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Crustal structure and regional tectonics of SE Sweden and the Baltic Sea

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ABSTRACT

In this desk study, the available geophysical and geological data on the crustal structure and regional tectonics of the wider surroundings of the Äspö site (SE Sweden and adjacent parts of the Baltic Sea) are compiled and assessed. The aim is to contribute to the knowledge base for long-term rock mechanical modelling, using the Äspö site as a proxy for a high-level radioactive waste repository site in Swedish bedrock. The geophysical data reviewed includes two new refraction/wide-angle reflection seismic experiments carried out within the EUROBRIDGE project, in addition to the numerous earlier refraction seismic profiles. The BABEL normal-incidence deep seismic profile is also considered. New geological data, presented at the EUROBRIDGE workshops at Oskarshamn (1996) and Vilnius (1997), and in recent SGU publications, are reviewed for the same area. In combination with the seismic data, these provide a base for interpreting the present composition and structure, and the Palaeoproterozoic-Mesoproterozoic evolution, of the crustal segment within which the Äspö site lies - the Småland mega-block This is characterized by having undergone little regionally significant deformation or magmatism since Neoproterozoic times (the last 1000 million years). It is shown that, at this scale of observation (of the order of 100 km), the long-term rheology of the lithosphere can be argued from a relatively tight observational network, when combined with the results of earlier SKB studies (seismo-tectonics, uplift patterns, state of stress, heat flow) and published research. Although many uncertainties exist, the present state of knowledge would suffice for first exploratory calculations and sensitivity studies of long-term, large-scale rock mechanics.

SAMMANFATTNING

I föreliggande studie har tillgängliga geofysiska och geologiska data överjordskorpan sammanställts och sammanvägts med den regionala tektoniken från ett vidare område kring Äspö 'Hard Rock Laboratory', (SÖ Sverige och angränsande delar av Östersjön). Studien är ett bidrag till den kunnskapsbas, som utgör grunden för modellering och för uppbyggandet av en långsiktig bergartsmekanisk modell, där Äspö bergartsmekaniska laboratorium utgör modellen för ett lager av högaktivt radioaktivt avfall. I de geofysiska data som presenteras här ingår två nya refraktionsseismiska vidvinkelprofiler som genomförts inom projektet EUROBRIDGE samt ett antal tidigare genomförda seismiska profiler. BABEL djupseismiska reflexionsprofil är även medtagen. Nya geologiska data, presenterade vid EUROBRIDGE arbetsmöte i Oskarshamn (1996) och Vilnius (1997) liksom i nyligen utgivena SGU publikationer, har även sammanställts för samma område. Tillsammans med de seismiska data utgör dessa data basen för tolkningen av den nuvarande sammansättningen och strukturen, liksom av den Palaeo- och Mesoproterozoiska utvecklingen hos det jordskorpesegment inom vilket Äspö laboratoriet ligger, det Småländska megablocket. Detta område karakteriseras av en obetydlig regional deformation eller magmatism efter Neoproterozoisk tid (de senaste 1000 millioner år). Det kan visas att, för den här gällande storleken av ifrågavarande jordskorpesegment (av storleksordning 100 km), den långsiktiga rheologiska utvecklingen hos litosfären kan bedömas utifrån ett relativt tätt observationsnät, när det kombineras med resultat från tidigare SKB studier (seismo-tektonik, landhöjningens mönster, stress tillstånd, värmeflöde) och redan publicerade forskningsresultat. Även om många osäkerheter återstår bör den nuvarande kunskapsnivån vara tillräcklig för en första beräkningsmodell av och sensitivitetsstudie över den långsiktiga och storskaliga bergartsreologin.

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SUMMARY AND CONCLUSIONS

The present report summarizes current geological and geophysical knowledge on the crustal structure of SE Sweden and adjacent parts of the Baltic Sea, to provide a regional tectonic context relevant to the problem of radioactive waste disposal. No disposal site is at present proposed in this region, but at its centre lies SKB's **Äspö Hard Rock Laboratory**, the surroundings of which have been the subject of intensive research in the past decade. The starting point of this desk study has been the availability of new geophysical and geological data in connection with the EUROBRIDGE project. The aim of the present work was to summarize this new information in such a way that it could be combined with the other types of data and integrated into a knowledge base capable of contributing to radwaste-relevant studies.

The **EUROBRIDGE project** is an integrated component of the EUROPROBE programme, a lithosphere dynamics programme concerned with the origin and evolution of the European continental crust and upper mantle, supported by the European Science Foundation. EUROBRIDGE focusses on the Precambrian crustal evolution of the East European Craton and includes a wide spectrum of research activities. These are bound together by an international **deep seismic sounding (DSS) experiment** along a 1500 km long, NW-SE trending transect, a seismic "bridge" between the Swedish mainland just north of the Äspö site and the Ukrainian Shield. The first part of the "bridge" - between Sweden and the Lithuanian coast - was shot in October 1994. At the same time, a supplementary NNE-SSW profile was shot in Swedish coastal waters - the so-called "coast profile" - from off Oskarshamn towards the Åland islands. First results from these refraction/wide-angle reflection seismic experiments, together with new results from geological and geochemical research within the project, were presented at two EUROBRIDGE workshops, at Oskarshamn in 1996 and in Vilnius in 1997. An attempt is made in this report to combine these with published data, in order to assess the present state of knowledge of the crustal structure and regional tectonics of the wider surroundings of the Äspö site.

The **seismic data**, including the results of the EUROBRIDGE DSS experiments, are summarized in **Chapter 2 (Crustal structure)** of this report, and compared with the published results from earlier experiments. In addition, the only available normal-incidence reflection seismic (CDP) images of the crust below the Baltic Sea are described (BABEL experiment, 1989), since these give the only physical images of crustal structure for comparison with surface geology (discussed in Chapter 4). The main **conclusions** from the compilation of the earlier DSS data, complemented by the new data from EUROBRIDGE are as follows:

(1) The DSS profiles are **velocity models**, produced by different research groups using different experimental conditions, modelling procedures and philosophies. Comparison shows many discrepancies, which are partly a reflection of this diversity, indicating that the plotted features are subject to a high degree of uncertainty.

(2) Nevertheless, the **depth-to-Moho** map confirms a general feature which is well-known, that the northern part of the Äspö region is underlain by thicker crust than the southern part. The area of thicker crust (45-55 km) in the north is part of a regional Moho depression, with the crust thinning to less than 40 km southwards (under Hanö Bay) and westwards (under lake Vänern), and with less pronounced crustal thinning to the north and east.

(3) No obvious **structural trend**, e.g. an elongation of the Moho depression in NW-SE direction, as suggested by some workers, can be distinguished in the present data. If any trend were to be interpreted, it would have to be NNE-SSW, since the EUROBRIDGE coast profile showed a significantly shallower Moho discontinuity than the lines on either side. Also, the proposed **"Moho step"** below the Äspö region along the FENNOLORA line, which was originally thought to image a deformation zone connected through the crust to a major EW-striking shear zone at the surface, and which became integrated in the EGT results, is not supported either by the BABEL data, or by the EUROBRIDGE coast profile.

(4) The disagreement between the several profiles with regard to the structure of the crust (level and number of **intra-crustal discontinuities**) is too great to allow any generalizations. However, an interesting feature of both the EUROBRIDGE profiles and earlier DSS data is the identification of a lowermost crustal layer with velocities > 7 km/sec. There is a tendency for the Moho depth variations to be compensated by variations in the thickness of high velocity material at the base of the crust, so that higher crustal discontinuities do not reflect the Moho depth variations.

Chapter 3 (Regional tectonics) describes the geological framework of the Äspö region based on surface observations, as presented at the Oskarshamn and Vilnius EUROBRIDGE workshops and in recent SGU compilations. It is not intended as an exhaustive review. The aim is to give some background for the interpretation of crustal structure and evolution, discussed in Chapter 4. The main conclusion is that the Äspö region lies within a major crustal unit, the **Småland mega-block**, within which the effects of three main phases of tectonic activity can be distinguished:

Palaeoproterozoic - accretionary phase and Svecokarelian orogeny (formation of the crust, synorogenic magmatism, ductile shearing)
Mesoproterozoic - cratonization phase (crustal consolidation, anorogenic magmatism, uplift/erosion)

Neoproterozoic and Phanerozoic - post-cratonization phase (oscillating uplift/erosion/subsidence, brittle deformation on a small scale - no large-scale structures)

The distinction of the Småland mega-block is based on the apparent lack of regionally significant Neoproterozoic and Phanerozoic effects ("regionally significant", as opposed to the ubiquitous local fracturing, which is not considered in this report). The deep seismic images outlined in Chapter 2 mainly reflect Palaeoproterozoic crust-forming and crust-reworking processes, dominated by **magmatism** in the lower crust and upper mantle (magmatic underplating). These continued into the Mesoproterozoic cratonization phase. With the low degree of resolution attainable in deep seismic surveys, no effects of younger age are likely to be distinguishable.

Of particular interest for the search for radioactive waste disposal sites in Sweden is the question of the geometry, orientation and mechanical significance of **ductile shear zones** (narrow, regionally extensive zones of intense ductile deformation characterized by the occurrence of mylonitic rocks), and their propensity for acting as zones of weakness during later phases of brittle deformation. The orogenic regime which accompanied the development of the ductile shear zones, such as the Loftahammar zone in the Äspö region, developed in response to the decoupling and sinking of lithospheric mantle and upwelling of asthenosphere, causing partial melting and magma production to occur far up into the crust. Continued shortening in a N-S direction was accomodated by "lateral extrusion" or "tectonic escape of continental lithospheric segments" rather than thrust-determined crustal-thickening tectonics. This means that the presently exposed subvertical ductile shear zones are **not expected to continue to great depth**, but rather that the movements at depth were accomodated by distributed strain within the largely molten or semi-molten substrate.

