases may indicate on-going propagating displacement. In some cases earthquakes line up in areas where no fault lines are found to match.

The size of the area needed to understand the structural setting of the Forsmark site is found to be, if the presented alternative interpretation is appropriate, much larger than the area studied by SKB and should incorporate an area covering central and northern Uppland and the sea areas to the north, northeast and east. Regarding the Laxemar regional area, studied by SKB, appears to be appropriate. However, the information about N-S trending faults recorded in Östersjön show the significance of such structures and their regional distribution.

17.1. Forsmark

For the Forsmark area it is found that the relief is more accentuated in the sea north and east of Forsmark than in land areas surrounding the site. At Forsmark, two sets of regional zones interfere. The most extensive of these trends WNW-ESE and follows the coast of northern Uppland and its width is some tens of kilometres. The other set consists of NNW-SSE to N-S trending faults which are well indicated along the northeast coast of Uppland and occur also in the inland. At Forsmark, the intersections of these two sets of faults outline an elongated prismatic block, resembling a lens. The Forsmark site is located in the northwestern wedge of this early block. Faults belonging to both of these sets have generally been reactivated. However, at Forsmark the late reactivation causing displacements of the sub-Cambrian peneplain has predominately been accommodated by the WNW-ESE set of fault resulting in a local uplift of a lath-shaped block, containing the Forsmark site. During this uplift the NNW-SSE fault, outlining the south-western side of the older prismatic block, appears to have been inactive. The relative vertical component of the late displacement along the southern boundary of the lath-shaped block, the Forsmark deformation zone, is less than 20m, while the relative vertical displacement along the north-eastern boundary, the Singö deformation zone, is some five metres. The relative displacement along these two faults is in agreement with fault displacements in the Ordovician limestone in Bottenhavet. Displacement of Jotnian sandstones in Ålands hav indicates that the accumulated vertical displacement along WNW-ESE trending faults can be at least in the order of one kilometre. If this is the case for these faults at Forsmark it will disturb all relationships with older structures that may have transected the WNW-ESE trending faults prior to the deposition of the Jotnian sediments. Structures along which the peneplain has a greater vertical offset than 20m, in the regional surroundings of the Forsmark site are found, e.g. along the western side of Gräsö (NNE-SSW fault, offset 30m, the block is tilted eastwards) and the fault along the eastern side of Väddö (slightly curved NNW-SSE fault, offset about 90m). SNSN earthquake recordings indicate distortions along WNW-ESE faults, mainly south of Forsmark and along a N-S trending fault which form a sharp incision in Södra Kvarken.

17.2. Laxemar

The Laxemar area is located within a regional area where the peneplain is very gently tilted towards the east. The inclination appears to be accomplished by minor displacement along both N-S and NNE-SSW trending faults which is reflected by the shift of the trend of the coast line at Oskarshamn; from NNE-SSW to N-S north of Oskarshamn. However, at Simpevarp the coastline form a bulb verging eastwards controlled by NE-SW trending deformation zones in its southern part and NW-SW trending zones in its northern part. A central E-W trending deformation zone, the Mederhult deformation zone, separates the bulge into two halves and it its eastwards continuation forms a trace in the bottom topography of the sea. A submarine canyon, Strupdjupet, is formed along the major N-W trending deformation zone along the northern side of the bulge and a furrow has been formed along the main zone, the Ävrö deformation zone, along the southern side of the bulge. Both zones meet the E-W trending central zone in the same area just outside the coast (cf. Appendix 1, Figure A1-5b).

The coast north of the bulge trend N-S and is perforated by NW-SE trending structures. A regional NW-SE trending fault, the Loftahammar fault, located north of Västervik (cf. Figure 4-4), can topographically be traced southeastwards. It crosses the southern part of Gotland and lines up with structures, the Neman zone that, by the marine geophysical investigations, are indicated to display neotectonic reactivations. Structures associated with the coastal bulge at Laxemar are not presented (not indicated?) in the description of the marine geophysical investigations performed by Flodén in 1980. However, minor earthquakes along the Mederhult zone indicate that differential movement, minor stress releases, may occur along the zone.

Within the archipelago along the coast, at the intersection between a N-S trending deformation zone and the central E-W trending, Mederhult deformation zone, there is a local deep of about 45m. This indicates that the porosity in the rock at the intersection of the two zones is increased and the rock is easily eroded. However, it is not apparent why this hollow is not filled with sediments. Intersections between N-S trending zones and the Mederhult zone occur along the northern boundary of the Laxemar area.

