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The geological history of the Baltic Sea a review of the literature and investigation tools

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Title: The geological history of the Baltic Sea a review of the literature and investigation tools.
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Date: September 2008

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 author/authors and do not necessarily coincide with those of the SSM.

Background
The bedrock in Sweden mainly comprises Proterozoic magmatic and metamorphic rocks older than a billion or one and a half billion years with few easily distinguished testimonies for the younger history. For construction of a geological repository for deposition of nuclear waste it is important to understand the late, brittle, geological events to be able to estimate its influence and consequences for the repository.

Purpose
The purpose of the current project is to compile published data related to the geological history of the Baltic Basin. The intention of the study is to contribute to the understanding and characterization of earlier and on-going and bedrock deformation in coastal areas outside Forsmark and Laxemar where the Swedish Nuclear Waste Management Co (SKB) recently has finished site investigations for a repository for spent nuclear fuel. Of special interest are structures with evident indications of late bedrock movements where also future movements cannot be excluded.

Results
The result of the compilation of available data indicate that the Baltic Sea with its Gulfs has almost since the beginning of history been the locus for rifting and extensional events, e.g. the rapakivi magmatism, 1.5-1.6 Ga, formation of the Mesoproterozoic Jotnian sandstone basins and the opening of the Tornquist Sea in the Neoproterozoic-Palaeozoic. A recent change in the stress regime and Pleistocene subsidence together with erosion has formed the present Baltic Basin.

The history of the Baltic Sea region is described with reference to illustrations in the reviewed literature and investigation methods with examples are given in an Appendix to this report.

Effects on SSM supervisory and regulatory task
An understanding of behaviour and influence of the accumulated vertical displacement along faults in the Baltic Basin outside Forsmark and Laxemar will give SSM improved knowledge about possible future movements in the investigated areas. The study has also given some indications when the faulting has taken place and been reactivated.

Project information
SSM reference: SSM 2008/148
Responsible at SSM has been Öivind Toverud

ABSTRACT

The bedrock in Sweden mainly comprises Proterozoic magmatic and metamorphic rocks older than a billion or one and a half billion years with few easily distinguished testimonies for the younger history. For the construction of a geological repository for deposition of nuclear waste this later, brittle, history is of great consequence.

In the Gulf of Bothnia, the Baltic Sea and the countries on the eastern and southern sides of the Baltic Sea, the Proterozoic bedrock of the Svecofennian Province continues underneath a cover of sedimentary rocks of Mesoproterozoic, Palaeozoic and in the south up to Tertiary age. By studying these, lithologies, basin analyses, preserved structures, topography, etc., information may be gained on the later history, not only in the basins but also in the exposed shield area.

The deformation is governed by the plate tectonic scenario and mantle configuration of a specific time and suitable structures are utilized and reactivated. The collision and amalgamation of the different tectonic terranes that comprise the basement left it strongly heterogeneous and the sutures between these rheologically different segments ample for future deformation and the adjustment between the segments to the changing and prevailing plate tectonic scenarios; the assembling and break-up of Rodinia, Laurasia and Pangea. Glaciations induce bending of the plate.

Suitable datum surfaces for assessment of the deformation are the base of major sedimentary sequences, often linked to plate tectonic cycles, specifically the sub-Cambrian peneplain, the base of the Devonian, Mesozoic, Oligocene, Rupelian and Pleistocene, as well as major differences in metamorphic grade and style of deformation in adjacent rock blocks.

The Baltic Sea with its Gulfs has almost since the beginning of history been the locus for rifting and extensional events, e.g. the rapakivi magmatism, 1.5-1.6Ga, formation of the Mesoproterozoic Jotnian sandstone basins and the opening of the Tornquist Sea in the Neoproterozoic-Palaeozoic. A recent change in the stress regime and Pleistocene subsidence together with erosion has given us the present Baltic Basin.

The history of the Baltic Sea region is described with reference to illustrations in the reviewed literature and investigation methods with examples are given in an Appendix.

Keywords: *Review, Baltic Sea, Fennoscandia, geological history, heterogeneous lithosphere, subsidence, extension, rapakivi magmatism, Jotnian sandstones, block-faulting, Palaeozoic basin, Caledonian, faults, erosion, earthquakes.*

SAMMANFATTNING

Litosfären, jordklotets skorpa och den övre manteln, är uppbyggd av olika segment som under bergskedjebildning kittats ihop och den är därför mycket heterogent sammansatt. Skarvarna mellan de olika enheterna utgör potentiella områden för deformation och justeringar mellan blocken då de anpassar sig efter den rådande plattektoniska situationen.

Östersjön, Bottenhavet och Bottenviken av idag är resultatet av sin drygt 1,5 miljon år långa historia; samspelet mellan olika litosfärskomponenter, orienteringen på strukturer, plattektonik och nedisningar. Östersjöns och Bottenhavets östra kuster, liksom djupstrukturerna i Bottenviken längre åt nordost, styrs av N-S strukturer (sammanfaller t ex utanför finska kusten nära med västgränsen för Korja et al.´s (2006) Keitelekontinent). Östersjön och Bottenhavet avgränsas norrut av mycket markanta, subparallella (östnordöstliga till) östliga topografiska brott. Dessa linjer är också parallella med de ordoviciska och siluriska klinterna i Estland som sträcker sig ut i Östersjön till norr om Gotland, de gotländska reven och strukturer i södra Bottenhavet och Gävlebukten.

Bottenviken och Bottenhavet skiljs åt av den grunda bryggan i Norra Kvarken och Bottenhavet och Östersjön separeras av en upphöjning mellan östra Svealand och Åland-Åboland. En höjdplatå sträcker sig norrut i Bottenhavet norrut från Gräsö, väster om ett stort seismiskt aktivt, N-S lineament, som söderut kan följas i linjen som separerar Landsortsbassängen och ryggen med Kopparstenarna och Gotska sandön. Gotlandsblocket fortsätter söderut i en undervattensplatå och länkar till Norra och Södra Midsjöbankarna i södra Östersjön öster om Öland och norr om Polen.

Det går en diffus linje från nordöstra Lettland längs Gotska sandön och nordsidan av Landsortsbassängen längs vilken lutningen på subkambriska peneplanet skiftar från SSO i öst till OSO i väst och syd.

Stora djup förkommer i avlånga bassänger utanför Örnsköldsvik-Härnösand (230m) i N-S, i Ålands hav (285m (218m)) i NV- (och O-V), längs den ordoviciska klinten och i synnerhet i N-S och NV vid Landsortsdjupet (459m), och i Gotlandsdjupet (245m). Dessa strukturer reflekterar strukturer i berggrunden men har också accentuerats genom glacial erosion. Erosion av en större flod har också föreslagits utanför finska västkusten, i Finska viken samt Stolpe ränna i mesozoiska lager mellan Södra Midsjöbanken och bankerna norr om Polen. Gdanskdepressionen går ner till 188m i mesozoiska lager. De danska trösklarna i Bälten ligger på 18m och i Öresund på 8m. Vätternsänkan orienterad i NNO-SSV är 130m djup med en vattenspegel på 89m ö h. Detta tråg måste vara en tämligen ung gravsänka, aktiv långt senare än paleozoikum.

De oförutsedda stora jordskalven i kaliningradområdet 2004 fäster ljuset på de långa tysta perioderna mellan återkommande katastrofala geologiska händelser. Vulkaner har länge ansetts som utdöda pga att ingen kommer ihåg det senaste utbrottet. Idag kan vi göra tillförlitliga studier över temperaturstrukturen. På samma sätt kan stora förkastningar ha en uppladdningsperiod som överstiger mänskligt minne. Riftperioder har inträffat med många hundratals miljoner år emellan. Slutsatsen att ingen har fastslagit rörelser längs en förkastning de senaste hundra miljonerna år och att de därför är döda säger kanske mer om hur detaljerad undersökningen och kunskapen om strukturen är än om strukturens sanna natur. Det som vanligen refereras till som den rådande situationen karakteriseras av öppningen av

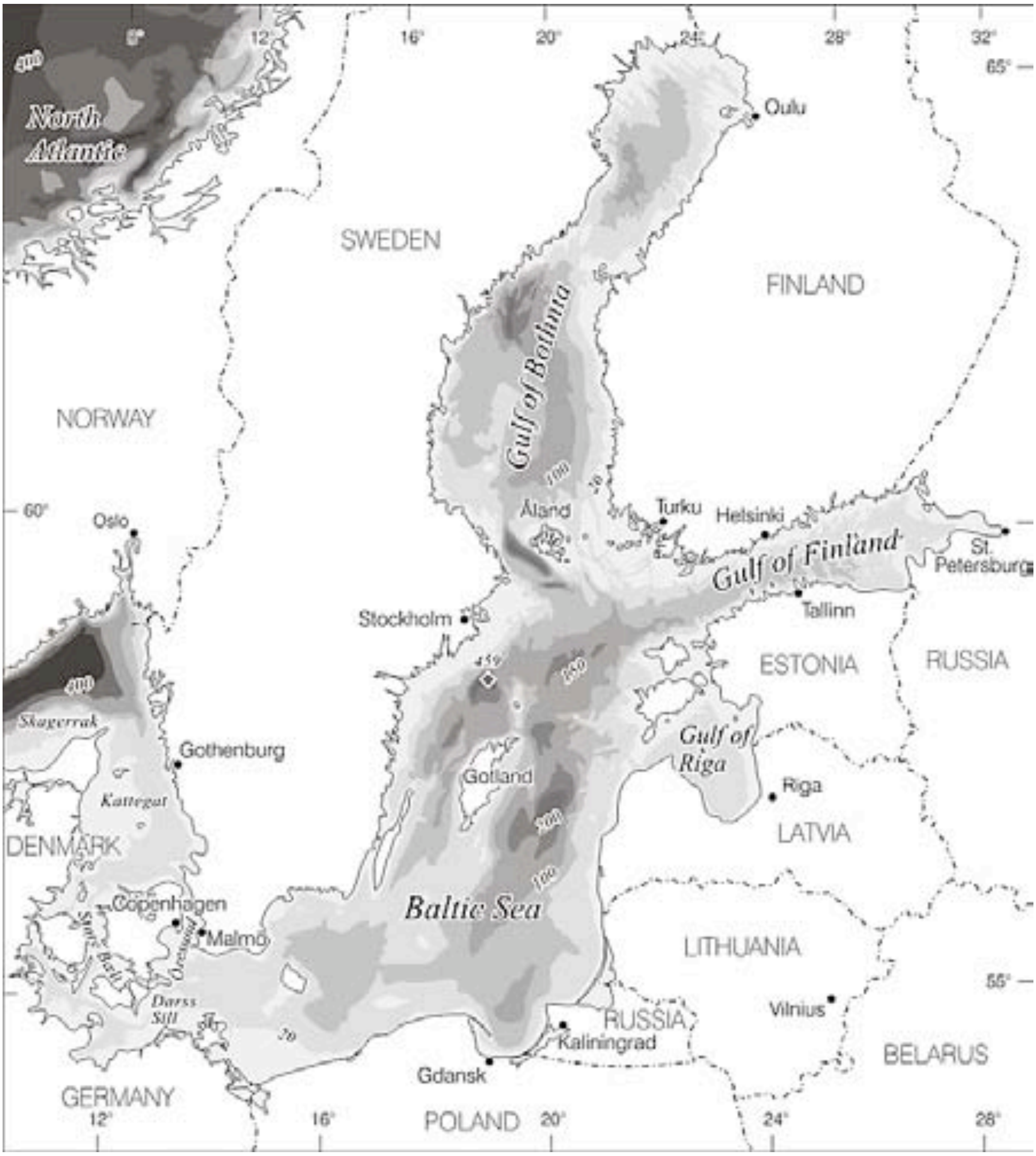

Figure i. The Baltic Sea and the surrounding region. From Tikkanen & Oksanen 2002.

Nordatlanten och spridningen vid den Nordatlantiska ryggen med Skandinavien som en passiv kontinentkant, samt kollisionen med afrikanska block som pressar norrut i södra Europa. Så har det i allmänhet varit de senaste hundra miljonerna år och om denna stressregim förändras kommer också rörelsemönstret för strukturer som inte detekterats som aktiva under mesozoikum och tertiär att kunna förändras. Den kvartära insjunkningsstrukturen som gett oss Östersjön och i östeuropeiska kratonens bassänger anses återspegla en nylig förändring i stressregimen.

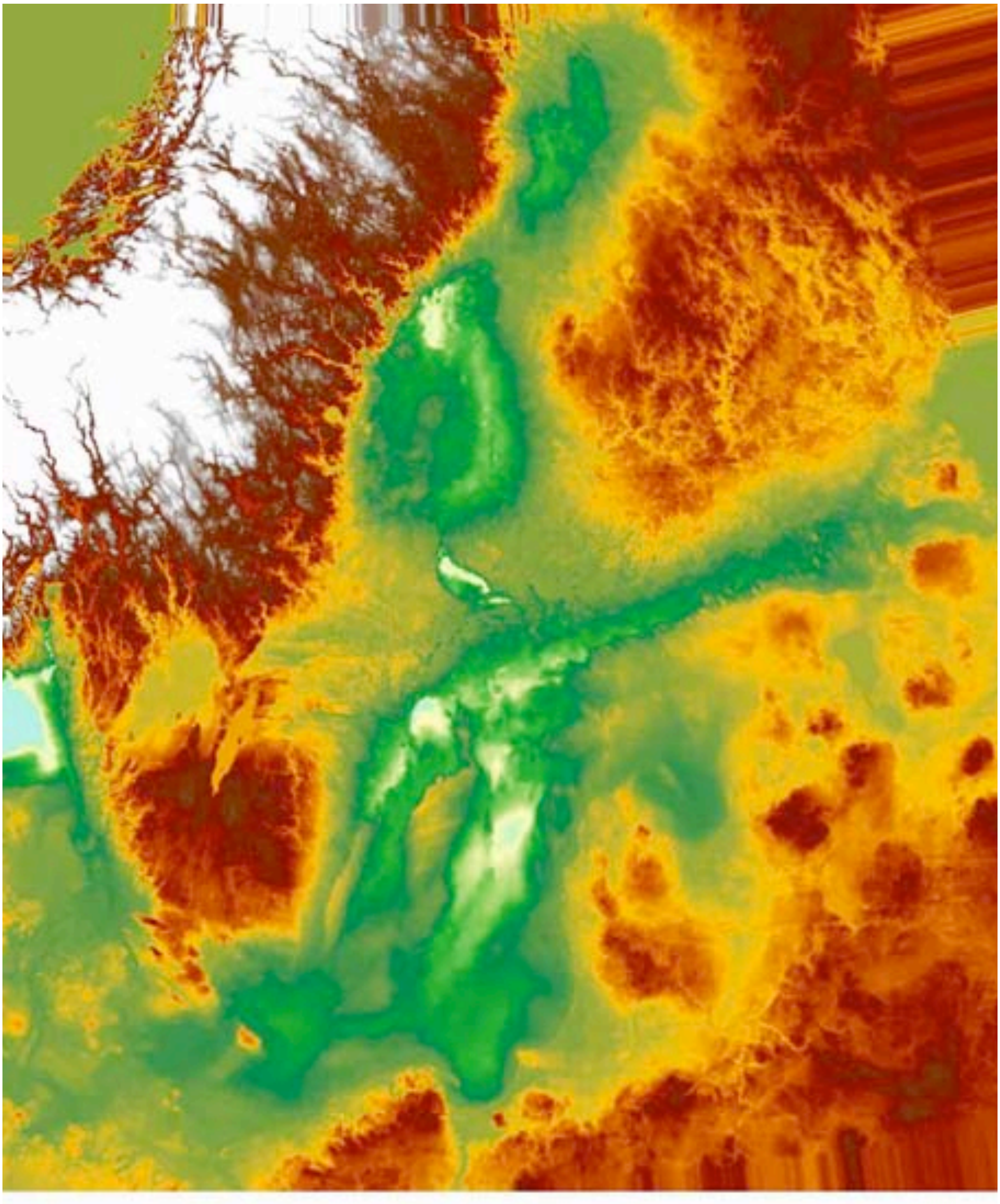

Figure ii.The Baltic Sea – Bathymetry and topography of surrounding countries. From Seifert et al. 2001.

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1 INTRODUCTION

The Baltic Sea, in a wide sense, comprises the water-covered areas between the Baltic States, Finland, Sweden, Denmark, Germany and Poland (Figs. i - ii and Figs. 1-2). Most of its bottoms are made up of low- or unmetamorphosed sedimentary rocks beneath a cover of Quaternary deposits. While the surrounding bedrock in Sweden and Finland is almost two billion years old, in the Baltic States, Poland, Germany and Denmark the crystalline bedrock is covered by Phanerozoic sedimentary rocks (Figs. 1 and 2) as are also the bottoms of the Baltic Sea. Differences between areas of occurrence of sedimentary rocks of varying age and the boundaries between these areas along with interpreted topographic breaks/lineaments may reveal probable lines for movement between major rock blocks.

1.1 Investigations

The bottom of the Baltic has been investigated in many different ways, by retrieving samples from the bottom (dredging and cored boreholes) or indirectly by geophysical investigations as e.g. reflection and refraction seismics and potential field measurements. Important contributions have come from Stockholm University (e.g. Flodén 1975, 1977, Axberg 1980, and co-workers), the Swedish Geological Survey (Ahlberg 1986, and detailed investigations, map sheets) the Geological Survey of Finland (Winterhalter 1988, Korja et al. 2006), Lithuanian studies (Šliaupa and co-workers, 1999 and onwards), and by cooperation between the countries bordering the Baltic Sea (Winterhalter et al. 1981, Gelumbauskaite et al. 1998, co-workers within the Eurobridge project (e.g. Bogdanova et al. 2006, Šliaupa et al. 2006). The knowledge of the crystalline bedrock in the Baltic States, Poland and Germany are based on boreholes. Topographic/bathymetric data have been presented by Lithuanian (Gelumbauskaite et al. 1998) and German workers (Seifert et al. 2001).

1.2 Method

Indication of movement can be manifold. Contacts between lithologies may reveal disturbance of the original arrangement by cutting relationships. Small-scale structures as slickensides, lineations and small-scale folding and different experiences of metamorphism may also indicate the sense of direction. The lack of later reference structures in the Precambrian basement may require laboratory work for evidence (fission-tracks, etc). Uplift and erosion can be studied in nearby sedimentary basins with analysis of the character of the sediments, transport directions and source rocks. Study of the topography may reveal varying levels and character of the ground surface. The location of earthquake epicentres may indicate the boundaries between different blocks.

Information has been collected from literature on structures and the timing of events that has involved movements in the crust and the building-up of stresses. Due to the time-scope of the study all available literature has not been thoroughly reviewed. Relevant figures from literature illustrate the text in the present report and are given with the original captions; the references are given as, e.g. *From Koistinen et al. 2002*. The different investigation methods used to gain information are treated in an appendix with further examples. Stratigraphic time tables are given in Appendix 1.

From the literature it is clear that the Earth´s crust has acted in a segmented fashion and blocks have been displaced and have rotated relative to each other through geologic history.

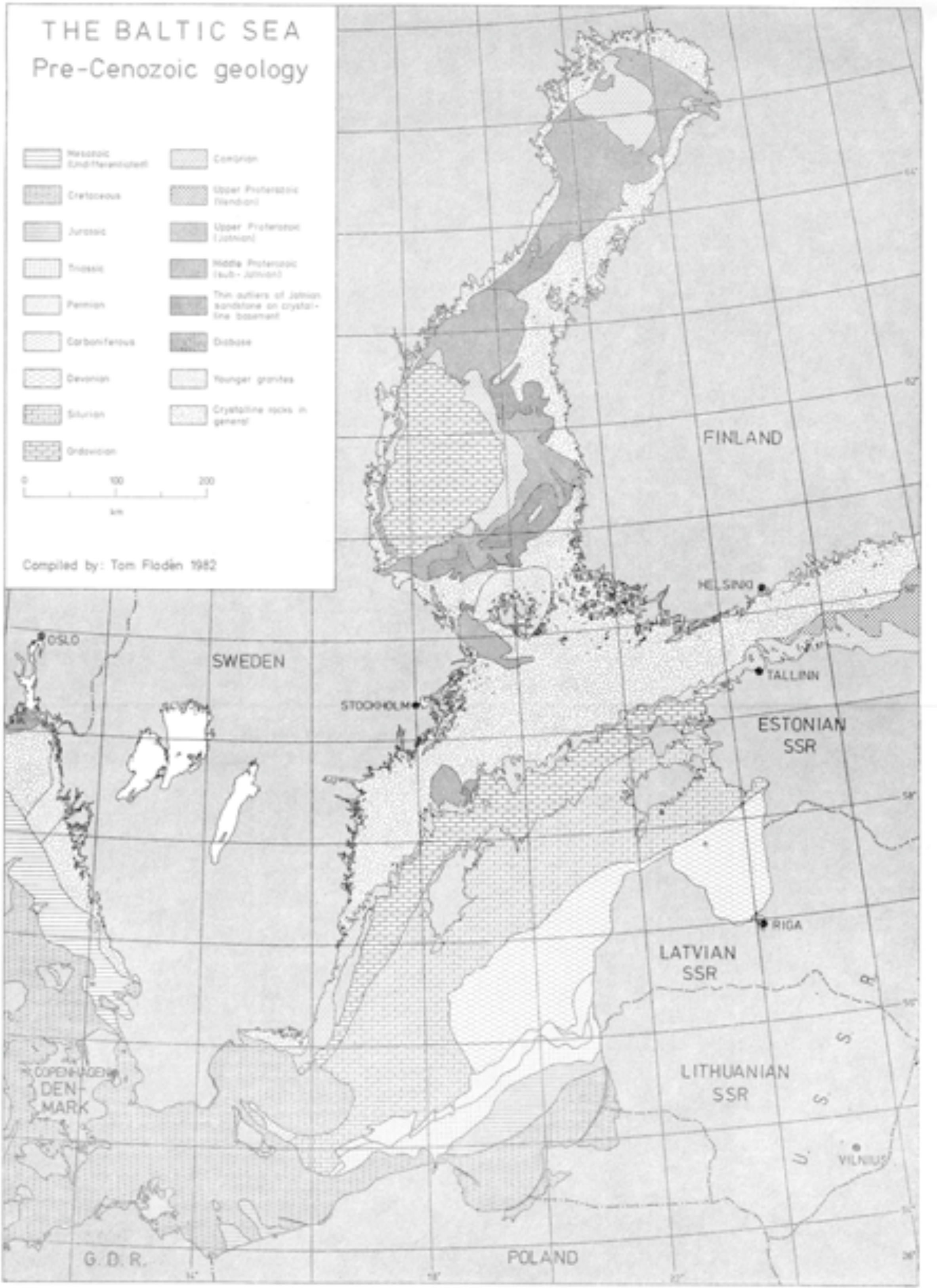


Figure 1. 1. Geology of the Baltic Sea from Flodén 1984.

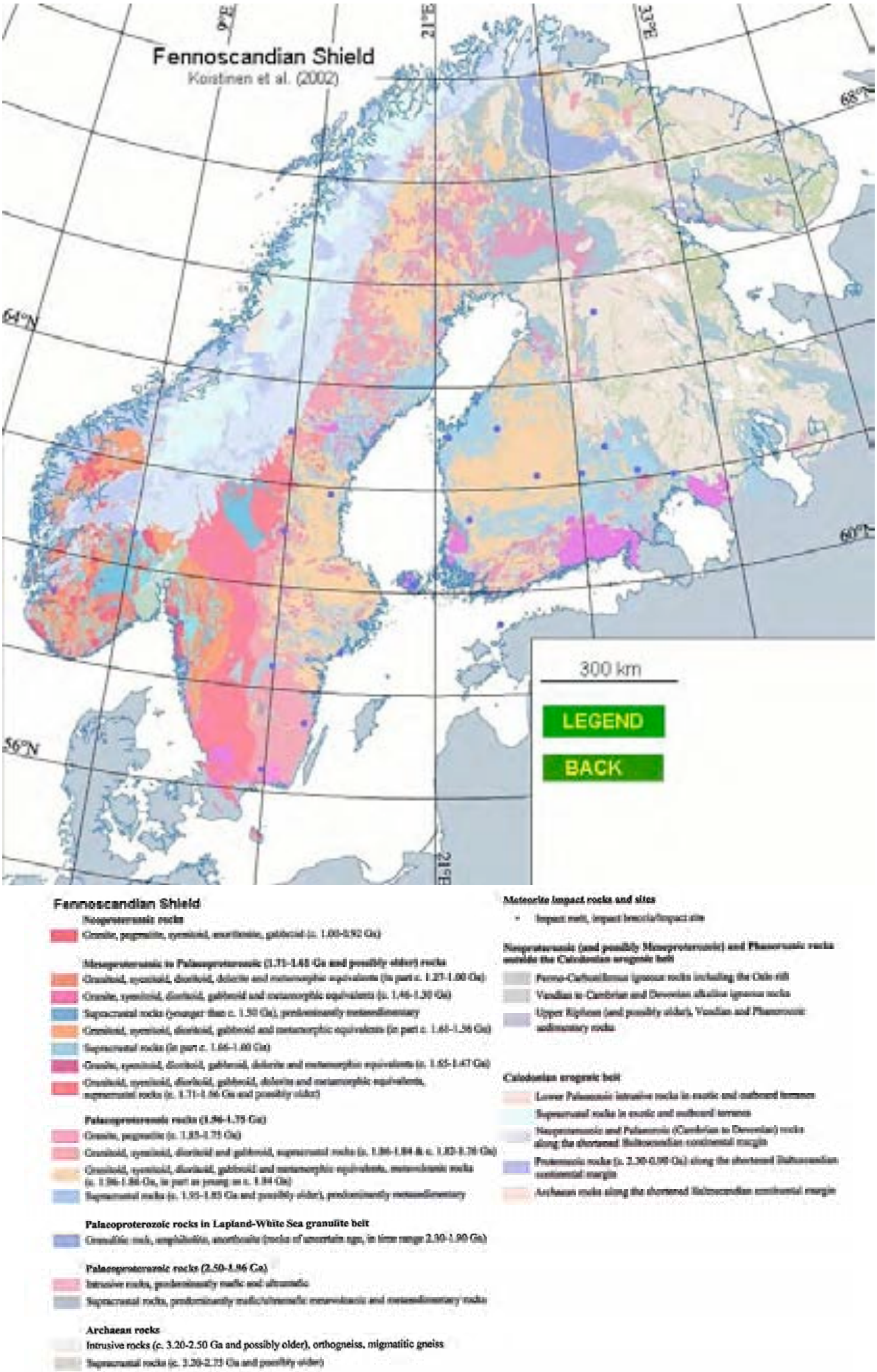


Figure 2. Bedrock of the Fennoscandian Shield. From Koistinen et al. 2002, cf. also Koistinen et al. 2001.

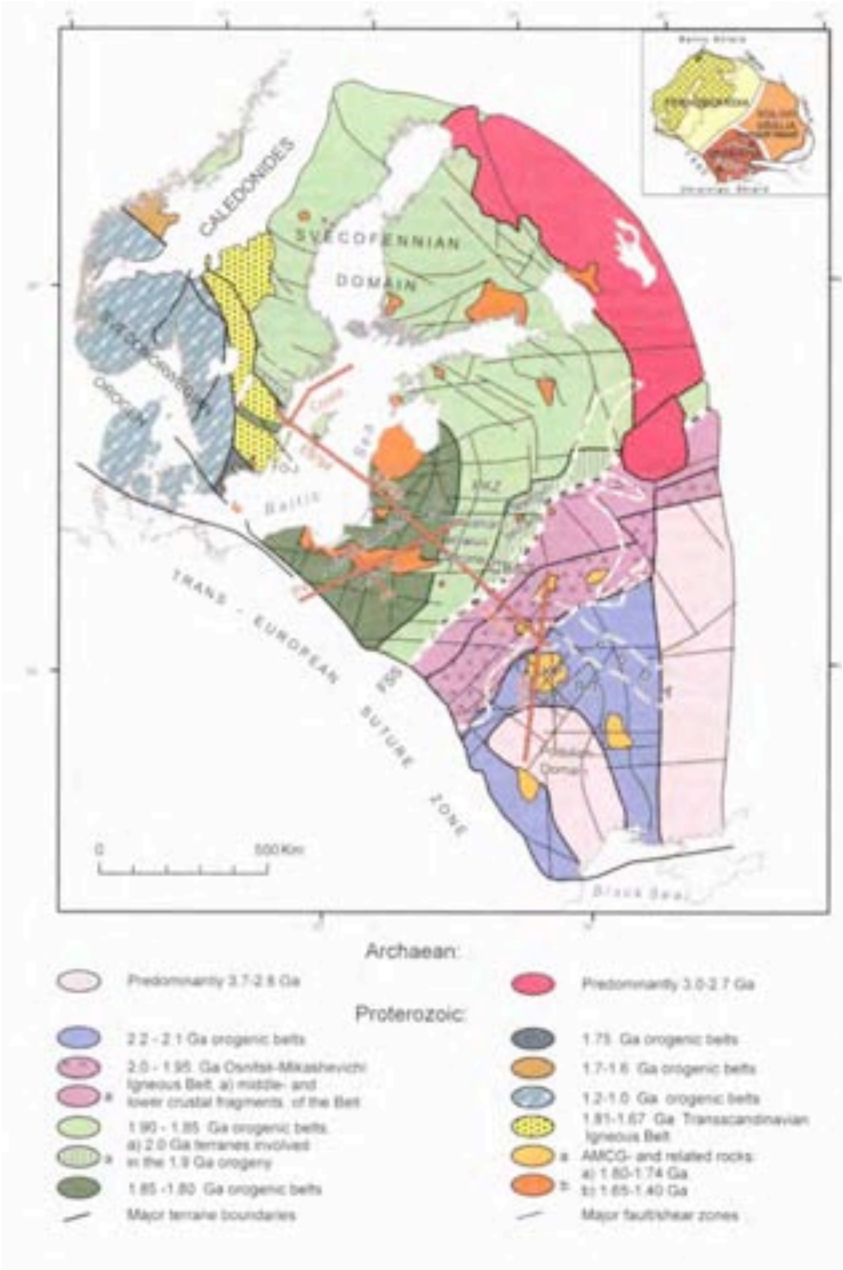


Figure 3a. Major tectonic subdivision of the crust in the west part of the East European Craton: CBSZ Central Belarus Suture Zone; KP, Korosten Pluton; LLDZ, Lofthammar-Linköping Deformation Zone; MLSZ, Mid-Lithuanian Suture Zone; O-J, Oskarshamn-Jönköping Belt; PDDA, Pripyat-Dniepr-Donets Aulacogen; PKZ, Polotsk-Kurzeme fault zone. The dashed light yellow line delimits the Volyn-Orsha Aulacogen. Red lines show the position of the EUROBRIDGE (EB'94; EB'95, EB'96 and EB'97), Coast and POLONAISE (P4 and P5) seismic profiles (from Bogdanova et al. 2006). The insert show the three-segment structure of the East European Craton. From Bogdanova 1993, Khain & Leonov 1996.

2 CRYSTALLINE BEDROCK

The bedrock record of what is now the Baltic Basin dates back almost 2Ga.

2.1 Svecofennian orogeny

The present-day Baltic Sea Basin is situated in a depression, in the south roughly coincident with the Silurian basin. It has been the site of several generations of sedimentary basins and uplift for over 1.5Gy. The underlying crystalline bedrock (Figs. 3a and b) was shaped and formed mainly during the Svecofennian orogeny, a collage of reworked Archaean microcontinents and Palaeoproterozoic island arcs and sedimentary basins with associated voluminous magmatism that occurred between 1.93Ga and 1.77Ga (Korja et al. 2006).

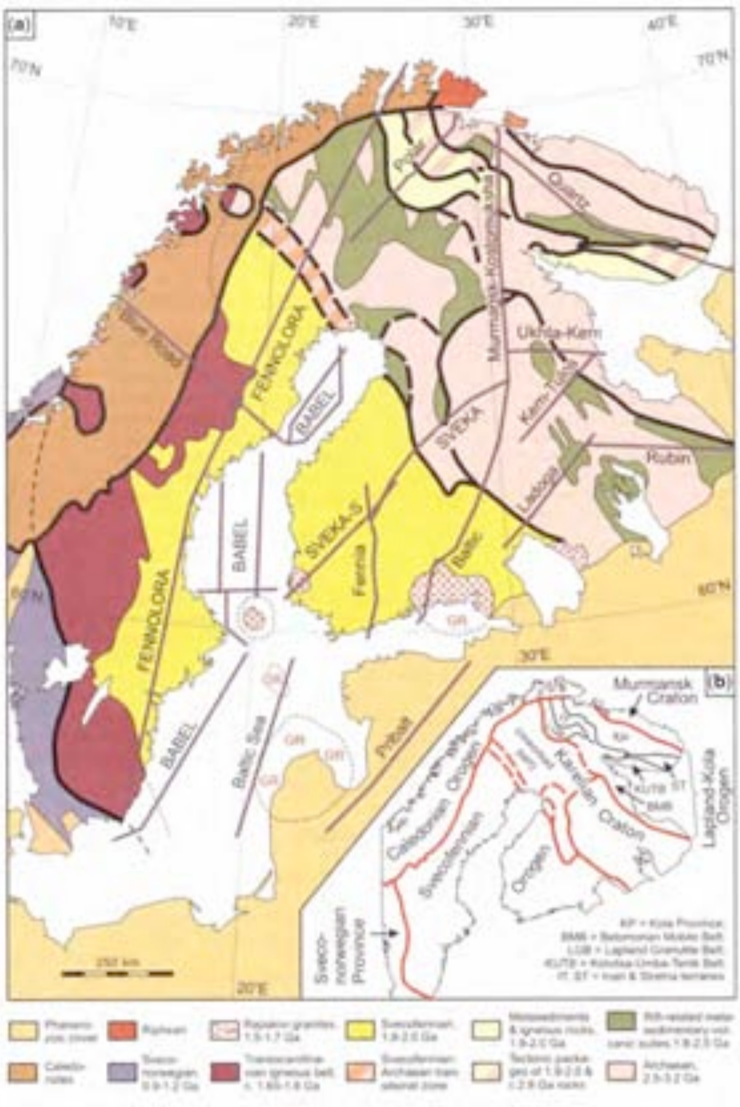


Figure 3b. Schematic geological (a) and tectonic (b) maps of the Fennoscandian Shield (data compiled from Gorbatschev & Bogdanova 1993; Balandsky 2002; Glaznev 2003) showing the location of the principal seismic refraction lines and the BABEL seismic reflection lines. Tectonic boundaries are shown as bold black lines (from Daly et al. 2006). Dashed outlines of unexposed rapakivi granites (GR) are based on geophysical data. From Glaznev 2003.

The Svecofennian crust was built by accretionary events around the Archaean nuclei with variously metamorphosed supracrustal rocks in collisional zones in various directions giving different grain in separate areas and with suture zones in N-S, NW, WNW and E-W (Fig. 4a and b). Although different processes operated simultaneously at different places, Korja et al. (2006) separate four major stages: microcontinent accretion at 1.92-1.88Ga, large-scale extension at 1.87-1.84Ga, continent–continent collision at 1.87-1.79Ga and, finally, gravitational collapse at 1.79 and 1.77Ga. As a result Fennoscandia was positioned in the middle of a supercontinent. Due to the mode of formation, the Svecofennian crust was very heterogeneous with different crustal thicknesses (Fig. 5). The collision-induced over-thickening of the crust resulted in orogen collapse and increased heat flow may have caused mafic underplating followed by partial melting and migmatite formation.