With regard to **brittle reactivation**, observations show that the localization of brittle deformation along pre-existing ductile shear zones in southern Sweden is **a tendency, but not a necessity**. Reactivation depends on the shear zone having a favourable orientation with respect to the potentially reactivating stress field, and on the presence or absence of other features, notably regionally sub-planar lithological heterogeneities, which provide weaker and/or more favourably orientated stress guides. The complex pattern of the post-Silurian faulting to the west and north of the Småland mega-block could be interpreted as due to (1) a complicated stress pattern (e.g. doming), (2) to a complex pattern of pre-existing structures, (3) to the superimposition of fractures of different ages, or a combination of all three.

In **Chapter 4 (Discussion)**, the main question addressed is: what parameters can be defined at the regional (100 km) scale which may be relevant for problems of **large-scale long-term rock mechanics**, based on the data reviewed in Chapters 2 and 3. With regard to this question, it is clear that this study is complimentary to a series of earlier works commissioned by SKB. Here, we confine ourselves to argued interpretations based on the large-scale geophysical and geological features of the crust.

We discuss first the interpretation of the seismic data in terms of bulk rock composition and deep structure. This leads to a review of present ideas on **crustal evolution**, combining the geophysical and geological data and interpretations with general ideas on Precambrian crust formation and remobilization. The geological model for the Småland mega-block which emerges is then compared with data relevant to large-scale rock mechanics ("bedrock stability"), particularly the present thermal and mechanical conditions which, together with crustal composition and structure, govern the **long-term rheology** and flexural rigidity of the crust. A tentative **conclusion** is that, because of the higher heat flow, the long-term strength of the lower crust beneath southern Sweden and the Baltic Sea is significantly lower than in central and northern Sweden, and that this will have to be taken into account in modelling, for instance, the tectonic effects of future ice ages. The data base for the Äspö region is becoming sufficiently good to allow large-scale **rock mechanical modelling**. The composition, structure and rheology of the lithosphere can be argued from a relatively tight observational network, as outlined in this report. The seismo-tectonics, uplift patterns and state of stress have been described in considerable detail in earlier SKB studies. Hence, although considerable uncertainties still exist (strength properties of fault zones, shear stiffness of fractured upper crust, depth limit of hydromechanical effects, pressure-dependence of frictional failure, strain softening v. strain hardening at depth, etc.), the present state of knowledge may suffice for preliminary, exploratory calculations and sensitivity studies.

1. INTRODUCTION

The present report summarizes current geological and geophysical knowledge on the crustal structure of SE Sweden and adjacent parts of the Baltic Sea, to provide the regional tectonic context relevant to the problem of radioactive waste disposal. No disposal site is at present proposed in this region, but at its centre lies SKB's Äspö Hard Rock Laboratory (HRL), the surroundings of which have been the subject of intensive research in the past decade (see SKB 1996). Several major experiments, including the testing of a (non-nuclear) prototype spent fuel repository, will be carried out at this site. Within this R&D programme, structural modelling of the fractured basement rocks will play a central rôle in hydrogeological and rock mechanical simulations, as it will, presumably, at the final repository site in Sweden, when this has been selected. Up to now, structural modelling has mainly been confined to the scale of the repository itself and its immediate surroundings, using core/borehole/tunnel data and local geophysics (e.g. Wikberg et al. 1991, Munier 1993a, Almen et al. 1994) . Nevertheless, different aspects of the regional picture have also been treated (e.g. Kornfält & Larsson 1987, Tirén & Beckholmen 1992, Munier 1993b, Muir-Wood 1993, 1995, Larson & Tullborg 1993) . As a complement to the latter works, the present report concentrates on a particular aspect of the regional setting of the HRL, namely the large-scale structure of the Earth's crust and its relation to surface geology. The starting point has been the availability of new geophysical and geological data in connection with the EUROBRIDGE project, which is part of the international EUROPROBE programme, as outlined below. The aim of the present work has been to summarize this new information in such a way that it could be combined with the other types of data and integrated into a knowledge base capable of contributing to radwaste-relevant studies. A short discussion from this point of view is added as Chapter 4.

The immediate incentive for the present report was the 1st workshop of the EUROBRIDGE project, held at Oskarhamn, 8-15 June, 1996. The workshop consisted of two and a half days of scientific presentations (detailed in the abstract booklet, Oskarshamn 1996) and three and a half days of geological excursions, including a visit to the recently opened Äspö laboratory. A second workshop was held in Vilnius-Dudingiai, Lithuania, from 12-16 June, 1997, and some of the results reported there (detailed in the abstract booklet, Vilnius 1997) are also included in this report. The EUROBRIDGE project is an integrated component of the EUROPROBE programme, a lithosphere dynamics programme concerned with the origin and evolution of the European continental crust and upper mantle. EUROPROBE evolved from the International Lithosphere Programme and since 1992 has been supported by the European Science Foundation. "EUROPROBE is dedicated to carrying out a new generation of major projects that will improve our understanding of the tectonic evolution of the Earth's crust and mantle, and the dynamic processes which controlled this evolution through time" (Gee & Zeyen 1996). EUROBRIDGE has been designated a major project within the programme, with the title "Palaeoproterozoic Accretion of Sarmatia and Fennoscandia". It focusses on the Precambrian crustal evolution of the East European Craton and includes a wide spectrum of research activities (see overview in Gee & Zeyen 1996). These are bound together by an international deep seismic sounding (DSS) experiment along a 1500 km long, NW-SE trending transect from SE Sweden to the Ukrainian Shield (Fig. 1-1). Preliminary results from the northwestern end of this major new DSS transect (SE Sweden and Baltic Sea) are presented below. EUROBRIDGE is one of a series of major projects concerned with the deep structure of the East European Craton

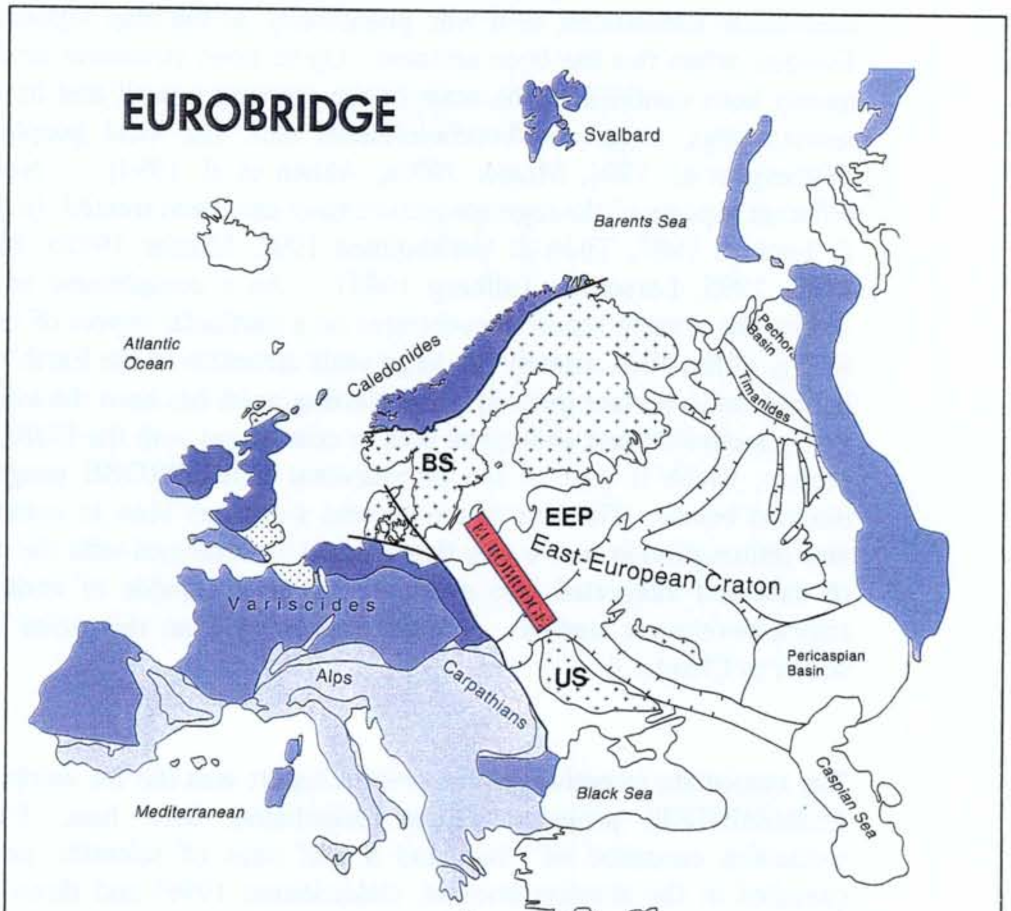


Fig. 1-1

Position of the main EUROBRIDGE profile within the European tectonic framework (from Gee & Zeyen 1996). BS = Baltic Shield, EEP = East European Platform, US = Ukrainian Shield: these constitute the East European Craton, which is bounded on all sides by Phanerozoic orogenic belts.

which are running at the present time, some under the auspices of EUROPROBE (SVEKALAPKO, GEORIFT, TESZ - see Gee & Zeyen 1996), some as part of the International Geological Correlation Programme (e.g. COPENA), and researchers involved in some of these were present at the Oskarshamn and Vilnius workshops.

The report consists of three chapters, following this introduction. Chapter 2 summarizes the results of the main seismic experiments which have been carried out in southern Sweden and the Baltic Sea. A main focus is on the EUROBRIDGE results, but these are compared with earlier DSS surveys (FENNOLORA, BABEL, etc.) and also with the BABEL near-vertical reflection seismic profile, which provides key data on deep crustal structure. In order to provide the geological background to interpretations of the seismic data, Chapter 3 focusses on the surface geology and its relation to crustal processes, both with respect to the formation of the crust in Palaeoproterozoic time and with respect to the later evolution of the crust from its stabilization (cratonization) in the Mesoproterozoic to the present time. The post-cratonization history suggests that the Äspö region lies wholly within a crustal segment which has been little affected by Phanerozoic events. This crustal segment we refer to as the Småland mega-block. In Chapter 4, the integration of the seismic data and geological information in Chapters 2 and 3 with other geophysical data is discussed, particularly with respect to estimating crustal rheology for use in large-scale rock mechanical modelling (for instance, in predicting the tectonic effects of past and future glaciations).