Vertical offsets of the sub-Cambrian peneplain are found in Egentliga Östersjön. Such offsets are not found along N-S trending deformation zones in the Laxemar area. The detailed topographical data of the surroundings of the Laxemar area indicate irregular geometries of rock blocks and that block faulting, offsetting the present ground surface, has occurred. The accumulated vertical component of relative movements along faults, since the formation of the sub-Cambrian peneplain, is in general less than some tens of metres.

References

Andrén, T., 1990: Till stratigraphy and ice recession in the Bothnian Bay. University of Stockholm, Department of Quaternary Research, Report 18, 59.

Artemieva, I.M., 2007: Dynamic topography of the East European craton: Shedding light upon lithospheric structure, composition and mantle dynamics. Global and Planetary Change, 58, 411-434.

Axberg, S., 1980: Seismic stratigraphy and bedrock geology of the Bothnian Sea, northern Baltic. Acta Universitatis Stockholmiensis, Stockholm Contributions in Geology, 36, 3, 153-213.

All, T., Floden, T., & Puura, V., 2006: A complex model of Mesoproterozoic sedimentary and igneous suits in graben setting north of Gotland, Baltic Sea. GFF, 128, 53-63.

Beckholmen M., & Tirén, S.A, 2009: The geological history of the Baltic Sea a review of the literature and investigation tools. Swedish Radiation Safety Authority (SSM), SSM Report number: 2009:21, 118.

Bogdanova, S.V., Gorbatschev, R., Grad, M, Janik, T., Guterch, A., Kozlovskaya, E., Motuza, G., Skridlaite, G., Starostenko, V., Taran, L., & Eurobridge and Polonaise working groups, 2006: EUROBRIDGE: new insight into the geodynamic evolution of the East European Craton. in D.G. Gee & R.A. Stephenson, (eds.), European Lithosphere Dynamics. Geological Society of London, Memoirs, 32, 599-625.

Bödvarsson, R., Lund, B., Roberts, R. & Slunga, R., 2006: Earthquake activity in Sweden. Study in connection with a proposed nuclear waste repository in Forsmark or Oskarshamn. Swedish Nuclear Waste and Management Co (SKB), Stockholm, report SKB R-06-67, 40.

Cruden, A.C., 2008: Emplacement mechanisms and structural influences of younger granite intrusion into older wall rock – a principal study with application to Götemar and Uthammar granites. Site-descriptive modelling, SDM-Site Laxemar. Swedish Nuclear Fuel and Waste Management Co (SKB) ,SKB report R-08-138, 48.

Elhammar, A., Axberg, A., & Kjellin, B., 1988: Maringeologiska kartbladet 079/470 Fårö. Geological Survey of Sweden, Maringeologiska kartan Serie A, nr2, 1-34 and 3 appendices.

Elo, S.; 1982: On the gravity studies of bedrock in Stakunta (in Finnish). Geological Survey of Finland, unpublished report Q20/21/1982/1, 17.

Flodén, T., 1980: Seismic stratigraphy and bedrock geology of the central Baltic. Acta Universitatis Stockholmiensis, Stockholm Contributions in Geology, 35, 240pp.

Flodén, T., 1984: Der Strukturbau im Seegebiet von Sweden. Zeitschrift für Angewandte Geologie, Band 30, Heft1, 1-17 + maps.

Gibbs, A.D., 1984: Structural evolution of extensional margins. Journal of the Geological Society of London, Vol. 141, 609-620.

Hjelth, S.E., Korja, T., Kozlovskaya, E., Lahti, I. Yliniemi, J. & BEAR and SVEKALAPKO Seismic Tomography Working Groups, 2006: Electrical conductivity and seismic velocity structures of the lithosphere beneath the Fennoscandian Shield. in D.G. Gee & R.A. Stephenson (eds.), European Lithosphere Dynamics. Geological Society of London, Memoirs, 32, 541-559.

http://www.baltic.vtt.fi/demo/baltmap.htm -Figure 2-1. Östersjön and its main parts, retrieved 2009-06-18.

Jackson, J. A (Ed.), 1997: Glossary of Geology. American Geological Institute, Alexandria, Viginia, Fourth Edition, 769

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 & N. White (eds.), Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. Geological Society of London, Special Publications 196, 183-207.

Karabanov, A. Garetsky, R., Aizberg, R., & Aronova, T. 2003: Main problems of Neodynamics phenomena investigation and mapping. http://kgp.wnoz.us.edu.pl/ARW/ARW_Karabanov.rtf

Korja, T, Heikkinen, P., & Aaro, S., 2001: Crustal structure of the northern Baltic Sea palaeorift. Tectonophysics 331 (4), 341-358.

Kresten, P, & and Chyssler, J., 1976: The Götemar massif in southeastern Sweden: A reconnaissance study. GFF 98, 155-161.