*Figure 4a. Simplified geological map of the Fennoscandian Shield, based on Kostinen et al. (2001). The shear zones are mainly interpreted from magnetic and gravity maps (Korhonen et al. 2002). (**a**) major geological units of the Fennoscandian Shield, after Gaál & Gorbatschev (1987). N, Northern Svecofennian Subprovince; C, Central Svecofennian Subprovince; S, Southern Svecofennian Subprovince, (**b**) Archaean cratonic terranes of the Shield. Archaean units: Norrbotten craton, Kola craton, and Karelian craton, including Belomorian. Palaeoproterozoic units in Kola peninsula: IA, Inari area; PeB, Pechenga Belt; IVB, Imandra Varzuga Belt; UGT, Umba Granulite Terrane; TT, Tersk Terrane. Palaeoproterozoic units in Finland: LGB, Lapland Granulite Belt; KA, Kittilä allochton; CLGC, Central Lapland Granitoid Complex; SB, Savo Belt; CFGC, Central Finland Granitoid Complex; TB, Tampere Belt; HB, Häme Belt; UB, Uusimaa Belt. Palaeoproterozoic units in Sweden: SD, Skellefte district; BB, Bothnian Basin; BA, Bergslagen area; SöB, Södermanland Basin, OJB, Oskarshamn-Jönköping Belt; TIB, Transscandinavian Igneous Belt. J, Jormua; K, Knaften; O, Outokumpu; R, Revsund; BBZ, Baltic-Bothnia Megashear; HSZ, Hassela Shear Zone; LBZ, Ladoga-Bothnia Bay Zone. From Korja et al. 2006.*

Today, parts of the Fennoscandian shield has very thick lithosphere (>200km) and in places very thick crust (50-60km in south-central Finland, >50km in northeastern Småland and Östergötland). A high-velocity, high density, mafic lower crust at 10-30km depth

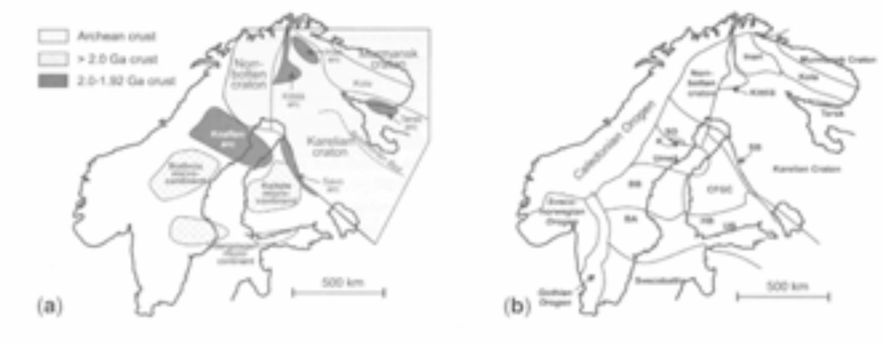


Figure 4b. Distribution of microcontinental nuclei, island arcs and terrane boundaries in the Fennoscandian Shield. Abbreviations are as in Figure "4a". (a) Older than 1.92 Ga, hidden and exposed suspect terranes found in the Svecofennian Orogen. (b) Major Palaeoproterozoic terranes of the Fennoscandian Shield. From Korja et al. 2006.

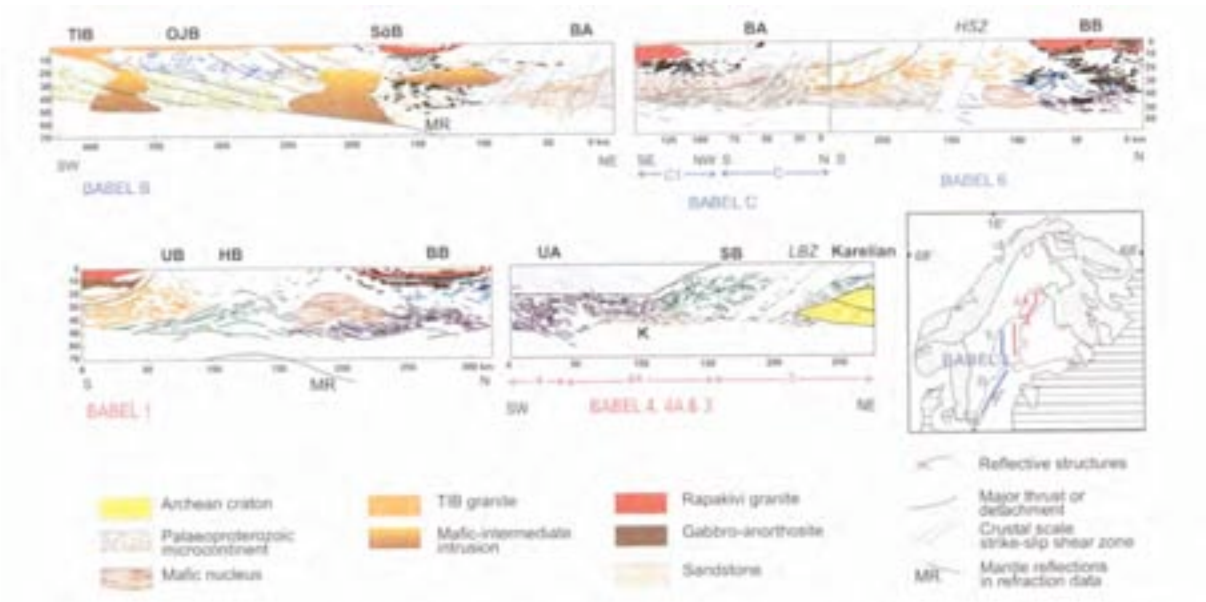


Figure 5. Crustal cross-section of the Fennoscandian Shield, modified after Korja & Heikkinen (2005). There is no vertical exaggeration. Coloured lines denote reflections arising from terranes with different reflection properties; diabase sills are in black (For abbreviations se Fig."4a".) Lower panel: Finnish west coast section; BABELl lines 3, 4 and 1. On profiles 3 nd 4 the Karelian continental margin is both over- and underthrust by island-arc affiliated material. A small crustal indentor in grey, interpreted as more rigid, older crust, is to the SW of a subduction zone and an accretionary prism (blue) is developed. On profile 1, the accretionary prism material (blue) continues and is pushed onto another continental indentor (brownish) further to the south. South of the indentor another subduction zone is preserved. In the following collision, the supracrustal packages were sequentially stacked onto the indentor (brownish), from the south. In a later Mesoproterozoic extensional stage, the compressional structures were reactivated and rapakivi granites were formed. Upper panel: Swedish coastal section; BABEL lines 6, C and B. The southern part of profile 6, profile C and the northern part of profile B are interpreted to image the imbrication of an

older continental margin involving the stacking of continental and supracrustal slices. In the southernmost part of profile B, another continent (unknown) accreted, after an ocean was consumed by northward subduction under Bergslagen microcontinent. A large basin between the continents was closed and the supracrustal rocks were thrust onto both of the converging continents. The collisional structure is overprinted by mantle-derived intrusions affiliated with the TIB. Rapakivi granites also overprint the collisional structure in the central part. From Korja et al. 2006.

compensates the crustal thickness variations and accounts for the flat topography (Korja et al. 2006). High velocities in the mantle lithosphere indicate high densities and low temperatures also there.

2.2 Sub-Jotnian rapakivi suites

A hundred to a hundred and fifty million years later (from c. 1.67Ga) the erosion had levelled the orogen so that in places the ground surface was close to that of the present day. During the next hundred and fifty million years, in a vague connection to old sutures between Svecofennian nuclei, the plate was subject to extensive crustal thinning when large batholiths of rapakivi magma were emplaced in the upper crust in essentially three extended pulses (Figs. 3, 5, 6 and 7a), leaving behind a 15-20km thinner crust.

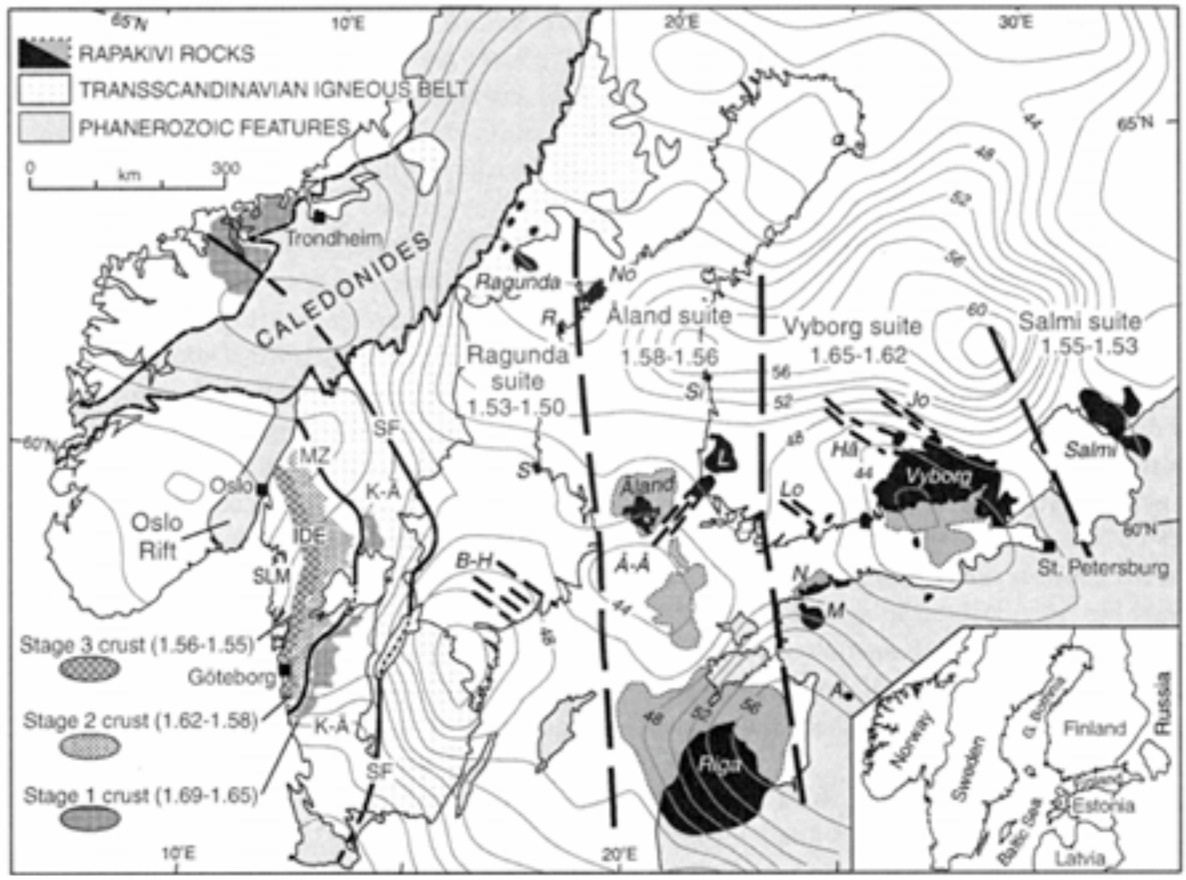


Figure 6. Simplified map showing east-west zonation of 1.65-1.50 Ga rapakivi suites in the Svecofennian domain, the Transscandinavian Igneous Belt, three Gothian growth zones between Göteborg and Trondheim, and the accreted Stora Le-Marstrand rocks (SLM) to the

west. Ages are Ga. SF marks eastern front of Sveconorwegian orogen, within which Mylonite Zone (MZ) separates Idefjorden terrane (IDE) from Klarälven-Ätran segment (K-Ä). Contours show depth to Moho in kilometres (after Korja et al., 1993). Rapakivi rock (black where exposed; gray where unexposed) bodies are estimated from coring and geophysical data (cf. Koistinen, 1994; Ahl et al., 1997). Small bodies: A - Abja, L - Laitila, M - Märjamaa, N - Naissaare, No - Nordingrå, R - Rödön, S - Strömsbro, Si - Siipyy. Dikes: Å-Å - Åland-Åbond, B-H – Breven-Hällefors, Hä – Hämö, Jo – Joutsa, and Lo – Lohja. White areas are undifferentiated Archean and Proterozoic domains not discussed in the paper. From Åhäll et al. 2000.

The term rapakivi is Finnish and means rotten stone. The typical granites are often coarse-grained and porphyritic with large ovoids of orthoclase surrounded by plagioclase mantles. The rapakivi suites comprise bimodal magmatic rocks of both mantle and crustal derivation. Partial melting of the upper mantle is manifested in mafic dykes, gabbro, anorthosite and some intermediate rocks, while heating and vapour-absent partial melting of intermediate to acid igneous or meta-igneous rocks in the lower and middle continental crust, with fractionation of feldspars, quartz and subalkaline mafic silicates, gave rise to the granitic magmas that were emplaced as sheet-formed bodies in the upper crust. They cut Svecofennian and Archaean formations. (Laitakari et al. 1996, Rämö et al. 2005)

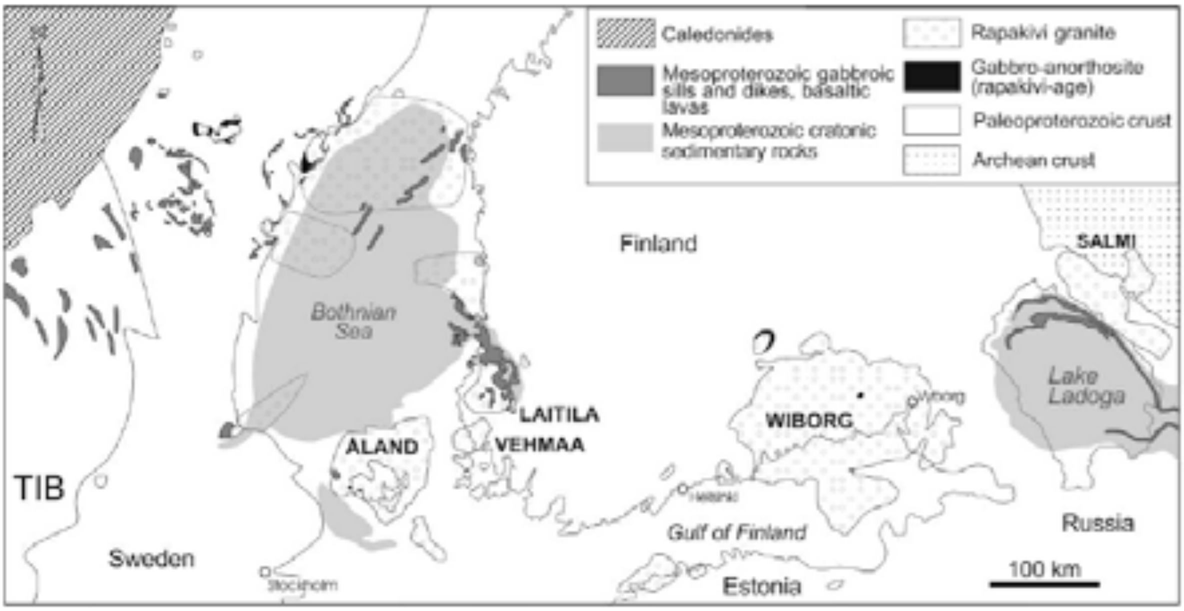


Figure 7a. Geological sketch map of southern Finland and vicinity showing the distribution of various Precambrian lithologic units as well as Caledonides in the west. TIB – Transscandinavian igneous belt. From Rämö et al. 2005).

First out was the Vyborg suite at 1.67-1.62Ga. It intruded during a long time, >30My at shallow depth, some kilometres from the sub-Jotnian surface, close to the present-day surface (Laitakari et al. 1996). Also volcanic components are preserved. The crust broke along old zones of weakness. The mafic dyke swarms of diverse age have different orientation, indicative of that the orientation of maximum stress changed during these 30My, 280° at 1667Ma, 300° at 1646Ma and 330° for younger dykes (Puura and Flodén 2000). The dykes occur at the same level as the magma chambers; mafics reached hundreds of km while the less mobile granitic magma solidified as plutons in sub-horizontal sheets or as laccoliths (Laitakari et al. 1996).

The second age group comprises the Åland, Gulf of Bothnia, Baltic Sea and Riga plutons in the 1.59-1.54Ga interval. The Riga suite displays a tilted position; in the north >140m volcanics are preserved while in Lithuania in the south, a deeper crustal level constitutes the upper surface (Puura and Flodén 2000). In contrast to the NW orientation of those in the older Vyborg suite, the Åland dykes are oriented in NNE but in agreement with the progressive clockwise rotation of the arrangements of the dykes. The Åland massif is more eroded in the northern part than in the southern (Puura and Flodén 2000), suggesting that this block rotated in an opposite direction to the Riga body.

Upsetting the general younging-westwards trend for the rapakivi age groups, a rapakivi massif was emplaced in Russian Karelia north of Lake Ladoga at 1.56-1.53Ga.

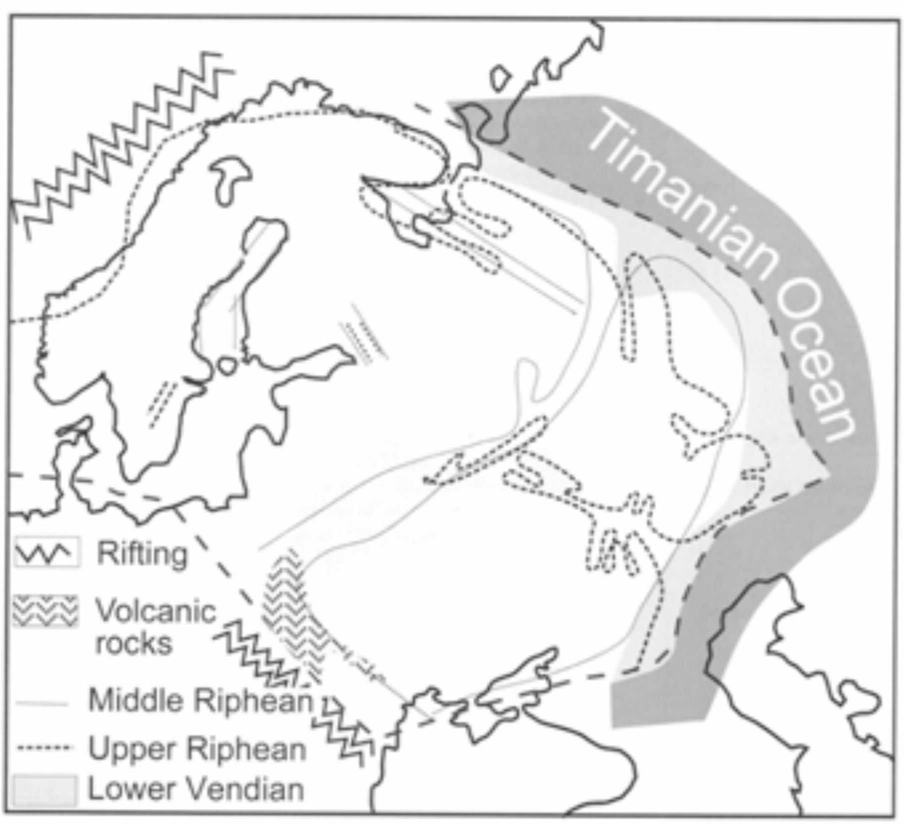


Figure 7b. Distribution of Middle and Upper Riphean and Lower Vendian (including volcanic rocks) sedimentary successions on the EEC. Neoproterozoic rifted and oceanic basins along the EEC margins are also indicated. From Šliaupa et al. 2006.

Westwards, the third major age group, at 1.59-1.47Ga, consists of, younging westwards, the Nordingrå and Ragunda complexes, the E-W to ESE-striking Breven-Hällefors dyke swarm and the west central Sweden rapakivi granites.

Bogdanova et al. (2006) presume the existence of 1.50-1.45Ga granitoids under the Baltic Sea and west Lithuania at 10km depth.

3 SEDIMENTARY COVER AND MAFIC DYKES AND VOLCANICS

3.1 Mesoproterozoic Jotnian sandstone basins

In close spatial connection to the rapakivi intrusions, the Mesoproterozoic red-type Jotnian sandstones have been preserved in fault basins as in the Gulf of Bothnia and Ålands hav (cf. Fig. 7a, 7b and 8a), at Landsortsdjupet, in the Ladoga Basin and in Dalarna (Koistinen et al. 2001). The fault basins may have inherited sub-Jotnian ring faults (Söderberg 1993). The Dalarna occurrence, with evidence also here for block-faulting (Nyström 1982), suggests that the Jotnian sandstones of today are only what have been selectively preserved of originally wider extensive deposits, due to later tectonic events. The deposits are poorly dated, usually referred to as something in between the rapakivi granites and later (and/or coeval with) intrusions of mafic dykes, 1.6-1.5Ga to 1.2Ga (Figs. 7, 8a and b). Russian literature refers to this evolution as part of the Riphean aulacogens in the East European Platform area (cf. e.g. Amantov et al. 1996). The Jotnian deposits are generally of very low metamorphic grade due to burial metamorphism (Nyström & Levi 1980).

The Jotnian sandstones are stratified and contain many types of primary structures such as lamination and ripples; at least parts of the sandstones have been deposited in running water and deltas (Amantov et al. 1996). The red colour along with raindrop imprints and dry cracks testify to partial exposure above the water level. Due to faulting during (and after) deposition the stratigraphic beds became tilted and large thicknesses were accumulated, <2000m. The source rock was the Svecofennian bedrock; at least in some areas the rapakivi granites were not exposed (Marttila 1969 in Amantov et al. 1996).

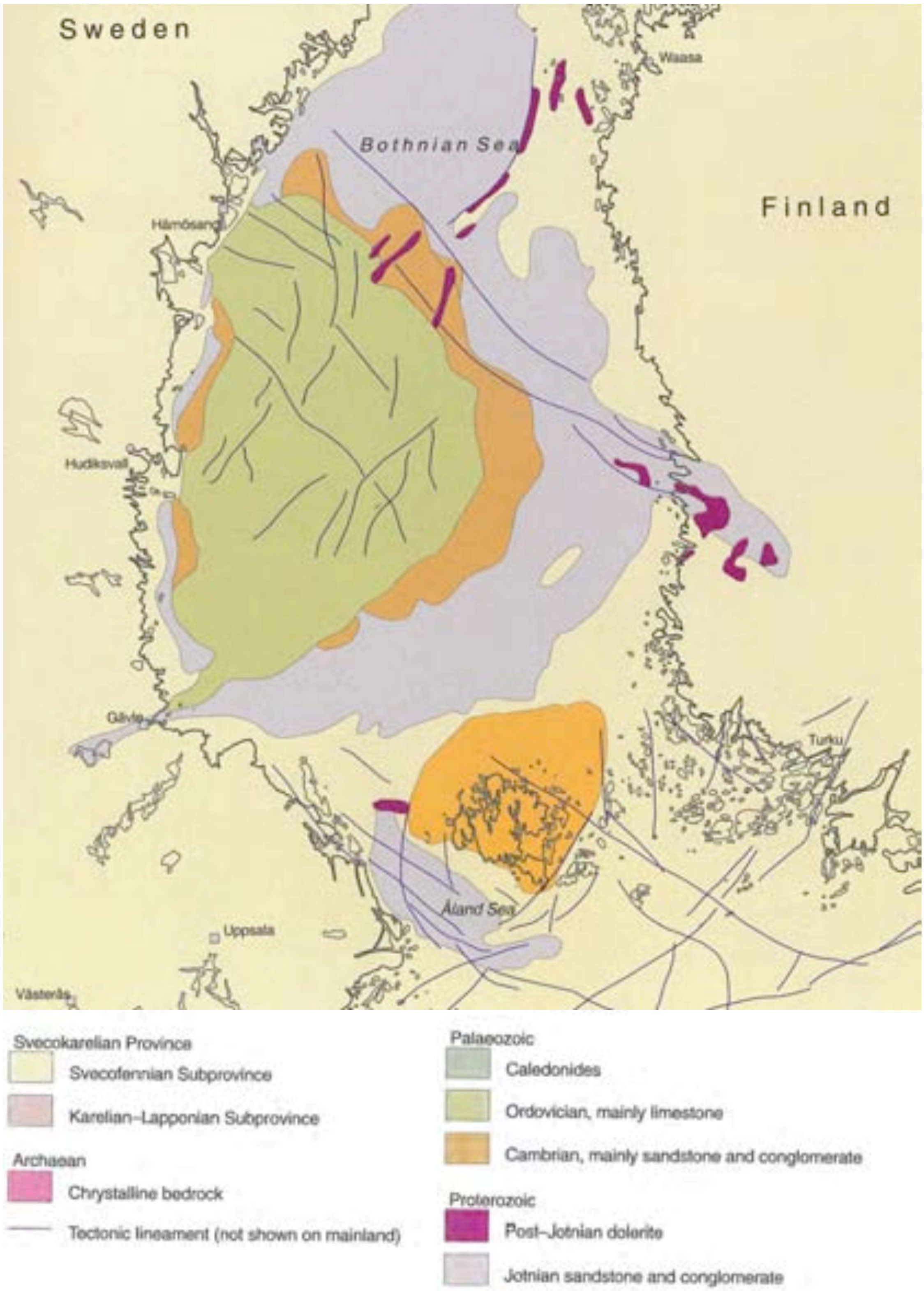
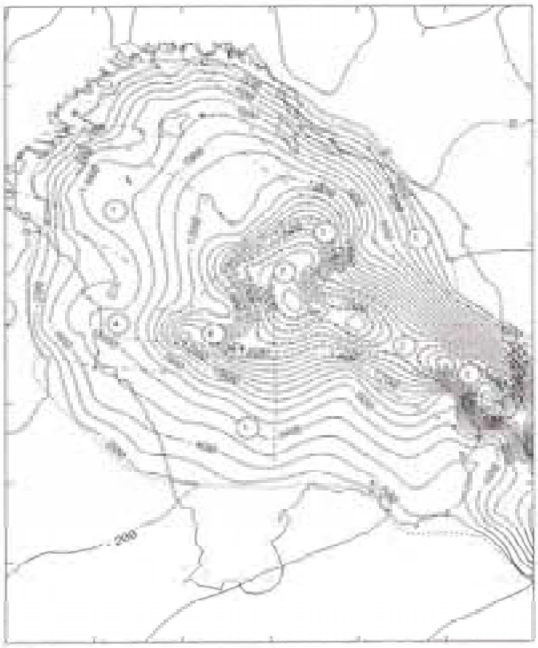
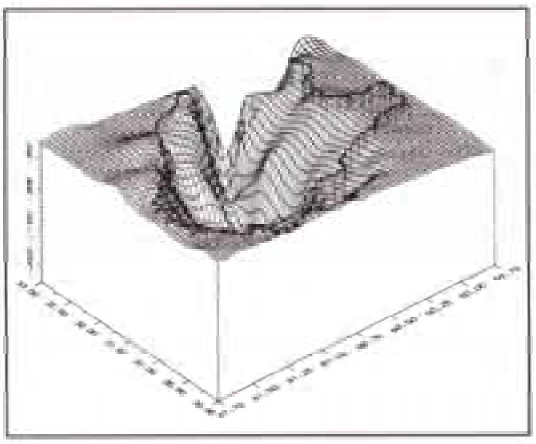


Figure 8a. Prequaternary rocks of the continental shelf modified. From Norling 1994; the figure is a part of a larger map.

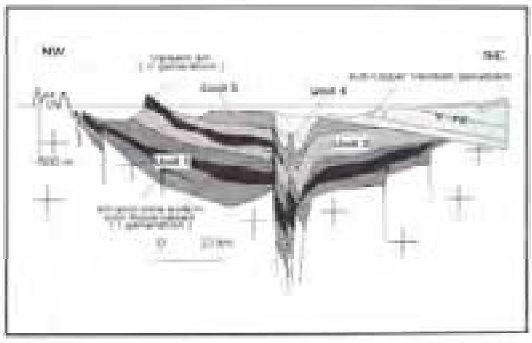
8b,i.



8b,ii.



8b,iii.



8b,iv.

Figure 8b. (i) Jotnian sandstones: Localities mentioned in the text, (ii) The present morphology of the sub-Jotnian nonconformity surface, (iii) The morphology of the sub-Jotnian nonconformity seen in three dimensions, looking southeast, along the Pasha graben and The Pasha graben continues out of the diagram, and (iv) Sketch cross section of the Ladoga – Pasha basin. From Amantov et al. 1996.

3.2 (Post-)Jotnian mafic dykes

Associated with the sandstone basins are mafic dykes and sills of 1.26-1.25Ga. These often postdate the sandstone deposits but some sills are interpreted to be coeval with the sedimentation. Sills occur in Satakunta, at Märket and are in Dalarna and at Lake Ladoga also accompanied by volcanics. These resemble continental flood basalts (Rämö 1991, Nyström 2004).

K-Ar dating of intercalated shales (1278-1097Ma) indicates that the sedimentation may have proceeded longer. In the Ladoga basin sedimentation continued (and is only(?) preserved) in a narrow fault-related basin oriented in WNW, up into the Vendian (Fig. 8b; Amantov et al. 1996).

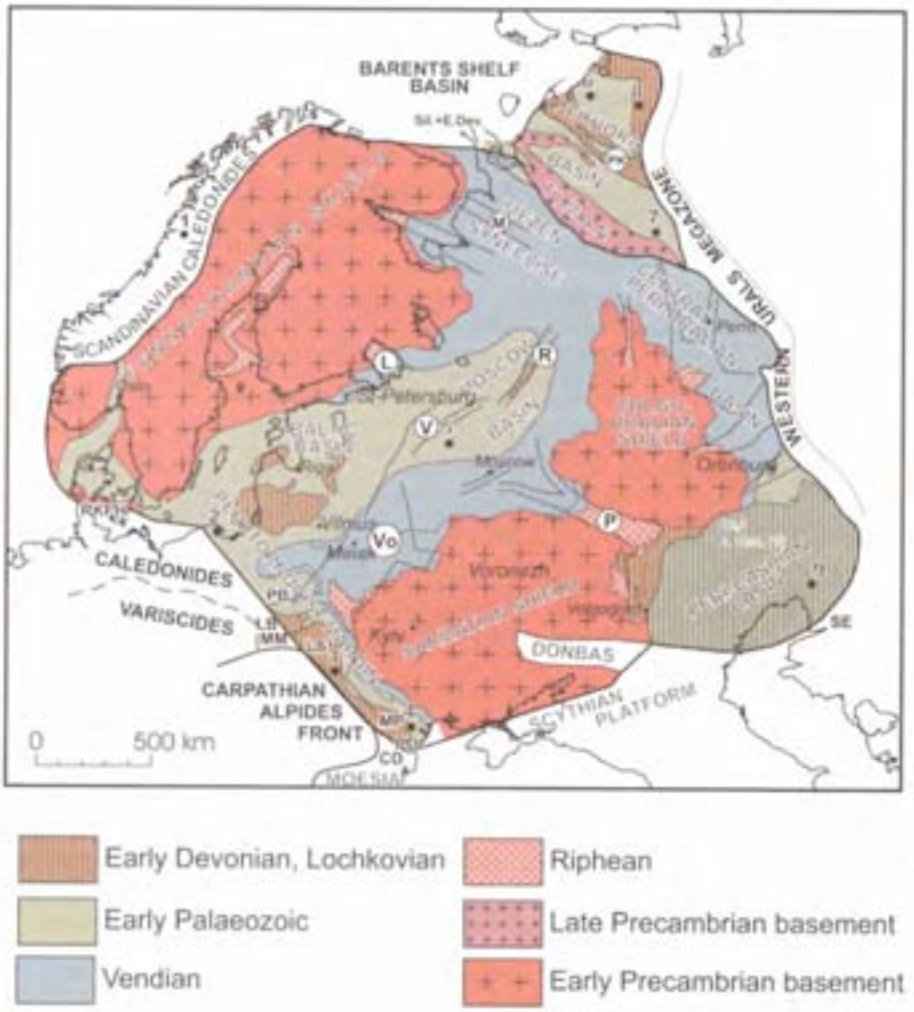


Figure 9. Locations of Vendian-Early Palaeozoic basins of the East European Craton (EEC) discussed in this paper. Palaeorifts are indicated by dashed lines with names in white circles: L, Ladoga; M, Mezen; P, Pachelma; PK, Pechora-Kolva; R, Roslyatino; V, Valday; Vo, Volhyn, Locations of modelled wells …. are also indicated (numbered black dots). Other abbreviations: CD, Central Dobrogea; LB, Łysogòry block; LS, Lviv slope; MP, Moldova platform comprising Dnestr marginal basins; MM, Malopolska massif; PD, Pre-Dobrogea depression; PB, Podlasie basin; RKFH, Ringkøbing-Fyn high; SE, South Emba. From Šliaupa et al. 2006.

3.3 Vendian

Late Proterozoic and Earliest Palaeozoic sediments were deposited in a basin from the Arctic Ocean via St Petersburg to Lviv and along the southern border of Baltica. Vendian sediments were deposited on the Swedish mainland, preserved in the Vättern graben, but are missing outside this graben under the Cambrian cover on the very extensive sub-Cambrian peneplain of the Swedish mainland and in the Baltic Sea (Figs. 9-10).

3.4 The Lower Palaeozoic – part of the break-up of Rodinia and assembling of Laurasia

After the Late Vendian onset of tectonic subsidence due to the breaking-up of Rodinia, the Baltic Basin was filled with sediments during the Lower Palaeozoic. The Palaeozoic Baltic

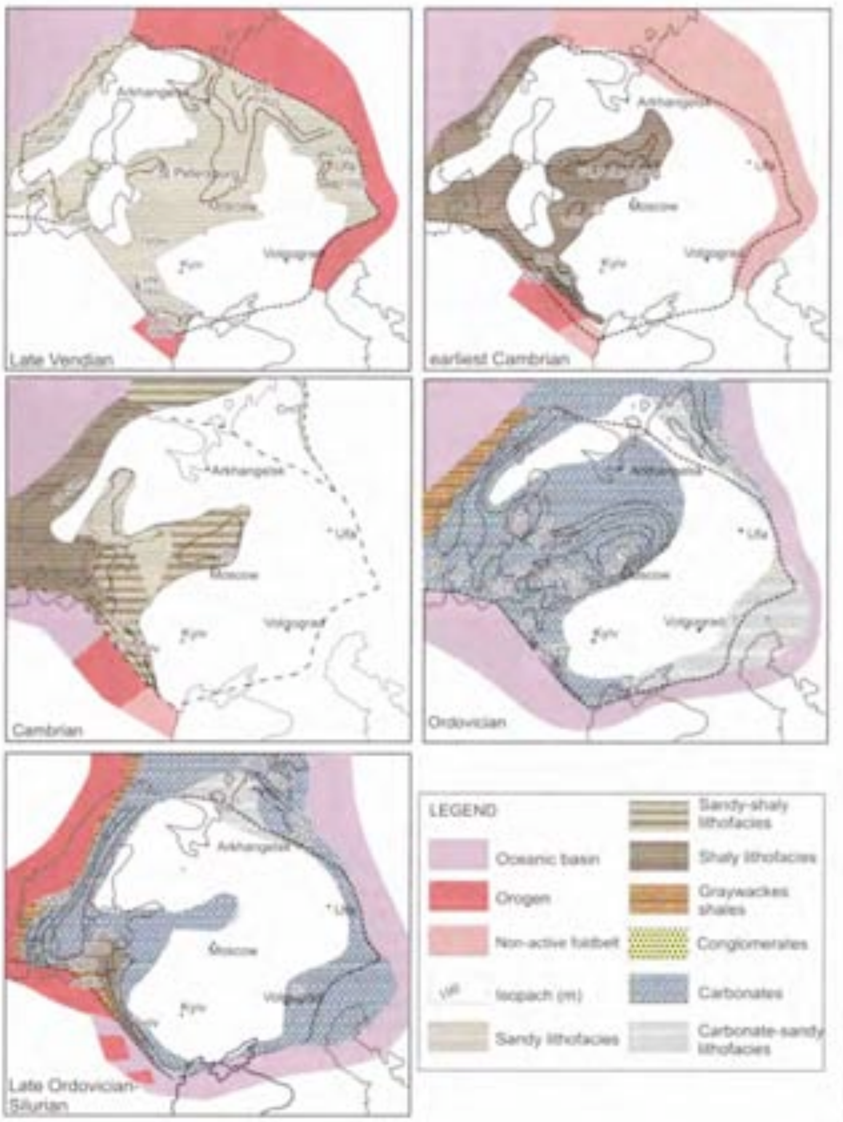


Figure 10. EEC sedimentary depocentres (isopach thicknesses shown in metres) and lithofacies for the Late Vendian, earliest Cambrian, Cambrian, Ordovician, and Late Ordovician (Ashgill)-Silurian. From Šliaupa et al. 2006.

Basin had a broader extension than the present preservation of Lower Palaeozoic sediments (Fig. 11) and the central axis has a more easterly position and orientation than that of the present Baltic Basin (Poprawa et al. 1999), centred around the Polish-Lithuanian Terrane (Bogdanova et al. 2006). It formed due to the post-rift thermal subsidence of the newly formed passive continental margin of the Tornquist Sea when it opened and the Baltic Depression formed the "southwestern" (present coordinates), passive margin of Baltica (Figs. 12-13).

Major changes in plate motion are marked by hiatuses and changes in subsidence rates and character of the sediments. Sediments that have been eroded away may also give information.