2. DEEP SEISMIC DATA

2.1 INTRODUCTION

Knowledge of the crustal structure of SE Sweden and the Baltic Sea is mainly derived from the results of wide-angle reflection/refraction seismic surveys (deep seismic sounding or DSS surveys) which have been carried out in the region over the past 20 years. The most recent ones are those integrated into the EUROBRIDGE project, which are not yet published and which are detailed below. Preliminary results were presented and discussed at the Oskarshamn and Vilnius workshops. A summary of these results, particularly of the 1994 and 1995 DSS surveys across the Baltic Sea and Lithuania, respectively, together with a first description of the 1994 cross-profile in Swedish coastal waters is given in Section 2.2. The locations of the profiles discussed are shown on Fig. 2-1. In Section 2.3, the published results of earlier DSS surveys are summarized and discussed in the light of the new EUROBRIDGE data. These surveys include the recent TTZ'92 survey (Makris & Wang 1994) and the BALTIC SEA profile (Ostrovsky et al.1994), as well as earlier experiments such as FENNOLORA (Guggisberg et al. 1991, Henkel et al. 1990), EUGENO-S (EUGENO-S Working Group 1988) and BABEL (BABEL Working Group 1993b, Barth & Klemperer 1996). During the BABEL survey, near-vertical deep seismic reflection data were acquired (common depth point or CDP data). These provide important additional insights into the seismic structure of the SE Swedish/Baltic Sea crust, as indicated in Section 2.4. The aim of this chapter is to summarize the geophysical data, in the first instance without detailed geological interpretation. Hence, the main result is a revised depth-to-Moho map for SE Sweden and the Baltic Sea, discussed in Section 2.5. General compilations of other types of geophysical data (gravity, magnetics, heat flow, etc.) are not detailed separately. These are to be found in the European Geotraverse book (Blundell et al. 1992) and in the geology volume of the National Atlas of Sweden (Fredén 1994), and will be referred in the discussion in Chapter 4.

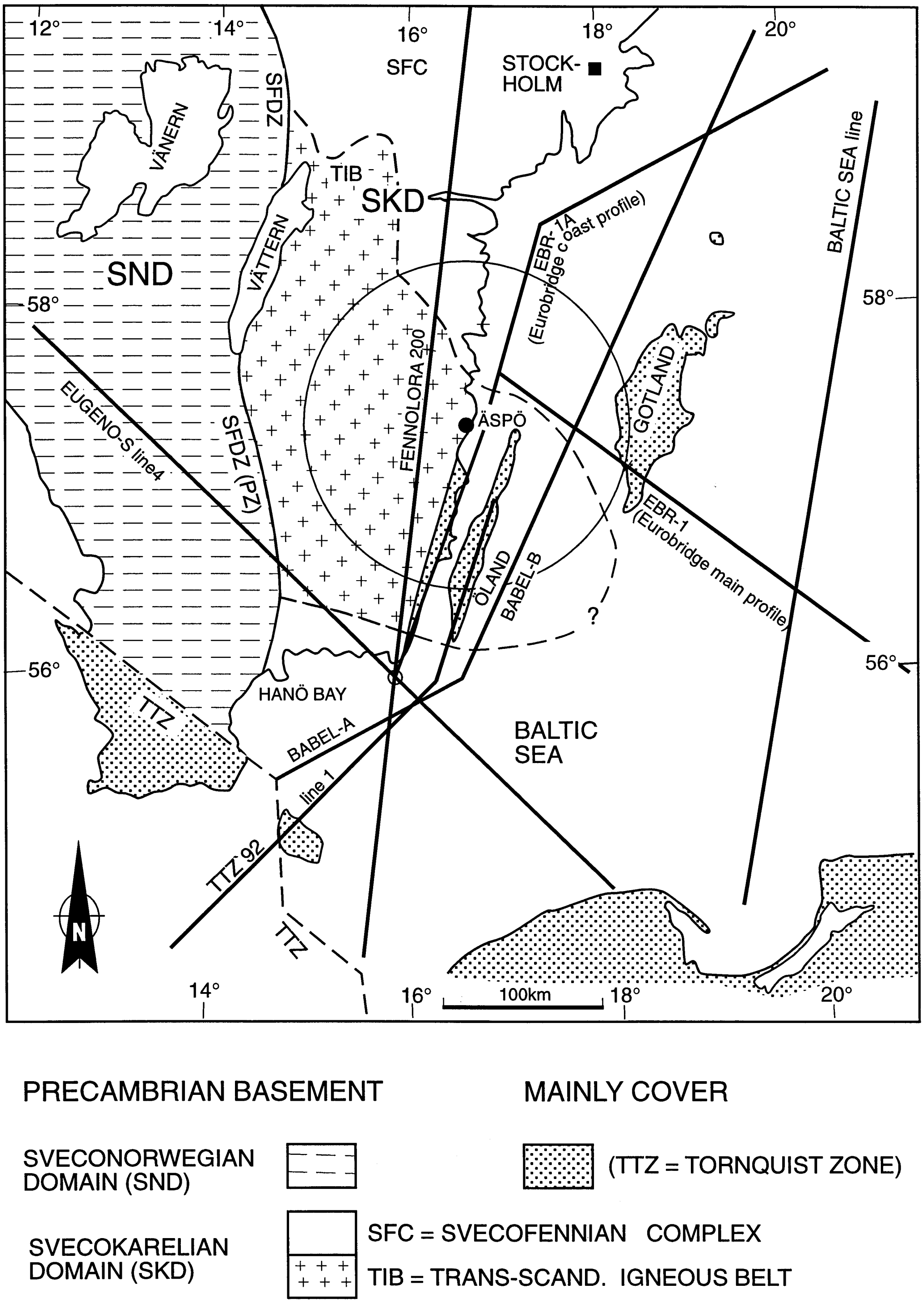


Fig. 2-1

Map of southern Sweden and the Baltic Sea, showing the position of the Äspö site and the location of the DSS (deep seismic sounding) surveys treated in the text. The wider surroundings of the Äspö site, marked by a circle of 100 km radius, will be referred to as the Äspö region to emphasize the scale treated in the present report. Abbreviations: SND - Sveconorwegian Domain, SKD - Svecokarelian Domain, SMC - Svecofennian Complex, TIB - Trans-Scandinavian Igneous Belt, SNDF - Sveconorwegian Deformation Front, PZ - Protogine Zone, TTZ - Tornquist-Teisseyre Zone (for geological background, see Chapter 3).

2.2 EUROBRIDGE DSS PROFILES

2.2.1 EUROBRIDGE main profile, EBR-1 (1994)

The EUROBRIDGE main profile, stretching for 1500 km from the Baltic Shield in SE Sweden to the Ukrainian Shield, forms the backbone of the EUROBRIDGE project. The first segment of this major DSS experiment, called here EBR-1, was carried out in October 1994 across the central Baltic Sea, along a line running NW-SE from the Swedish mainland at about Västervik to the coast of Lithuania, crossing the southern tip of Gotland (Fig. 2-2). The experiment was carried out by scientists aboard the Lithuanian research vessel, *R/V Vejas*, using a 60 l airgun source fired at 250 m intervals along the 270 km long profile. Recording stations were 18 ocean bottom seismographs (OBS) deployed along the offshore part of the profile and 8 land-based seismographs deployed along the NW end of the profile and its continuation on the Swedish mainland (Fig. 2.2). Unfortunately, the data quality from the OBSs was rather poor and the velocity model derived from the recordings (Makris et al. 1996) must be regarded as unreliable. However, the land stations produced good recordings (Lund & Lysynchuk,

Fig. 2-2

Location of the main EUROBRIDGE deep seismic sounding (DSS) profiles. The 1994 experiment across the Baltic Sea is called EBR-1 in the text and is shown on Fig. 2-3. Fig. 2-3 is constructed using the recording stations S1-S7 on land in southern Sweden because the records from the ocean bottom seismographs (OBS-1 to OBS-18) were poor. L1 shows the location of a large explosive charge used in the main experiment.

in Vilnius 1997), and these could be interpreted in terms of the velocity model shown on Fig. 2-3. Horizontal mid-crustal discontinuities, C1 and C2, are distinguished at the 18 km and 35 km levels, with velocities varying between 6.00 and 6.4 km/s in the upper crust, 6.5 and 6.8 km/s in the middle crust and 6.8 and 6.95 km/s in the lower crust. Between Gotland and the Swedish coast, the recordings indicate the existence of an anomalous lowermost crustal "root" with velocities > 7 km/s, below a deeper crustal discontinuity, C3. The Moho discontinuity to the southeast of the "root", M1, lies at a constant depth of about 44 km (Lund & Lysynchuk, in Vilnius 1977). A similar level is suggested immediately to the northwest of the "root", but further northwest it is not very well controlled.

In 1995, the EUROBRIDGE main profile was continued on land across Lithuania (Giese et al., in Vilnius 1997). According to the preliminary results, the crust in northwestern Lithuania shows mid-crustal discontinuities at 20 km and 30 km levels, similar to EBR-1. The Moho, M1, is defined by a sharp P-wave velocity jump from 6.9 km/s to about 8.3 km/s at around 44 km depth near the coast (as on EBR-1, Fig. 2-3), descending southeastwards to about 50 km at the Lithuania/Belarussia border. In addition, a clear reflection event is observed from an interface at 60-70 km depth within the upper mantle (intra-mantle discontinuity, M2).