Lahtinen, R., Garde, A. A., & Melezhik, A., 2008: Paleoproterozoic evolution of Fennoscandia and Greenland. Episodes, vol. 31, No. 1, 20-28.

Largerbäck, R., & Sundh, M., 2008: Early Holoceene faulting and paleoseismicity in northern Sweden. Geological Survey of Sweden, Research Paper C 836, 80.

Lidmar-Bergström, K., 1994: Landsforms of the bedrock. In K. Fredén (Ed): Geology, the National Atlas of Sweden, 44-55.

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

Ludwig, A.O., 2001: Vertical movements since the beginning of the Rupelian stage (map 1). Brandenburger Geowissenschaftliche Beiträge, 8, 1, 5-12.

Meyer, M., 2003: Modelling prognostic coastline scenarios for the southern Baltic Sea. Baltica, 16, 21-32.

Munier, R., 1993: Segmentation, fragmentation and jostling of the Baltic Shield with time. Acta Univeritatis Upsaliensis, Uppsala Dissertation from Faculty of Science No 37, 96.

Mörner, N.-A., 2003: Paleoseismicity of Sweden, a novel paradigm. Produced and distributed by Nils-Axel Mörner, Paleogeophysics & Geodynamics, Stockholm University.

Nenonen, K., 1995: Pleistocene stratigraphy and reference sections in southern and western Finland. Geological Survey of Finland, Regional Office for Mid-Finland, Kuopio, 94pp.

Nikishin, A.M., Ziegler, P.A., Stepenson, R.A., Cloeting, S.A.P.L., Furne, A.V., Foki, P.A., Ershov, A.V., Bolotov, S.N., Korotaev, M.V., Alekseev, A.S., Gorbachev, V.I., Shipilov, E.V., Lankrejer, A., Bembinova, E.Yu & Shalimov, I.V, 1996: Late Precambrian to Triassic history of the East European Craton: dynamics of sedimentary basin evolution. Tectonophysics, 268, 23-63.

Paulamäki, S., & Kuivamäki, A., 2006: Depositional History and Tectonic Regimes within and in the Margins of the Fennoscandian Shield During the last 1300 Million years. Posiva Working Report 2006-43

Paulamäki, S., Paananen, & Elo, S., 2002: Structure and geological evolution of the bedrock at southern Satakunta, SW Finland. Posiva, report Posiva 2002-04, 119.

Puura, V., & Flodén, T., 2000: Rapakivi-related basement structures in the Baltic Sea area: a regional approach. GFF, 122, 257-272.

Puura, V., Flodén, T., & Mokrik, R., 2003: The Baltic Sea Basin in the geology of Fennoscandia and Baltic region. Litosfera, Vilnius, 7, 134-137.

Rudberg, S., 1954: Västerbottens berggrundsmorfologi. Geographica 25, 457.

Seifert, T., Tauber, F., & Kayser. B., 2001: Baltic Sea topography. Baltic Sea Research Institute Warnemunde, http://www.io-warnemuende.de/research/en_iowtopo.html, retrieved 2008-02-26.

Selonen, O., Ehlers, C., Luodes, H., & Lerssi, J., 2005: The Vehmaa granite batholith – an assemblage of successive intrusions indicating a piston-type collapsing centre. Bulletin of the Geological Society of Finland, Vol. 77, 65-70.

Paulamäki, S., & Kuivamäki, A., 2006: Depositional History and Tectonic Regimes within and in the Margins of the Fennoscandian Shield During the last 1300 Million years. Posiva Working Report 2006-43

Šliaupa, S., 2002: Balitijos kambro baseino genese ir geodinamine evoliucija (Genesis and geodynamic evolution of the Baltic Cambrian basin). Geologija, Tektonika, 37, 31-43.

Šliaupa, S. Fokin, P., Lazauskiene, J., & Stephenson, R., 2006: The Vendian-Early Palaeozoic sedimentary basins of the East European Craton. in D.G. Gee & Stephenson, R.A. (eds.), European Lithosphere Dynamics. Geological society of London, Memoirs, 32, 449-462.

SNSN -Swedish National Seismic Net (Svenska nationella seismiska nätet), Uppsala University, Department of Earth Sciences, www.geofys.uu.se/snsn .

Snäll, S., 1977: Silurian and Ordovician bentonites of Gotland ((Sweden). Acta Universitatis Stockholmiensis, Stockholm Contributions in Geology, 31 past 1, 1-80.

SKB, 2008: Site description of Fosmark at completion of the site investigation phase, SDM-Site Forsmark. Swedish Nuclear Fuel and Waste Management Co (SKB) ,SKB report TR-08-05, 545.