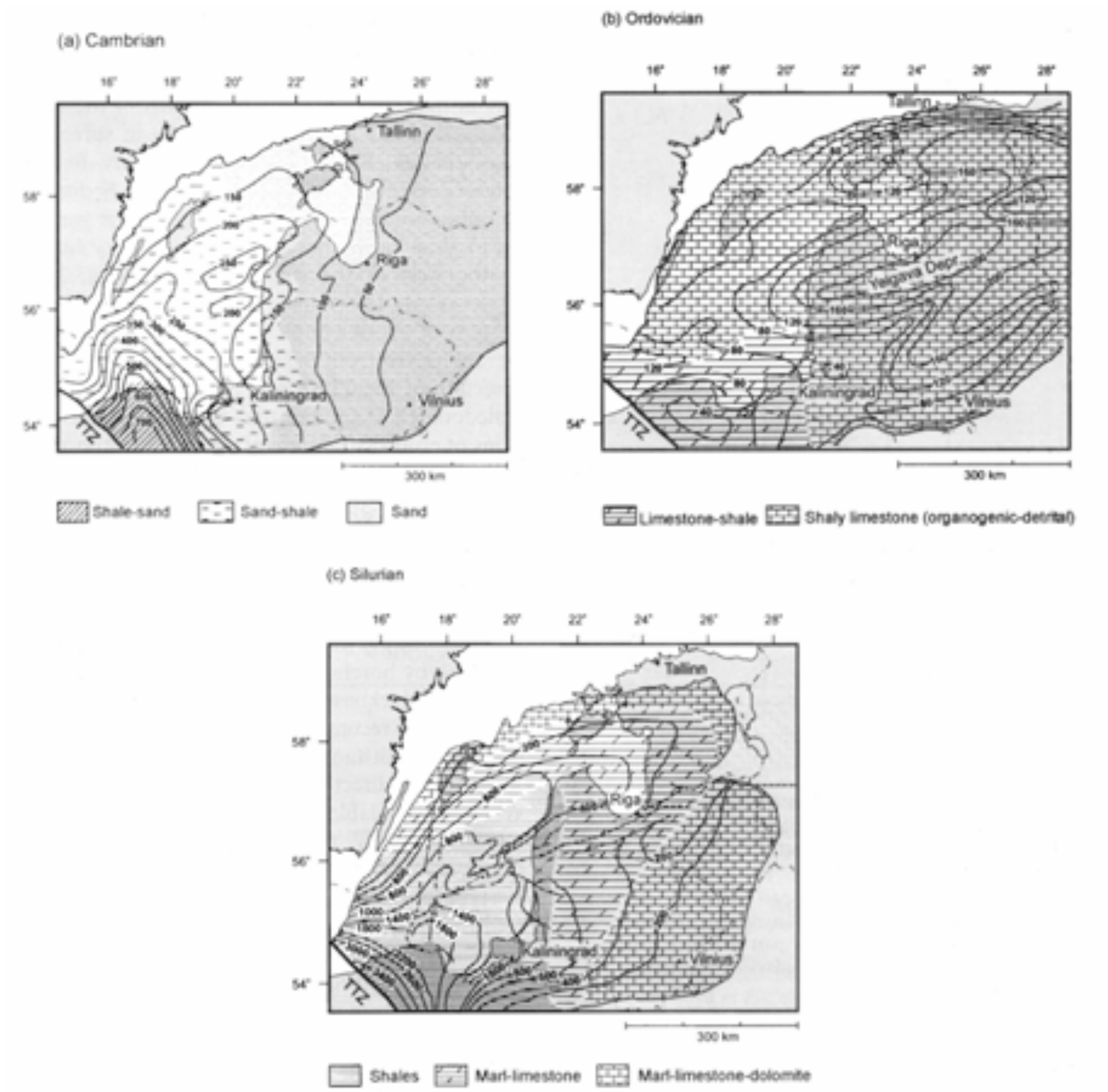


Figure 11. For part of the study area: (a) present thickness of Cambrian deposits (after Grigelis, 1991; Paskevicius, 1994) and lithofacies of Middle Cambrian (after Zinovenko, 1986); (b) thickness of Ordovician deposits (from Grigelis, 1991; Paskevicius, 1994) and lithofacies of the Caradoc-Ashgill succession (after Laskov, 1987); and (c) thickness of Silurian deposits (Grigelis, 1991, Paskevicius, 1994) and Ludlovian-Wenlokian lithofacies. Isolines in metre. From Poprawa et al. 1999).

The Late Vendian - Middle Cambrian marks the separation of microplates and extension, and after a hiatus in the Upper Cambrian, the Late Cambrian - Middle Ordovician represents the passive margin deposits. Plate convergence starting already in the Late Cambrian(?) was apparent in the Late Ordovician and the Baltic turned into a Late Ordovician - Silurian

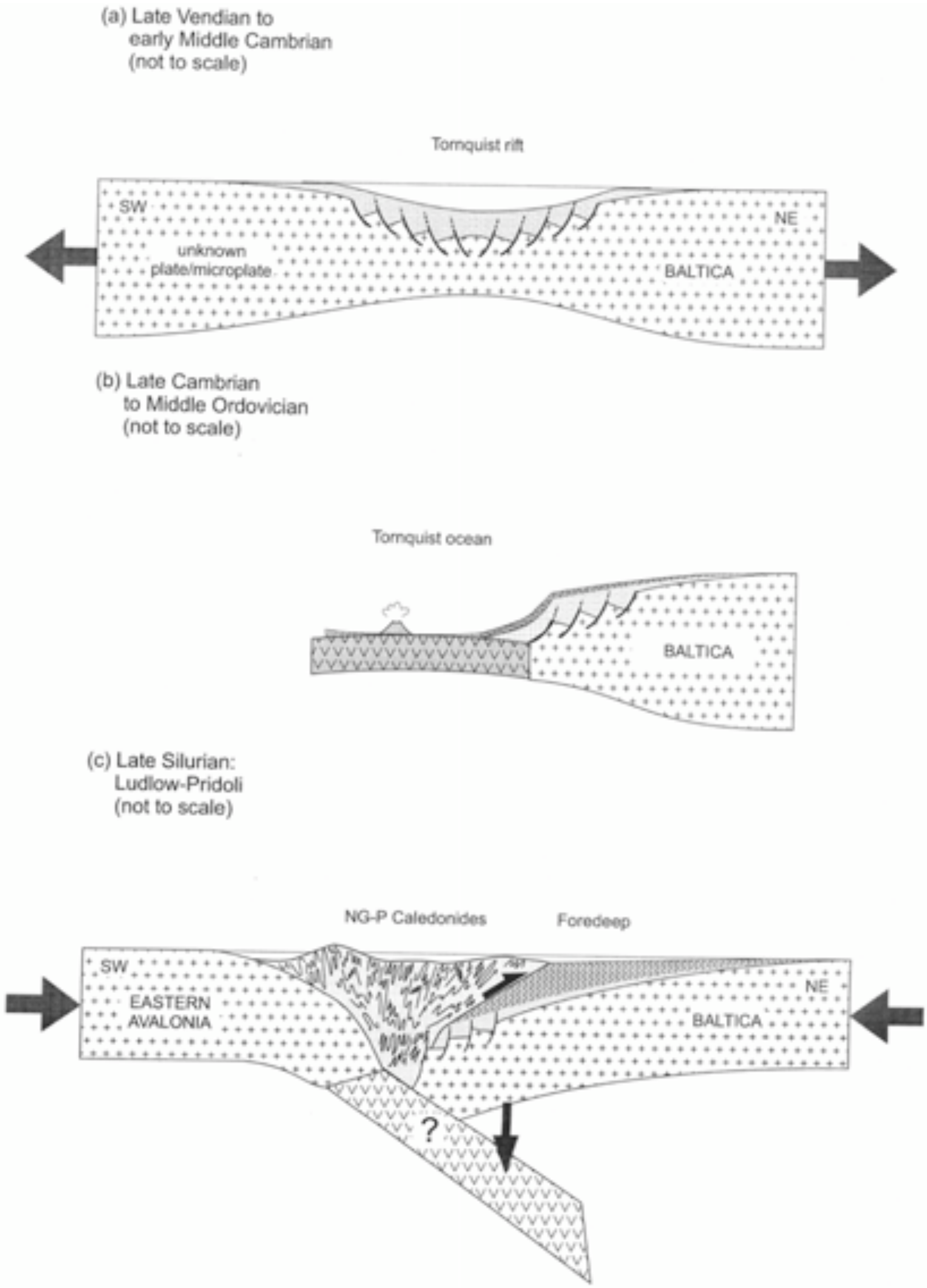


Figure 12. Cartoons showing the interpreted tectonic setting of the Baltic Basin in (a) Late Vendian to earliest Cambrian, active extension/rifting along the axis of the future Tornquist Sea; (b) Late Cambrian to Middle Ordovician passive margin evolution; and (c) Late Silurian plate convergence, orogenic activity and foredeep development. From Poprawa et al. 1999.

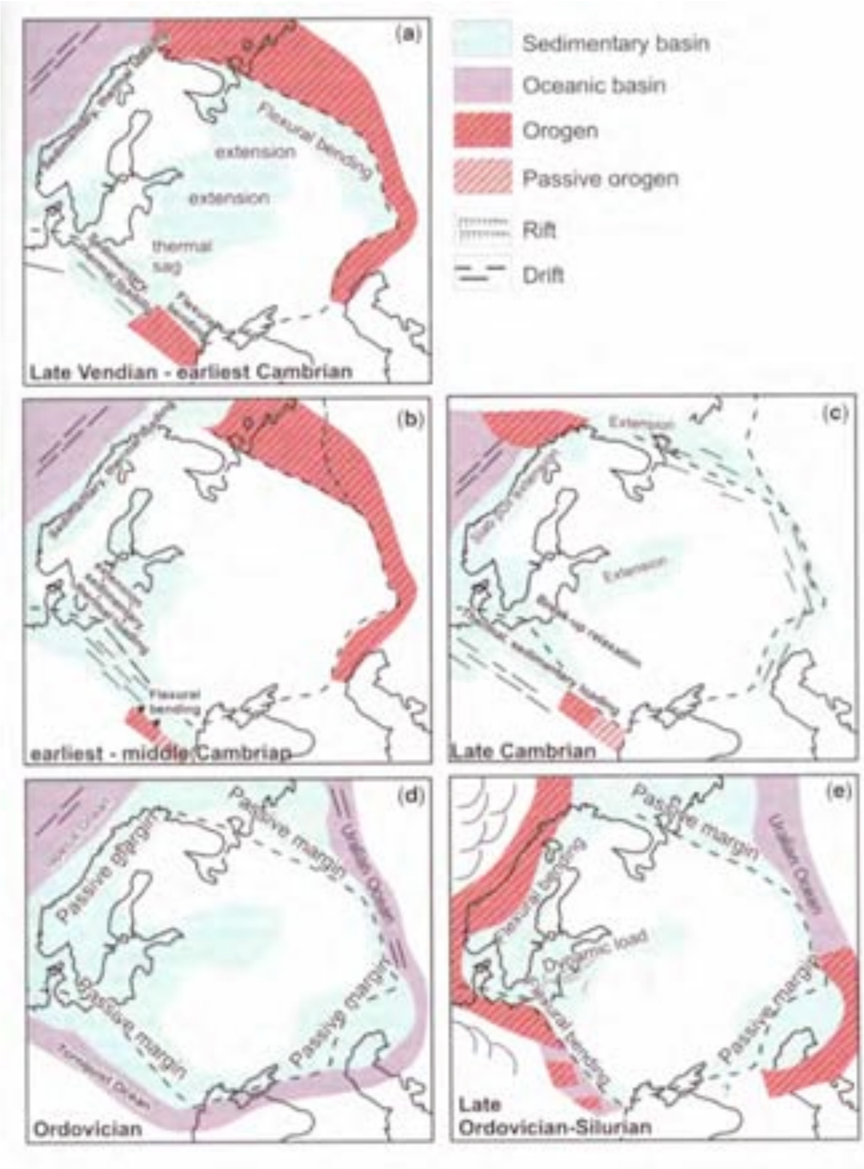


Figure 13. Tectonic setting and major driving mechanisms of Late Vendian-Early Palaeozoic sedimentary basins of the EEC for different time slices (a) Late Vendian-earliest Cambrian; (b) earliest –mid-Cambrian; (c) Late Cambrian; (d) Ordovician; (e) Late Ordovician-Silurian. From Šliaupa et al. 2006.

foreland basin with lithosphere flexure in front of the obliquely advancing Avalonian plate. The Tornquist Sea opened from the southwest and closed from the west when Eastern Avalonia docked with Baltica to form the North German - Polish Caledonides. (Poprawa et al. 1999).

At approximately the same Lower Palaeozoic time a northwestern passive margin to Baltica formed, developed and in repeated orogeny closed the Iapetus Ocean, finally to end with a continent-continent collision of much greater impact than the docking of Avalonia. Stresses from the northwest influenced the Baltic Depression and in Mid-Late Cambrian the central Baltic was uplifted perhaps as a response to the convergence in a Pre-Scandian Caradoc (Ordovician) event (Šliaupa et al. 2006). Stresses prevailed during the Ordovician and increased in Late Silurian, enough to reactivate older basement faults in SW-NE and WSW-ENE with a climax in earliest Devonian (Lochkovian), giving rise to a regular network of

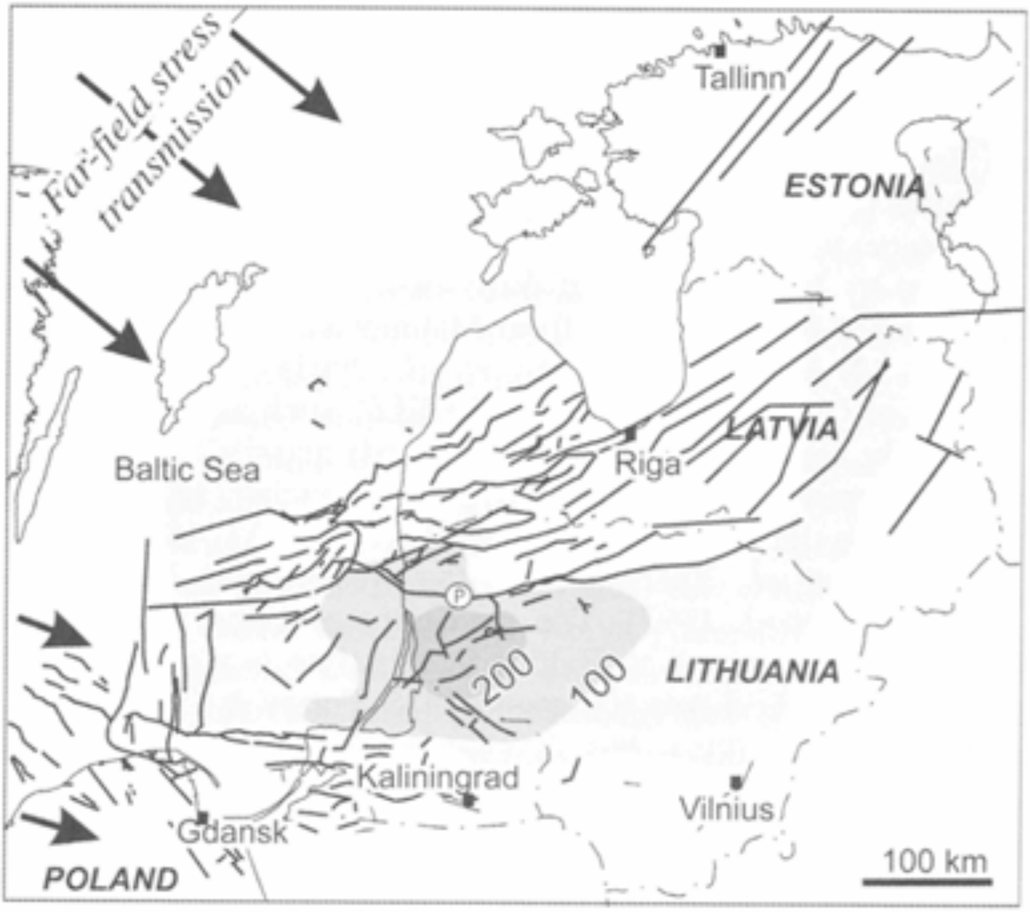


Figure 14. Late Caledonian faults and isopachs (metres) for Early Devonian (Lochkovian) time the Baltic Basin. P shows the location of seismic profile shown in Figure 7 in Šliaupa et al. 2006. Arrows indicate the presumed source and direction of horizontal compression during Late Silurian-Early Devonian times. From Šliaupa et al. 2006.

transpressional high-angle reverse faults (Fig. 14) with offsets in Lithuania of 100-200 metres (Lazauskiene et al. 2002, Poprawa et al. 1999). In front of the advancing Scandinavian Caledonides, with dimensions like the present-day Himalaya, a flexural depression and a forebulge migrated across Scandinavia. The high thermal maturity of preserved sediments gives evidence for a deep foreland molasse basin (Larson et al. 1999, Šliaupa et al. 2006) when the forebulge collapsed (Šliaupa 2003). The Scandian orogeny induced a dense system of reverse faults in the Baltic Basin, at a distance of 1000km (Šliaupa et al. 2006).

3.5 The Upper Palaeozoic – continued assembling of continents to form Pangea

Devonian sandstones are preserved in front of the Scandinavian and North German – Polish Caledonides with a maximum near Latvia of 1.1km (Emelyanov and Kharin 1988, Brangulis et al. 1998, cf. Fig. 15b). Much of the Fennoscandian shield may have been above sea level due to the position behind mountain chains after the Caledonian orogenies, inversion of the basin and global low-stand in sea-level (Nikishin et al. 1996). The Devonian and

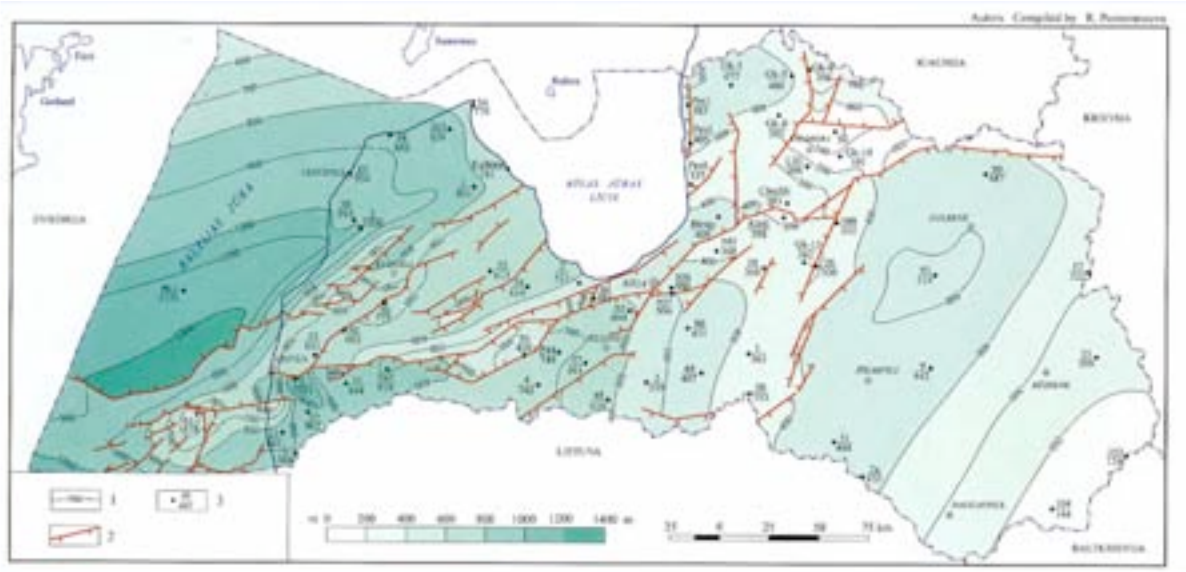


Figure 15a. Caledonian structures in Latvia. From Brangulis & Kanevs 2002.

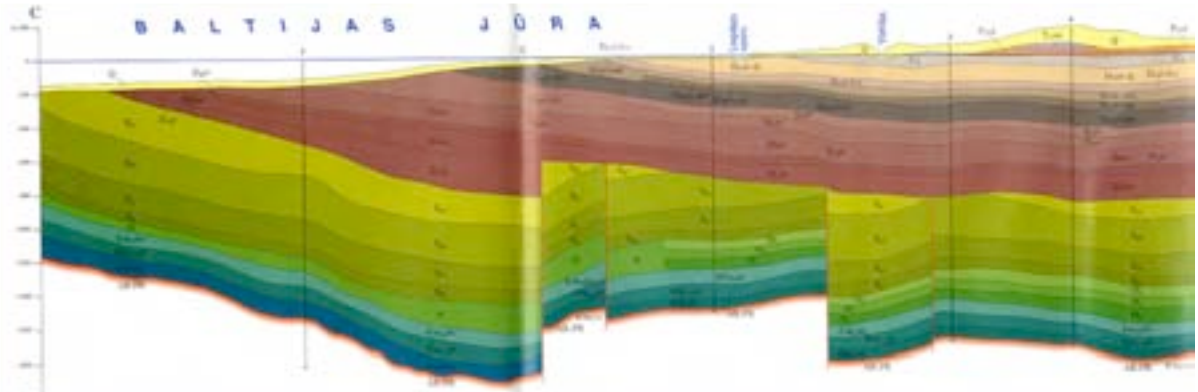


Figure 15b. Major tectonic event in the Baltic Sea region at the Lochkovian/Pragian boundary. From Brangulis et al. 1998.

Carboniferous sediments were eroded before the deposition of the Permian in the southern Baltic (Emelyanov and Kharin 1988) and the shield area in the Carboniferous - Early Permian formed a relatively low relief highland (Ziegler 1989). However, the sedimentary basins on the East European Platform record several phases of subsidence and uplifts due to the Variscan and Uralian orogenies at the southern and eastern borders of Baltica (Nikishin et al. 1996). The present Baltic Basin was separated from its eastern continuation during this time by the Belarus-Mazur anteclise. Mafic dyke magmatism occurred from west Belarus to the Baltic Sea at 330-370Ma (Puura et al. 2003).

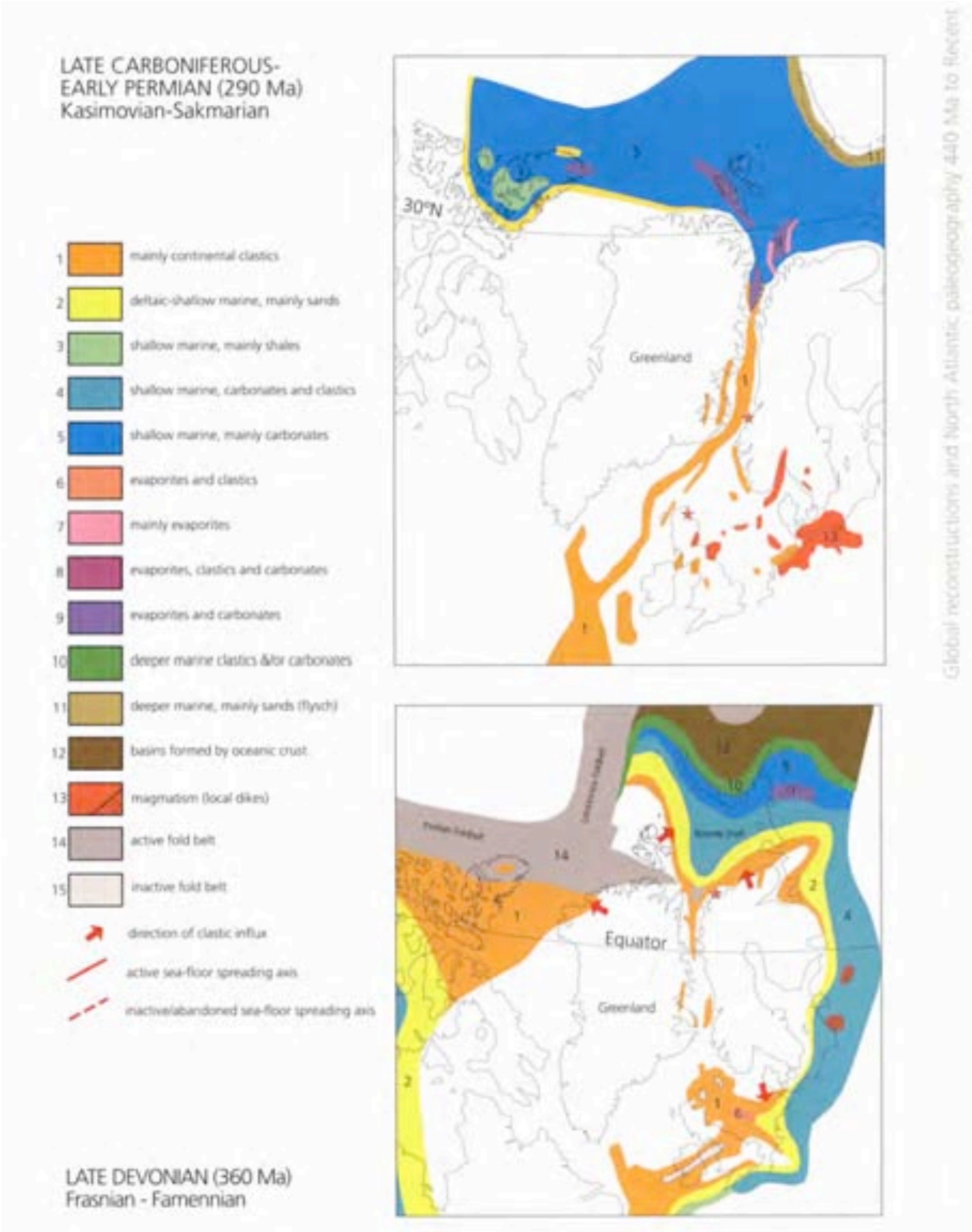


Figure 16. Reconstruction of the north Atlantic paleogeography. From Torsvik et al. 2002.

Early Permian also saw the incipient break-up preceding the future Atlantic Ocean with the development of the Oslo rift and magmatism in Västergötland and the southern Baltic Sea region (Fig. 16). Permian inversion of the Caledonide foreland basin (Fig. 17) removed all

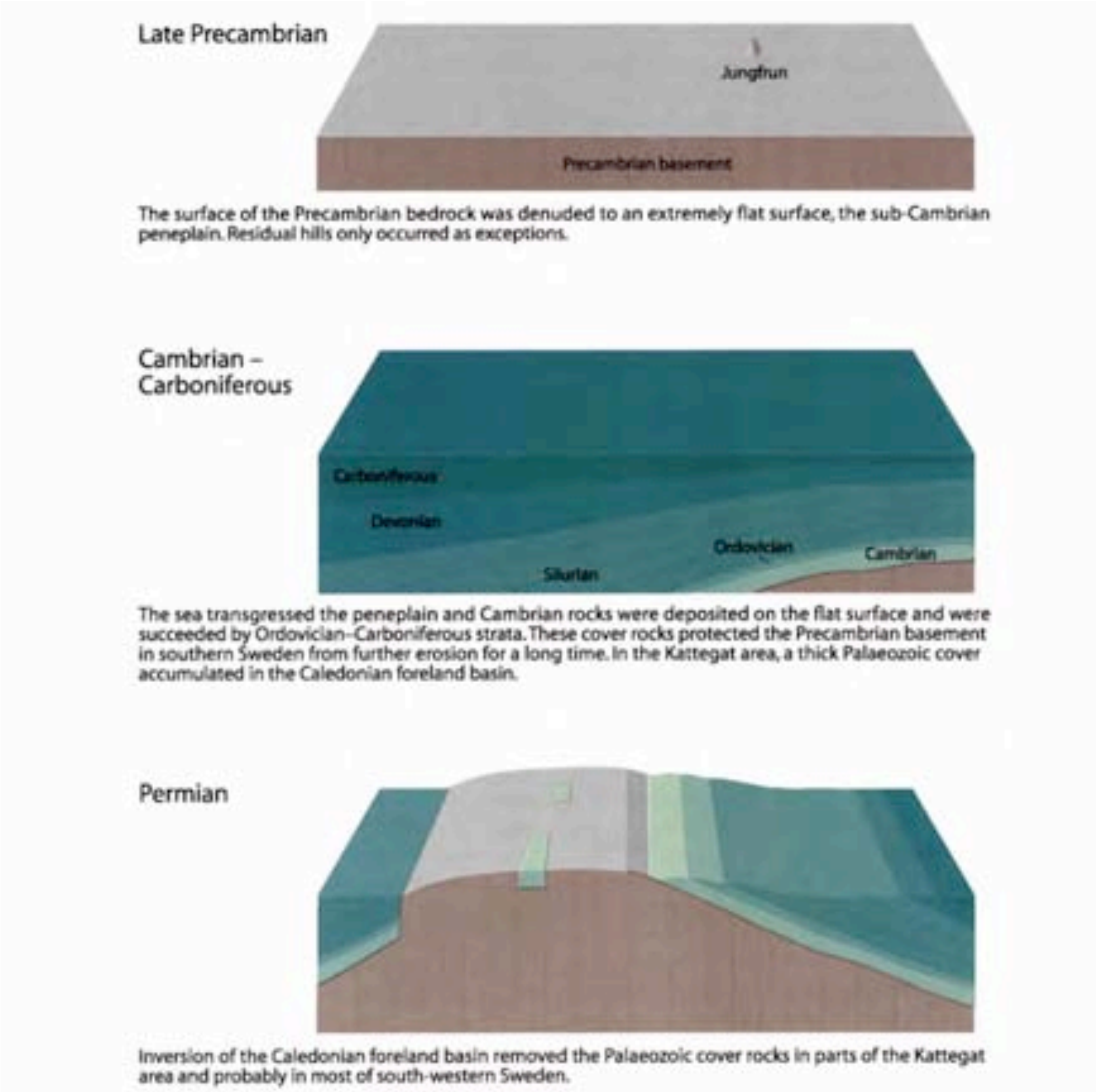


Figure 17. Block diagrams illustrating the development of bedrock relief in southern Sweden between the Kattegat and the Baltic …... Neogene uplift and erosion is assumed to have been initiated in two phases (?mid-Miocene, Pliocene). The final diagram illustrates how the South Swedish Dome is composed of surface facets from widely different periods. Surface features are exaggerated and Quaternary deposits are not shown in the final diagram. SCP, Sub-Cambrian Peneplain; SCr, Sub-Cretaceous hilly relief; SSP, South Småland Peneplain. Modified from Nielsen & Japsen (1991), Fredén (1994), Buchardt et al. (1997) and Vejbæk (1997). To be continued.

Palaeozoic in parts of Kattegat and probably also in southwestern Sweden (Japsen et al. 2002).

3.6 The Mesozoic-Tertiary – the Atlantic break-up and Alpine orogeny

At the boundary to the Mesozoic the global sea level again reached a minimum (Ross and Ross 1987). The Fennoscandian shield was uplifted as seen in deltas in the Kola-Barents Sea region (Nikishin et al. 1996) possibly due to doming in the North Atlantic rift zone (Ziegler 1988, 1990). Early Mesozoic sediments in the southern Baltic Basin are of evaporite type. In

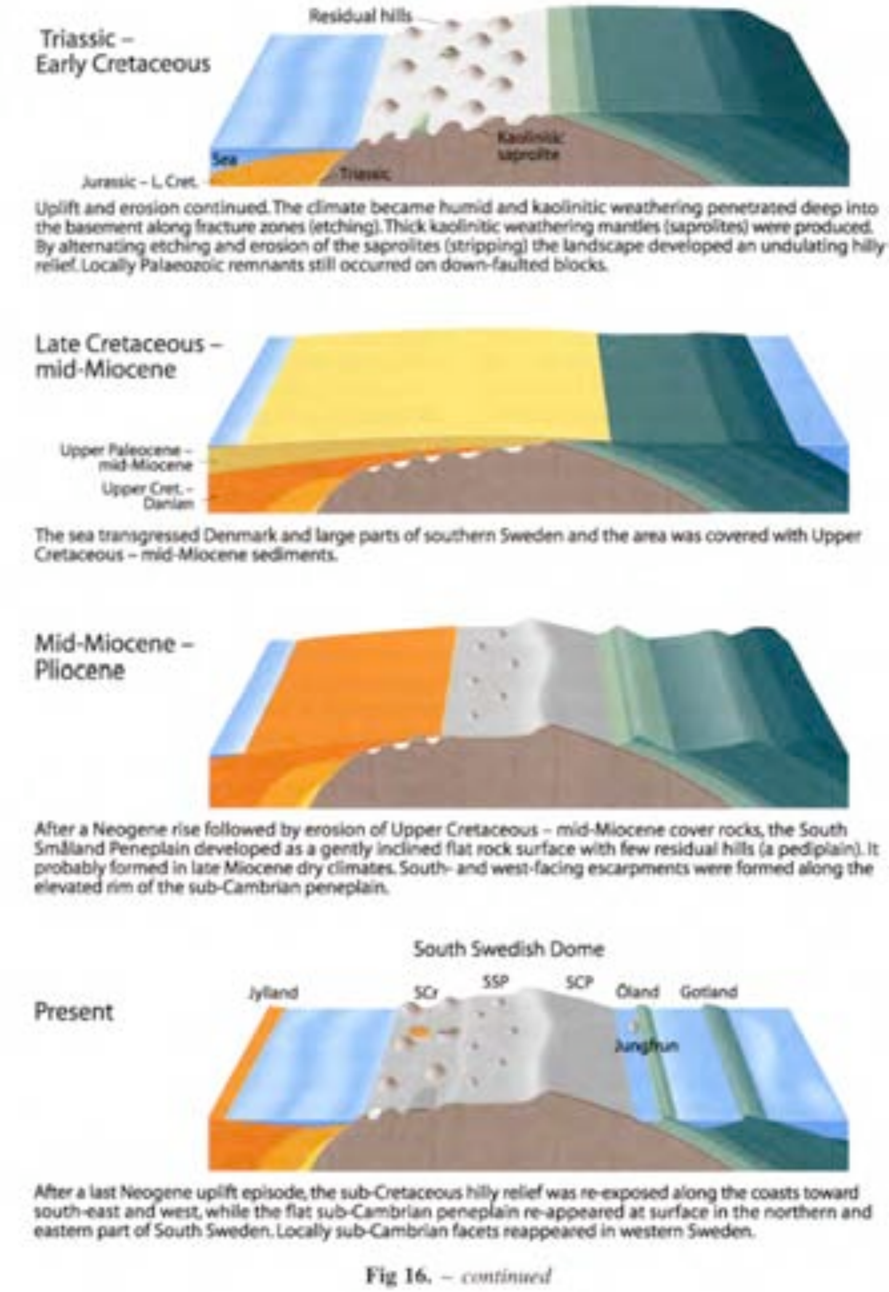


Figure 17, continued. From Japsen et al. 2002.

southern Sweden the sub-Cambrian peneplain was re-exposed to the Triassic - Early Cretaceous warm and humid climate seen in thick kaolinic saphrolites (Lidmar-Bergström 1995).

The Late Cretaceous – mid-Miocene saw a transgression in the southern Baltic Basin followed by uplift and erosion of the Tertiary and Mesozoic strata in the mid-Miocene - Pliocene in Denmark and southern Sweden (Japsen et al. 2002). The Scandes were uplifted in the Palaeogene as a response to the opening of the North Atlantic. The southern Scandes also experienced a major pulse of uplift in Neogene time in accordance with a Neogene onset of erosion in northern Denmark (Lidmar-Bergström et al. 2000). The sub-Cambrian peneplain in southern Sweden was uplifted and exposed during the Cenozoic (Lidmar-Bergström 1991). The South Swedish Dome started to develop in the Palaeozoic and continued in the Mesozoic and during the coeval Neogene uplift of the southern Scandes (Fig. 17). This Neogene episode reached from the Baltic to the North Sea.

3.7. Pleistocene

In southern Scandinavia there is a basin-wide hiatus at the base of the Pliocene - Pleistocene deposits that is younger than 2.4Ma (Japsen et al. 2002). Also in the North Atlantic there is an unconformity at the base of the Quaternary. The hiatus increases eastwards in the Skagerrak-Kattegat where Neogene and older strata are truncated. Fission-track studies reveal that 650m of Upper Cretaceous - Palaeogene sediments have been removed from southwestern Sweden and 1000m from southeastern Sweden (Cederbom 2002) and Mesozoic strata have been c. 500m more deeply buried in Denmark than today, missing sections in Kattegat-Skagerrak are as much as 1000m along the Tornquist line (Japsen et al. 2002).

Most of Fennoscandia experienced a Quaternary reburial younger than 0.3Ma; the age of the oldest "Quaternary" sediments. These sediments with a major glaciogenic input are in places rather thick.

4 BLOCK-FAULTING

Fennoscandia grew from a lot of different pieces with individual lithosphere characteristics. This heterogeneity often marked the locus for later differential vertical movement between different segments when subject to horizontal stresses. Korja et al. (2006) distinguish several components of different origin and lithospheric character in the Svecofennian crust (Figs. 4b and 5). The boundaries of these have a dominant east-west direction and some a north-southerly and northwesterly. The north-south, western boundary of the Keitele microcontinent and the east-west, northern boundary of the Bergslagen microcontinent obviously played a significant role in the location of the Mesoproterozoic (Middle Riphean) Sub-Jotnian basins with rapakivi injection and the preservation of the later Jotnian sedimentation, as did the northwesterly boundary to the Archaean in the Ladoga area (Figs. 3 and 4). These structures have obviously been reactivated later, although Korja et al. (2001) conclude that the current crustal geometry and the Moho topography of the Gulf of Bothnia region were attained in the sub-Jotnian.

The metamorphic grade of the rocks now at the surface also calls for large displacement between different rock blocks. Thus, the eclogite terranes in the Eastern segment of the southwestern Sweden units were brought up from at least 50km depth to shallower levels while Jotnian sediments occur in Småland not far to the east. The eclogite terrane was exhumed soon after the Sveconorwegian orogeny since it would not have survived at high-temperature conditions for more than a few million years. Responsible for the exhumation was the gravitational collapse of the orogen or an overall WNW-ESE extension (Möller 1998).

The surface cutting of rapakivi batholiths demonstrates tilting of blocks, the Riga pluton was tilted northwards and the Åland massif southwards. Parts of the rapakivis are at the same crustal level now as 1.6G years ago while others show a much deeper cutting.