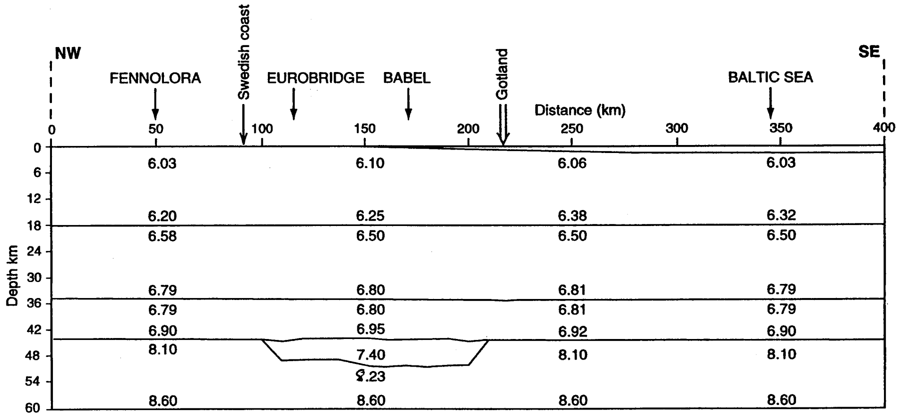


Fig. 2-3

Vp velocity structure of the EBR-1 profile (using on-land recording stations in southeastern Sweden, see Lund & Lyschynuk, in Vilnius 1997). Intersections with other seismic profiles marked: EUROBRIDGE = EBR-1A (the coast profile, Fig. 2-5), BALTIC SEA profile (Fig. 2-7), BABEL = BABEL-B profile (Fig. 2-8), FENNOLORA profile (Fig. 2-10). Note the flat Moho, M1, at about 44 km depth interrupted by the anomalous "root" between Gotland and the Swedish coast (cf. Figs. 2-5 and 2-8)

2.2.2 EUROBRIDGE coast profile, EBR-1A (1994)

In autumn 1994, a supplementary profile was shot in Swedish coastal waters, approximately at right angles to EBR-1, the "coast profile", here labelled EBR-1A (Fig. 2-1). The shooting vessel was the Russian research ship *Alexander Karpinsky* towing a 4 x 20 l airgun array along the track marked on Fig. 2-4, with shot points every 270 m along a total track length of 280 km. Seven recording stations were placed along the Swedish east coast and one in Finland (Fig. 2-4). For details of the experiment, and the data processing and modelling, see Lund & Smirnov (in press). This "coast profile" (Fig. 2-5), shows a similar seismic structure to EBR-1, with mid-crustal discontinuities, C1 and C2, at 17-23 km and 35-40 km depth, respectively, and a prominent Moho, M1. However, in contrast to EBR-1, anomalous lowermost crustal velocities were not modelled. M1 shows considerable depth variations along the profile, reaching maximum depths of ca. 50 km near, and northeast of, the bend in the profile, decreasing to 44 km at the northeastern end and to nearly 36 km in the extreme south (FENNOLORA shot point B, see below). At the crossing point with EBR-1, Moho depth is well controlled at 44 km, fitting well with the results of the main profile (Fig. 2-3). One feature is visible on the coast profile which was not picked up on EBR-1. An intra-mantle discontinuity is visible at about 62 km depth (M2), which is completely flat and does not mimic the depth variations in M1. Although not shown on Fig. 2-3 (EBR-1 velocity model based on land stations), M2 was distinguished on the OBS records as a flat discontinuity at 63-64 km depth (Makris et al. 1996), connecting with the intra-mantle reflector under Lithuania, noted above.

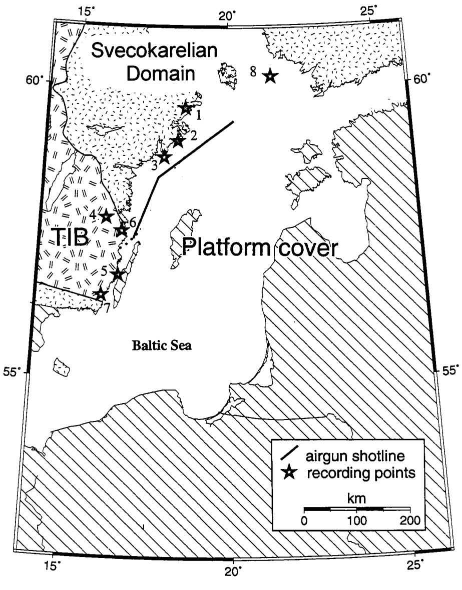


Fig. 2-4

Map of the Baltic Sea showing the ship trace of the EUROBRIDGE coast profile (called EBR-1A in the text, see Fig. 2-5) and the position of the recording stations on land (from Lund & Smirnov, in press).

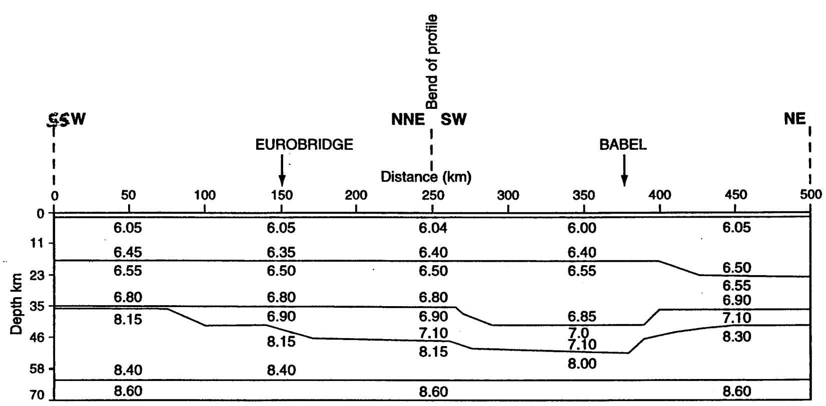


Fig. 2-5

Vp velocity structure of the EUROBRIDGE coast profile, EBR-1A (from Lund & Smirnov, in press). Intersections with other profiles are marked: EUROBRIDGE = EBR-1 (the main profile, Fig. 2-3), BABEL = BABEL-B profile (Fig. 2-8). Note the changes in Moho depth along the profile, with depths greater than 50 km north of the bend in the ship trace (cf. Fig. 2-4), not mimicked by the intra-mantle discontinuity, M2, at about 62 km.

2.3 EARLIER DSS PROFILES

2.3.1 TTZ'92 Profile I (1992)

The TTZ'92 marine DSS survey was targetted at the Tornquist-Teisseyre Zone which crosses the southern tip of Sweden in a NW-SE direction (cf. EUGENO-S Working Group 1988, Erlström et al 1997). The experiment was carried in September 1992 in the southern Baltic Sea (Makris & Wang 1994). Along profile I, 38 OBS and 20 mobile land stations recorded signals from an 80 l airgun source. The land stations in the north were spread along central and southern Öland. The northern extension of TTZ'92 profile I enters the Äspö region and intersects a number of earlier profiles (Fig. 2-1). From the area of intersection, it runs in a NNE direction and ends on central Öland, about 100 km south of the northwest end of EBR-1. This northern extension is the part of interest here (Fig. 2-6): as in the case of other profiles, discussed below, we concentrate on the crustal structure of the Äspö region, from Hanö Bay northwards.

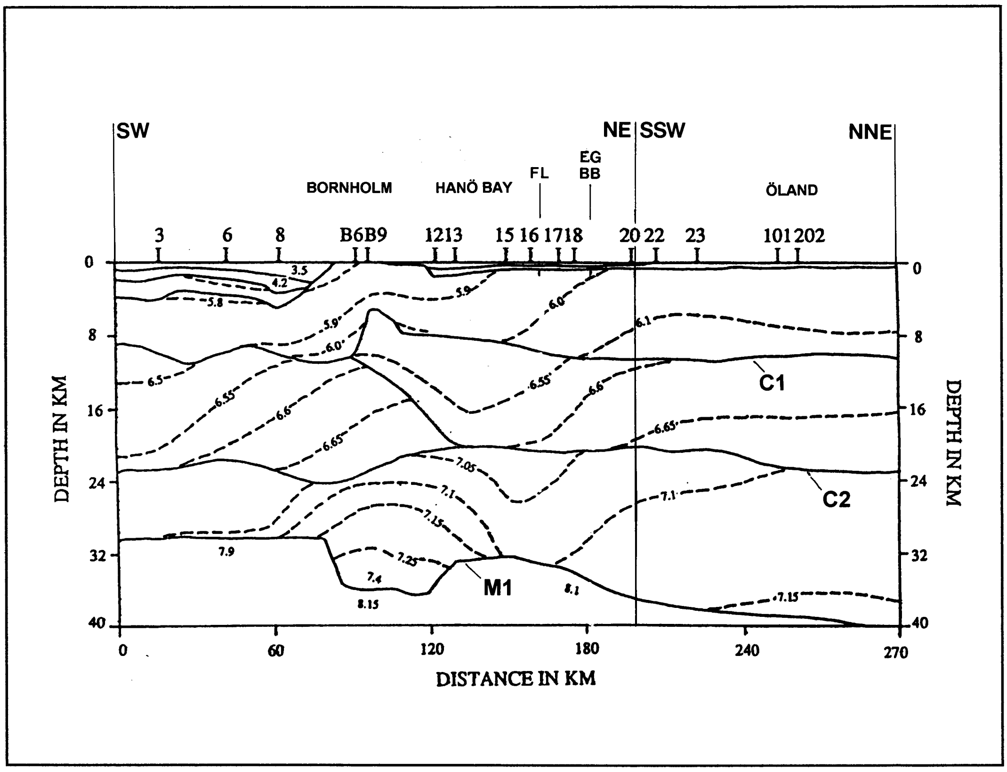


Fig. 2-6

Vp velocity structure of the TTZ'92 profile I, from Makris & Wang (1994). For location, see Fig. 2-1. Intersections with other seismic profiles are marked: FL = FENNOLORA profile (Fig. 2-10); EG = EUGENO-S profile 4 (Fig. 2-9); BB = BABEL profile (Fig. 2-8).