Strömgren, M., & Brydsten, L., 2008a: Digital elevation models of Laxemar-Simpevarp. Swedish Nuclear Fuel and Waste Management Co (SKB) SKB Report R-08-63, 23.

Strömgren, M., & Brydsten, L., 2008b:Digital elevation models of Forsmark Site descriptive modelling SDM-Site Forsmark Nuclear Fuel and Waste Management Co (SKB), SKB Report R-08-62, 25.

Suominen, V., 1991: The chronostratigraphy of southwestern Finland with special reference to Postjotnian and Subjotnian diabases. Geological Survey of Finland, Bullitin 356, 100.

Suominen, V., 1987. Mafic dyke rocks in southwestern. Finland. In K. Aro & I. Laitakari (Eds.): Diabases and other mafic dyke rocks in Finland. Geological Survey of Finland, Report of Investigation 76 (In Finnish with English abstract), 151–72.

Söderberg, P., 1993: Seismic stratigraphy, tectonics and gas migration in Åland Sea, northern Baltic Proper. Acta Universitatis Stockholmiensis, Stockholm Contributions in Geology, 43 past 1, 1-67.

Tirén, S. A., & Beckholmen, M., 1989: Block faulting in southeastern Sweden interpreted from digital terrain models. GFF 111, 171-179.

Tirén, S. A. & Beckholmen, M., 2007: Structural interpretation of topographic data –Rock block configuration on regional scales, and the distribution of earthquakes, in the regional surroundings of the Forsmark and Laxemar areas, Sweden. Swedish Nuclear Power Inspectorate (SKI), Stockholm, report SKI-INSITE TRD-07-02, 12pp.

Wannäs, K. O., 1989: Seismic stratigraphy and tectonic development of the Upper Proterozoic to Lower Paleozoic of the Bothnian Bay, Baltic Sea. Acta Universitatis Stockholmiensis Stockholm Contributions in Geology, 40, 3, 83-168.

Wannäs, K., & Flodén, T., 1994: Tectonic framework of the Hanö Bay area, southern Baltic Sea. Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, report SKB TR-94-09, 40pp.

Winterhalter, B., 1986: “The Deep Conditions”, in Relief and Landforms, Atlas of Finland, folio 121-2, National Board of Survey and Geographical Society of Finland, 1-20.

Winterhalter, B., Flodén, T., Ignatius, H., Axberg, S., & Niemistö, L., 1981: Geology of the Baltic Sea.. In A. Voipio (Ed.) The Baltic Sea. Elsevier Scientific Publishing Company, Elsevier Oceanography Series, 30, (1981). 1-121.