Jotnian sandstones show spatial association to rapakivi intrusions and their deposition and preservation may be connected with magma chamber collapse; deep basins formed on top (Korja et al. 2001, All et al. 2006). The Mesoproterozoic showed a prolonged period of crustal thinning and extension. The areas in the Baltic Sea and its gulfs have since displayed crustal weakness.

Neoproterozoic sedimentation was restricted to long narrow rift zones related to the ancient sutures of major cratonic crustal segments (Šliaupa et al. 2006). Sediments were deposited in Lake Ladoga, in the northernmost part of the Gulf of Bothnia and its continuation in southern Sweden. These rocks are now preserved in Ladoga, the Gulf of Bothnia and the Vättern graben. Lower Palaeozoic deposits overlie these in the north and east while in the south they occur in basins separate from the Neoproterozoic ones preserved thanks to Late Carboniferous faulting (Purra et al. 2003). A major difference between them is that the Palaeozoic strata rest on the vast sub-Cambrian peneplain.

Figure 18a. Tectonics in relation to the sub-Cambrian peneplain as interpreted from profiles, contours maps, and remnants of cover rocks. From Lidmar-Bergström 1996.

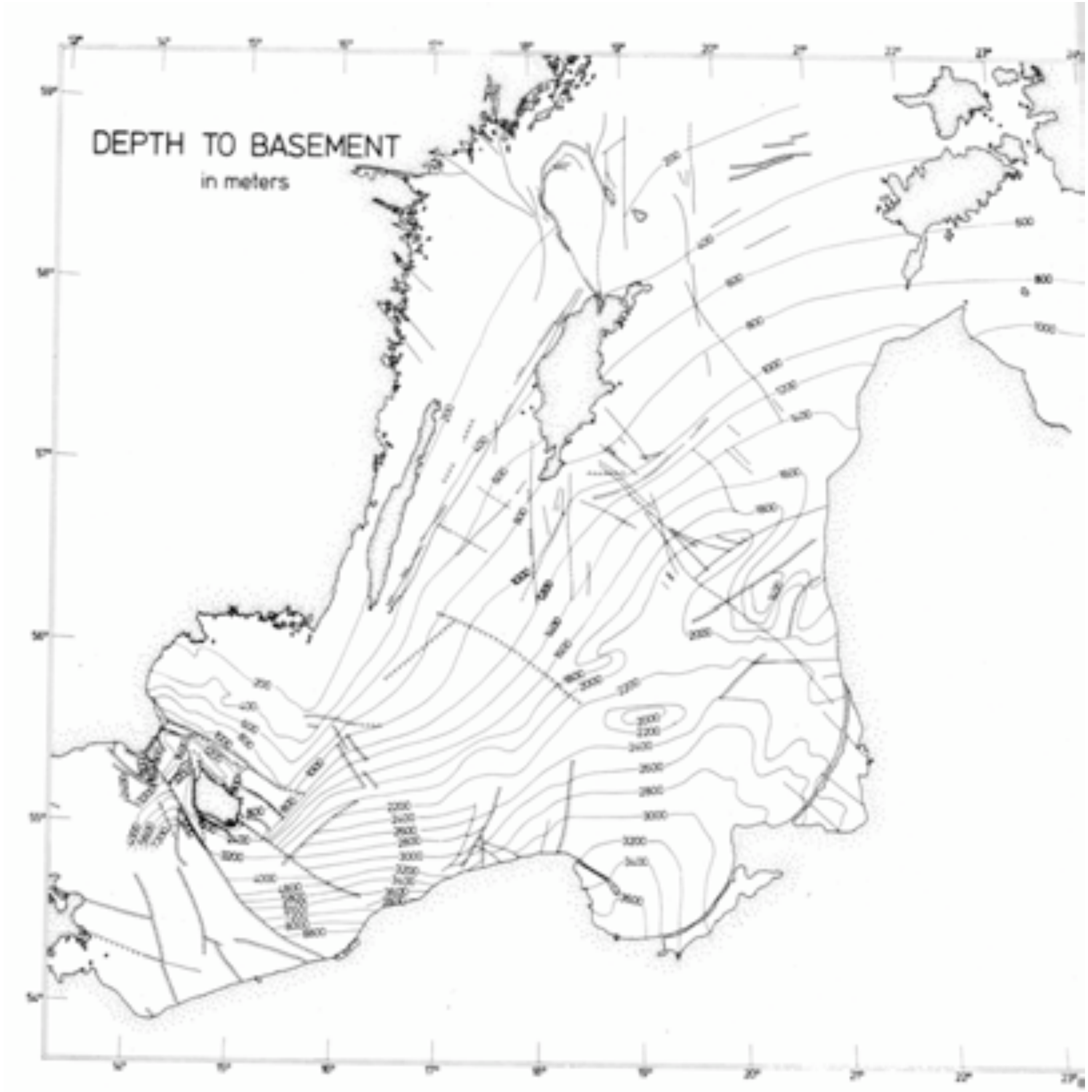
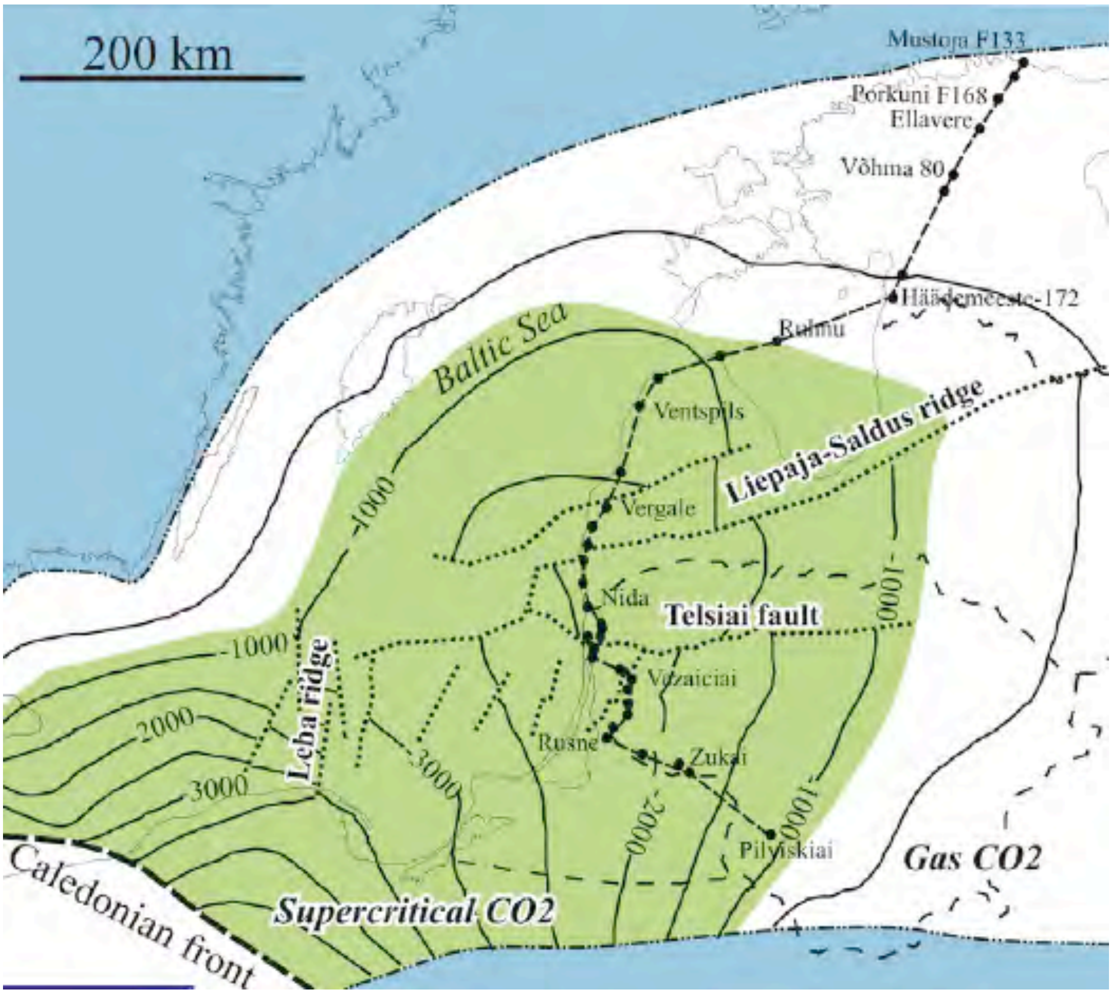


Figure 18b. Map showing the depth to the basement, in metres, in the central and southern parts of the Baltic Proper. From Winterhalter et al. 1981.

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 generally rests 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).

In response to the Caledonian orogeny a system of reverse faults were active in Lithuania and in Latvia block-movements occurred with vertical displacements of up to 500m, documented along ENE-trending faults, from the Baltic Sea to the Russian border during the Lochkovian-Pragian (Poprawa et al. 1999, Alm et al. 2005).

The sub-Cambrian peneplain occurs at different altitude and has been variously tilted (cf. e.g. Figs. 18a-d). It is clearly down-faulted along much of the Swedish east coast north of Stockholm, at places several hundreds of metres. Major hiatuses mark vertical movement in



Depths of top of the Cambrian aquifer.

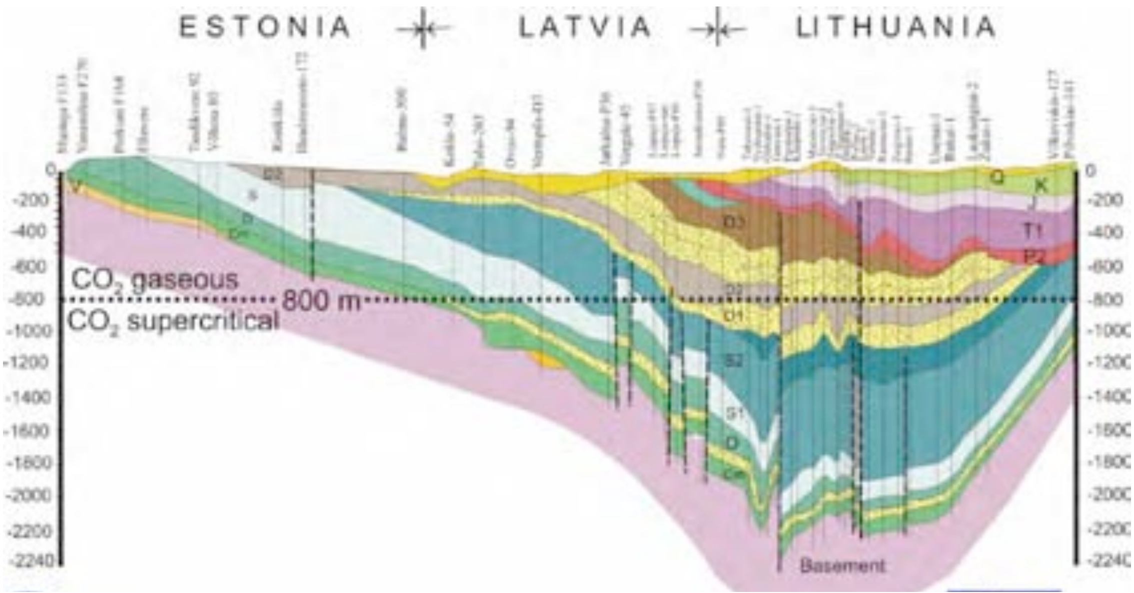


Figure 18c and d. Depths of top of the Cambrian aquifer (Fig. 8c) and geological cross-section through Estonia-Latvia-Lithuania (Fig. 8d. From Shogenova et al. 2007.

response to horizontal plate motions that occurred in the mid-Mid - Late Cambrian, when the central part of the Baltic Basin was uplifted (Šliaupa et al. 2006), the mid Ordovician, the Ordovician - Silurian and Late Silurian - Early Devonian in response to the Caledonian orogenic events, in the Late Devonian - Carboniferous and Late Permian in response to the Variscan orogenies, the Middle - Late Triassic, Cretaceous and Early Palaeogene in response to the opening of the Atlantic and in the Pliocene - Pleistocene. These movements gave rise to major unconformities and groupings of sedimentary sequences with various tilted attitudes. Not to be confused with that the variations in subsidence and accumulation rates also may give a gross wedge shape over large areas.

Mesozoic and Cenozoic movements are related to the present plate configuration, the breaking-up and opening of the North Atlantic and the continued compression induced from the African plate mainly manifested in the Alpine orogeny.

Along the Tornquist Line a vertical displacement of exceeding 7000m is estimated (Winterhalter et al. 1981). The crystalline bedrock of Fennoscandia falls to several thousands of metres underneath Denmark and northern Germany. Intricate block-faulting is revealed in the horsts and grabens in Skåne and Hanöbukten (Kumpas 1978, 1980). In Hanöbukten most of the Palaeozoic strata were removed prior to the deposition of Mesozoic strata which off Simrishamn attain a thickness of 800m, while at Bornholm further to the southeast Precambrian basement is outcropping (Kumpas 1978). Fission-track studies reveal that before 200Ma southeastern Sweden was covered by more than 4km of sedimentary rocks and a 100Ma later by less than 1km (Söderlund 2008). After this, 650m of Upper Cretaceous-Palaeogene sediments have been removed from southwestern Sweden and 1000m from southeastern Sweden (Cederbom 2002). Mesozoic strata have been c. 500m more deeply buried in Denmark than today; missing sections in Kattegat-Skagerrak are as much as 1000m along the Tornquist line (Japsen et al. 2002). The Mesozoic strata in western Poland and the Cretaceous - Tertiary in eastern Poland are tilted underneath the Quaternary cover (U´scinowicz et al. 1988).

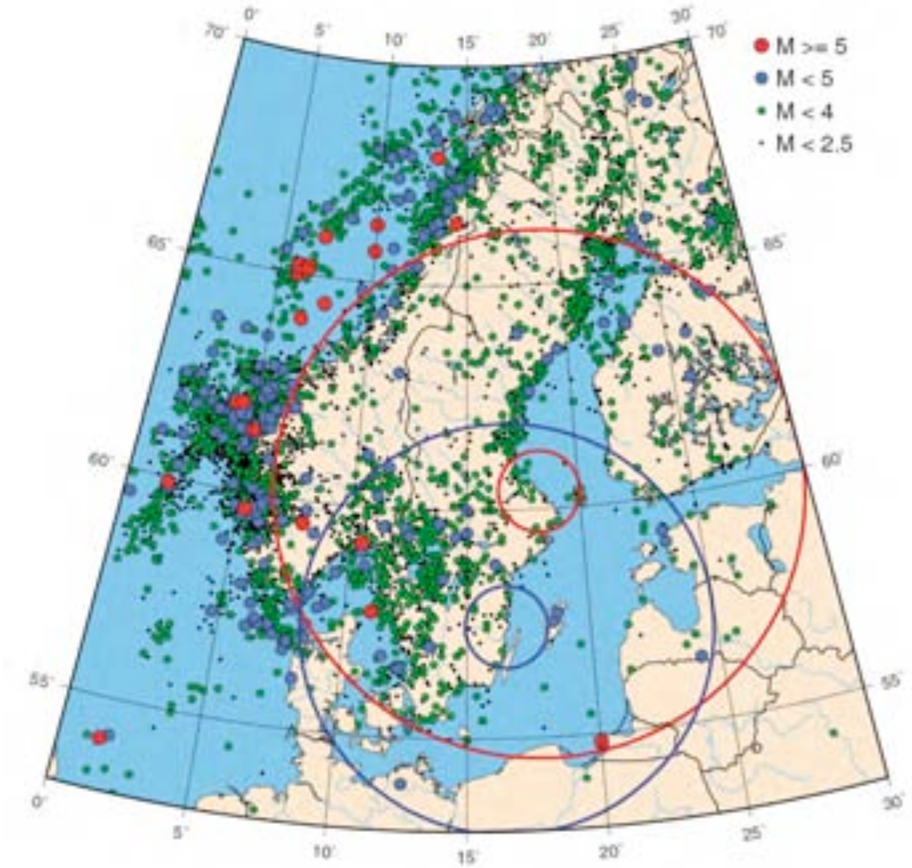


Figure 19. Known earthquakes in the Nordic region from 1375 to 2005. The large red circle has a 650 km radius from Forsmark and the large blue circle has a 500 km radius from Simpevarp. Small circles have radius 100 km. From Bödvarsson et al. 2006.

5 EARTHQUAKES

The magnitude of the seismicity in the Baltic Sea region is generally low, well below M=6, cf. Fig. 19 (Bödvarsson et al. 2006). However, long recurrence between rupture along a specific structure and poor historical records may give rise to surprises like the Kaliningrad earthquakes on 21st Sept 2004, when a WNW-ESE/near vertical right lateral strike-slip movement occurred at 16-20km depth, in two major events of magnitude 5.0 and 5.2, due to NNW-SSE horizontal compressional stress release induced by ridge-push forces from the Mid-Atlantic Ridge and forces inflicted on the Eurasian Plate by the African Plate pushing from the south (Gregersen et al. 2007).

Šliaupa et al. (1999) report on N-S lineaments that are seismically active along the axis of the Gdansk Depression and seismic events cluster along the axial part of the Baltic Sea.

Still, the seismicity in the Baltic Sea is claimed to be almost absent and cannot be explained by missing recordings (Grünthal and Strohmeyer 2003). The Tornquist line is not seismic according to Grünthal and Strohmeyer (2003), still, on 15th June 1985, an earthquake of magnitude 4.6 occurred 45km westsouthwest of Halmstad followed on 1st April 1986 by one of 4.0 (Per Ahlberg 1986). The isostatic rebound in southeast Sweden is aseismic (Slunga 1988).

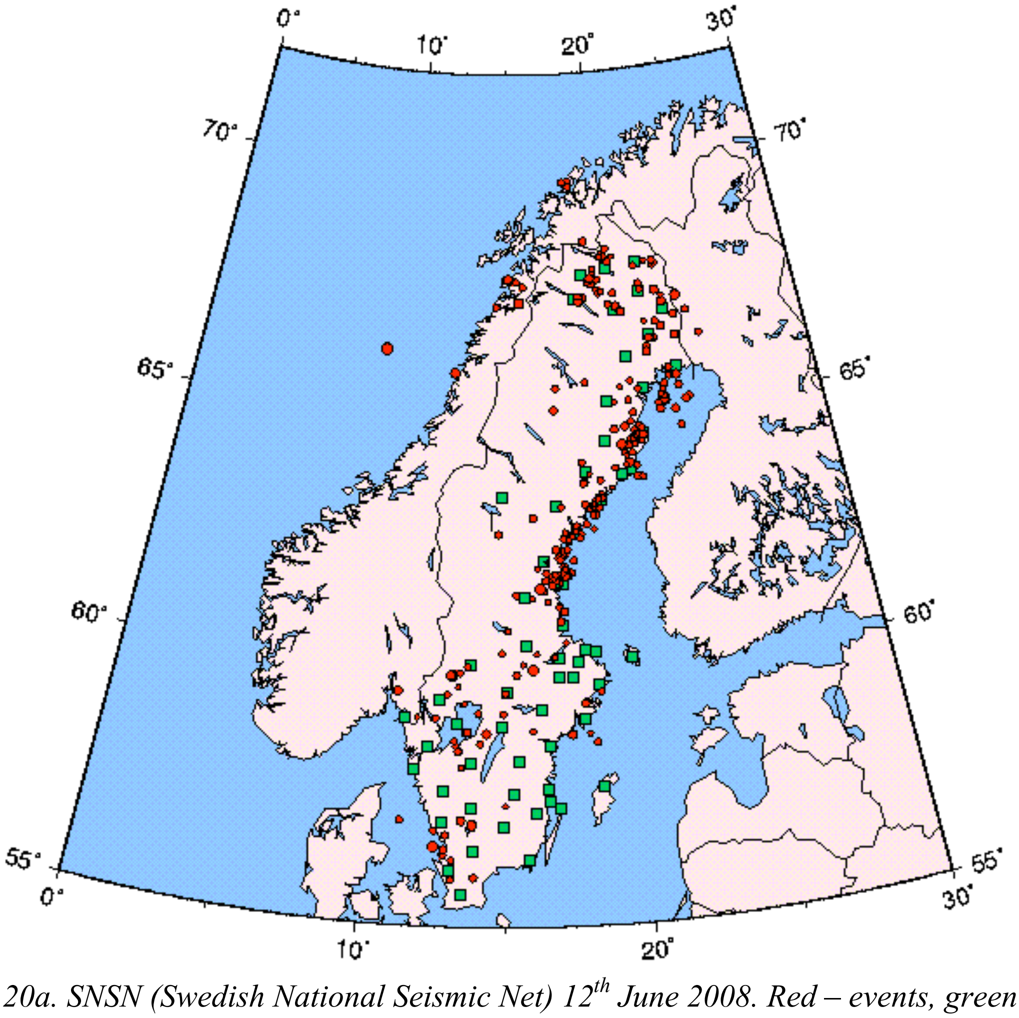


Figure 20a. SNSN (Swedish National Seismic Net) 12th June 2008. Red – events, green - recording stations.

6 THE FORMATION OF THE PRESENT BALTIC SEA

In the literature, the origin of the Baltic Sea is either attributed to glacial erosion or has tectonic reasons and its appearance today is obviously the result of both.

As seen from the description above, the Baltic-Bothnian Basins rest on suture zones and were subject to crustal thinning and possibly aborted rifts during the Mesoproterozoic and latest Neoproterozoic. A purely flexural uplift of Scandinavia fits badly with the marked break along the seismically active Swedish coast along the Bothnian Gulf (Fig. 20a). Here, there is a difference in altitude of the sub-Cambrian peneplain of many hundreds of metres between that on land in the hilly Northern upland terrain (norrlandsterrängen) and at sea bottom underneath the Cambro-Ordovician strata (Fig. 20b).

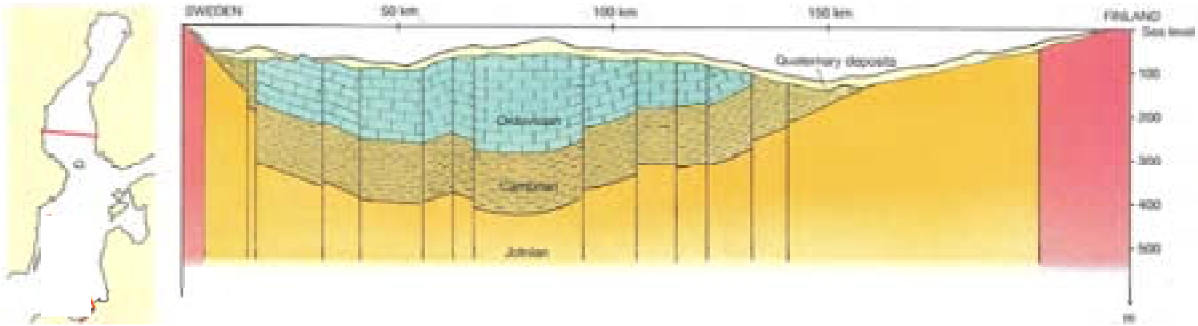


Figure 20b. Norling 1994 West-east oriented geological cross-section through the Bothnian Sea at Hudiksval. From Norling 1994.

During the Quaternary the water-covered area southeast of the Fennoscandian shield has varied in size and form; e.g. during the Eem stage at c. 0.12Ma, there was a relatively broad connection between the Baltic Basin and the ocean and probably also with the White Sea Basin (Eronen 1988, Wolfarth et al. 2008, cf. Fig. 21). In spite of this submerged position, there are no indications of late pre-Quaternary sediments (Puura et al. 2003). Only in the very south, close to the Tornquist line, Tertiary or Mesozoic rocks occur underneath the Quaternary cover. Until Early Pleistocene there is no evidence for the existence of the Baltic Sea and thus the present Baltic Basin is a Quaternary phenomenon that is post-Holsteinian in age, c. 0.4Ma; (Karabanov et al. 2003). Björck (1995) starts his geological history of the Baltic Sea with the end of the Weichselian Glaciation about 13 000BP; the recent geographic picture was formed by the Litorina transgression mainly starting 8 000BP (Meyer 2003).

The morphology of the sea bottom is also influenced by the glacial erosion, especially when the glacial flow direction coincided with structurally weak zones in the bedrock and considerable deepening and widening of channels and valleys were caused by glacial gouging (Winterhalter et al. 1981). Repeated active ice streams eroded the present day Gotland Deep, Gulf of Riga and Pra-Neva-Eridanos (cf. Fig. 28) rivers and the Gulf of Bothnia was deepened during the Pleistocene (Puura et al. 2003). The post-Palaeozoic erosion in the southeastern Baltic is shown in Fig. 22a.

Figure 21. The extent of the Eemian Sea at around 120 ka BP Between the Baltic and White Sea basins, modified after Saarnisto et al. (2002). From Wolfarth et al. 2008.

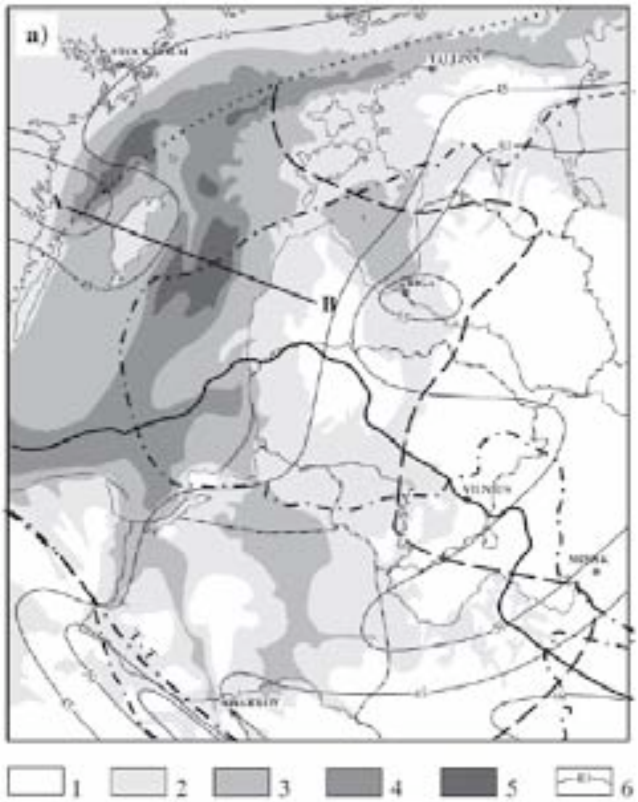
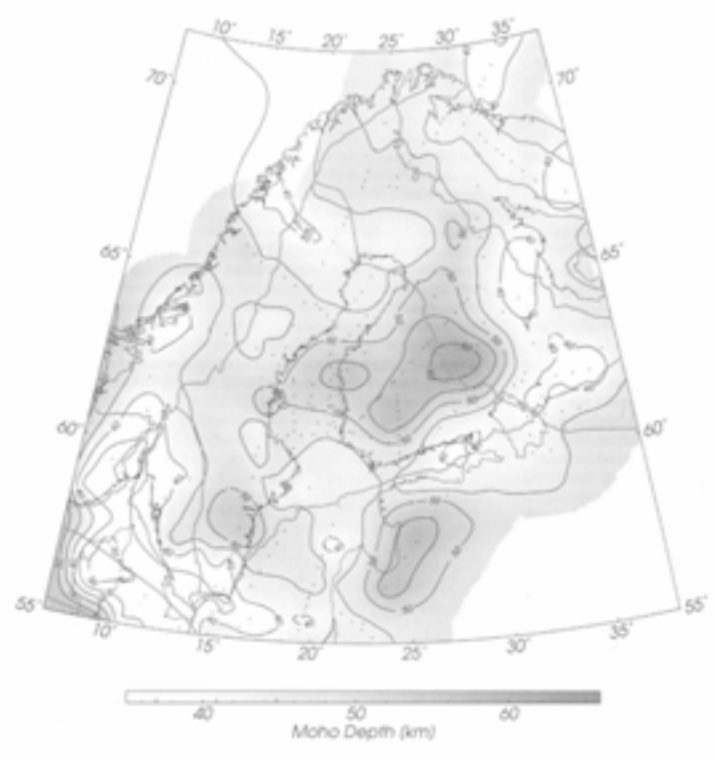
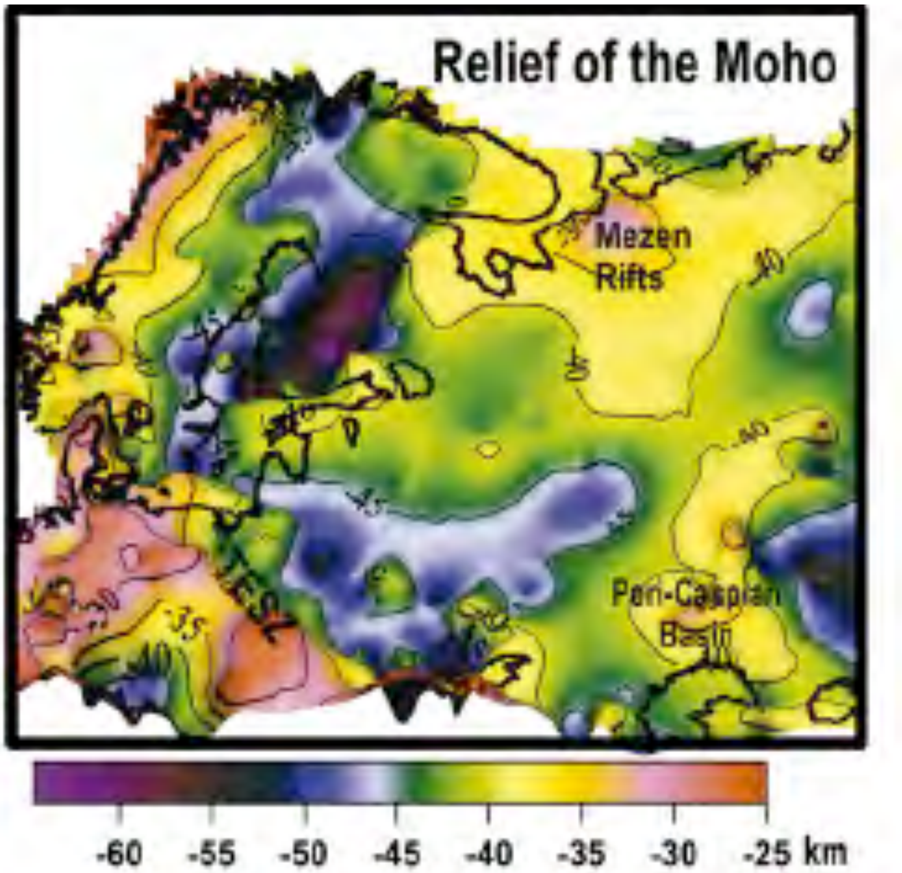


Figure 22a. Postpalaeosoic magnitudes of erosion in the Baltic region: ……. 1-5 – denudation bulk, m: 1-less 40, 2 – 40-120, 3 – 120-200, 4 – 200-280, 5 – more 280; 6 – Moho depth. From Puura et al. 2003.



b.



b.

c.

Figure 22b and c. The Moho depth map of Fennoscandia drawn from data collected by Luosto (1991, 1997), Korsman et al. (1999), and Sandoval et a., (2003). Black dots show original data points (=sampling of velocity models) of Korsman et al. (1999) (Fig. 22b), and Relief of the Moho from Artemieva 2007(Fig. 22c). From Hjelth et al. 2006.

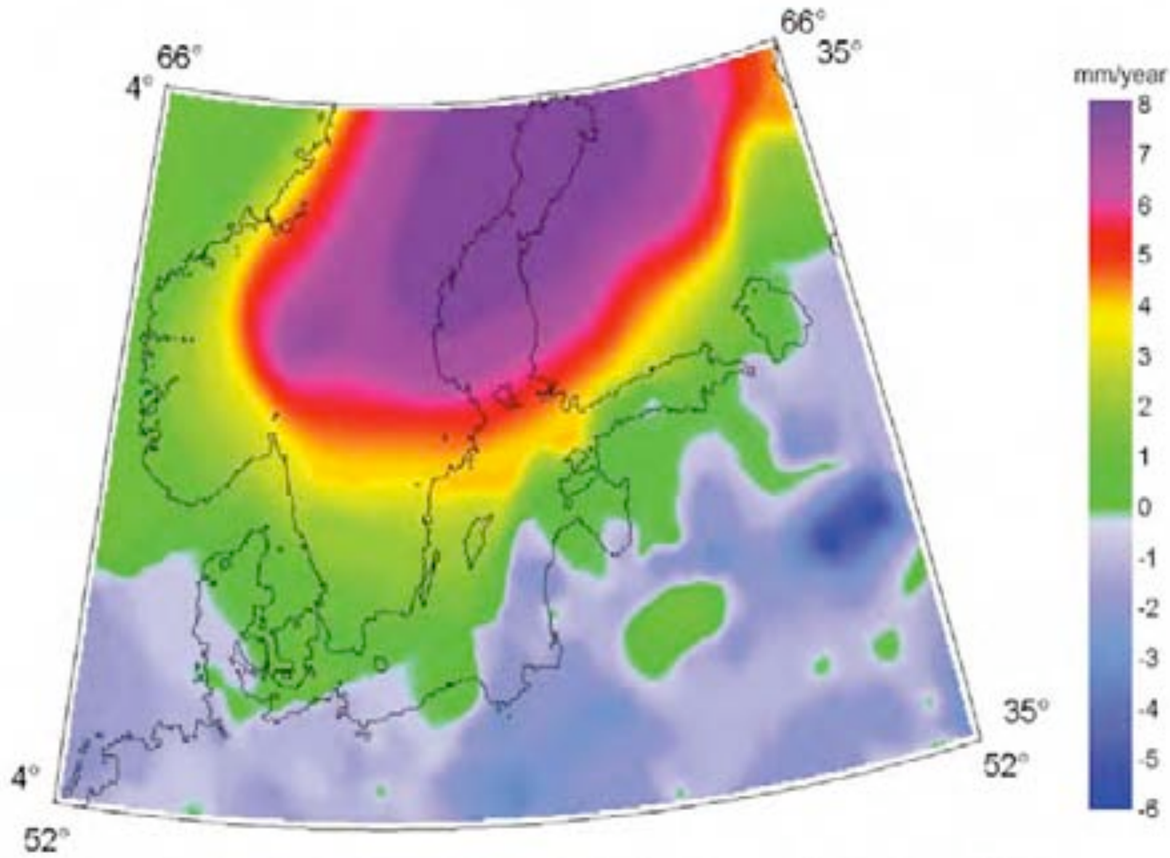


Figure 23. Isostatic data grid. This map was created by interpolation of material provided by Garetsky et al. (2001). From Meyer 2003.

The crust is thinner under the main Baltic Basin in the bathymetric deeps of the Gotland Deep and the Gotland, Fårö and Landsort Depressions; depth to Moho is less than 45km (Puura, et al. 2003, Fig. 22a, Hjelth et al. 2006, Fig. 22b, Artemieva 2007, Fig. 22c). Magnetic and gravimetric characteristics are shown in Figures 24a and 24b. The old river system in the Gulf of Finland presently rests at 100-200m below sea level (Puura et al. 2003). The decreases in crustal thickness east of Gotland and in the Gulfs of Bothnia and Finland have been suggested to be embryonic rifts in a triple-arm system. (Karabanov et al. 2003). The Central Gotland Uplift is by them interpreted as a horst, while Puura et al. (2003) distinguish the north-south 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 lands south and east of the Baltic Sea (Meyer 2003) reveals a marked roughly north-south structure through the Baltic Sea east of Gotland separating areas that rise or sink in relation to the present sea level (Fig. 23). The northernmost tip of Estonia also shows up as subsiding.

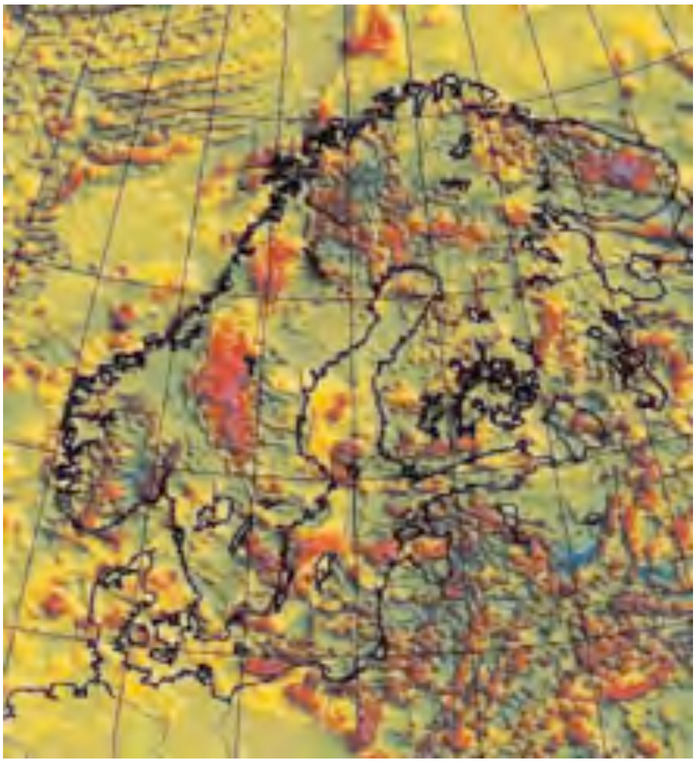


Figure 24a. Magnetic map. From Gee & Stephenson, eds. 2006.