The velocity model of the northern part of TTZ'92I (Makris & Wang 1994) shows an upper crustal discontinuity at 10 km, rising to 8 km under Hanö Bay (C1), and a mid-crustal discontinuity at 23 km, rising southwards to 20 km (C2). The Moho, M1, rises from 40 km in the north to 33 km immediately south of Hanö Bay, where the complications of the Tornquist Zone are reflected in a sudden change in seismic structure. In the northern part of TTZ'92I, Vp velocities in the upper crust are 5.8-6.2 km/sec, in the middle crust 6.5-6.7 km/sec and in the lower crust 7.0-7.2 km/sec and the profile shows pronounced lateral velocity variations in all three layers (Makris & Wang 1994). Although the velocity model is more detailed, comparison with the closely parallel "coast profile", EBR-1A (Fig. 2-5), shows a general correspondence with regard to the depth and slope of the Moho, but no correlations between the intracrustal discontinuities.

2.3.2 BALTIC SEA Profile (1989)

The BALTIC SEA marine DSS survey was carried out during summer 1989 from the Russian research vessel *Professor Shtockmann* in the central Baltic Sea (Ostrovsky et al. 1994). The profile was run twice, with 2 OBS functioning in the northern part on Run 1 (100 km apart) and 3 OBS in the southern part on Run 2 (50 km apart), using a 120 l airgun as source with shots every 770m. The Moho discontinuity, M1, was well imaged and special tests were made to estimate the accuracy of the model, which showed that Moho depths were correct to +/- 1 km. M1 depth correlates well with that on EBR-1 at the crossing point (45 km depth) but the Vp values indicated are appreciably lower (7.8-7.9 km/sec, as opposed to 8.1-8.3 km/sec). M1 rises southwards and northwards from EBR-1 to 39 km depth (Fig. 2-7). The BALTIC SEA profile also revealed an intra-mantle discontinuity at approximately the same level as M2 on the OBS records along EBR-1 (60 km). Only weak intra-crustal discontinuities were identified, upper and mid-crustal features at 8-11 km and 17-23 km respectively, C1 and C2, and a lower crustal discontinuity (C3) at 34 km. The most prominent feature on the profile is the broad Moho depression, mimicked by C2 and C3, in which M1 lies below 45 km over a distance of over 100 km. At the Oskarshamn workshop, diverging interpretations of the BALTIC SEA seismic data were presented (Ostrovsky, and Pavlenkova et al., in Oskarshamn 1996), so the profile presented here (Fig. 2-7, from Ostrovsky et al. 1994) is of preliminary nature.

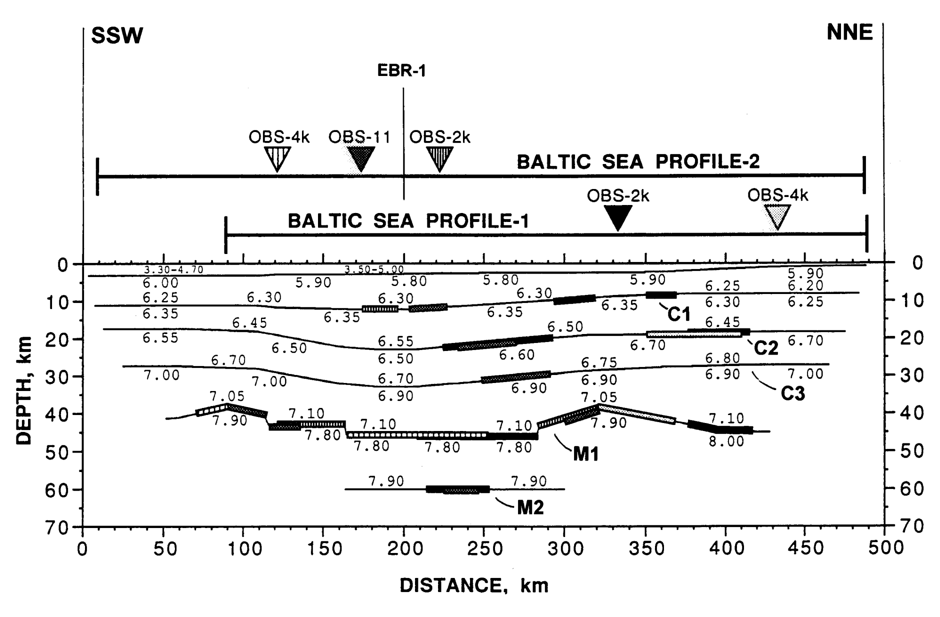


Fig. 2-7

Vp velocity structure of the BALTIC SEA profile, from Ostrovsky et al. (1994). For location, see Fig. 2-1. Intersections with other seismic profiles are marked: EBR-1 = EUROBRIDGE main profile (Fig. 2-3). Note the broad Moho depression astride the intersection with EBR-1 (depths around 45 km).

2.3.3 BABEL (1989), DSS profiles AC and B

The BABEL survey was a major seismic experiment in which both DSS and CDP data were acquired along a series of profiles in the Baltic Sea and Gulf of Bothnia in 1989 (BABEL Working Group 1993a, 1993b, Barth & Klemperer 1996). Profiles A and B in the Baltic Sea, the ones relevant to the Äspö region (Fig. 2-1), were run in September-October using the seismic vessel *Mintrop* of Prakla-Seismos AG. The source was a 120 l airgun shot along profile A every 50 m and along profile B every 75 m. In addition to the 3000m long streamer, the shots were recorded at 16 land stations, 6 of which

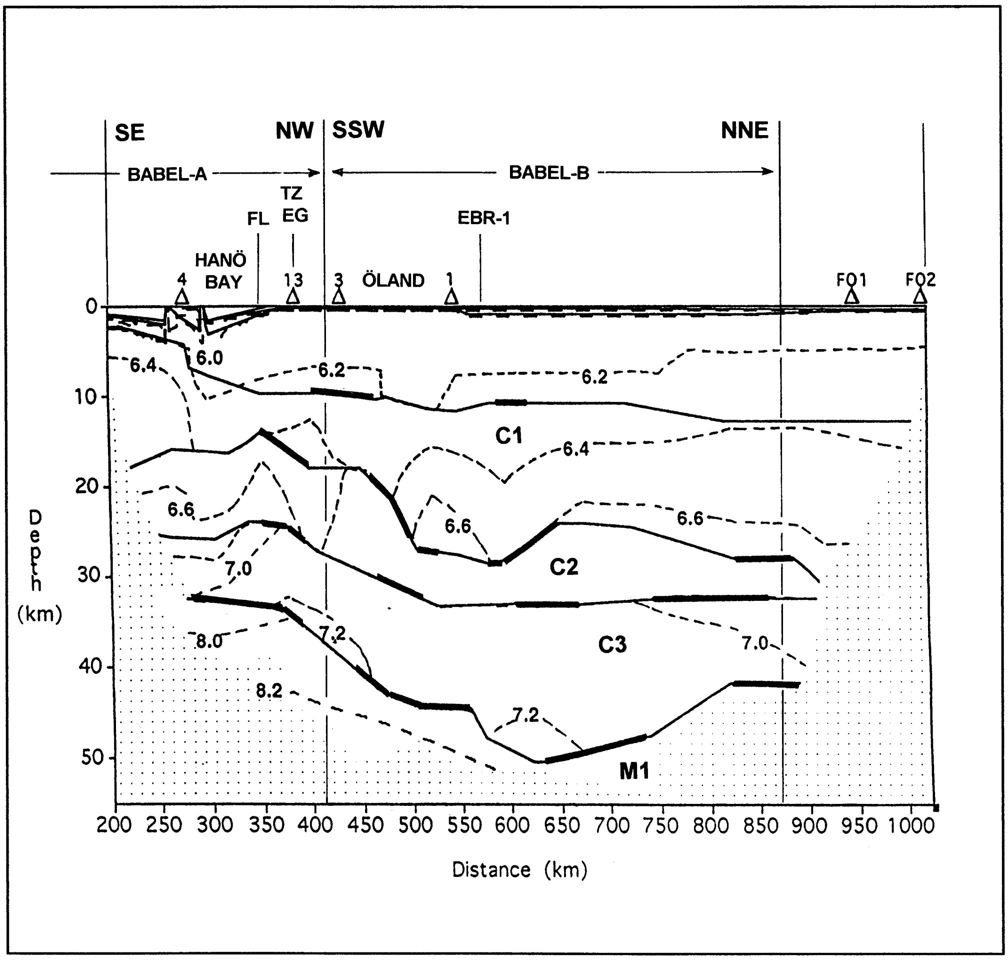


Fig. 2-8

Vp velocity structure along the BABEL profiles A (northern part) and B, from Barth & Klemperer (1996). For location, see Fig. 2-1. The reflection seismic profile along the same line is reproduced in Fig. 2-11. Intersections with other seismic profiles are marked: EBR-1 = EUROBRIDGE main profile (Fig. 2-3), TZ = TTZ'92 profile I (Fig. 2-6), EG = EUGENO-S profile 4 (Fig. 2-9), FL = FENNOLORA profile (Fig. 2-10). Note the marked depression of the Moho, M1, to a maximum depth of 50 km immediately north of the intersection with EBR-1 (cf. BALTIC SEA profile, Fig. 2-7).

were used for the model shown (Fig. 2-8). Profile B of the BABEL project crosses the offshore part of the Äspö region to the east of TTZ'92/I, subparallel to, and 100-200 km west of, the BALTIC SEA profile. It joins in the south with the northeast end (AC) of BABEL profile A, which has a more southwesterly trend (Fig. 2-1). Both near-vertical and wide-angle seismic data were acquired and processed together along these lines, and the results were published as an integrated study (BABEL Working Group 1993b). Recently, a paper showing reprocessed profiles, matching both P- and S-wave traveltimes, has been published for the segment of interest here (Barth & Klemperer 1996), and these will be used for the following outline (Fig. 2-8).