Appendix 1

Structural maps of the Östersjön area

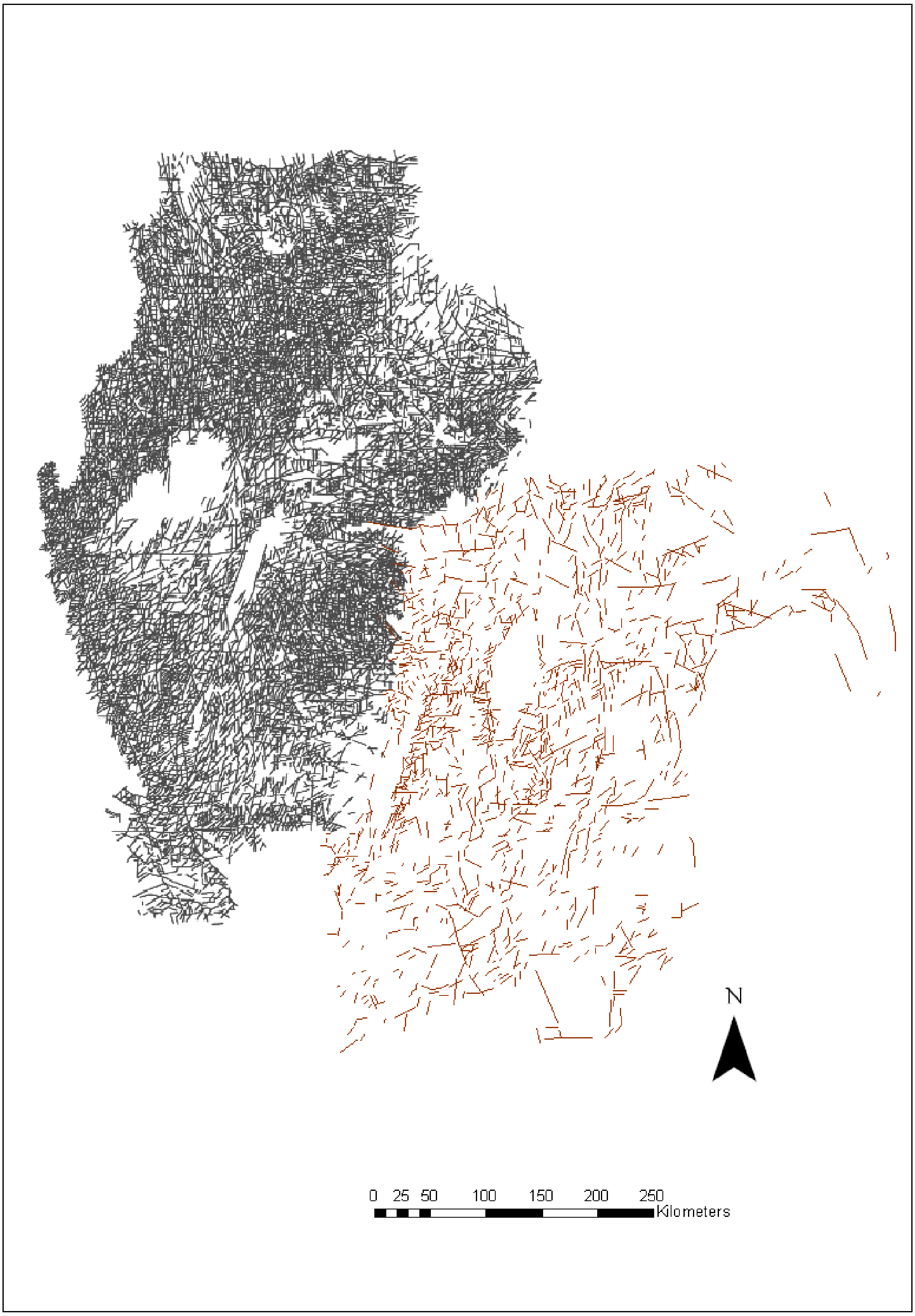


Figure A1-1: Lineament interpretation of southern Sweden (Tirén & Beckholmen 1990 and 1992) and south-eastern Östersjön.