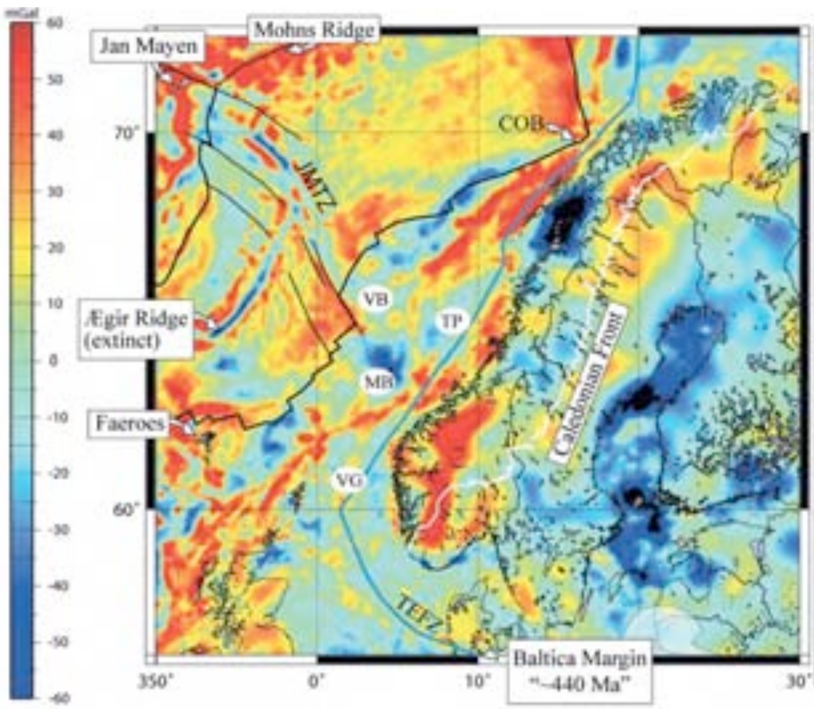


Figure 24b. Free-air gravity map (Smith & Sandwell 1997) for Scandinavia (western Baltica), the Norwegian passive margin and the adjacent oceanic lithosphere. COB=Continent-Ocean Boundary; JMTZ=Jan Mayen Transfer Zone; MB=Møre Basin; TEFZ=Trans-European Fault Zone (Thor Suture at around 440 Ma); TP=Trøndelag Platform; VB=Vøring Basin; VG=Viking Graben. From Torsvik & Cocks 2005.

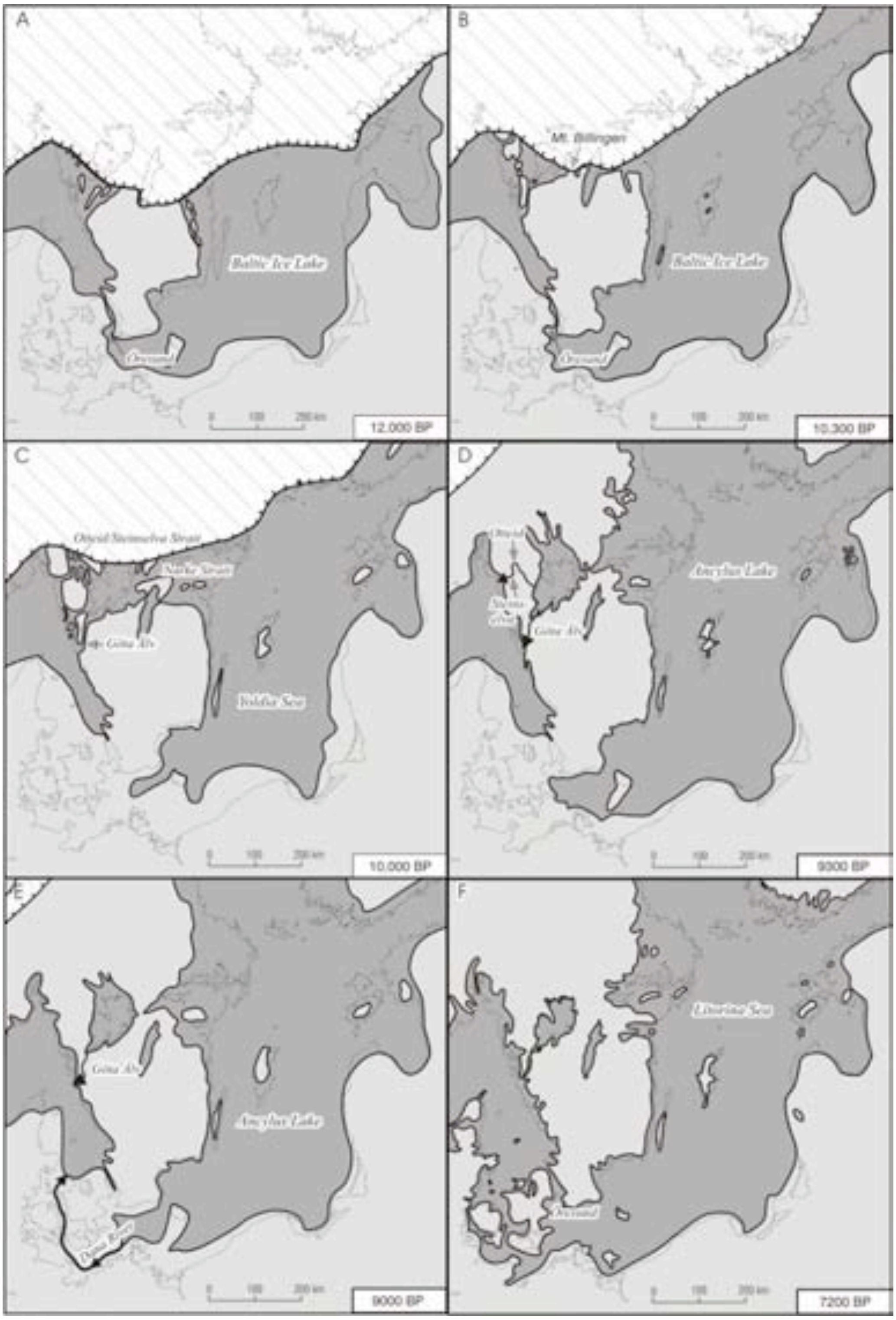


Figure 25a. Subaquatic regions of the Baltic basin and connections from the southern Baltic to the ocean, 12,000-7200 BP (Eronen 1990; Björk 1995. From Tikkanen & Oksanen 2002.

Since the Early Cambrian, the Baltic Syneclise has subsided more than 3km. Still the shape of the Baltic Syneclise as defined by the sub-Quaternary surface is quite close to that of the

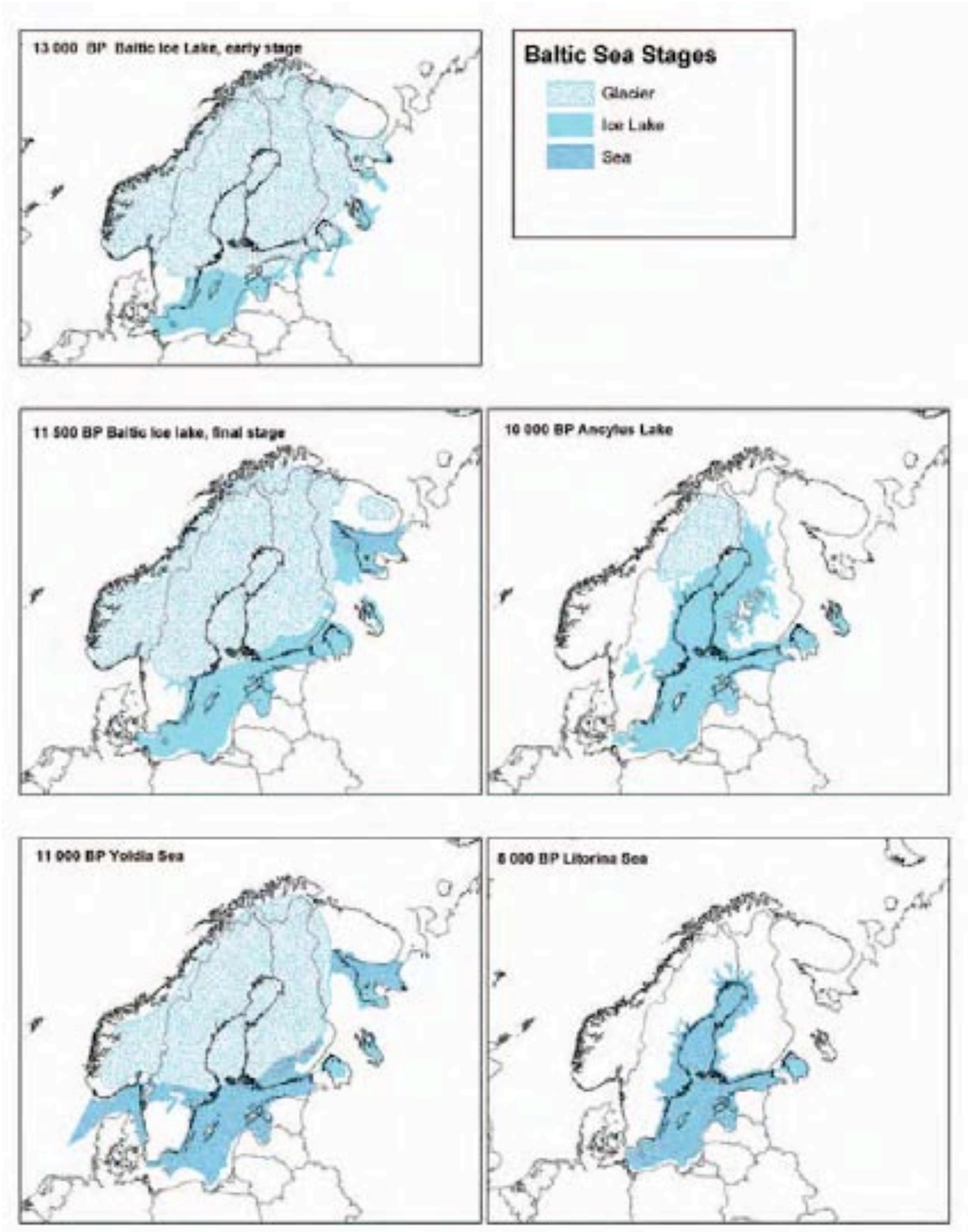


Figure 25b. Evolution of the Baltic Sea (Saamisto 2003, drawing Olli Sallasmaa). From Breilin et al. 2004.

Palaeozoic (Šliaupa and Šliaupa 1999). During the Neogene the basin was essentially a continuation of the Alpine events but since, there has been a drastic change in the pattern with a westwards increasing subsidence (Šliaupa and Šliaupa 1999).

The effects of recent change on water cover in response to varying subsidence, uplift and thresholds after the last glaciation is shown in Figures 25a, 25b and 26.

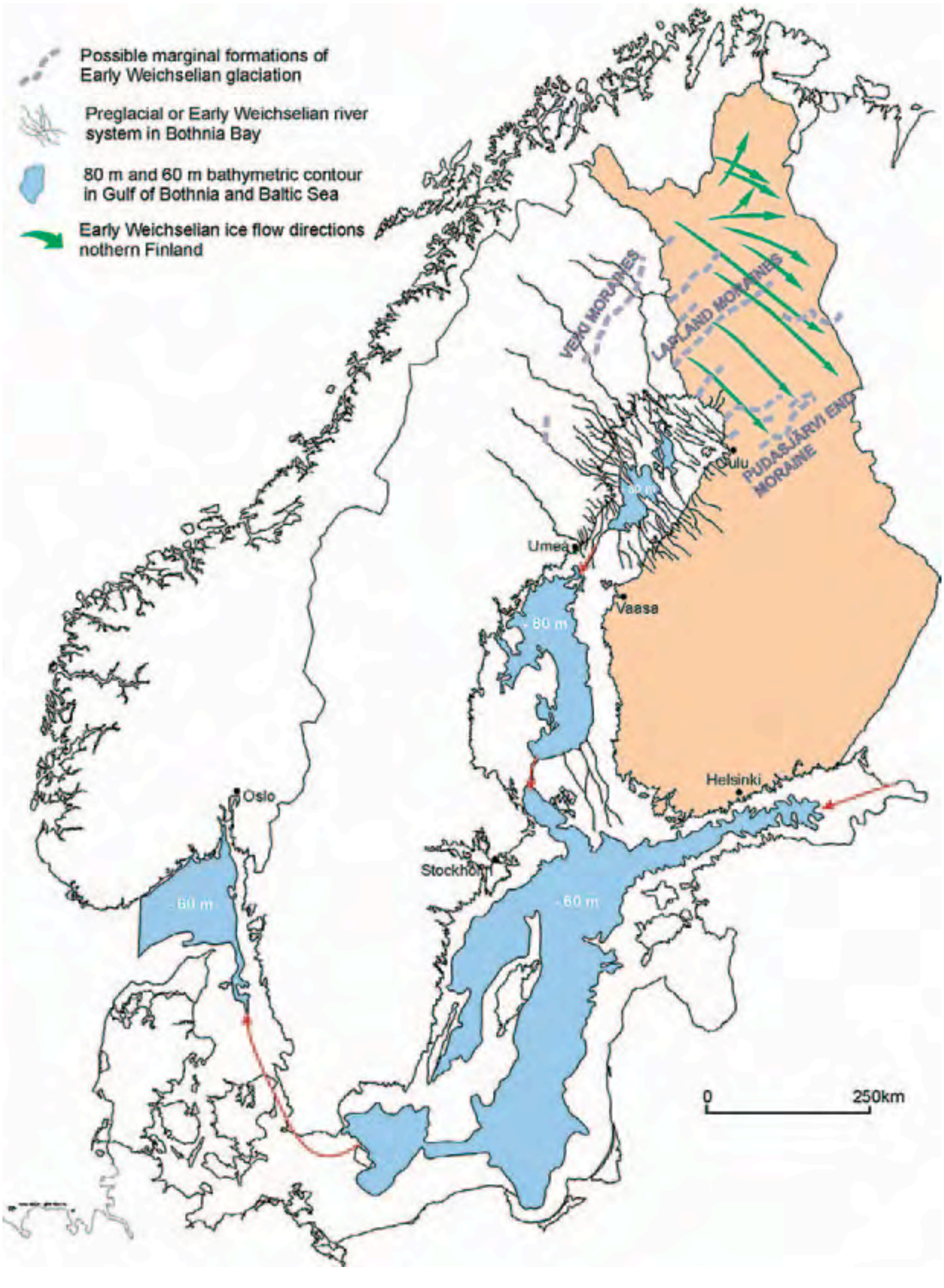


Figure 26. Bothnian Bay and Baltic Sea area during Weichselian interstadials (Nenonen 1995). From Breilin et al. 2004.

7 MORPHOLOGY OF THE SEA BOTTOM

Figure 27. The Baltic and Silurian Klints in the Baltic Sea region. From Suuroja 2007.

Old pre-glacial river channels, tens of metres deep, have been found on the seafloor of the Bothnian Bay and the Bothnian Sea as extensions of present-day rivers (Tulkki 1977); the channels extend to the central parts of the marine area, to a depth of 80m below present sea level, thus showing the probable ancient shoreline (Fig. 26, Breilin et al. 2004). The outcrop boundary of the Ordovician and Silurian strata on the underlying bedrock is marked by high cliffs (Fig. 27). This has been explained to be due to the erosion by the Pra-Neva River (cf. Suuroja 2007). The Eridanos River is claimed to have ceased to exist about a million years ago. If so, the questions why this river flew west of Gotland instead of into the deeps east of Gotland can be explained by that the deeps are younger (Fig. 28).

Figure 28. Major paleorivers in the Baltic Sea region. From Suuroja 2007.

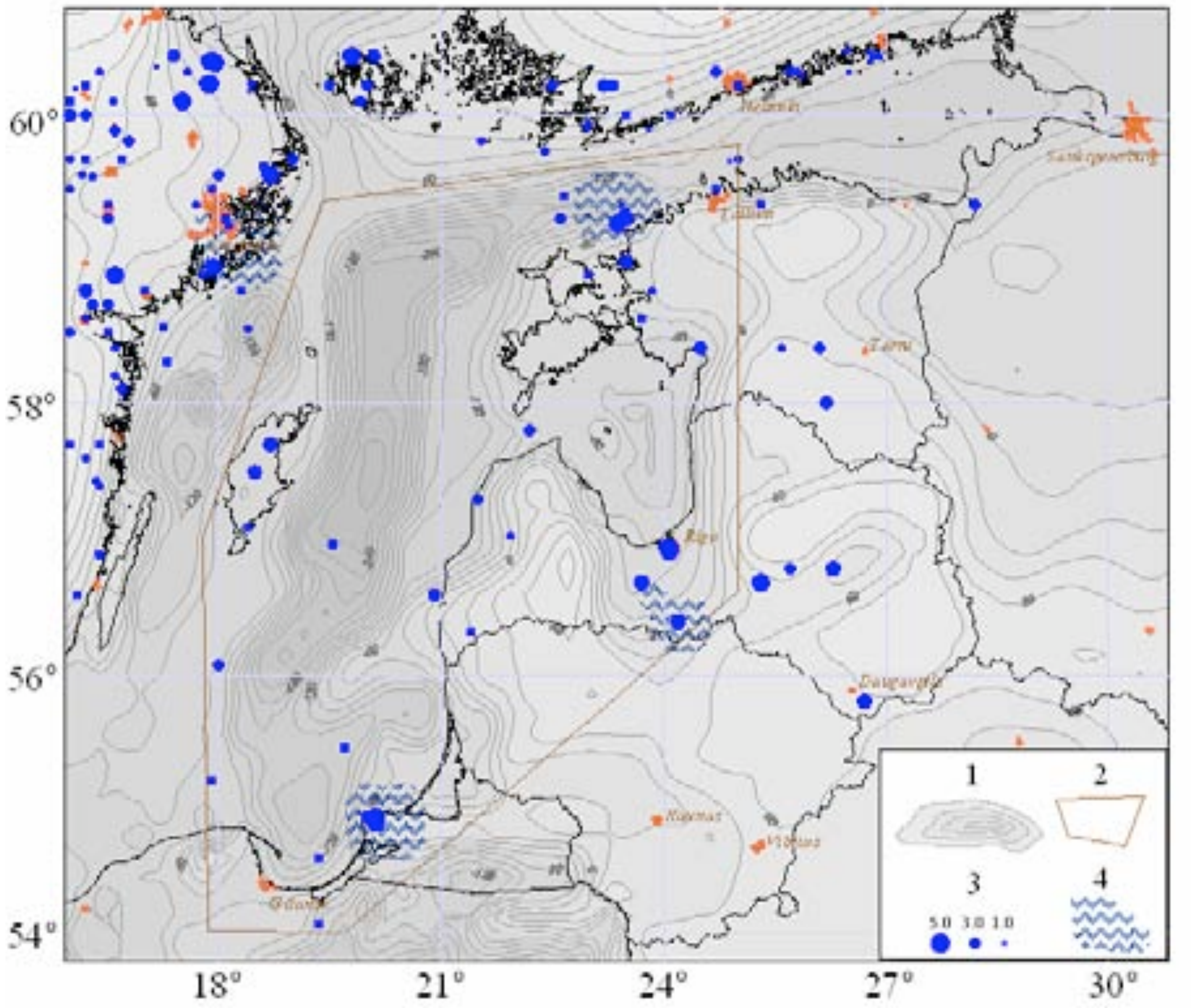


Figure 29. Total amplitudes of neotectonic motions of the earth's crust and epicentres of earthquakes of the Baltic region (1375–2006). 1 – lines of equal values of total neotectonic amplitudes in meters, 2 – area of neotectonic depressions of the Baltic Sea and coast of Baltic countries, 3 – epicentres of earthquakes (the diameter of circumference corresponds the size of moment magnitude Mw), 4 – areas of the maximal accumulated seismic moment M_0. From Nikulin 2007.

According to research on the sinking eastern and southern shores of the Baltic Sea these deeps are actively sinking (e.g. Figs. 29, 30, cf. also Fig. 23).

Bathymetric maps and maps showing subsidence (Fig. 23) and character of the sea bottom (Fig. 31) reveal the affinity of Öland and Gotland to the western Swedish block. Southeast of Öland (Southern Middle Bank) and on the east coast, grain size of the bottom sediments is generally coarser. Especially the area covered by Devonian rocks outside Latvia (Klaipeda Bank) stand out as a less sinking region with coarser grain size.

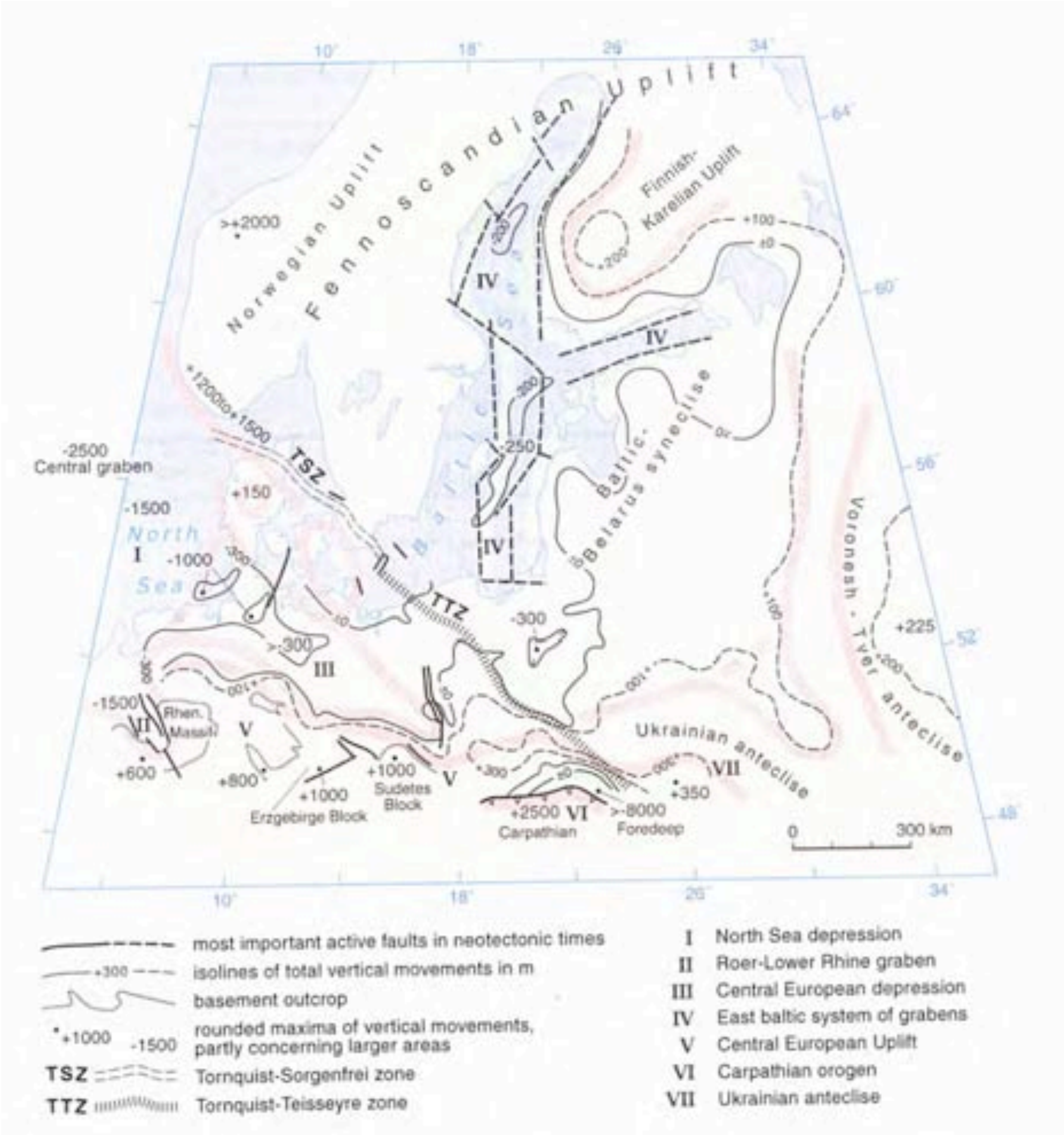


Figure 30. Most important areas of neotectonic subsidence/uplift, maximum vertical displacements used map no. 1 and data from Jensen and Schmidt (1993). From Ludwig 2001.

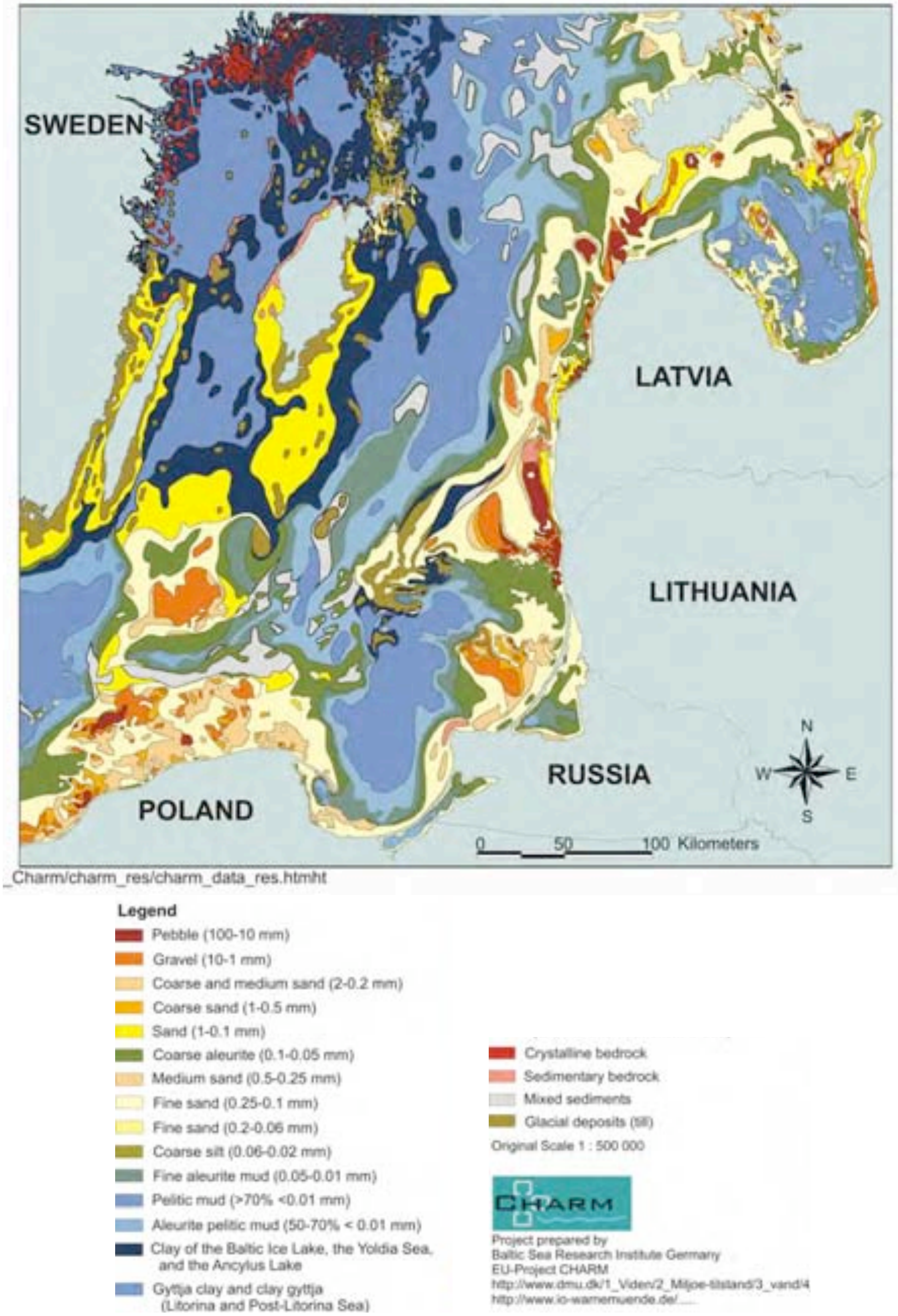


Figure 31. Soft sedimentary cover and bedrock in the Baltic Sea. From Gelumbauskaite et al. 1999.

Figure 32. Bathymetry (from Seifert et al. 2001), Rapakivi and associated granites and Jotnian sediments (compiled from cited references, esp. Koistinen et al. 2001, Rämö et al. 2005) and faults (from Winterhalter et al. 1981, Koistinen et al. 2001).

8 DISCUSSION AND CONCLUSIONS

The lithosphere (crust and upper mantle) in Fennoscandia is strongly heterogeneous and was built up by separate segments that were welded together. These suture zones later provided the locus for deformation and adjustment between the segments to changing and prevailing plate tectonic scenarios; assembling and break-up of Rodinia, Laurasia, Pangea.

The forces active in the formation of such an extensive morphological structure as the Baltic Sea Basin within a cratonic area had influence also on the bedrock in its surroundings. The location of the Baltic Sea depression to some extent coincides with that of earlier thinning of the crust associated with the intrusion of rapakivi granites at c. 1.6Ga and it roughly coincides with the Early Palaeozoic sedimentary Baltic Basin, possibly a failed rift arm of the Tornquist Sea. What forces that have acted on the area can be read in the distribution of, and structures in, the surviving sedimentary cover. This cover forms the floor of much of the Baltic and Bothnian Seas and the bedrock of the Baltic States and Poland.

The present configuration in the Baltic Sea is the result of the interplay of several different systems and orientations of structures. Prominent structures are oriented in N-S, ENE to NE, and NW. Thus, the eastern coasts of the Baltic Proper and Bothnian Sea, and the Bothnian Gulf further to the northeast are defined by roughly N-S structures, as are major basins of subsidence in the Seas. The Norrland west coast of the Bothnian Sea is seismically active. The southern part runs N-S and the northern part which lies within the area of maximum post-glacial uplift, has an en echelon configuration of NNE trending faults. The Baltic Proper and the Bothnian Sea are both terminated northward by very strong sub-parallel ENE to E lines. These lines are also parallel to the Ordovician and Silurian klints in Estonia and in the Baltic Sea to west of Gotland, the reefs on Gotland, and the structures of the southern Bothnian Sea and the Jotnian basin at Gävlebukten. True east-westerly structures are not indicated for the Baltic Sea but occur in the Baltic States and in the Swedish shoreline, (Blekinge and Bråviken) and on land e.g. the Oskarshamn lines and appear in the bathymetry e.g. east of northern Gotland.

The Baltic and Bothnian Seas are separated by a high between Östra Svealand and Åland – Åboland. Another high separates the Bothnian Sea from the Bothnian Bay. A block plateau stretches northwards in the middle of the Bothnian Sea north of Gräsö west of a major, seismically active (Beckholmen & Tirén in press) N-S structure, the southward projection of which separates the hollow of the Landsort Deep and the Kopparstenarna – Gotska Sandön ridge. The Gotland block extends southwards and almost connects westwards with the Northern and Southern Middle Banks of the southern Baltic Sea.

There is a diffuse hinge-line from northwestern Latvia along Gotska Sandön and the northern side of the Landsort Deep where the slope of the sub-Cambrian peneplain changes from SSE to ESE (Flodén 1975).

Very deep hollows occur in N-S east of Örnsköldsvik-Härnösand in the northern Bothnian Sea (230m), NW (and E-W) southwest of the Åland archipelago (285m, (218m)), along the Ordovician klint and, especially, N-S and NE in the Landsort Deep (459m), and in the Gotland Deep (245m). These reflect bedrock structures but may have been enhanced by glacial erosion. Drainage erosion is also postulated for the N-S structure along the Finnish west and south coasts and in the Słupsk Furrow in the Mesozoic strata between the Southern Middle Bank and the banks north of Poland. The tectonic Gdansk Depression is 116m in

Mesozoic strata. The Danish thresholds are just 8m in Öresund and 18m in the Belts. On the Swedish mainland the Vättern graben is 130m deep with a water table at 89m a. s. l. This deep has to be a fairly recent structure, active far later than the Palaeozoicum.

The unexpected strong earthquakes in the Kaliningrad region 2004 draw light to the long quiet periods between the recurrences of catastrophic geological events. Volcanoes have been considered extinct because none remembers the last eruption. Today we can make more reliable measurements of the temperature structure. In the same way major faults may have a recurrence that outlasts human memory. Rifting episodes have occurred with many hundreds of millions years in between. The conclusion that, since no one has detected motion on faults for a few hundred millions of years, they therefore are dead, perhaps say more about the details of the investigations and knowledge of a structure than it does about the true nature. What is usually referred to as the present situation is the regime that is characterized by the opening of the North Atlantic with a Scandinavian passive margin and the collision with African blocks pushing northwards in southern Europe. This has generally been the case for the last hundreds of millions of years and the "no-detection-of-motion" on old faults during the Mesozoic and Tertiary may change when the stress regime shifts. The Quaternary subsidence structure of the Baltic Sea and in the East European Craton basins is considered to reflect a recent change in the stress regime (Šliaupa & Šliaupa 1999, Šliaupa & Stephenson 2006).

The present study has revealed that Phanerozoic deformation in the Precambrian crystalline basement is common and that the formation of the Baltic Sea has to be considered in the description of the geological evolution of Fennoscandian bedrock, especially when characterizing a potential site for nuclear waste on its margins.