In the reprocessed profiles, three intra-crustal discontinuities are distinguished, C1 at 8-12 km, C2 at 15-29 km and C3 at 25-34 km depth (Fig. 2-8), but with considerable lateral velocity variations. The Moho, M1, is well defined and descends from about 34 km under Hanö Bay to depths of 40-45 km under Öland, and reaches maximum depths of 50 km under Gotland. Towards the north it then shallows again to 42 km at the latitude of Stockholm (Fig. 2-8). This Moho depression is practically identical to that modelled on the original BABEL profiles (BABEL Working Group 1993b) and correlates easily with the similar depressions on EBR-1 (Fig. 2-3) and EBR-1A (Fig. 2-5). Based on this correlation, the 50 km Moho depth contour in this area delineates a N-S trending structure (see below).

2.3.4 EUGENO-S (1984), Profile 4

The EUGENO-S project included a series of land-based field experiments using high explosives at 20 shot points in southwestern Sweden, Denmark and northern Germany (EUGENO-S Working Group 1988). Observations were made at 800 recording stations along 5 profiles with a total length of 2100 km. Profile 4 (Fig. 2-9) was shot 13-14 June 1984 and had 4 shotpoints along the Swedish part of the profile, with 104 recording stations at an average spacing of 3.5 km. Seven record sections were acquired, all of good quality, with section lengths varying from 70 to 365 km. Shot point SP7, at the SE end of this NW-SE trending profile, lay in Hanö Bay just south of Karlskrona (Fig. 2-1) and coincides with shot point B on the FENNOLORA profile.

Fig. 2-9 shows the velocity structure under the 4 main shot points, where the profile lies closest to the Äspö region. Extrapolated a short distance to the southeast, it crosses TTZ'92 /I, BABEL-A and FENNOLORA where they intersect each other, and at this position the Moho, M1, gives excellent depth correlation with the other lines (36-38 km). M1 runs from there northwestwards with constant depth until it descends in two steps to a maximum depth of 47 km under shot point SP 23. In addition, two intra-crustal discontinuities are identified at 8 km and 19 km depth, C1 and C2, whereby C1 lies at the base of a low-velocity zone. The crust can be subdivided into three seismic layers: upper crust (Vp varying on this profile

5.9-6.3 km/sec, with inversions and considerable lateral variation), middle crust (6.3-6.5 km/sec) and lower crust (6.6-6.9 km/sec, up to 7.2 km/sec under SP23, where the Moho reaches a maximum depth). Both vertical and horizontal upper mantle heterogeneities have been distinguished along this profile (Lund 1990, Thybo & Perchuc, in Oskarshamn 1996).

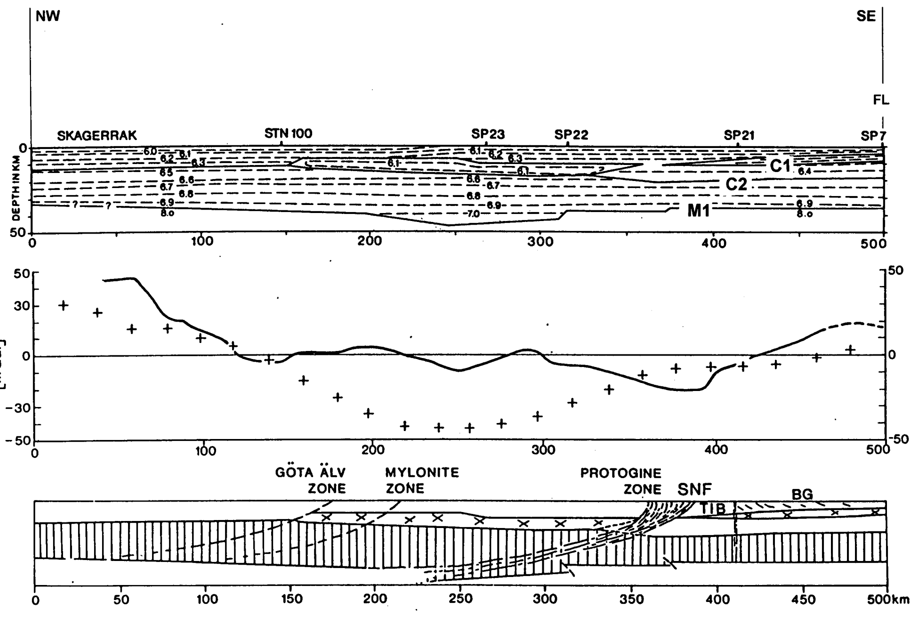


Fig. 2-9

Vp velocity structure of EUGENO-S profile 4, from EUGENO-S Working Group (1988). For location, see Fig. 2-1. (a) Velocity model - the segment between SP23 and SP7 is discussed in the text. (b) Gravity model (crosses) compared with observed Bougier anomaly curve. (c) Suggested relation between velocity model and geological features. "Protogine Zone" = SNF (Sveconorwegian Frontal Deformation Zone), TIB = Trans-Scandinavian Igneous Belt, BG = Blekinge Gneiss. Intersections with other seismic profiles are marked: FL = FENNOLORA profile (Fig. 2-10).

An interesting feature of this profile is that a major tectonic element at the surface can be convincingly traced through the upper crust, and possibly down to the mantle (EUGENO-S Working Group 1988). The position and orientation of the highly sheared rocks along the Sveconorwegian Frontal Deformation Zone (here marked SNF, coinciding with the "Protogine Zone", Bylund & Pisarevsky, in Oskarshamn 1996, see also Andreasson & Rodhe 1992), although cut through obliquely by the profile and therefore showing a low apparent dip, seems to coincide with a marked lateral discontinuity in the upper and middle crust One low velocity layer terminates and another appears at a different level, and C2 changes level across a zone in which no discontinuities can be modelled. If the zone is tentatively projected downwards, one encounters a Moho step in the neighbourhood of the area of maximum Moho depth (Fig. 2-9). It seems to subdivide the crust into two parts, of different crustal structure, and, by correlation with surface geology, different geological histories (Sveconorwegian and Svecokarelian Domains, see Chapter 3).

2.3.5 FENNOLORA Profile (1979), shotpoints B-C

The FENNOLORA experiment was carried out in August 1979 with two main shot points (of which B was one) and 5 intermediate ones, each about 300 km apart. Recording stations were placed at intervals of about 3 km. The part of the 1900 km long profile which is relevant for the present discussion is that between shotpoints B and C (Fig. 2-10). This segment was modelled on the basis of record sections W-N, B-N, C-S, C-N and D-S (Guggisberg et al. 1991: record sections, Figs. 4-8; ray trace diagrams, Figs.

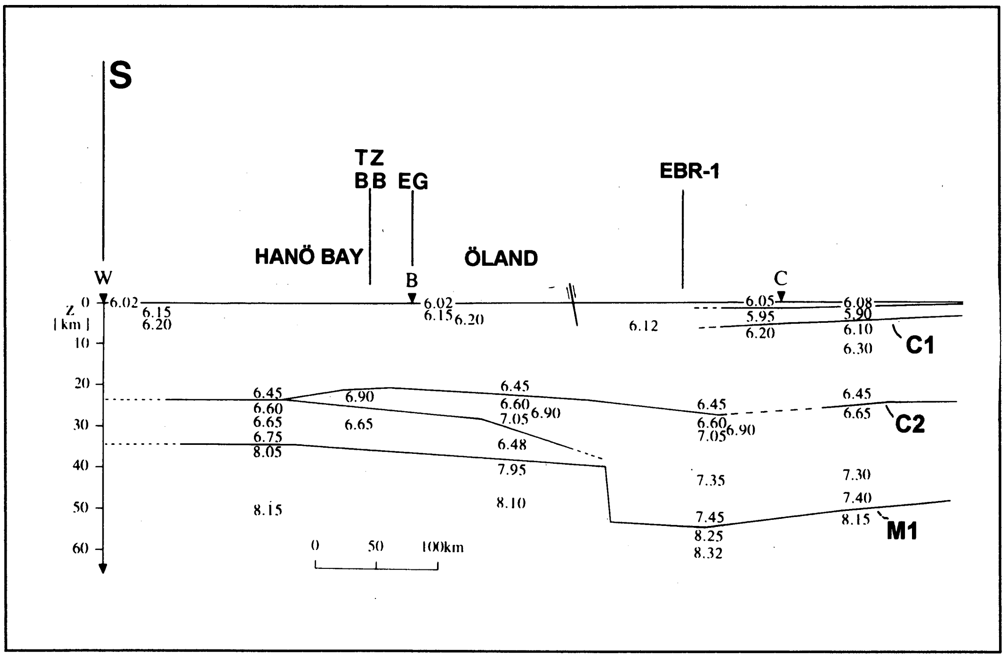


Fig. 2-10

Vp velocity structure of the FENNOLORA profile between shot points B and C, from Guggisberg et al. (1991). For location, see Fig. 2-1. Intersections with other seismic profiles are marked: EBR-1 = EUROBRIDGE main profile (Fig. 2-3), TZ = profile TTZ/92I (Fig. 2-6), BB = BABEL profile (Fig.2-8), EG = EUGENO-S line 4 (Fig. 2-9) The "Moho step" imaged in this profile has since been smoothen out, but the Moho depression, to depths of about 55 km between shotpoints B and C is still considered reliable.