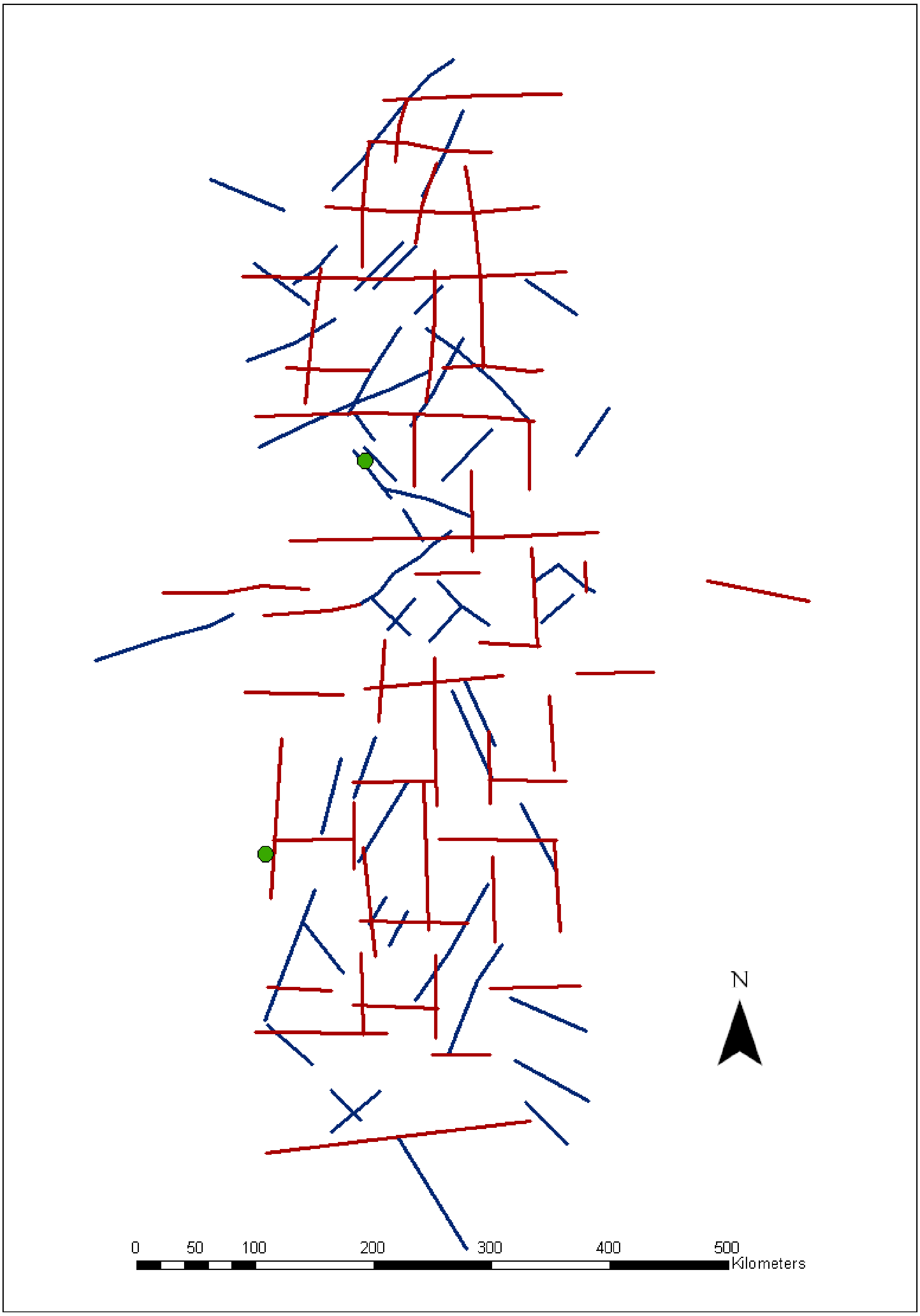


Figure A1-2: Major lineaments in the main Baltic-Sea depression. Green dots are the location of SKB sites: Forsmark to the north and Laxemar to the south