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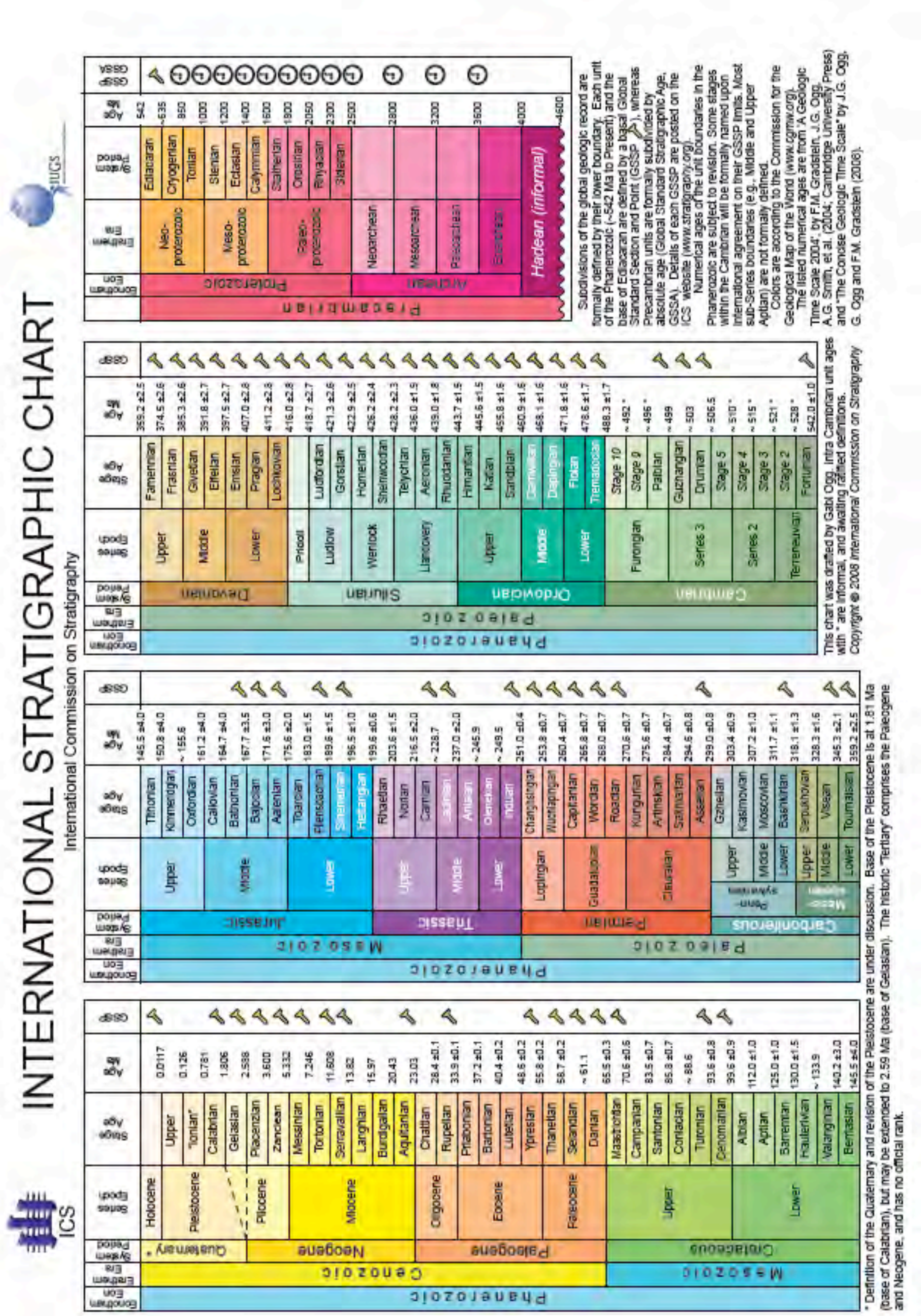
APPENDIX 1

Table 1: Stratigraphic chart

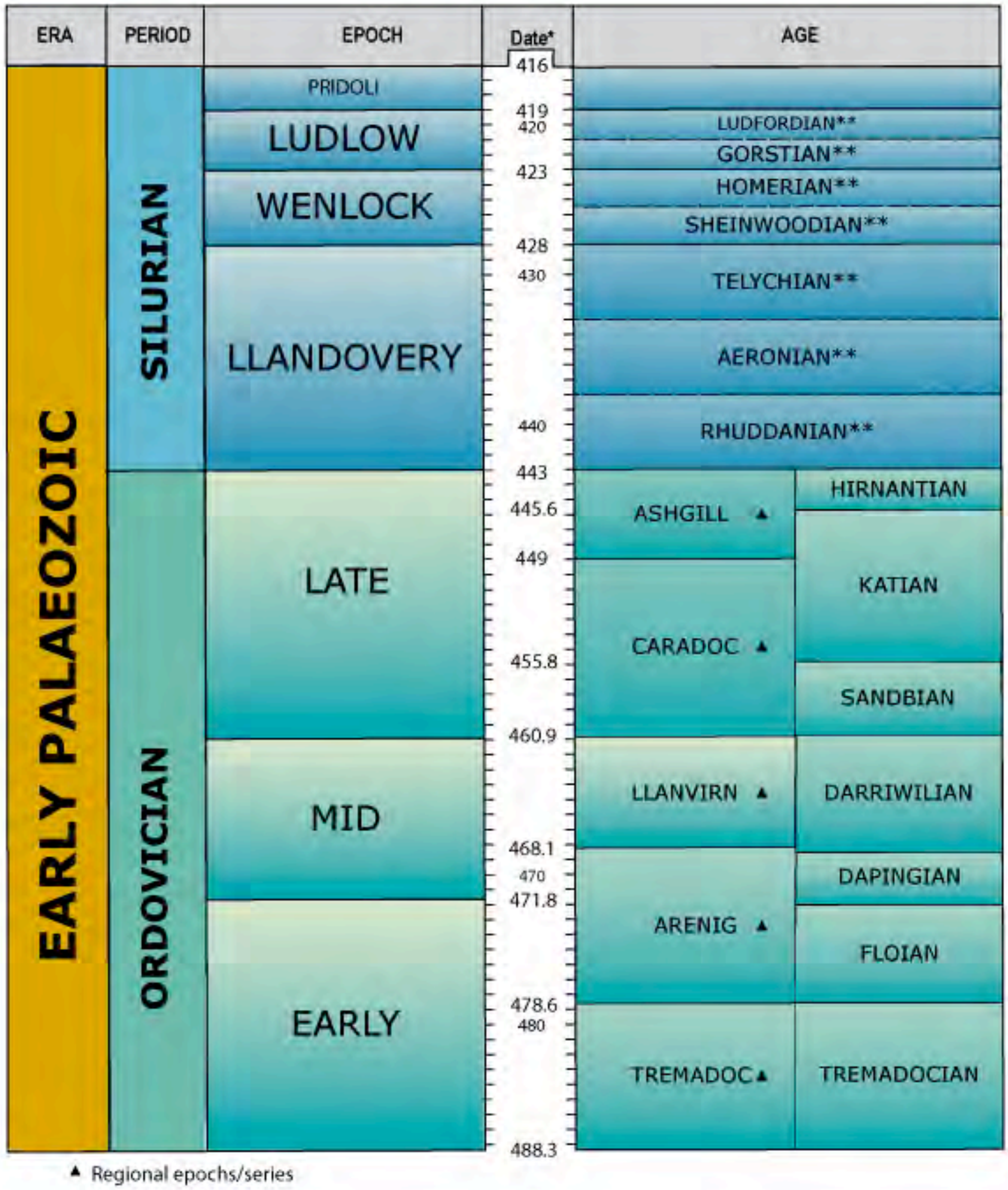


International Commission on Stratigraphy, International Stratigraphic Chart

Table 2: Stratigraphic chart with North European (EEC) regional names

Eon	Era	Period	ended:	becan:
Phenerozoic	Cenozoic	Neogene	0 Ma	23.03 Ma
		Paleogene	23.03 Ma	65.5 ± 0.3 Ma
	Mesozoic	Cretaceous	65.5 ± 0.3 Ma	145.5 ± 4.0 Ma
		Jurassic	145.5 ± 4.0 Ma	199.6 ± 0.6 Ma
		Triassic	199.6 ± 0.6 Ma	251.0 ± 0.4 Ma
	Paleozoic	Permian	251.0 ± 0.4 Ma	299.0 ± 0.8 Ma
		Carboniferous	299.0 ± 0.8 Ma	359.2 ± 2.5 Ma
		Devonian	359.2 ± 2.5 Ma	416.0 ± 2.8 Ma
		Silurian [Gothlandian]	416.0 ± 2.8 Ma	443.7 ± 1.5 Ma
		Ordovician	443.7 ± 1.5 Ma	488.3 ± 1.7 Ma
		Cambrian	488.3 ± 1.7 Ma	542.0 ± 1.0 Ma
Proterozoic	Neoproterozoic	Ediacaran [Vendian]	542.0 ± 1.0 Ma	650 Ma
		Cryogenian	650 Ma	850 Ma
		Tonian	850 Ma	1000 Ma
	Mesoproterozoic ["Riphean"]	Stenian ["Karatavian"/"Yurmatian"] [Dalslandian?]	1000 Ma	1200 Ma
		Ectasian ["Dalslandian"/"Jotnian"]	1200 Ma	1400 Ma
		Calymmian ["Burzyanian"] ["Jotnian"?]	1400 Ma	1600 Ma
	Paleoproterozoic	Statherian ["Ulcanian"] ["Jotnian"?]	1600 Ma	1800 Ma
		Orosirian ["Gothian"/"Karelian"]	1800 Ma	2050 Ma
		Rhyacian ["Udocanian"] ["Svecofennian"]	2050 Ma	2300 Ma
		Siderian ["Udocanian"] ["Svecofennian"]	2300 Ma	2500 Ma
Archean	Neoarchean		2500 Ma	2800 Ma
	Mesoarchean		2800 Ma	3200 Ma
	Paleoarchean ["Isuan"]		3200 Ma	3600 Ma
	Eoarchean		3600 Ma	not defined
"Hadean"				

Table 3: Stratigraphic chart with North European (Brittish) regional names



BGS Geological Timechart – www.bgs.ac.uk

Table 4: Major tectonic events and orientation of structures and stress-regimes in the Fennoscandian Shield

Age in Ga	Characteristics	
3.5	*Zircons*	
>3.1	*Igneous rocks*	
3.0-2.8	*Greenstone belts*	
2.8	*Ophiolites*	
2.8	*Magmatism*	
2.7-2.65	*Thrusting*	
2.5	*Cratonization complete*	
2.5-2.0	*Rifting and Break-up(?)*	
2.45-2.1	*Mafic dyke maxima*	
2.0	*Subduction*	*Beneath Volga-Sarmatia*
1.96	*Ophiolites*	
1.96-1.85	*Lapland-Kola collisional orogeny*	*Collage of reworked Late Archaean*
1.93	*Subduction and back-arc rifting*	
1.92-1.88	*Microcontinent accretion*	
1.91	*Subduction*	*SW; reversed to plunge beneath Archaean NE*
1.91	*Peak Lapland-Kola and Lapland-Savo orogeneses*	
1.9	*Svecofennian orogeny*	*New crust Cordilleran type*
1.90-1.88	*Two volcanic belts*	
1.89	*Beginning Fennian, initiaion of Southern Svecofennian province*	
1.890-1.889	*Accretion of S-continental arc to N-continental arcs*	*Fennian*
1.89-1.88	*Synorogenic granitoids, TTG, <D2-D2*	*Magmatic underplating*
	High T - low P, D2-<D3	
1.87	*TTG*	
1.87-1.84	*Large-scale extension of the accreted crust*	
1.87-1.79	*Continent-continent collision*	
1.86-1.84	*Extension and crustal thinning*	
1.86-1.84	*Plutons of granitoids in SW along intra-orogenic boundaries*	
1.85	*"Svecofenninan craton" consolidated*	
1.85	*Subduction, large-scale extension in the interior*	
1.84-1.83	*Accretion*	*Compression*
1.84-1.80	*Crustal shortening*	*Svecobaltic*
	Crustal-scale transpressional shear zone	
	High T, S-type	*Magmatic underplating*
1.84-1.80	*Docking of Fennoscandia with Sarmatia*	
	Subduction of Fennoscandian crust into the mantle	
1.84-1.78	*Granitic magmatism no mafics, compression and thickening*	
1.83-1.82	*Oskarshamn-Jönköping belt, WNW-ESE E-W*	*Northwards*
1.83-1.78	*NW-trending transpressive shearing*	*WNW-ESE E-W, dextral*
	Early TIB	*N-S shortening*
1.83-1.65	*Contraction and thrusting*	*NW-SE compression*
1.825	*Peak metamorphism, back-arc spreading*	
1.82-1.77	*Post-orogenic intrusives*	*Finland and Estonia*
1.81-1.78	*Accretion*	*Compression*
1.81-1.78	*Late-post orogenic granites,*	*Extension*
1.81-1.77	*TIB*	

1.8	Amalgamation supercontinent		
1.80	Intense uplift		
1.80-1.78	LLDZ	WNW-ESE E-W	
1.80-1.74	AMCG Sarmatia		Extension Sarmatia
1.78	Orogenic collapse and delamination		
1.75	Subduction(?)	NE	
1.73-1.67	Subduction, E in SW Sweden		N-S belt of juvenile crust
1.71-1.67	Gothian orogeny, Lithuania-Central Norway		Accretion
1.70-1.67	Dala		
1.67	Vyborg	E-W	Rapakivi magmatism
1.66-1.50	Anorogenic rapakivi		
1.65	Vyborg	WNW	Rapakivi magmatism
1.65	Graben formation		
1.65-1.55	Extension		Rapakivi thermal dome
	Cooling – subsidence		Graben formation
1.64-1.62			Rapakivi
1.62?	Vyborg	NNW	Rapakivi magmatism
1.6-1.5	Kongsberg event		New crust
1.6	Riga pluton		Rapakivi magmatism
1.6-1.5	Mafic dyke maxima	WNW	Extension
1.59	Åland	NNE	Rapakivi magmatism
1.585-1.545	Extensive melting of lower crust		Rapakivi magmatism
	into existing shear zones		
1.57	Rapakivi		Rapakivi magmatism
1.57	Värmland	NW	Hyperite amphibolites
1.56	Dolerites	NE-SW, E-W	
1.54-1.50	Mazury complex		Rapakivi magmatism
1.53	Breven-Hällefors	WNW	Rapakivi magmatism
1.5	Rapakivi		Rapakivi magmatism
1.5-1.4	Danopolonian orogeny		Collisional event
	High-grade metamorphism		
	N-S faults, thrusts and suture zones in most S Scandinavia		
1.47-1.46	Tuna		Dykes
1.4	Jotnian		
1.37-1.35	Illite in fractures		
1.3	Västergötland	NNE	West of mylonite zone
1.3	Alluvial sandstones		Before Rapakivi exposure
	Block faulting		
1.3-1.2	Mafic dyke maxima		Extension
	Grabens prior to Sv-N(?)	NE-SW	Extension
1.30-1.10	Extension		Sveco-Norwegian
1.27-1.26	CSDG	ENE	Sills
1.27-1.25	Dolerites, Rifting flood basalts		Sveco-Norwegian
1.22	Protoginzonen	N-S	
1.18	Dolerites		Protogine zone
1.03	Illite in fractures		
1.10-0.95	Collision Baltica and ??		Sveco-Norwegian
1.1-0.9	Sveconorwegian orogeny, 1-5 GPa		Collisional event
	N-S faults, thrusts and suture zones in most S Scandinavia		
0.98-0.95	BDD	N-S	Sv-N foreland

0.97-0.95	*Mafic dyke maxima*	*Extension*	
0.93	*Blekinge-Dalarna dyke swarm*	*NNE-SSW*	
0.93	*Rapakivi*	*Rapakivi magmatism*	
0.91	*Illite in fractures*		
0.90-0.60	*Exhumation*		
0.80-0.75	*Extension*		*Rifts, Vättern*
0.65-0.60	*Reactivation of Senja-Oulunjoki Tectonic Zone*		*NW-SE*
0.60	*Alnön, Kimberlites in eastern Finland*		
0.60-0.42	*Platform sedimentation*		
	Cambrian sandstone dykes	*NNE to ENE*	
0.55	*Illite in fractures*		
0.505-0.5	*Peak of Finnmarkian*		*NW Baltica*
0.45	*Late Ordovician thermal event in Skåne*		
0.45-0.44	*Baltica-Avalonia*		*Docking*
0.44-0.40	*Fluorite and galena veins NNE to ENE/steep*		*reaching 1km depth*
0.425-0.41	*Baltica-Laurentia collision*		*Collisional event*
0.42	*Uplift of BB*		
0.4	*Climax uplift*	*ENE, NE*	*Transpression ENE, NE*
0.42-0.35	*Caledonian foreland*	*NW-SE*	
	Main structures latest S-earliest D	*E-W, WSW-ENE, SW-NE, SSW-NNE*	
0.41	*Block movements vertical displacement <500m ENE*		*Latvia*
0.37-0.33	*Uplift, mafic dykes eastern Baltic Sea*		
0.35	*Faulting in Närke, Östergötland*	*ENE, WNW*	
0.35-0.30	*Peneplanation of Scandinavian Caledonides*		
0.30-0.25	*Isotope systems U-Pb intercept in Swedish Precambrian*		
	Inversion of the Baltic	*Permian steeper than Silurian*	
0.294	*Permo-Carboniferous dykes in Skåne*	*// TESZ, WNW, NW*	
		N-S, E-W	
0.28	*Perm Variscan*		*Sills, OSLO rift*
	Scandian foreland basin stripped		
	Lower Paleozoic fossils in Mesozoic sediments in S Sweden		
0.2-0.1	*>4km uplift in southern Sweden*		
0.191-0.18	*Mafic Magmatism Skåne*		
0.145	*Mafic Magmatism Skåne*		
0.11	*Mafic Magmatism Skåne*		
0.08	*Change in drift direction of the continental plates*		
0.07-0.06	*Inversion in Southern Baltic*		
0.061-0.040	*Sea-floor spreading in the Labrador Sea*		
0.054	*Opening of the North Atlantic-Norwegian Sea, Alpine closure*		
0.035	*The Jan Mayen rift*		
0.025	*Ægir Ridge extinct*		
0.027-	*Glaciations*		

AMCG – Anorthosite-mangerite-charnockite-granite, BDD – Blekinge-Dalarna Dolerites, CSDG – Central Scandinavian Dolerite Group, LLDZ – Loftahammar-Linköping Deformation Zone, TIB – Trans-Scandinavian Igneous Belt, TTG – Tonalite-trondhjemite-granodiotite.

Table 5: Mafic Dykes

Age	Region	Orientation	Characteristics
1.67	*Vyborg*	*E-W*	*Rapakivi magmatism*
1.65	*Vyborg*	*WNW*	*Rapakivi magmatism*
1.62?	*Vyborg*	*NNW*	*Rapakivi magmatism*
1.59	*Åland*	*NNE*	*Rapakivi magmatism*
1.57	*Värmland*	*NW*	*Hyperite amphibolites*
1.53	*Breven-Hällefors*	*WNW*	*Rapakivi magmatism*
1.47-1.46	*Tuna*		*Dykes*
1.3	*Västergötland*	*NNE*	*West of mylonite zone*
1.27-1.26	*CSDG*	*ENE*	*Sills*
1.22	*Protoginzonen*	*N-S*	
0.98-0.95	*BDD*	*N-S*	*Sv-N foreland*
0.93	*Göteborg*	*WNW*	*With faults*
0.28	*Perm Variscan*		*Sills OSLO*
0.19-0.18	*Skåne*		
0.15	*Skåne*		
0.11	*Skåne*		

Table 6: Baltic earthquakes M>3

Age	Magnitude	Location	Characteristics	Offset
1303		*Prussia*	*(Kaliningrad)*	
1328		*Central Lithuania*		
16160630	*4.8*	*Bauska*	*E-W 300km*	*50m offset Pal*
18210221	*3.4*	*Koknese*		
19081229	*4.6*	*Daugavpils*	*NW*	*10km 4mm/y uplift*
19081230	*4.5*	*Gudogai*	*NW >400km/N-S 250km*	*20-30m? PQ*
1974	*4.75*	*Osmussaare*	*NNE topoexpression in Baltic Sea*	
20040921	*4.4*	*Kaliningrad*	*right lat strike-slip WNW*	*10-18km*
20040921	*5.0*	*Kaliningrad*		*10-18km*
20040921	*3.4*	*Kaliningrad*		*10-18km*

Information in the Tables compiled from the following references:
Alm et al. 2005, Andrén & Wannäs 1988, Beunk & Page 2001, Bogdanova 2001, Bogdanova et al. 2005, Bogdanova et al. 2006, Coocks & Torsvik 2005, Korja et al. 2006, Laitakari et al. 1996, Larson & Tullborg 1998, Mansfeld et al. 2005, Monkevicus & Šliaupa 2007, Peulvast 1985, Puura & Flodén 2000, Puura et al 2003, Rämö et al. 2005, Söderlund 2008, Torsvik & Rehnström 2003.

APPENDIX 2

Investigations and investigation methods supporting mapping of Phanerozoic deformation in the Baltic Sea

1. Introduction

1.1 General

Fennoscandia is a cratonic area dominated by Proterozoic and older crystalline bedrock (Fig. 1-1), which is unique in a European perspective. Special in a worldwide perspective is also that the ground-surface in large parts coincides with an old peneplain, the sub-Cambrian peneplain >550 Ma old. The formation of such a peneplain implies that the area must have been extremely stable during a long period at the end of the Precambrian as the variation in elevation within the plain was in the order of just tenths of metres (Rudberg 1954).

The sub-Cambrian peneplain was then covered by a pile of Cambrian and younger sediments (total thickness exceeding 4km). It was deformed (block-faulting and tilting, cf. Figs. 1-2 to 1-4) and in large parts denudated; locally new erosion facets were formed.

On the present Swedish mainland, the Phanerozoic sediments are found in Skåne and southeastern Småland, and along the Scandinavian Caledonides in the west. Isolated remnants of Cambro-Silurian sedimentary rocks also occur in protected positions due to faulting, tilting, impacts and magmatic caps. In Finland Palaeozoic and younger sedimentary rocks are very rare. The most extensive occurrences of Phanerozoic sedimentary rocks within the Fennoscandian Shield are found in the Bothnian and Baltic Seas. Sedimentary rocks are well exposed on the larger islands of Öland and Gotland and are continuous with Russian Platform sediments in the countries at the southeastern and southern shores of the Baltic Sea.

The southern boundary of the Fennoscandian Shield is a WNW-ESE trending deformation zone (denoted TTZ, STZ; part of the Trans European Suture Zone, TESZ, a plate boundary), running across Skåne, the southern Baltic Sea and across Poland, Fig. 1-1. This boundary is of Caledonian age and has been reactivated since. The Bothnian and Baltic Seas are large scale depressions and coincide with what is considered to be an aulacogen, a failed arm of a plate tectonic rift. Such a structure affects the thickness of the crust. The sequence of sedimentary rocks in the Bothnian and Baltic Seas areas contains a memory of the Phanerozoic structural evolution in the Fennoscandian Shield, revealing reactivation of older structures and the formation of new ones in the underlying basement. The morphology of the sea bed may reveal the very late deformation in the area, the neotectonic structures (definition, see below). Together they present the later structural history that is hard to recognize when studying the hard 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).

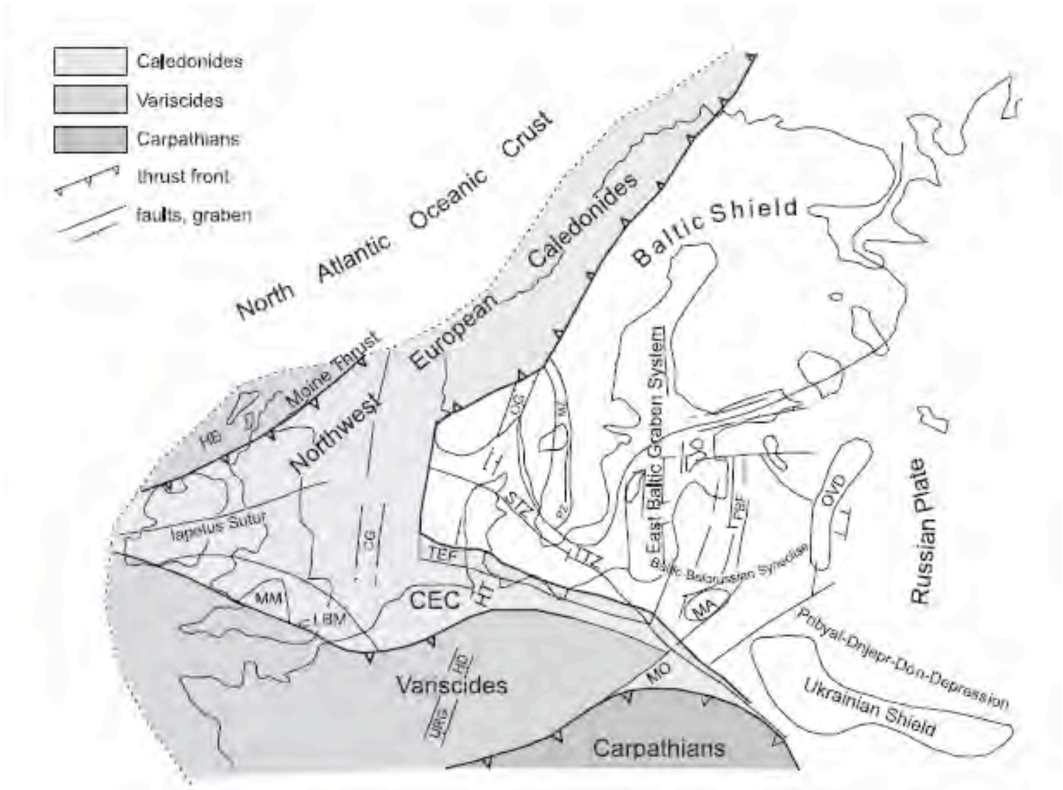


Figure 1-1. All geological maps are thematical – they emphasise different types of geological aspects, one example (Harff et al. 2001):
Regional tectonic units of northern Europe. The deep-fracture Tornquist-Teisseyre Zone (TTZ) and its northwestern prolongation, the Sorgenfrei-Tornquist Zone (STZ), separate the main tectonic units of the Baltic area: the East European Platform and the West European Platform. The first one consists of the Baltic (Fennoscandian) Shield with outcropping Precambrian crystalline rocks and the Russian Plate with flat-lying Phanerozoic sediments on a Precambrian basement. The Northwest European Caledonides border the Baltic Shield in the northwest. West of the TTZ the Central European Caledonides and Variscides together form the Central European Depression. HB: Hebridic Shield; MM: Midland Massif; LBM: London Brabant Massif; CG: Central Graben; MZ: Mylonite Zone; PZ: Protogin Zone; MA: Masurian Anteclise; OVD: Orsha-Valday Depression; PBF: Pribaltic Faults; MO: Moravosilesian; TEF: Trans-European Fault; CEC: Central European Caledonides; URG: Upper Rhein Graben; HD: Hessian Depression; HT: Hamburg Trog; OG: Oslo Graben.

Other examples of geological maps are given in the main text of this report (Figs. 1, 2, 3a, 3b, 4a, 6, 7a, 7b, 8a, 9, 10, 11, 13, 16, 18a, 30, 32 in the main report).

Figure 1-2. Compilation of tectonic structures in the sea-covered parts in the Nordic-Baltic area (Flodén 1984, cf. Flodén 1977. Maps of sedimentary rocks in the Baltic are presented by Winterhalter et al. 1972 and Flodén 1984, cf. Fig. 1 in the main report).

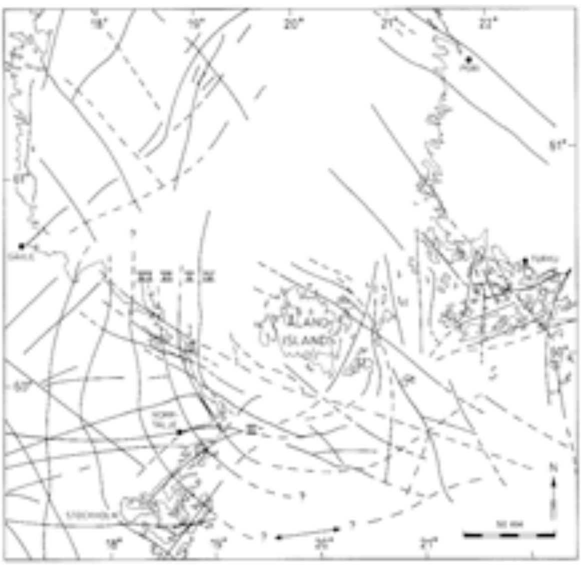


Figure 1-3. Structural map emphasising the concentric tectonic structures centred on Åland, an area of approximately 1.6 Ga old rapakivi granites (Söderberg 1993).

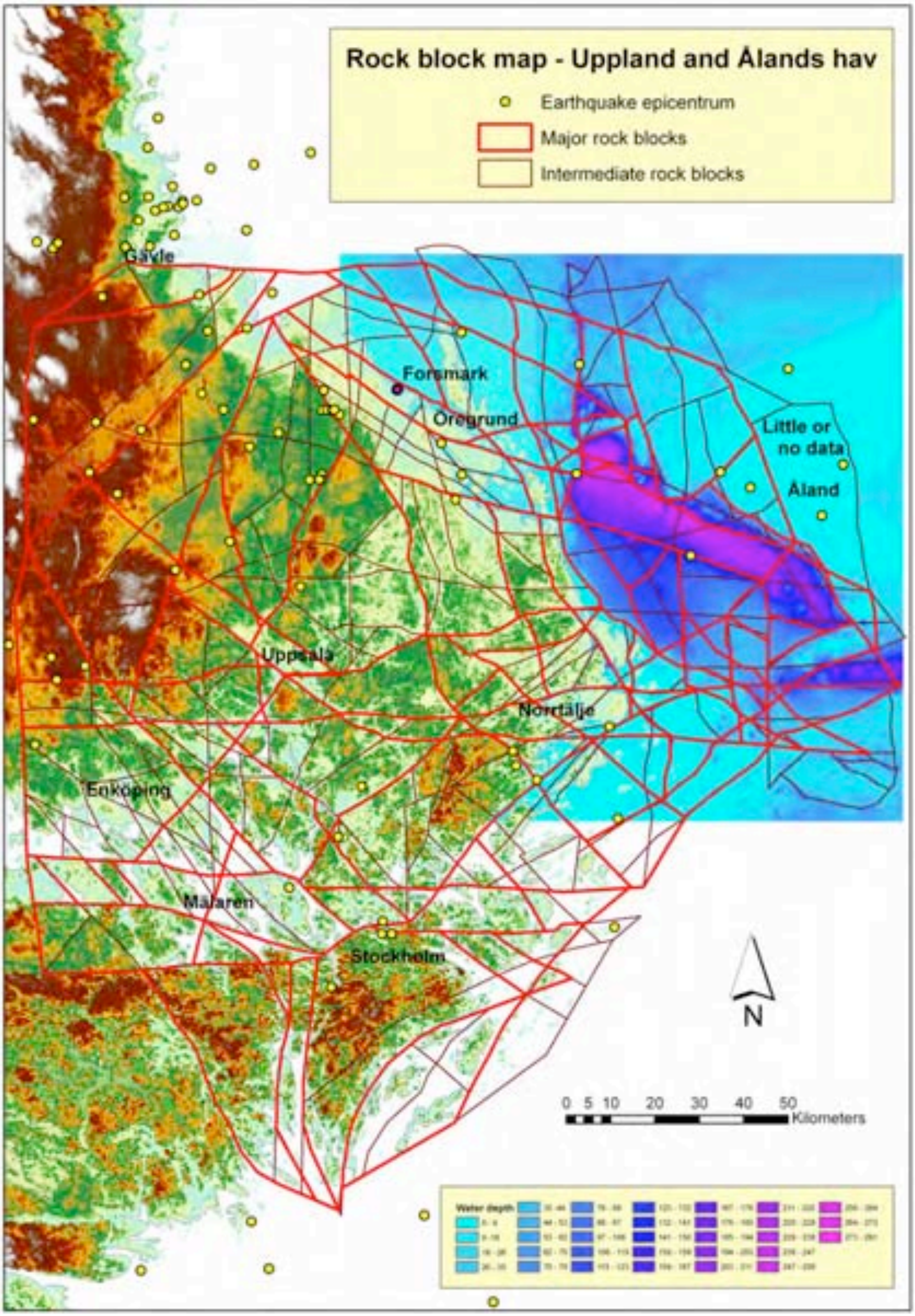


Figure 1-4. Rock block map of the Uppland – Ålands-hav area (Beckholmen and Tirén, in press, 2008b). "Elevation displayed on land by a 500m grid with the exclusion of altitudes above 115m and a transparent 50m grid and in sea-covered areas by an inverse distance weighted interpolation grid (ESRI, ArcGIS 9.2) based on spot checks from sea charts. Earthquake data from (SNSN) and the Helsinki Catalog of earthquakes in Northern Europe since 1375."

Formation of brittle features always has a cause and is, generally, related to some regional-scale tectonic and /or isostatic event. However, the relation between cause and effect may not always be clear. A first step to understand the formation of a structural feature is to describe it.

The objective of the present study is to give a brief summary of investigations performed in the Bothnian and Baltic Seas area that contribute to the understanding of the Phanerozoic and earlier structural evolution (presented in the main part of the present report), cf. Figs. 1-1 to 1-4.

Examples of applied techniques/methodologies/investigations, except field mapping, that give information about the distribution of lithologies and structures are presented in this Appendix (Appendix 2) and they comprise:

- Geographical positioning of information, elevation and bathymetrical data (section 2.1).
- Deep penetrating geophysical measurements (Regional geophysical investigation; section 2.2).
- Shallow marine seismics (section 2.3.1).
- Sonar (section 2.3.1).
- Drilling (section 2.3.1).
- Examples of tectonic structures found in the sedimentary rock cover in the Baltic (section 2.3.2).
- Reference structures in soft sediments at the sea bottom (section 2.3.3).
- Character of sea beds (section 2.3.4).
- Waters circulation in the Baltic (section 2.3.5).
- Present rate of sedimentation and erosion (section 2.3.5).
- Uplift (section 2.4).
- Earthquakes/seismicity (section 2.5).
- Regional rock stress data (section 2.6).
- Impacts (section 2.7).
- Datum surfaces (section 2.8).
- Global to regional geological reconstructions (section 2.9).

First some definitions are presented regarding the relative age of structures and references to the identification of such structures and general attributes of reactivated structures (section 1.2).

1.2 Definition of neotectonic and post-glacial structures

The term *neotectonics* was first introduced by W.A. Obrutschow in the beginning of 20th century (cf. Murawski 1972) denoting the youngest geological history, the last 24 Ma (Miocene to present). A thematic neotectonic map (e.g. Dennis 1967) displays “vertical movements after a specific geological date, normally the beginning of Miocene”. Becker (1993) proposed that deformation can be denoted as neotectonic, i.e. a new era of tectonics (e.g. related to the evolution of the northern Mid-Atlantic ridge and the northern Mediterranean convergence zone), if it has taken place within the last 10 Ma. According to Jackson (1997) neotectonics comprise studies of post-Miocene structures and the structural history of the Earth’s crust, i.e. structures younger than 5 Ma. In a craton with repeated glaciation, during the Quaternary period (Lundqvist, 1994), as in northern Europe, the concept neotectonic becomes indistinct. Glacial erosion and sedimentation may obliterate the surface traces of pre-glacial faults. The first *post-glacial faults* (PGF), faults formed after, or at a late stage of, the latest deglaciation, were recognized in the 1960´s and 1970´s. In northern Europe such faults are approximately 10 000 years old or younger. Neotectonic faults in cratonic areas are generally found to have older precursors. Criteria for the identification of post-glacial faults (PGF)/reactivated faults have been discussed by, e.g. Muir-Wood and Mallard (1992), Holdsworth et al. (1997), Butler et al. (1997), Hansson et al. (1999), Munier and Fenton (2004), Wheeler (2006) and Butler et al. (2007). Faults that displace the sub-Cambrian peneplain or post-date the Precambrian are here denoted as *late faults*.

2. Investigation methodology – Base data

2.1 Geographical positioning of information and elevation and bathymetrical data

Positioning of geoinformation in three dimensions is essential for the understanding of the relation between different sets of field observations and recorded geodata (e.g. geophysical measurements). It is the base for all modelling of the distribution of lithologies and structures and the cross-correlation between different geodisciplines, e.g. correlation between geophysical anomalies (e.g. in reflection seismics, magnetic and gravity measurements) and earthquakes.

The morphology of a terrain, as presented by topographical and/or bathymetrical data, is the product of the geological evolution the area, i.e. rock forming processes, tectonics, denudation and deposition of sediments. In other words, the form of the ground surface may reflect distribution of lithologies and tectonic structures.

Table 2-1: Data on the Baltic Sea (cf. http://www.io-warnemuende.de/admin/en_index.html).

Parameter		Comments
Area	412 560km²	
Volume	21 631km³	
Drainage areas of the Baltic Basin	1 665 000km²	
N-S extension	about 1300km	(54° - 66° N)
W-E extension	about 1000km	(10° - 30° E)
Max width	about 300km	
Mean depth	52m	
Maximum depth	459m	Landsortsdjupet

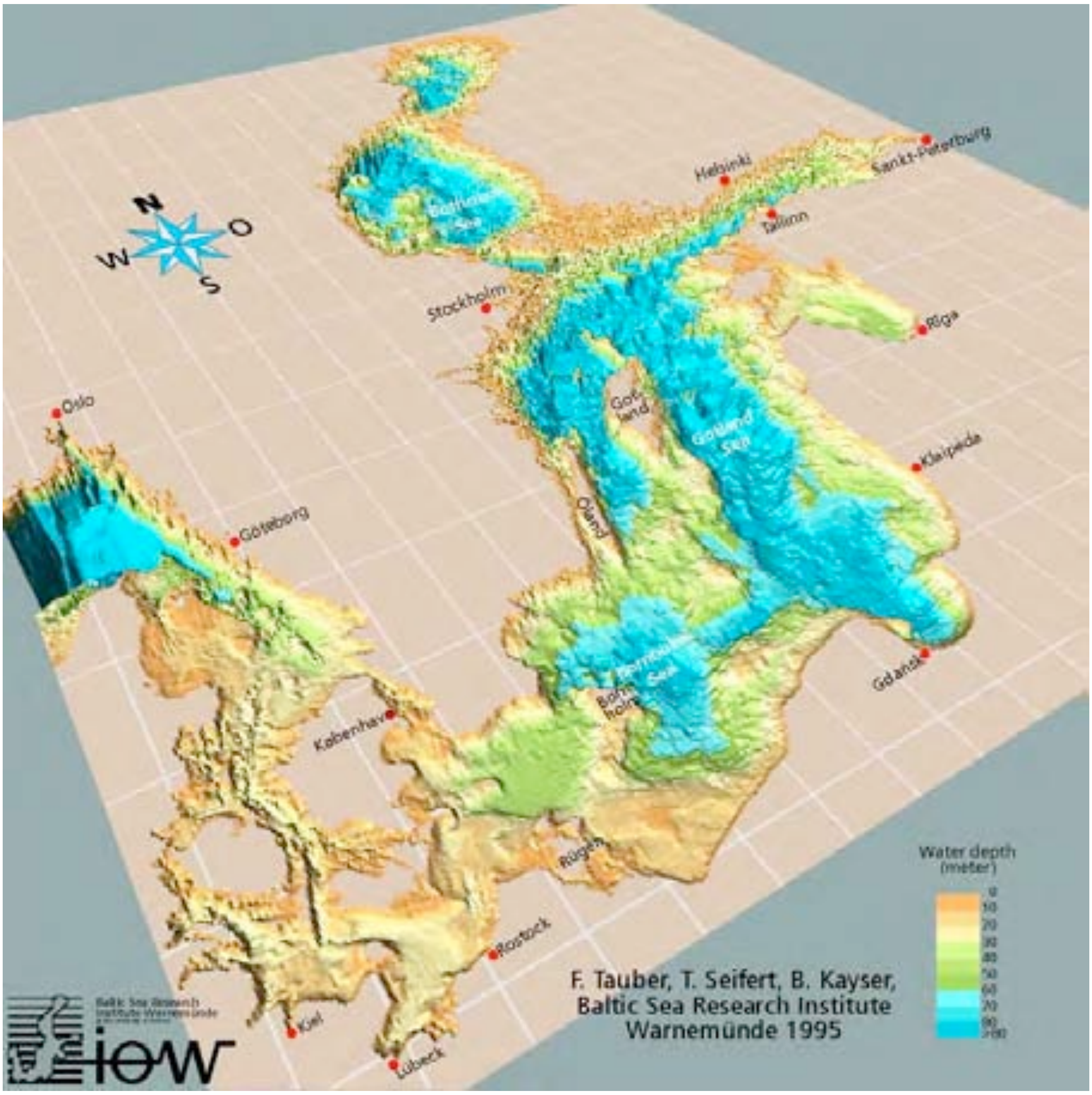


*Figure 2-1. The Baltic Sea (*http://www.io-warnemuende.de/admin/en_index.html*). Precambrian bedrock constitutes the land areas in Sweden and Finland around the Bothnian Sea and the Gulf of Bothnia. The Precambrian bedrock surface dips southwards from southern Finland and southeastwards from southeastern Sweden (cf. Fig. 18b in the main report).*

The Baltic Sea region is a topographical anomaly in the shield area (Fig. 1-1, Table 2-1). In the north it is mainly controlled by tectonic structures, block faulting and erosion (cf. Figs. 2-1 and 2-13), while in the south, in the Baltic Proper, it is also controlled by the general tilting of the peneplain, the bedding in the Phanerozoic sedimentary rocks combined with locally more enhanced erosion (cf. Fig. 22a in the main report). The topographic pattern in the Baltic Sea can be visualized by processing of elevation and bathymetrical data (cf. Fig. 2-1 and Figs. *i and ii* in the main report).