19-20). The segment BC (Fig. 2-10) is characterized by a well-defined mid-crustal discontinuity, C2, with a velocity jump from 6.4-6.6 km/sec, which sinks from 21 km depth in the south, at the intersection with the other profiles (shot point B), to 28 km under shot point C. It then rises slightly northwards, where it can be followed persistently along the whole profile at about 20 km depth. An upper crustal discontinuity was not distinguished in the FENNOLORA data, and the upper+middle crust was characterized by considerable lateral variations, with poorly defined inversions modelled at various places. The velocity inversion mapped on the EUGENO-S profile (Fig. 2-9) is not imaged on FENNOLORA , probably because of the poor coverage with recording stations south of shot point B (Guggisberg et al. 1991). The Moho, M1, on FENNOLORA is well-defined and at the same level as the other profiles (36-38 km depth) in the area around shot point B. From B northwards, M1 descends rapidly to about 55 km depth, 100 km NNW of the Äspö site, and then rises slowly northwards. In the original profile, a Moho step of 10 km was modelled about 150 km north of B (Fig. 2-10). This was confirmed during independent processing at Uppsala (Lund 1990), but later reprocessing (Hauser & Stangl 1990, Henkel et al. 1990), as well as comparisons with closely parallel profiles (EBR-1A, Fig. 2-5; BABEL, Fig. 2-8), suggests a smoother depth change. Nevertheless, the maximum Moho depth of 55 km, which is the deepest known in southern Sweden, is still considered reliable.

The seismic lower crust and upper part of the mantle along this part of FENNOLORA shows some special features. Firstly, the Moho "root" to the north of the "step" shows exceptionally high velocities (7.1-7.5 km/sec) and the 7.1 km/sec velocity isoline, like the overlying C2 discontinuity, does not reflect the Moho shape (Fig. 2-10). Secondly, the 7.1 km/sec isoline continues from the "root" southwards to join C2 at the position of profile TTZ'92I, with a zone of reduced velocity below it - a velocity inversion in the lower crust which was not modelled on the EUGENO-S4 line (Fig. 2-9). Thirdly, the lithospheric structure between B and C shows a velocity inversion at about 65 km as the uppermost of a series of inversions which have been mapped out in the upper mantle (not shown on Fig. 2-10, see Blundell et al. 1992). This discontinuity may correspond to M2 on the other profiles, although on those there is no suggestion of inversion. Irrespective of this, however, it is important to note that this uppermost mantle discontinuity is also perfectly flat as it passes under the Moho depression. As on the EUROBRIDGE coast profile (Fig. 2-5), the depression occurs only in the Moho and is hardly mimicked by the discontinuities immediately above or below.

2.4 BABEL CDP PROFILES

The aim of the 1989 BABEL survey was to provide wide-angle reflection/refraction (DSS) and near-vertical, normal incidence reflection (CDP) images of the Baltic Shield crust and upper mantle (BABEL = "Baltic and Bothnian Echoes from the Lithosphere"). The velocity structure derived from the DSS data along the Baltic Sea legs (profiles A and B) of the survey has been described briefly above (Fig. 2-8). The near-vertical CDP data were migrated using 1D velocity functions derived from the wide-angle observations and models, and the resulting profiles were published in 1993 (BABEL Working Group 1993a, 1993b). The CDP images of the northern part of profile A and the whole of profile B are reproduced on Fig. 2-11, with the original kilometer marks, together with the kilometer marks used in a recent re-interpretation (Abramovitz et al. 1997, discussed in more detail in Chapter 4.2). The latter are used in the following description. Profile A has a NE-SW trend in its northern part and joins the south end of profile B at a point near the south end of Öland (Fig. 2-1). From this point, profile B takes a NNE-SSW course, between Öland and Gotland, towards the Åland islands.

The Moho along most of the profile is not observed as a clear reflector in the near-vertical data, but the M1 reflector in the wide-angle data (Fig. 2-8) coincides with a marked change in near-vertical reflectivity, from reflective, above, to non-reflective, below. This is taken to represent the crust and the upper mantle, respectively. Within the upper mantle, clear reflections are only observed at a few points, such as just south of km 500 on profile B, and in a zone from about km 50-150 along profile A (Fig. 2-11). In both cases, a constant northeastward plunge of the reflector traces is observed. On profile A, the mantle reflectors are clearly continuous with similar reflectors in the lower and middle crust. In this area, between Bornholm and Öland, the lower crust is dominated by heterogeneously bundled reflectors with northeast plunging traces which cross the subhorizontal Moho, here lying at about 37 km depth (about 12 secs twt). This "structural grain" continues northwards to about km 300 on profile B (central Öland, see also Midgley & Blundell 1997, Fig. 3), where it seems to be confined below a major reflective zone. This intersects the whole crust, from about km 200, at the surface (southern tip of Öland), to about km 350 (northern tip of Öland, opposite Äspö), where it flattens and runs into the Moho at 45 km depth (Fig. 2-11, zone a-b, cf. BABEL Working Group 1993b, Abramovitch et al. 1997). Although there is a transparent gap, this reflective zone is on-line with the upper mantle reflectors mentioned above at about km 500. Northeast of, and above, the reflective zone, the reflective structure of the crust is nebulous and little structured (below Gotland) until km 450, when irregularly distributed bundles of subhorizontal reflections appear in the middle and lower crust (below 5 secs twt), whilst the upper crust remains more or less isotropic.

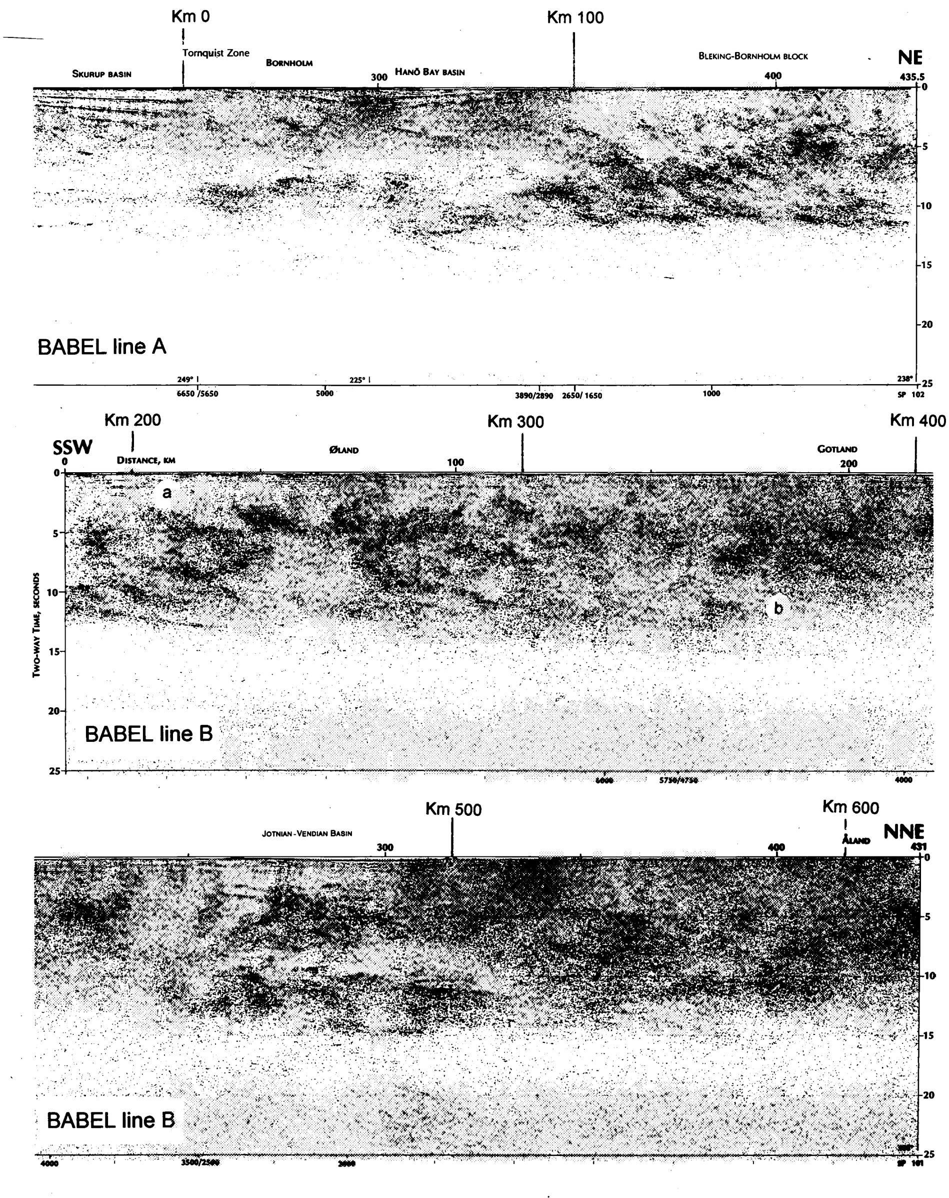


Fig. 2-11

Reproduction of the BABEL near-vertical seismic reflection (CDP) profiles along the northern part of line A and the whole of line B as migrated final stacks (from BABEL Working Group 1993b, with kilometer marks from Abramovitz et al. 1997 added, cf. Fig. 4.2). The change from reflective to non-reflective lithosphere between 10 and 15 seconds two-way time approximately corresponds to the Moho, M1, on the DSS velocity model (depths 35-50 km, see Fig. 2-8).

These are the main outlines of the seismic structure of the crust as imaged by near-vertical reflections - the geological interpretation of these images will be returned to in Chapter 4. Their importance lies in the fact that they are the *only* physical images of crustal structure available for comparison with surface geology. The DSS profiles discussed in this chapter, although more numerous, give modelled boundaries of unknown geological significance (the modelling procedure *assumes* the existence of subhorizontal discontinuities), although the seismic Moho is generally considered to approximately correspond to the petrographic Moho in most areas. CDP images of the deep crust, based on experience from shallow reflection seismic profiling, where reflectors can be identified by drilling, are assumed to "reflect" more directly significant geological structures, albeit only planar and gently dipping ones, as discussed later.