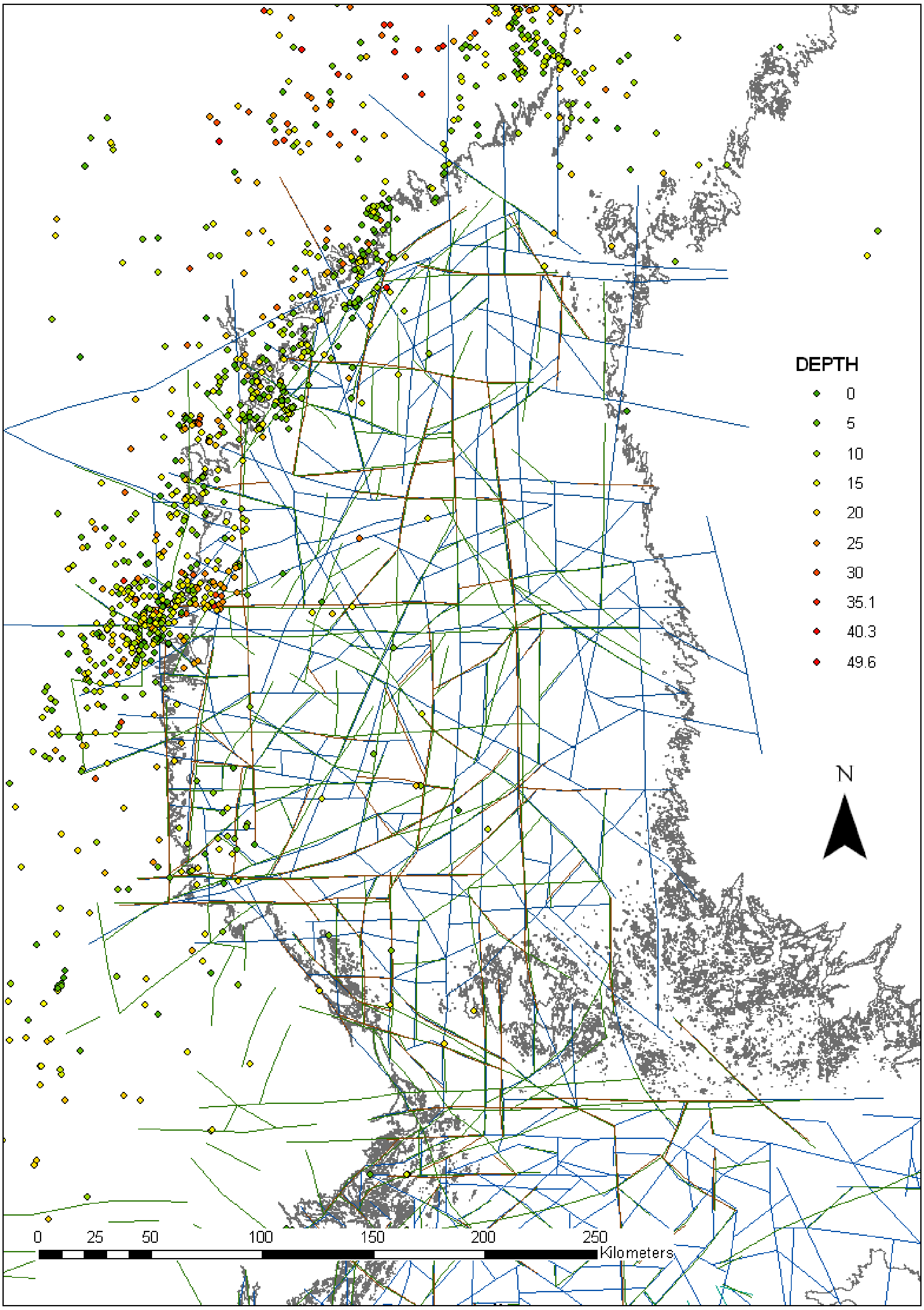


Figure A1-3: Sets of different lineament interpretations (selected colours) in the Norra Kvarken–Bottenhavet–Ålands-hav area and SNSN earthquake events 2002-2008 (colours indicate depth to epicentres).

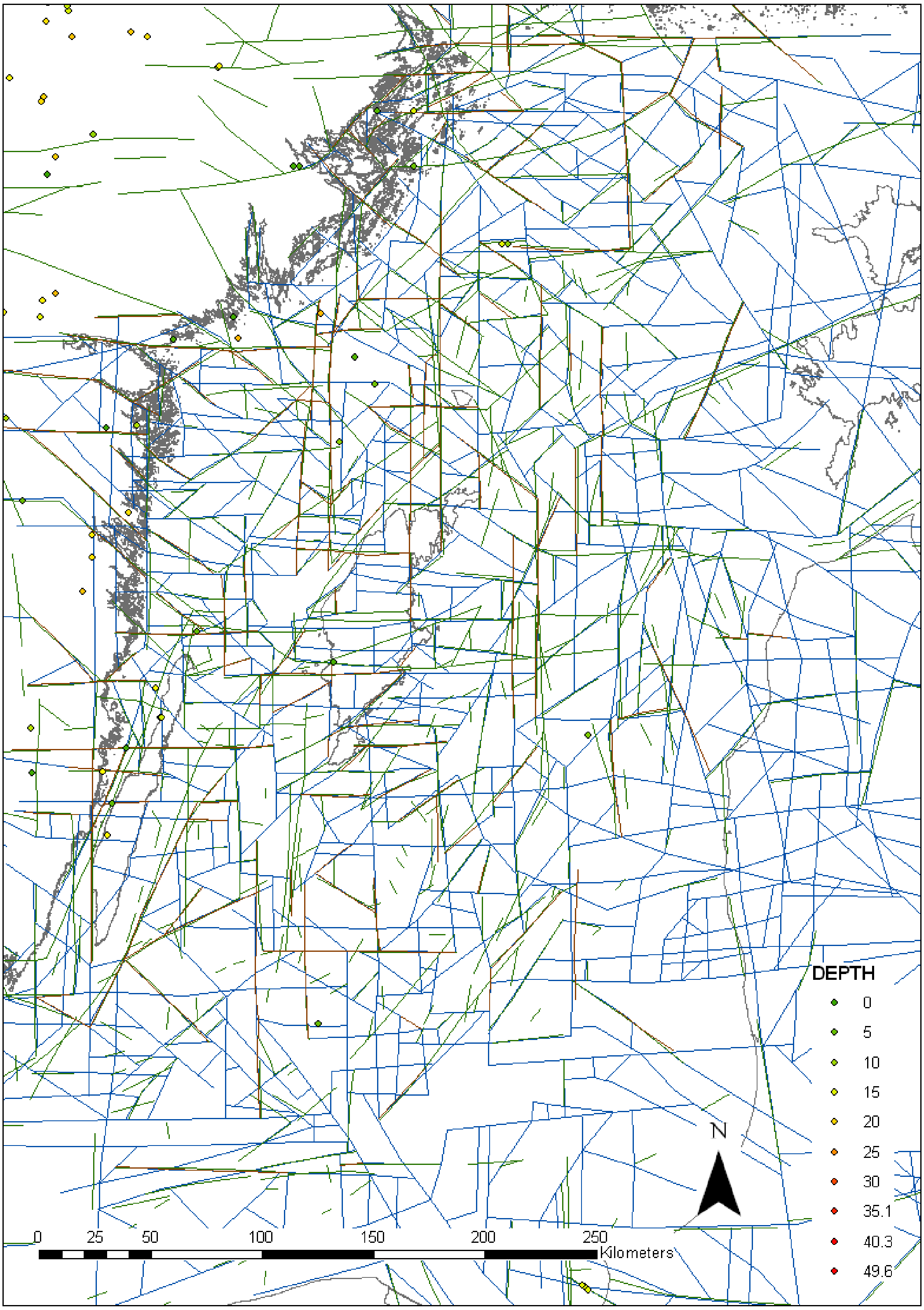


Figure A1-4: Sets of different lineament interpretations (selected colours) in northern and central Egentliga Östersjön and SNSN earthquake events 2002-2008 (colours indicate depth to epicentres).