2.2 Deep penetrating geophysical investigations

Late deformation in a craton is related to several factors of which the character of the crust is of greatest importance; its thickness and framework of tectonic structures. Other factors are the forces acting on the craton; plate tectonics and isostatic adjustments. Gravity and magnetic measurements and deep reflection seismics are examples of investigations performed to characterize the crust. These are briefly treated in the main report (e.g. Figs. 3b, 5, 6, 22, 23 in the main report).

2.3 Marine investigations

2.3.1 Shallow marine seismics and drilling

The Baltic Sea area differs from the main part of Fennoscandian Shield in that it is an area where the Precambrian rocks are mainly covered by late Precambrian and younger sedimentary rocks. The geological memory reflected in the sedimentary rocks is more easily read than that in the underlying basement.

To improve coordination, cooperation and exchange of information in marine science and technology amongst geoscientists a website was formed, www.eu-seased.net. EU-SEASED is a European Commission-conducted programme supported by the Geological Surveys of the EU-countries and Norway. The website contains the following thematic databases (incl. search-tool):

- EUROCORE – meta-database of seabed samples from the ocean basins (depth>200m)
- EUMARSIN – marine sediment meta-databases
- EUROSEISMIC – marine seismic meta-data.

The EUROSEISMIC meta-database contains the following types of measurements:

- Long/short range side-scan sonar
- Seismic refraction
- Gravity
- Magnetic
- Single- and multi-beam echo soundings
- Single- and multi-channel seismic reflection.

However, marine investigations in the Baltic Sea have not only been performed by the geological surveys but also by universities and petroleum prospecting companies. Extensive shallow marine seismics have been performed by the University of Stockholm and the results are published in articles and monographs. No overview of the surveyed areas and measured profile lines has yet been compiled (Tom Flodén written communication in May 2008). Applied seismic techniques and location of measured profile lines are given in the reports and they are from north to south:

- Gulf of Bothnia (also denoted Bothnian Bay): Flodén et al. (1979a, 1979b), Wannäs (1989),
- Bothnian Sea: Axberg (1980),
- Åland Sea and Northern Baltic Sea: Söderberg and Flodén (1992), Söderberg (1993),
- Central Baltic Sea (Baltic Proper): Kumpas (1977), Flodén (1980),
- Hanö Bay, southern Baltic sea: Kumpas (1978, 1980, 1982), Andrén and Wannäs (1988), Wannäs and Flodén (1993, 1994),
- STZ: Wannäs (1979), Kumpas (1985), Kumpas et al. (1990a, b).

Investigations performed in the western part of the Baltic Proper by other universities are for example:

- University of Helsinki - Southeastern Bothnian Sea outside Olkiluoto (Kotilainen and Hutri 2004, and Hutri 2007).
- University of Tartu (Tilk 2006).

Flodén (1984) concluded in his overview of the geology of the Baltic Sea that neotectonic movements occur in the Baltic and they are restricted to pre-existing tectonic zones, while the majority of mapped tectonic structures do not indicate any late displacement. Wannäs and Flodén (1994) found post-glacial (Yoldian) deformation, block faulting, in the Palaeozoic rocks east of the Hanö Bay in the southern Baltic Sea. Hutri (2007) found early post-glacial faulting (early Holocene) in the sea beds close to Olkiluoto, southwestern Finland. Thorslund and Axberg (1979) have presented a geological map of the Bothnian Sea displaying the faults along the east-coast of central and northern Sweden.

Petroleum prospecting in the Swedish part of the Baltic was performed by OPAB (Oljeprospektering AB, founded in 1969). Results from all investigations performed by OPAB are stored at the library of the Swedish Geological Survey, Uppsala. The seismic investigations have been summarized by Linder (1985). On-going prospection is focussed on an area in the southeastern part of the Baltic, Project Dalders (OPAB 2007, Fig. 2-2).

a. 

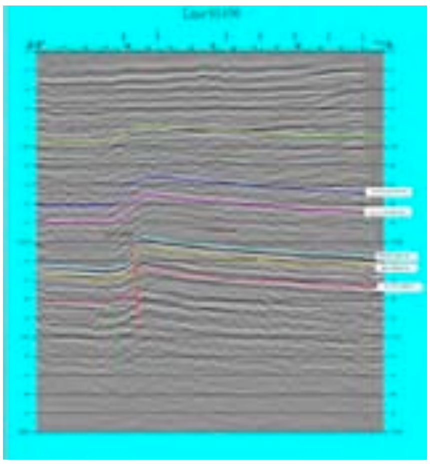
b. 

Figure 2-2. a) Location of the Dalders project. Dark blue dots are boreholes previously drilled by OPAB. Light blue dots (circles) are drillholes where oil was found. Dark lines show the national economical zones. b) Seismogram (right) with a Caledonian-induced flexure reactivated during the Hercynian orogeny, an assumed trap for oil (Figures produced by INDOK for OPAB 2007).

2.3.2 Examples of tectonic structures found in the cover of sedimentary rocks in the Baltic

Tectonic structures in the sedimentary rocks are revealed by reflection seismic measurements**.** Possible existence of three-dimensional reflection seismics performed in the Baltic is not known to the authors. The deformation in the sedimentary rocks is generally related to deformation in the underlying Precambrian basement. The age of structures is displayed by the relation between structures and the layering in the sediments (the structural history is presented in the main part of the report), Figs. 2-3 to 2-6. The geometry of formed structures may reflect the regional stress orientation during the formation of the structures, (cf. Dooley et al. 1999, Krzywiec 2002) cf. Fig. 2-5a.

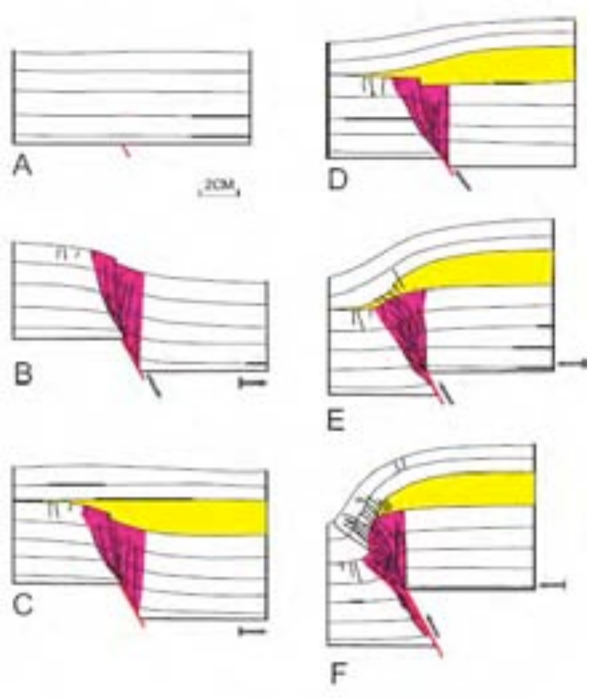


Figure 2-3. Inversion of normal fault - results of analogue modelling. Stages (a)–(c): extension, stages (d)–(f): inversion. Yellow – syn-extensional deposits (slightly adjusted from Mitra and Islam 1994 by Krzywiec 2002).

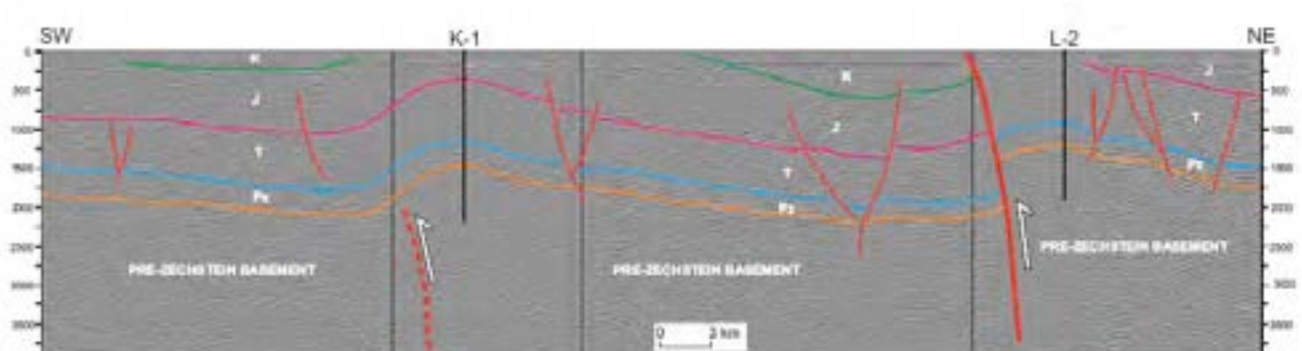
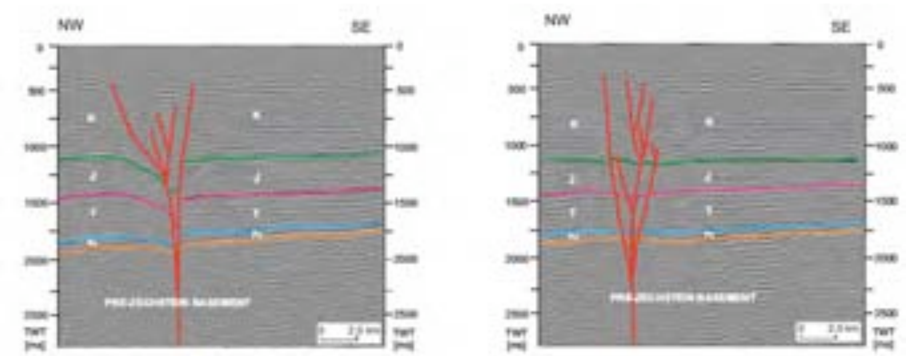
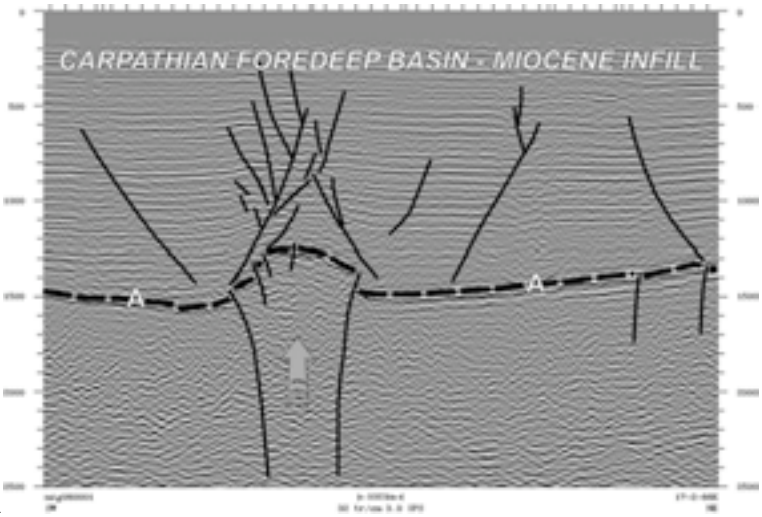


Figure 2-4. An example of distortion in the sedimentary rocks formed during displacement along major deep-seated fault zones (Krzywiec 2002), seismic profile from the western part of the south Baltic Sea (NW Mid-Polish Trough) showing major inversion structures (Pz – Zechstein, T – Triassic, J – Jurassic, K – Cretaceous, K-1 and L-2 are drill holes, cf. Fig. 2-5a).

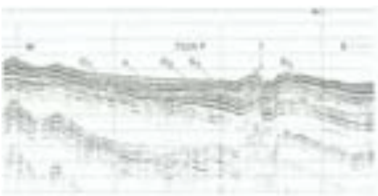


a.



b.

Figure 2-5. a) Two seismic examples of strike-slip NE-SW fault (central part of the Mid-Polish Trough, Krzywiec 2002). Note various modes of deformation − from transpression (positive flower structure − right profile) to transtension (negative flower structure − left profile), and b) basement pop-up structure related to strike-slip movements, Ryszkowa Wola High (south of the Baltic), Poland (Krywiec et al. 2003).


a.

b.

c.

Figure 2-6. Examples of seismic profiles (Flodén 1980) showing the geometry of the sea-bottom and structures in the sea-bed and the sedimentary rock; a) $O_{1,2}$=Ordovician strata, S_1=Silurian strata, a=sedimentary structure in the Cambrian sediments and f=fault, W-E profile east of Öland, b) a=glacially eroded fracture valley common in the area south and southeast of Gotland, $S_{7,9,10}$=Silurian strata, and c) a=erosion trench filled with soft sediments (tunnel valley), b=slightly down-warped reflectors in the sedimentary rock below the trench, D_4= Devonian strata and C_1=Carboniferous strata, the bottom is planar and gently inclined northward, southeast of Gotland.

a. 

b. 

Figure 2-7. a) Top of the Precambrian basement in Estonia is shown by contours (Shogenova et al. 2007), flexures above the basement faults are shown by yellow lines, b) Caledonian structures in Lithuania (Brangulis and Kanevs 2002).

Caledonian deformation (about 400 Ma) is well documented in the Baltic States, Fig. 2-7, and corresponding deformation also has affected the Fennoscandian Shield (cf. Milnes and Gee 1992, Cosgrove and Röshoff 2002, Alm et al. 2005).

The structural pattern in the underlying Precambrian basement is interpreted from deep reflection seismic surveys (cf. main report Fig. 3b). Structures in the sedimentary rocks may be detected by marine seismics, but the trace of faults on the sea bottom may be obliterated, cf. Fig. 2-6. Tectonic pop-up structures (cf. Fig. 2-5b) generally form asymmetrical ridges at the sea bottom (cf. Jacobi et al. 2007).

2.3.3 Reference structures in soft sediments at the sea bottom

In the structural interpretation of deformation in the soft sedimentary rocks, the sedimentary bedding and sedimentary discontinuities are used as reference surfaces. A special type of late markers are glacially incised and filled valleys (e.g. Bjerkéus et al. 1994, Monkevicius 1999) cut both in soft sediments and sedimentary rocks. They may correspond to a specific type of gorges found above the highest marine level (cf. Olvmo 1989), and some narrow marine furrows (Tirén et al. 1996). Glacial incisions are common in, e.g. northern Germany, Denmark and in the North Sea (cf. Grube 1983, Ehlers and Linke 1989, Ehlers and Wingfield 1991). The incisions are interpreted to be formed as tunnel valleys below the ice and along tectonic structures (cf. Kehew and Koxlowski 2007), some may predate the last glaciation (cf. Binzer and Stockmarr 1985, Bjerkéus et al. 1994, Endler et al. 1995), Fig. 2-6c. Other non-tectonic structures in the sea bottom are old river systems, e.g. in the Bothnian and Åland Seas (Nenonen 1995; Fig. 26 in the main part of the report). The age of the deformation may be confined more accurately where the interplay of glaciotectonic distortion of soft beds and the formation of Quaternary valleys occur, cf. Huuse and Lyckke-Andersen (2000). Very late markers are plough/drag-marks formed by drifting icebergs, Fig. 2-8. Worth mentioning is that similar plough-marks are found by 3D seismics in, e.g. 1.5 Ma old sediments, 300m below the present sea floor, on the Norwegian continental margin (Ottesen 2006), Fig. 2-8b.

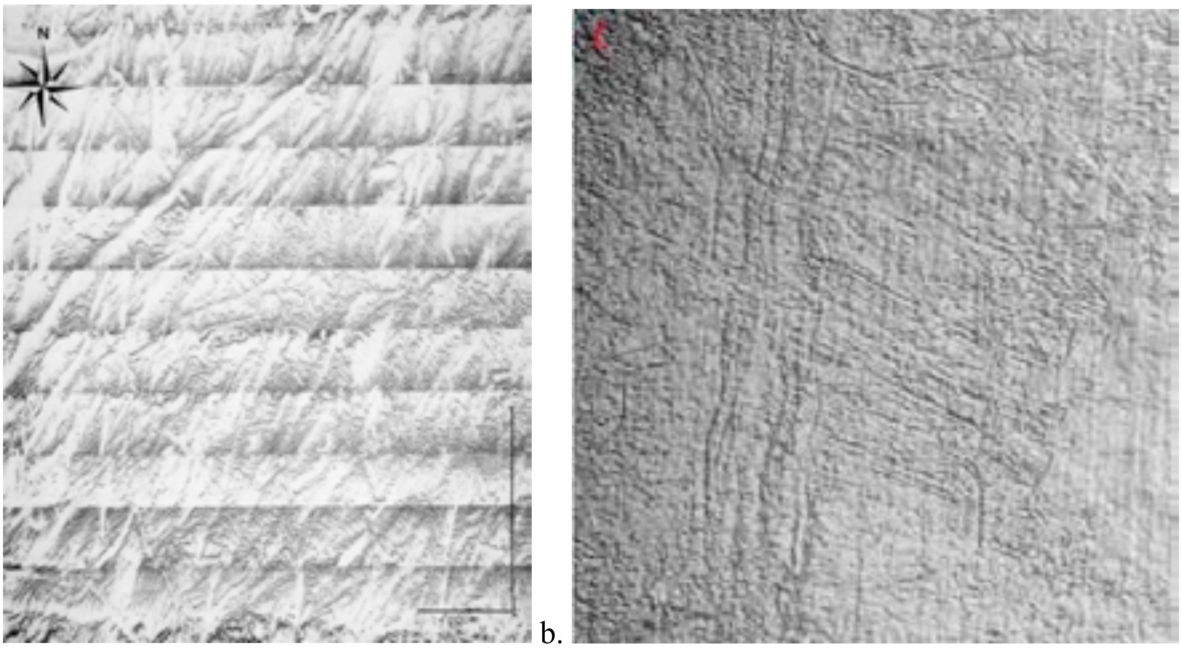

a. b.

Figure 2-8. a) The picture is a side-scan sonar image of the sea floor some 30km east of Gotland, Baltic Proper. The layering in the sea sediments is seen in the serrated layers while the plough/drag marks created by icebergs are the course lines trending NNE-SSW (Elhammar et al. 1988). There are also fine lines trending NNW-SSE (e.g. from the upper left corner) and these lines are conform to the dominant orientation of deformation zones on the Swedish mainland. However, their origin is not determined but they may represent late reactivations. b) Tomographic seismic image of bedforms (WNW) and iceberg plough-marks (N-S) from Haltenbanken, part of the continental shelf west of Trøndelag (mid Norway), about 300m below the present sea floor, a seabed approximately 1.5 Ma old (Ottesen 2006; scale not presented).

Pockmarks are shallow seabed depressions formed in soft, fine-grained sediments. These are up to some tens of metres across and a few metres deep. They may form either by escaping, venting gas, composed mainly of methane (Hovland and Judd 1988, Kelley et al. 1994, Vogt et al. 1994, Judd 2001, cf. Fig. 2-9), by discharge of groundwater or by freshwater ice rafting in high latitudes (Paull et al. 1999). The gas may be formed in the sea bed or be seeping along tectonic zones into the sea beds. Where pockmarks line up they may indicate the existence of an open deformation zone in the bedrock (cf. Söderberg 1993, Hutri 2007). However, it is also found that linear arrangement of pockmarks can be artefacts, initiated by distortions of the sea bed performed by anchors and drag fishing (Gontz 2002).

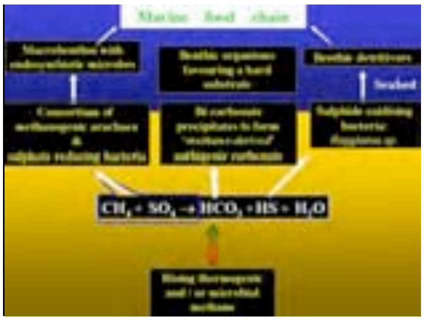
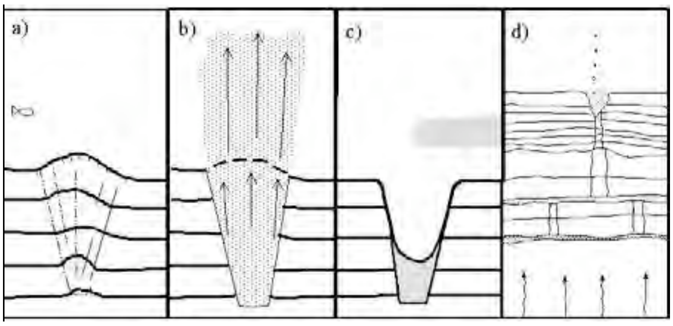
a.  b. 

Figure 2-9: a) The source of methane at the seabed (Judd 2001). b)A conceptual model for the formation of pockmarks (after Hovland and Judd 1988)

2.3.4 Character of the sea bed

Structures formed at the sea floor are to a large extent related to the character of the sea bottom and the transport of water along the sea bottom (see below). In the Bothnian Sea the proportion of hard bottoms (till and bedrock) is higher than in the Baltic Proper, Fig. 2-10. Generally, the deeper parts of the sea have soft bottoms.

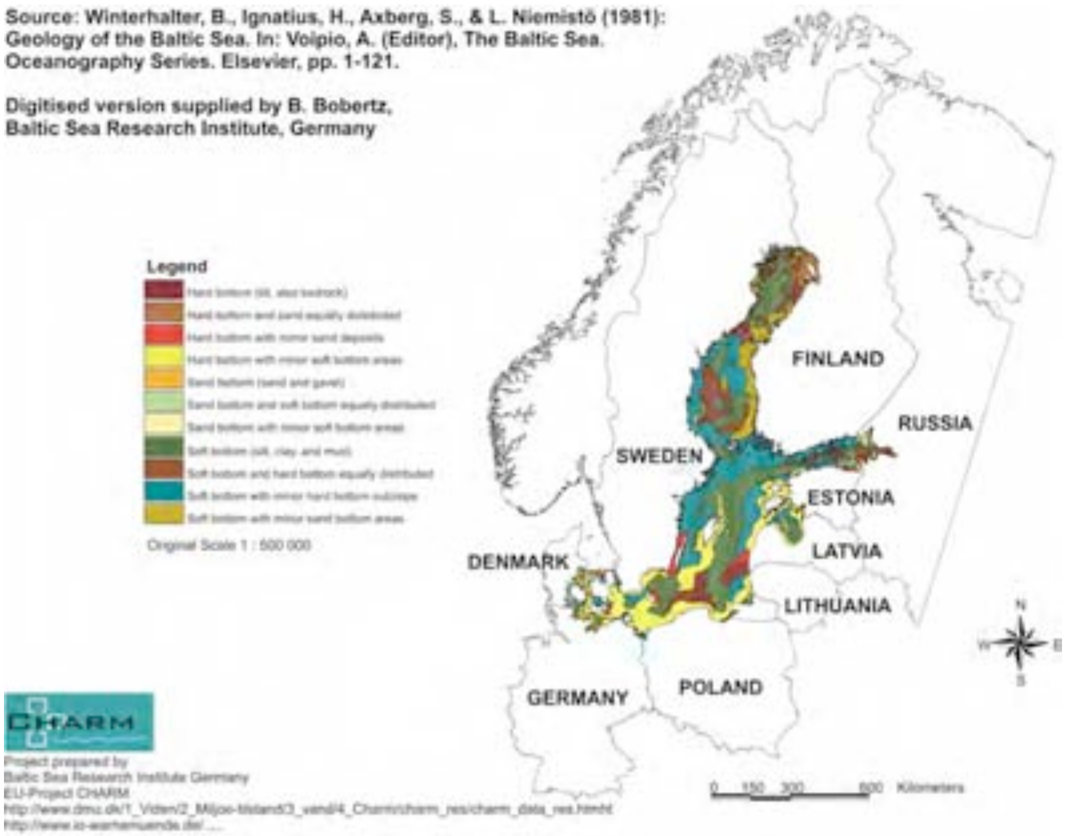
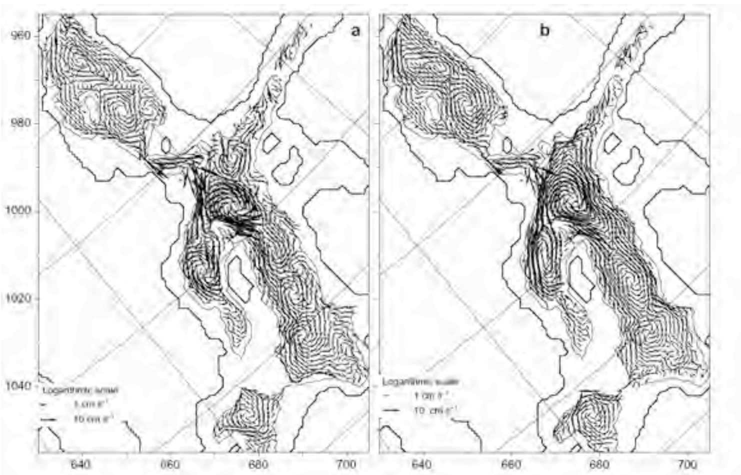


Figure 2-10. Overview of the character of the sea bottom in the Baltic Sea. http://www2.dmu.dk/1_Viden/2_Miljoe-tilstand/3_vand/4_Charm/charm_res/data/WP1/Deliverable9/charm_all%20maps.htm. *A more detailed map of the Baltic Proper is given in the main report (cf. Fig. 31, in the main report).*

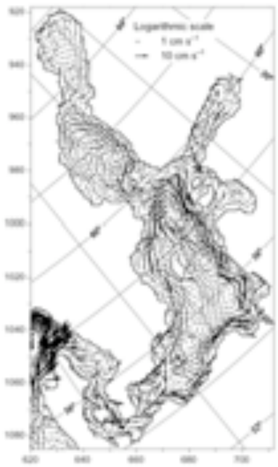
2.3.5 Water circulation, sedimentation and erosion in the Baltic and Bothnian Seas

Distortions of the sea bed, the bottom surface, may reflect e.g. post-glacial movements. When such features are formed the question is how long time they will remain visible before they are eroded or buried below sediments. This topic is related to the following factors:

- *The orientation of the displacement and the magnitude of the displacement along the active fault.*
- *The character of the sea bed; soft or hard.*
- *The rate of erosion of bottom structures, e.g. by sea currents.*
- *The rate of deposition of sediments.*



a-b.



c.

Figure 2-11. Water-circulation in the present Baltic Sea, the mean velocity at depths 42–53 m in: a) February 1981, and b) November 1981, and c) mean velocities averaged over the depth interval 0-33 m during the months of November 1979 to1981 (Maslowski and Walczowski 2002).

The water transport in the Baltic Sea system is related to both the influx of water and the bottom topography. The circulation pattern in the shallow waters differs somewhat from the currents at deeper levels, Fig. 2-11. There is a pronounced southward transporting bottom stream in the narrow channel between Åland and eastern Sweden, in the Åland Sea. Along the coast of southeastern Sweden the shallow water moves more or less uniformly southwards, while the water in deeper sections forms a large-scale anticlockwise whirl between Gotland and the mainland. In the coastal sea regions close to the SKB Sites in Forsmark and Laxemar/Simpevarp, the average velocity of the water is a few centimetres per second or less.

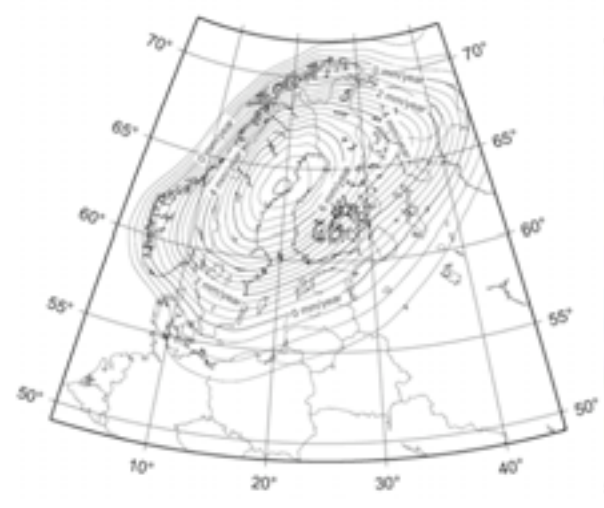
Deep trawling equipment creates linear plough-marks in the sea floor (well indicated by the side-scan sonar). Such marks may be erased within a couple of weeks. Offsets in the sea beds indicated by shallow marine seismics are in some cases found to be erased when repeating the measurement the following year (Tom Flodén personal comments c. 1995). The rate of deposition of sediments can be achieved from, e.g. clay varve chronology data (De Geer 1912, Boygle 1993, Holmquist and Wohlfarth 1998) or by absolute dating (e.g. Mazeika et al. 2004), who used ^{210}Pb to record the present rate of sedimentation in the Baltic at water depths greater than c. 50m and found that between Gotland and the Baltic States the sedimentation rate is uniformly about 1 to 2mm per year, while in the depression southwest of Åland it is slightly higher (2.7mm per year) and highest in the southeasternmost part of the Baltic (4.3mm per year), north of Gdansk. Still higher sedimentation rates are locally found in the Gulf of Finland.

Due to erosion related to the uplift, the redeposition of sediments in the Baltic Sea is much higher than the influx of sediments carried by rivers and streams from the drainage areas of the Baltic Basin (1 665 000km²). Notable is the existence of washed cobble fields and washed moraines at a depth of 5 to 13m north of Gotland (e.g. Kjellin et al. 1987, Elhammer et al. 1988, and Axberg et al. 1988). Axelsson (1997) found that sediments are accumulated (sedimentation-bottoms) on 25% of the Baltic Sea bottom, while erosion dominates in only a third of the of the sea bottom (erosion-bottoms). On the remaining parts of the Baltic sea bottoms sedimentation and erosion interacts but sedimentation dominates. This implies that the character of the sea bottom changes with time. The magnitude of post-Palaeozoic erosion (Puura et al. 2003 (cf. Fig. 22a in the main report), including repeated glacial erosion, may be exceptional, locally more than 280m.

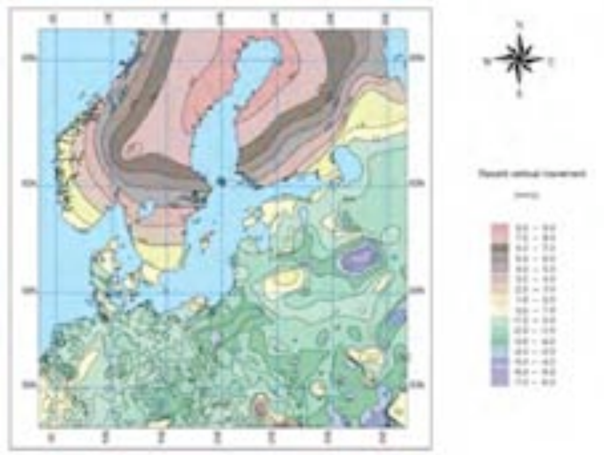
2.4 Uplift

A new post-glacial land uplift model, NKG2005LU, for the Nordic countries has been presented (Ågren and Svensson 2007), Fig. 2-12a. The model is denoted “mathematical” as it is based on levelling observations for the whole network of the *Baltic Levelling Ring (BLR).* The centre of uplift is located at the coast, west of the central part of the Bothnian Sea. This model, as well as previous models focusing on the uplift in Scandinavia, shows a relatively symmetric pattern. However, there are other models of northern Europe that indicate also location of local maxima, Figs. 2-12b and c. Uplift is taking place by differential movements in the crust that may cause reactivation of faults, which may be either seismic or aseismic. The uplift may also affect the stress-field in the rocks.

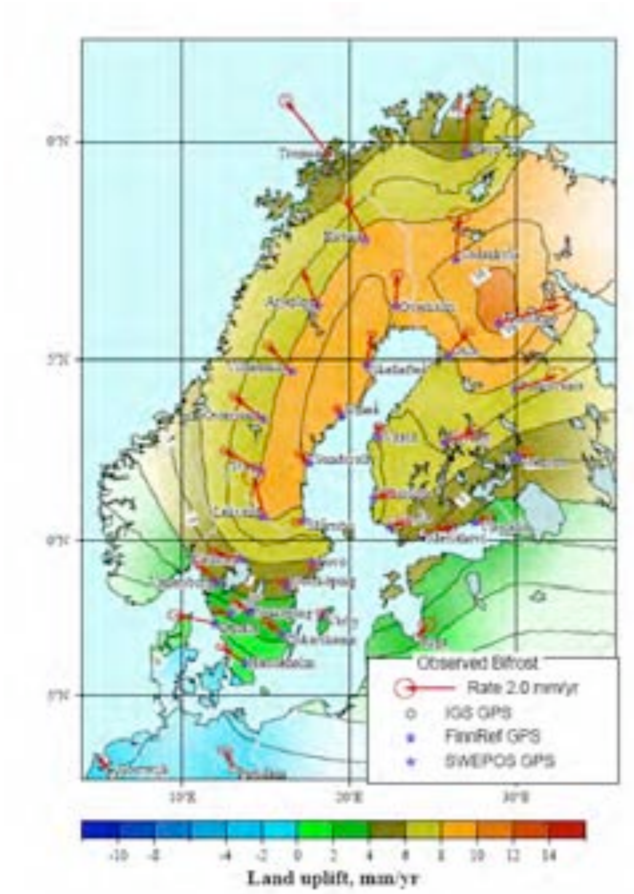
The Bothnian Sea depression has an asymmetric form; a steep western flank on the Swedish side and gently dipping eastern flank on the Finnish side. This is well expressed at Norra Kvarken, located just at the area of highest apparent uplift and enhanced seismic activity, cf. Figs. 2-1, 2-12, 2-13, 2-16 and 2-17.



a.



b.



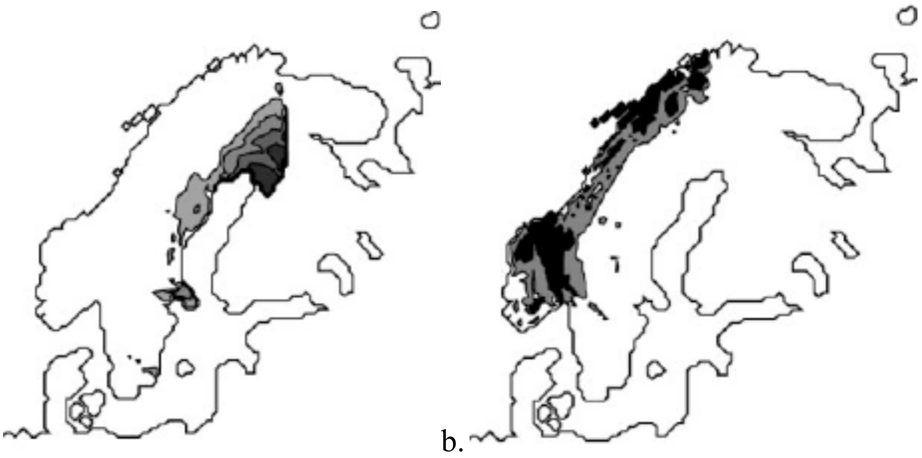
c.

Figure 2-12: Models of uplift for northern Europe: a) Apparent uplift for the land uplift model NKG2005LU (RH 2000 LU) of the Nordic countries (Ågren and Svensson 2007, cf. Ekman 1998), b) recent vertical uplift of northwestern Europe (Harff et al. 2001), and c) the post-glacial rebound in Fennoscandia using continuous GPS measurements, the vertical standard deviation is typically 0.25 to 0.35 mm/yr in Sweden; the somewhat shorter observation time span in Finland causes error limits near 0.5 mm/yr, BIFROST (Scherneck 2001).

Figure 2-13. Model of the area of highest apparent uplift in Scandinavia, located just west of Kvarken (the straight between the Bothnian Sea and Bay (Gulf)). The ring-formed structures in Finland are impacts (from Rinkieva-Kantola and Ollqvist 2004, cf. *Breilin 2004*).