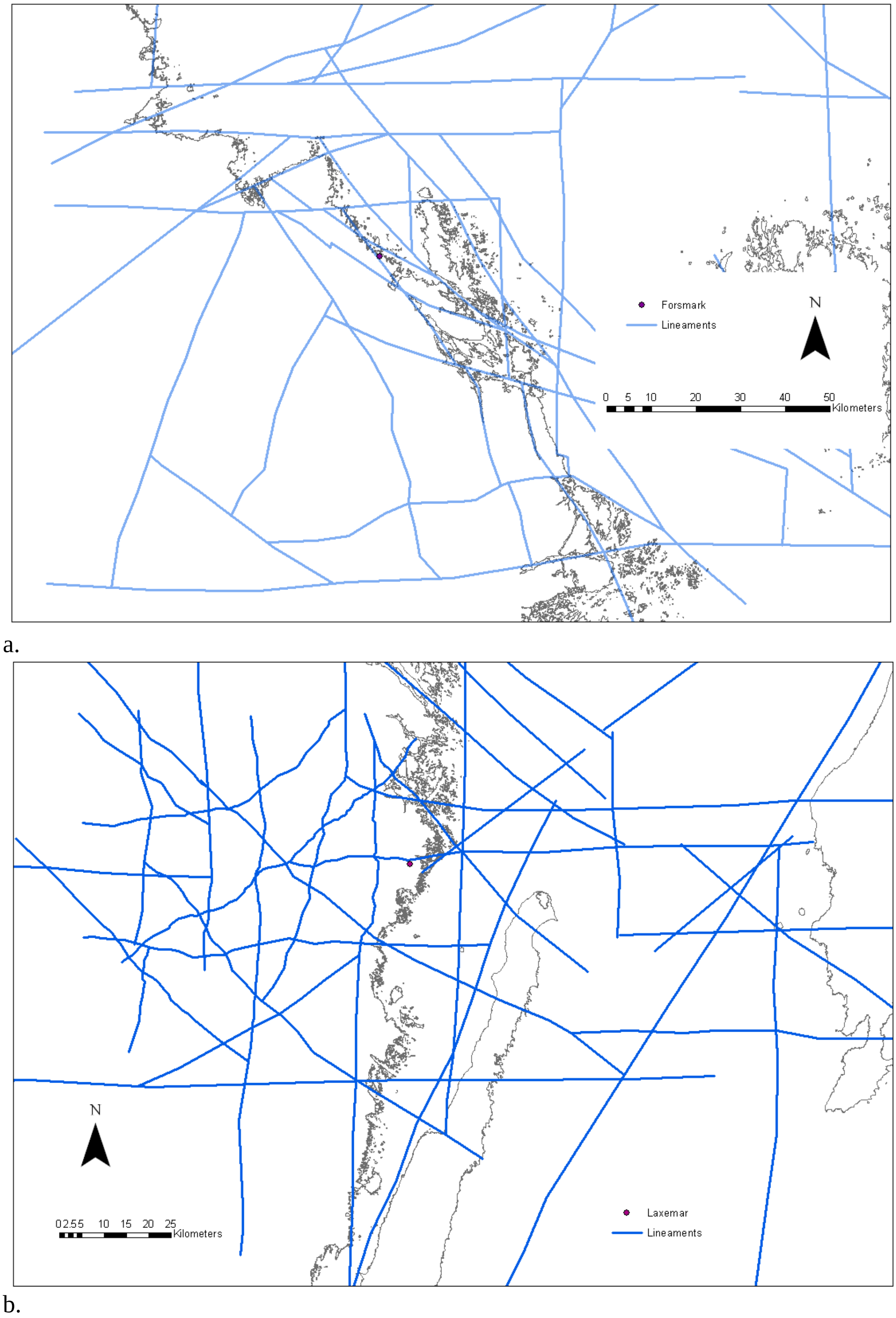


Figure A1-5: Regional lineaments in a rock block interpretation of the regional areas surrounding SKB sites (red dots):

a. the Forsmark area and

b. the Laxemar area.

References

Tirén, S.A, & Beckholmen, M., 1990: Influence of regional shear zones on the lithological patter in central Sweden. GFF, 112, 197-199.

Tirén, S.A, & Beckholmen, M., 1992: Rock block map analysis of southern Sweden. GFF, 114, 253-269.

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