One interesting result from the BIFROST project (observing the post-glacial rebound in Fennoscandia using GPS, with a network of 84 continuous GNSS stations with geodetic quality and the aim to discriminate limitations of current models of glacial isostatic adjustment, is the indication of non-uniform horizontal components of movements in northern Europe (Scherneck et al. 2001), Figs. 2-14 and 2-12c. Such movements can induce differential movements and affect the regional stress-field.

Figure 2-14. Predicted present day horizontal velocities from the visco-elastic earth model and observed motion estimated from the BIFROST network; dark blue arrows and confidence circles (Scherneck et al. 2001, cf. Fig. 2-12c).



a. b.

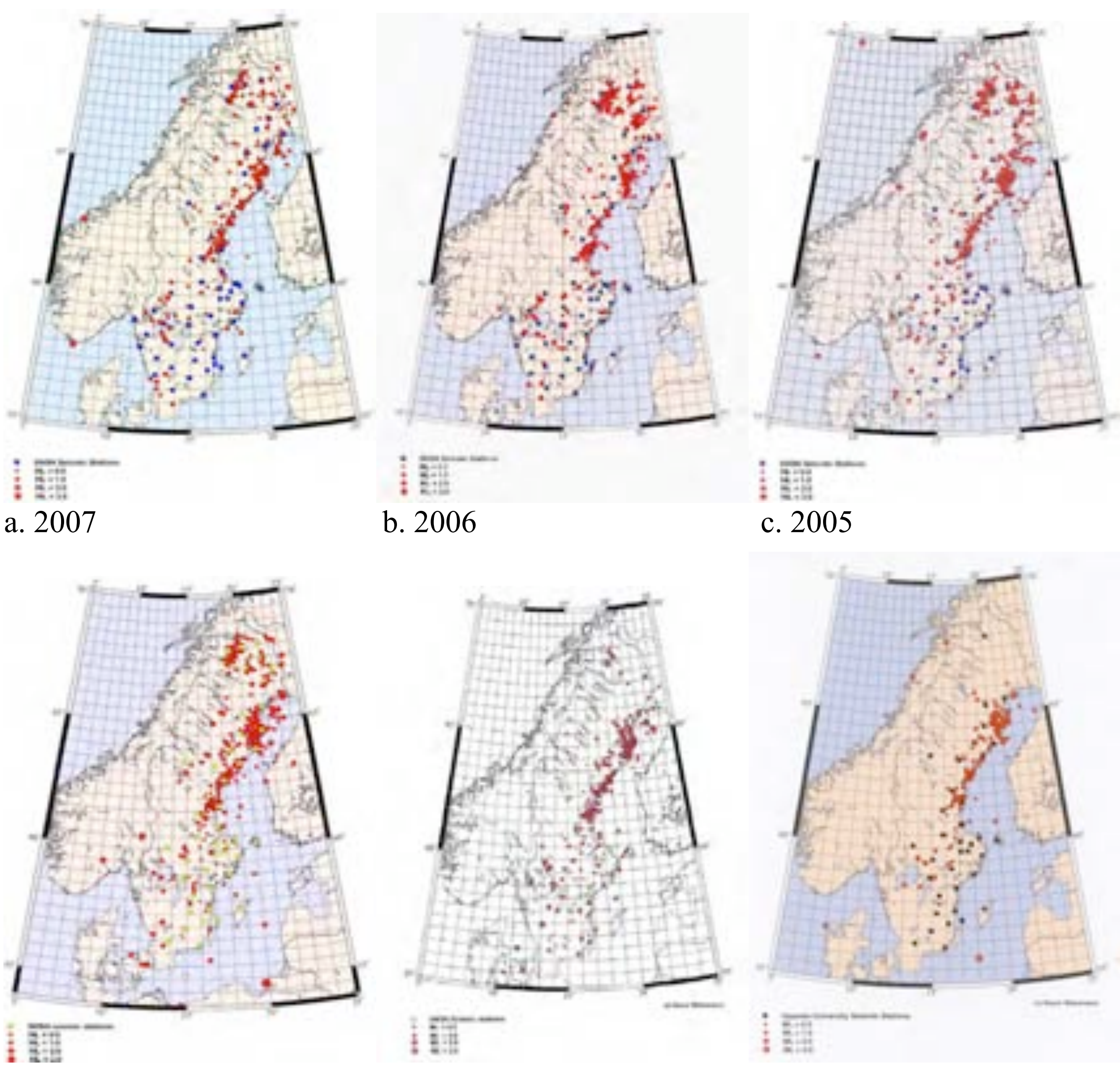
Figure 2-15. a) Areas with significant negative deviations (1.0 mm/yr) between the observations and the calculated glacial isostatic uplift, and b) Areas with significant positive deviations (1.0 mm/yr) between the observations and the calculated glacial isostatic uplift (Fjeldskaar et al. 2000).

Areas where there is a deviation between observed and calculated glacial isostatic uplift (Fjeldskaar et al. 2000) agree to a large extent with areas of enhanced seismic activity (cf. Figs 2-15 to 2-17). Notable is the negative deviation at the southern part of the western coast of the Bothnian Sea, at Gävlebukten, just northwest of the SKB Forsmark Site and at Oskarshamn just south of the SKB Laxemar Site. There is an enhanced seismic activity at Gävlebukten, though minor, while the seismic activity in the Oskarshamn area is very low, in spite of the location at a regional E-W trending regional deformation zone.

2.5 Earthquakes

The detailed net of Swedish seismic stations (59 and two under construction) is administrated by the University of Uppsala (Swedish National Seismic Net, SNSN, http://www.geofys.uu.se/snsn/net). Earthquake data for the other Nordic countries are given by the Norwegian Seismic Array NORSAR, http://www.norsar.no, the Norwegian National Seismic Network NSNN, http://www.geo.uib.no/seismo/nnsn/index_eng.html, the Geological survey of Denmark and Greenland, http://www.geus.dk/geuspage-uk.htm and the Helsingfors Catalogue, FENCAT, http://www.seismo.helsinki.fi. The recognitions of earthquakes in sea areas are mainly restricted to the latest period, when instrumental registrations have been used. A review of seismotectonics of Sweden is presented by Muir Wood (1993), an elucidation of older earthquakes in Fennoscandia, the Baltic States and western Russia is given by Mäntyniemi et al. (2004) and the locations of earthquakes at the two SKB Sites Forsmark and Laxemar/Simpevarp are presented by Bödvarsson et al. (2006), Tirén and Beckholmen (2007) and Beckholmen and Tirén (2008 a and b in press). However, by comparing different earthquake catalogues (see below) it is obvious that they are not fully identical (Figs. 2-16 and 2-17).

Tectonic stresses and glacial rebound stresses are needed to explain the distribution and style of contemporary earthquake activity in Fennoscandia (cf. Wu et al. 1999, Stewart et al. 2000). Wu et al. (1999) discuss the role that the post-glacial rebound plays in triggering seismicity in Fennoscandia. Seismic activity from Norway to the Atlantic Ridge is presented in, e.g. Dehls et al. (2000), Fjeldskaar et al. (2000), Tvedt et al. (2002), Gregersen (2006), and Havskov (2007).



a. 2007 b. 2006 c. 2005

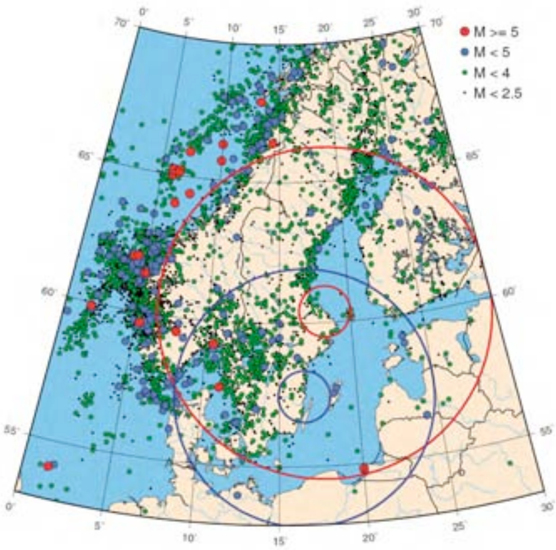
d. 2004 e. 2003 f. 2002

Figure 2-16. Red dots – earthquakes recorded by the SNSN network during the years 2002-2007 (Bödvarsson, 2003, 2004, 2005, 2006, 2007, 2008). (Cf. the distribution of earthquakes in northwestern Europe and the northern Atlantic during 1990 to 2000 in Tvedt et al. 2002.)

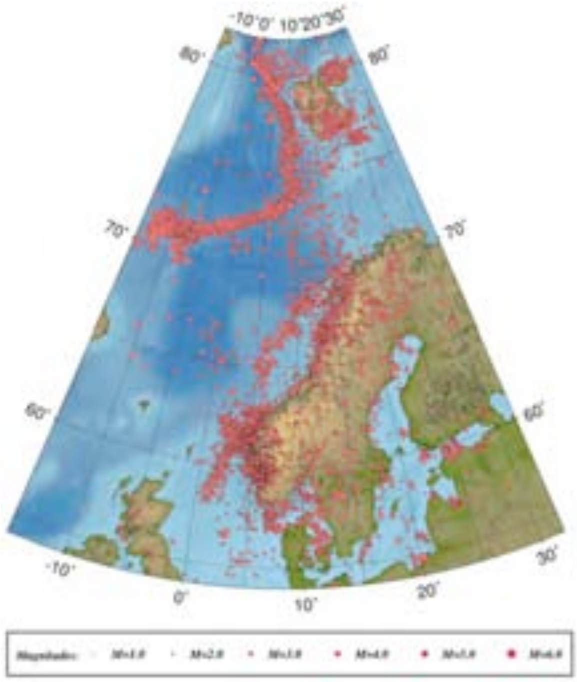
The number of SNSN seismic stations has increased from 2002 to 2004 and this is especially reflected in the number of recorded earthquakes in the northern part of Sweden. The number of registered minor earthquakes (M_L <2) is affected by the location of the seismic stations. To cover the sea areas along the east coast of southern Sweden, stations are located on the larger islands (Öland, Gotland and Åland). Complementary seismic stations in Finland may refine the monitoring of earthquakes in the Bothnian Sea. However, the number of seismic events decreases markedly when going east across the Bothnian Sea and the Gulf of Bothnia.

SNSN-registered earthquakes occur most densely along the western coast of the Bothnian Sea and the Gulf of Bothnia. These earthquakes appear to be more enhanced now than in the historical record of earthquakes (Figs. 2-17b). This may, to some degree, reflect the

a.



b.



c.

Figure 2-17. a) Earthquakes registered by the Swedish National Seismic Network between August 2000 and December 2005. Large red circle has a 650 km radius from Forsmark and the large blue circle has a 500 km radius from Simpevarp. Small circles have a radius of 100 km around the Sites, b) Earthquakes recorded from 1375 to 2005 (Bödvarsson et al. 2006, and c) The seismicity of Norway and surrounding areas, 1985-2005 (the Norwegian National Seismic Network, NNSN, known and probable explosions are not included in the map; Bøttger Sørensen 2006).

number of observers (density of inhabitants trough time) in the different areas. The annual record of earthquakes in the SNSN-catalogue during the short period 2004-2007 is comparable, although some variations do occur (Fig. 2-16).

In Sweden earthquakes, as displayed by the SNSN archive, show:

- A vacancy of earthquakes in the inland of central Sweden.
- Dispersed and scattered distribution of earthquakes in southern Sweden and in large parts of the Norrland inland.
- Enhanced seismic activity in the north of Scandinavia where the post-glacial faults are located (e.g. Pärve, Landsjärv, Skellefteå).
- Enhanced seismic activity within a NNE-SSW trending domain that is located along the coast of Norrland and which extends southward, although less well expressed, across southwestern Sweden to Skagerrak.

Earthquakes east and west of the NNE-SSE domain, up to a distance of c. 75km, have a tendency to line up parallel to the domain. This domain, centred at Höga Kusten (at Kvarken, cf. Figs. 2-13, 2-16, 2-17a, 2-17b) has the characteristics of active post-glacial faulting.

In northern Uppland, at the location of the SKB Forsmark Site, the number of earthquakes is low and most frequently they occur along an ENE-WSW trending zone in Gävlebukten (a bay) northwest of Forsmark. Earthquakes closer to Forsmark are recorded along WNW-ESE trending deformation zones. Earthquakes occur also along a N-S trending incision located in the sea west of Åland (western boundary of a down-faulted block with Precambrian, Jotnian sandstones). Very few seismic events have been recorded in the coastal areas of Småland where the SKB Simpevarp/Laxemar Site is located. Some of these occurred below Öland.

It is found that continental intraplate earthquakes are episodic, clustered and migrate (Stein 2007). It is clear that earthquakes are related to displacement along tectonic structures and it may be possible that earthquakes recorded today are "aftershocks of larger past events" (Stein 2007). Hough (2007) found that displacement along existing tectonic structures may be triggered up to a distance of up to 200km from a large earthquake (M>7) when the structures are located in areas of local stress concentration. Kafka (2007) found that future earthquakes have a higher probability to occur at a distance of some tens of kilometres away from a past earthquake than within half that distance. Swafford and Stein (2007) address the uncertainty in the record of earthquakes and point out that many of the irregularities seen in the distribution of earthquakes in time and space along a structure can be due to the short sampling period. They also point at that the future large scale earthquakes in a "seismic zone" may occur outside areas of present seismic activity. However, SNSN data show a tendency that minor earthquakes may migrate along structures (cf. Tirén and Beckholmen 2007).

Distortion of Quaternary sedimentary structures induced by paleoseismicity has been described, e.g. from areas in northern Fennoscandia (Lagerbäck 1990, Sutinen et al. 2007) along the coast of the Bothnian Sea (Mörner et al. 2000, Mörner 2003) and in the Stockholm area (Tröften 2000). Mörner (2003) has listed palaeoseismic events in Sweden (late to post-glacial, M>5 and affected areas). Submarine earthquakes may cause tsunamis and thereby be traceable in distorted strata far from the epicentre. The largest PGFs are estimated to have had a magnitude greater than 8. As a comparison, an earthquakes (M_w=8.1) occurred off the coast of Antarctica in 1998 (Tsuboi et al. 2000) and was interpreted to be the response to a change in the load of the ice mass, i.e. a post-glacial fault.

2.6 Regional rock stress

The state of rock stress in the Earth's crust of the Baltic Sea region (cf. Fig. 2-18) is caused by the following processes and mechanisms:

- Plate tectonics, and in particular the ridge push from the Mid-Atlantic Ridge, differential horizontal stress. - Regional component.
- Isostacy, loading from deposition of sediments and glaciers, glaciation, and unloading from deglaciation and erosion. - Regional component
- The weight of the overlying rock, lithostatic stress. - Local component.

The regional stress is reflected in the seismicity (cf. Dehls et al. 2000). World-wide stress measurements are stored in the World Stress Map – project (WSM) at the Heidelberg Academy of Sciences and Humanities, University of Karlsruhe in Germany (http://www-wsm.physik.uni-karlsruhe.de/index.html), Fig. 2-18.

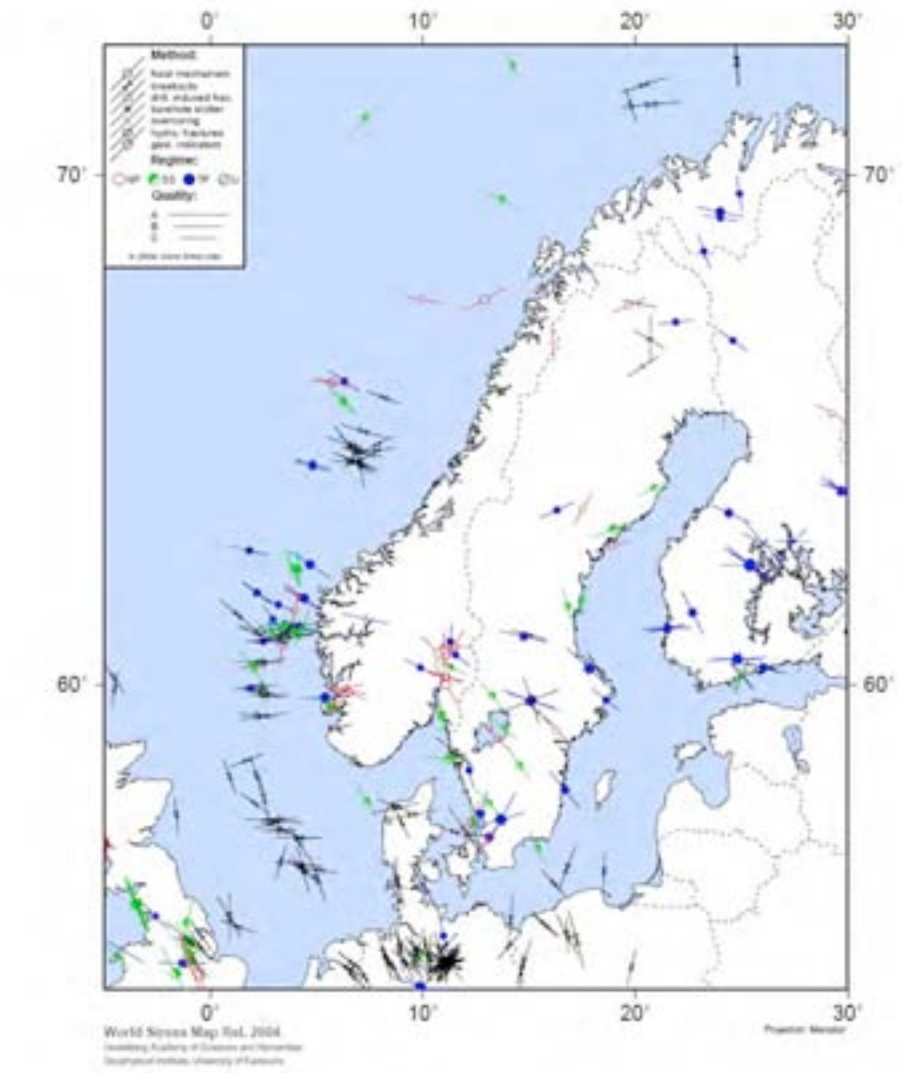


Figure 2-18. Scandinavian stress map, after Reinecker et al. (2004). Colours indicate stress regimes with red for normal faulting (NF), green for strike-slip faulting (SS), blue for thrust faulting (TF), and black for unknown regimes (U). Lines represent the orientation of maximum horizontal compressional stress (SH), line length is proportional to quality.

The orientation of the regional rock stress is, in general terms, related to the spreading along the Atlantic ridge, but also to the orientation of regional tectonic structures. In south central Sweden the main horizontal stress is mainly oriented NW-SE, while it shifts to be subparallel to the Norrland east coast of middle Sweden, i.e. line up along the long axis of the uplift ellipse and the domain of enhanced seismic activity. In southern Finland the main stress is trending approximately E-W, while in other parts of Finland the stress is more NW-SE. In the southern Baltic the main stress direction is subparallel to N-S trending faults. The stress regime can also be inferred from earthquake focal mechanisms, Fig. 2-19.

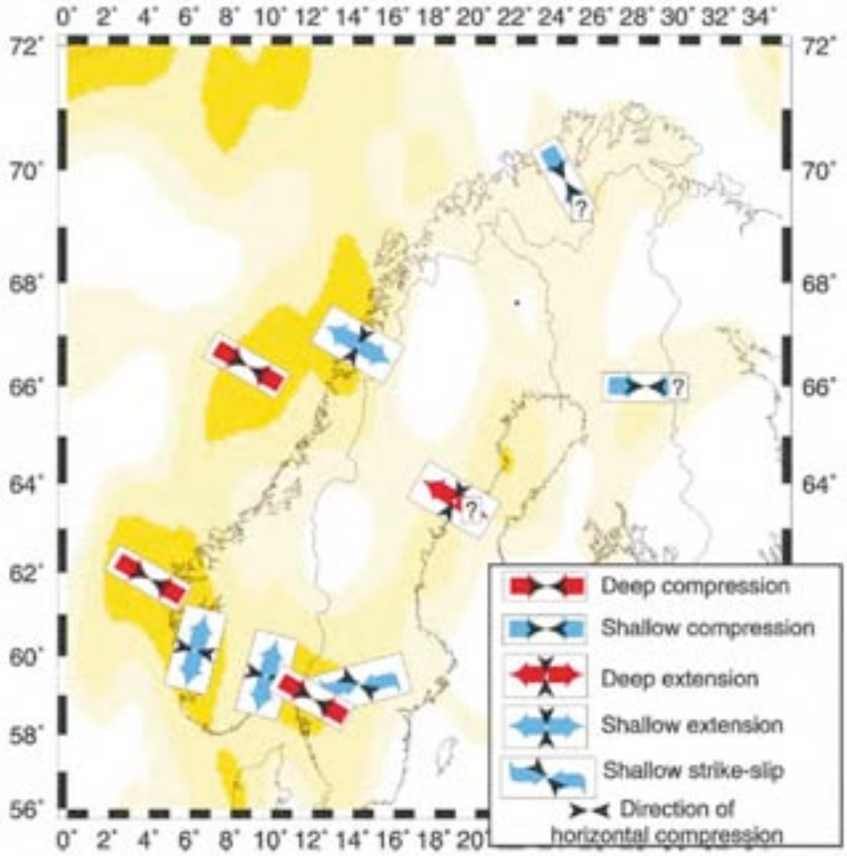
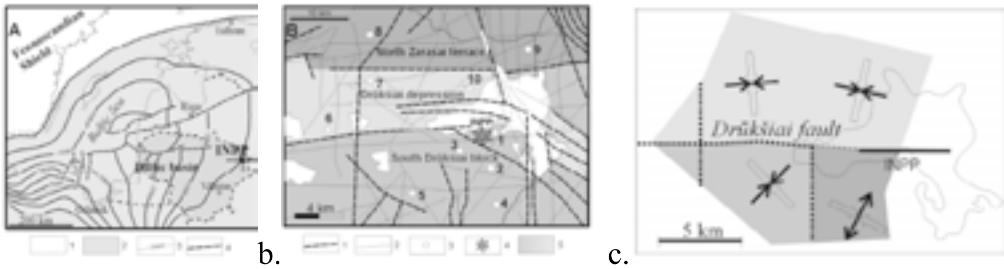


Figure 2-19. Stress directions, type of faulting and focal depths synthesized from earthquake focal mechanisms and in situ stress measurements. Areas with less data are indicated by question marks. The yellow shading indicates intensity of seismicity (in Fjeldskaar et al. 2000, based on Hicks et al. 2000).

An example of local variation of rock stresses, both with regard to their orientations and types, is shown in Fig. 2-20. The relation between the magnitude and orientation of the local rock stress and character of existing bedrock structures influences the stability of an area. Another example is the study by Kaiser et al. (2005) where they show recordings of present day displacement along faults in a fault system in northern Germany. The area is located south of the TESZ, thus just outside the Fennoscandian Shield. However, the measures give an indication of the order of displacement that may occur, Fig. 2-21, and how the type of faulting is related to the regional stress field, cf. Fig. 2-18.



a. b. c.

Figure 2-20. Variation in stress orientation within adjacent rock blocks, an example from Lithuania (Šliaupa et al. 2006): a) Regional setting, displaying major faults and depth to the basement, b) Local faults in the Ignalina area, and c) Rock stress in rock blocks.

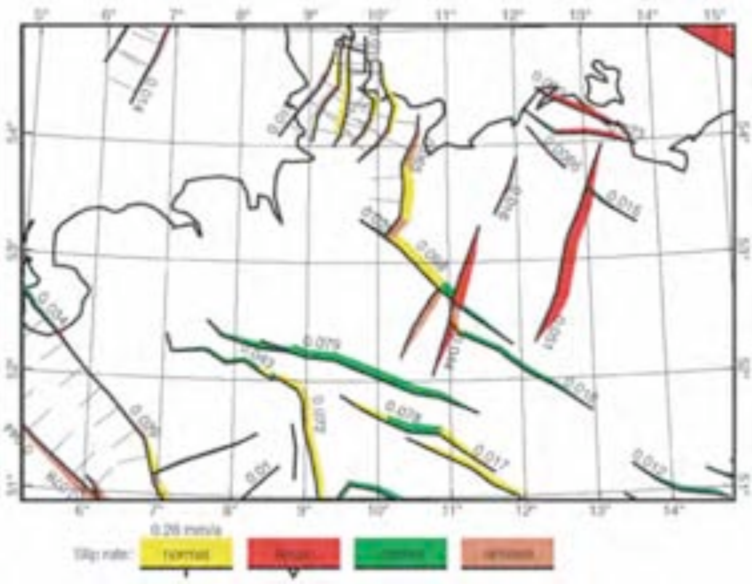


Figure 2-21. Variation in displacements (sense and rate) along faults of various orientations in the North German Basin – insights from thin shell FE-modelling based on residual GPS-velocities (Kaiser et al. 2005). The regional stress field is given in Figure 2-18.

2.7 Impacts

All recorded impacts are located on land or close to the coast, Fig. 2-22. The impacts at Lumparen on Åland and Björkö in Mälaren are the two detected closest to the SKB Forsmark Site (90km and 120km) and the impact at Hummeln the closet to the SKB Laxemar Site (c. 20km).

The effect of an impact may be relatively local but can also have a regional effect depending on size and inclination of the incoming meteorite. Impacts in water-covered areas may cause tsunamis and disturbances in soft sediments far away from the actual impact location, resembling the effect of post-glacial faulting.

a.  b. 

Figure 2-22: Impact structures in the Baltic area: a. Henkel et al. (2004) and b. Dypvik et al. (2008).

2.8 Datum surfaces

In structural mapping reference structures are of great importance to identify a fault and derive a relative age. It is an advantage if such a structure has a regional extent and a known age. In the Baltic area there are four major datum surfaces:

1. The sub-Cambrian peneplain.
2. The base of the Devonian sediments.
3. The base of the Mesozoic sediments.
4. The base of the Quaternary sediments.

Minor reference surfaces are internal bedding planes in sedimentary rocks and soft sediments.

In the Fennoscandian Shield the bedrock is dominated by Precambrian rocks and an extensive peneplain of late Precambrian age is still mappable within vast areas in the shield (Rudberg 1954, and Elvhage and Lidmar-Bergström 1987; cf. Fig. 2-23). The formation and preservation of a peneplain (Phillips 2002), is extraordinary. A peneplain is the outcome of a long period of tectonic stability, a low-relief erosion surface worn near to base level, formed during relative constancy in sea level, climate, and other factors that influence erosion and deposition of erosion products and it truncates all types of rock types and has sub-continental extent (Phillips 2002). The survival of the sub-Cambrian peneplain is however due to the fact that it has been covered by sediments for much of its existence and in many parts uncovered from the much softer cover rocks fairly recently

The base of the Devonian sediments forms an angle unconformity to the lower Palaeozoic sediments and is generally less faulted than the underlying sequence of sedimentary rocks; the older deformation in the sedimentary rocks is mainly Caledonian. The Mesozoic unconformity is found in the southern part of the Baltic Sea and the rocks above the unconformity is dominated by Cretaceous limestone; the unconformity is related to the Alpine deformation.

The latest regional unconformity is the base to the Quaternary sediments. The glacial erosion during the latest glaciation is in many areas found to be relatively restricted (cf. Påsse 2004, and Lagerbäck 2007). The variation in the extent and thickness of an inland ice and its basal temperature are some parameters that effect the erosion by the ice of the substratum.

The latest inland ice reached a calculated thickness of approximately 2700m (Svendsen et al. 2004), the thickest parts located above the Gulf of Bothnia approximately 14 000 years ago. The ice had a thickness-axis that trended ENE-WSW, i.e. slightly oblique to the long-axis of the present uplift in Scandinavia which is more NNE-SSE (Fig. 2-12). However, the land area west of the Bothnian Sea - Gulf of Bothnia was the last area to be deglaciated and 9500 years ago it was still glaciated (Lundqvist 1994). The map of the deglaciation (Lundqvist 1994) contributes to the dating of post-glacial faults.

Figure 2-23. Denudations surfaces in Sweden (Elvhage and Lidmar-Bergström 1987).

2.9 Global to regional geological reconstructions

A global reconstruction gives perspective on the geological evolution of an area (cf. Torsvik and Steinberger 2008, Torsvik et al. 2008). A global reconstruction is a synthesis of available geoinformation (e.g. palaeomagnetism; Meert and Torsvik in press, Steinberger and Torsvik 2008). It considers the plate motions and thereby the geographical position of an area in a global perspective, also the timing of tectonic events and the direction of deformation forces. The reconstructions give that the plates have to adjust their shapes continuously according to the geoid and the contacts to other plate boundaries (e.g. continent-continent collisions and fragmentation), Fig. 2-24. The visualization of the plate tectonic models can be found on the net (e.g. http://www.geodynamics.no/platemotions/500-400/ and references therein, http://www-sst.unil.ch/research/plate_tecto/alp_tet.htm) and in articles (focussed on Fennoscandia; e.g. Hartz and Torsvik 2002**,** Cocks and Torsvik 2005, 2006, and globally; e.g. Stampfli and Borel 2002). Lahtinen et al. (2008) has reconstructed the structural evolution of the early Proterozoic core of the Svecofennian Shield (2.5 to 2.0 Ga) and the accretion during the Svecofennian orogeny (1.93 to1.78 Ga). Väisinen and Skyttä (2007) presented a regional overview of reactivations of shear zones in southwestern Finland in relation to changes in the regional stress-field; from a contractional stage between c. 1.83 to 1.79 Ga to repeated extensional stages at c. 1.79 to 1.77, 1.64 to 1.55, and 1.26 Ga. All these stages of deformation involve block-faulting with shifts in the sense of displacements. The successive opening directions of the Atlantic have shifted (Mosar et al. 2002) which resulted in changes in the regional stress orientation in Fennoscandia (Fig. 2-26). The geological evolution of the Baltic Sea region is the objective of the main report.

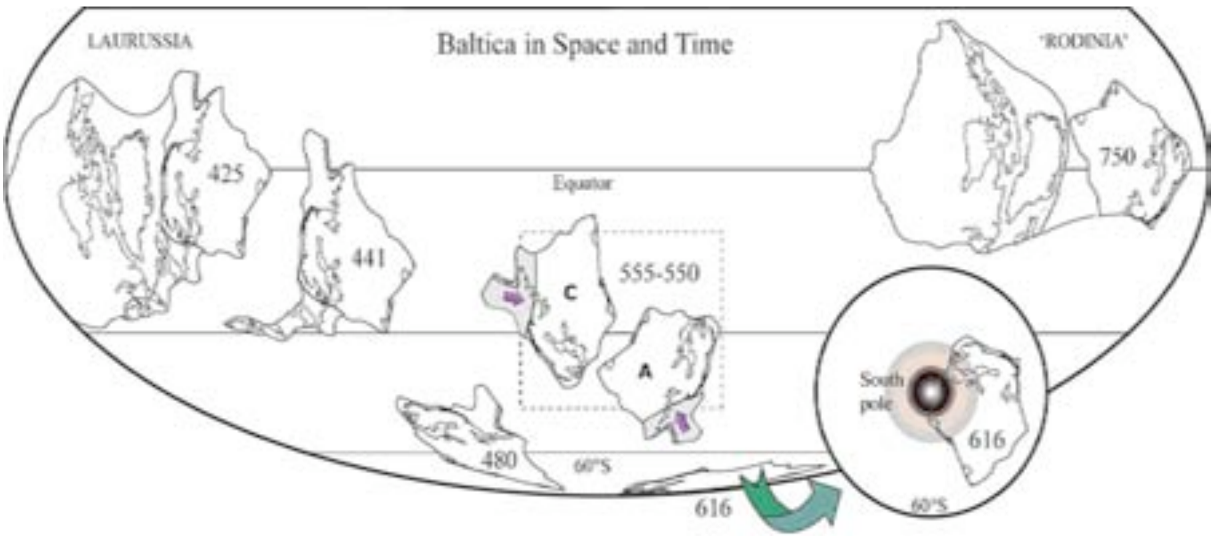


Figure 2-24. Progressive palaeolatitudes of Baltica and contiguous terranes through time, 750 to 425 Ma ago (Cocks and Torsvik 2005). Geological events (Ma): 620 Varangian glaciation, 530 Timanian, 490 Finnmarkian and not included in the figure are 410 Shelveian; Closure Tornquist Sea, Baltica-Avalonian collision, 400 Scandian; Closure Iapetus Ocean, Formation of Laurussia, 300 Variscan: Pangea Assembly, Laurussia-Gondwana collision, and 30 opening NE Atlantic (Hartz and Torsvik 2002).

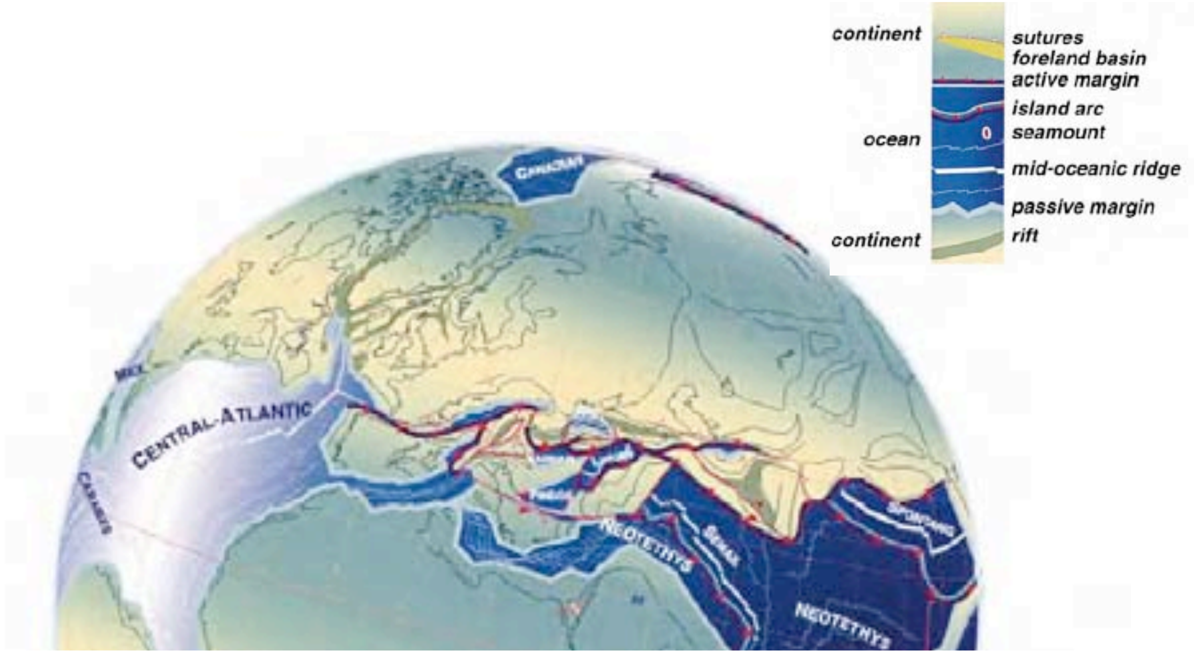


Figure 2-25. A plate tectonic model by Stampfli and Borel (2002) displaying the plate configuration 135 Ma ago (the figure belongs to a series of figures showing plate tectonics during Palaeozoic and Mesozoic time).

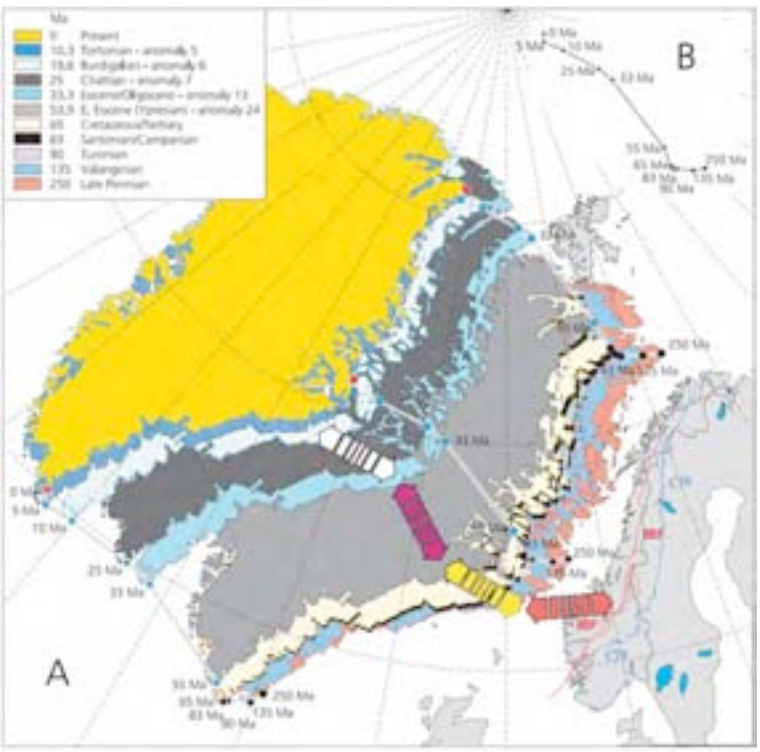


Figure 2-26. The opening of the Atlantic: the dots and connecting lines show the trajectories of three distinct points on Greenland (Mosar et al. 2002).

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