2.5 SUMMARY

The aim of this chapter has been to give a structured overview of the crustal seismic data collected in SE Sweden and the Baltic Sea, and to outline the main results, without discussing its geological significance. Only the main features and patterns have been presented, for later comparison with the regional tectonic picture which emerges from the surface geology (Chapter 3). The DSS data, including the new EUROBRIDGE profiles, are summarized in Table 2-1.

Some of the main features can be summarized as follows:

- The profiles are velocity models, produced by different research groups using different experimental conditions, modelling procedures and philosophies. Comparison shows many discrepancies, which are partly a reflection of this diversity, indicating that the plotted features are subject to a high degree of uncertainty, a fact which is often obscured by the apparent objectivity of the illustrations. For instance, for the Moho, the most obvious discontinuity modelled, we estimate the uncertainty in depth determination is probably at least +/- 5%, i.e. about +/- 2.5 km in the present area.

- Nevertheless, particularly for the Moho, a general feature can be distinguished which is certainly real. The northern part of the Äspö region is underlain by thicker crust than the southern part, as illustrated by the segments of the profiles with crustal thickness greater than 45 km (Fig. 2-12) and the more limited areas of 50+ km depth shown in some of the profiles. Comparing this result with earlier compilations (Blundell et al. 1992, Atlas Map 2; Kinck et al. 1993, Fig. 8, Korja et al. 1993, Fig. 3) shows basic agreement in spite of the considerable variations in the contour patterns, and suggests that the area of increased thickness is part of a regional Moho depression, with the crust thinning to less than 40 km southwards (under Hanö Bay, Fig. 2-12) and westwards (under lake Vänern), and with less pronounced crustal thinning to the north and east.

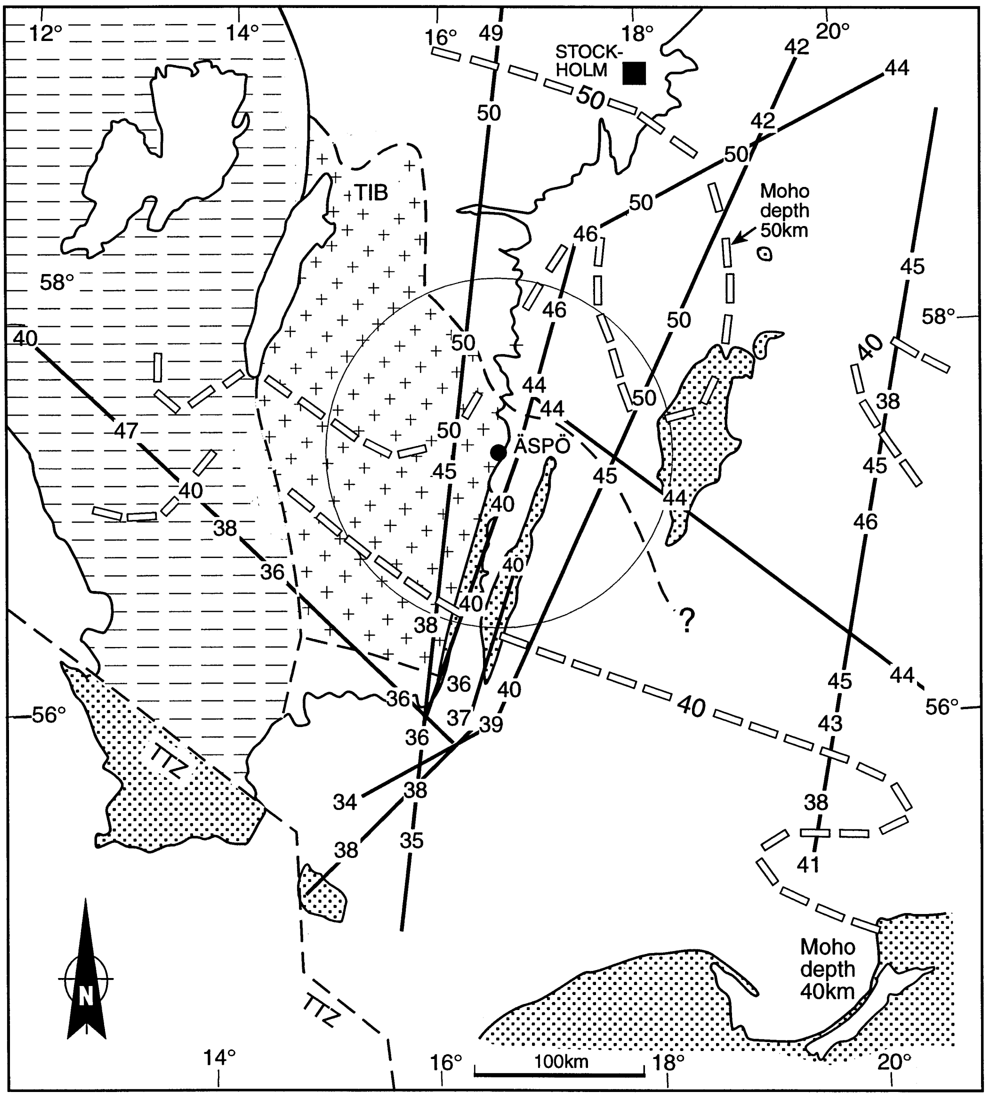


Fig. 2-12

Depth-to-Moho (discontinuitiy M_1) map based on the data presented and discussed in this chapter. The depth uncertainty is estimated to be about +/- 5% which means that little reliability can be placed on the shape of the depth contours. The data suggest an irregular Moho, without clear trends, below the Äspö region, rising from around 50 km in the north to around 40 km in the south.

- Bearing in mind the uncertainties mentioned above, however, it seems that an obvious trend, i.e. an elongation of the Moho depression, in NW-SE direction, as suggested, for instance, by Ostrovsky et al. (1994), cannot be distinguished in the present data. If any trend were to be interpreted, it would have to be N-S, as shown on Fig. 2-12, since the EUROBRIDGE coast profile (Fig. 2-5) showed significantly shallower Moho discontinuities than the lines on either side (BABEL, Fig. 2-8 and FENNOLORA, Fig. 2-10). Also, the proposed "step" in the Moho below the Äspö region along the FENNOLORA line (Fig. 2-10), which was originally thought to image a deformation zone connected through the crust to a major EW-striking shear zone at the surface, and which became integrated in the EGT results (Blundell et al. 1992), is not supported either by the BABEL data (Figs. 2-8 and 2-11), or by the EUROBRIDGE coast profile (Fig. 2-5).

- The disagreement between the several profiles with regard to the structure of the crust (level and number of intra-crustal discontinuities) is too great to allow any generalizations. However, an interesting feature of both the EUROBRIDGE coast profile (Fig. 2-5) and FENNOLORA (Fig. 2-10) is the identification of a lowermost crustal layer with velocities > 7 km/sec and the existence of such high velocities in the lowermost crust in other profiles. As noted by Korja et al. (1993), there is a tendency for the Moho depth variations to be compensated by variations in the thickness of high velocity material at the base of the crust, so that higher crustal discontinuities do not reflect the Moho depth variations. The same is true of the intra-mantle discontinuity, M2, when this is observed.

Table 2-1: Summary of crustal velocity data from DSS profiles in southern Sweden and the Baltic Sea (approximate Vp velocities in km/sec)

	EBR-1 (Fig. 2-3)	EUGEN O-S/4 (Fig. 2-9)	EBR-1A (Fig. 2-5)	TTZ'92I (Fig. 2-6) north end	BALTIC SEA (Fig. 2-7)	BABEL A-B (Fig. 2-8)	FENNO-LORA B-D (Fig. 2-10)
	SE-NW profiles		SSW-NNE and SW-NE profiles				
upper crust	6.0 6.4	5.9 inversion in lower part 6.3	6.0 6.4	5.9 laterally variable 6.2	5.8 6.3	6.0 laterally variable 6.2	5.9 laterally variable, inversions
C1	18 km	8 km (SE of PZ)	17-23 km	8-10 km	8-12 km	8-12 km	not ident.
middle crust	6.5 6.8	6.3 6.5	6.5 6.8	6.5 laterally variable 6.7	6.3 6.5	6.3 laterally variable 6.6	6.5
C2	35 km	19 km (SE of PZ)	35-40 km	20-25 km		15-29 km	21-28 km
lower crust	6.8 6.95	6.6	6.9 7.1	7.0 laterally variable	6.6 6.8	6.6 6.7	6.6 inversion to SE
C3	(44 km)	not ident. (SE of PZ)	35-52 km	not ident.	27-33 km	25-34 km	not ident.
lower-most crust	("root" 7.4)	6.9	7.0 7.3	7.2	6.9 7.1	6.9 7.2	high vel. "root" 7.5
M1	44-(50) km	37-39 km (SE of PZ)	41-52 km	33-40 km	39-46 km	33-51 km	35-?55 km
upper-most mantle	8.1 (8.8)	8.0 8.2	8.2 8.4	8.1	7.8 8.0	8.0	8.0
M2	(60-70 km)		62 km		60 km		65 km
upper mantle		several discont. & inversions	8.6				inversion

3. REGIONAL TECTONICS

3.1 INTRODUCTION

The segment of the Earth's crust which underlies and surrounds the Äspö site forms, geotectonically speaking, part of the East European Craton (Fig. 1-1), a crustal unit which has remained geologically stable since late Precambrian times, a large part of it since the mid-Proterozoic. The East European Craton is bounded on all sides by younger (Phanerozoic) mobile belts and is covered over large areas by practically undisturbed Phanerozoic sedimentary rocks. The areas where the Precambrian basement is exposed at the present time are referred to as shields, and the covered areas as platforms. The Äspö region lies at the eastern edge of the Baltic Shield and the western edge of the East European Platform. However, this subdivision has little tectonic significance. More important is the subdivision of the cratonic crust into three subunits (Fig. 3-1) - Fennoscandia, Sarmatia, Volgo-

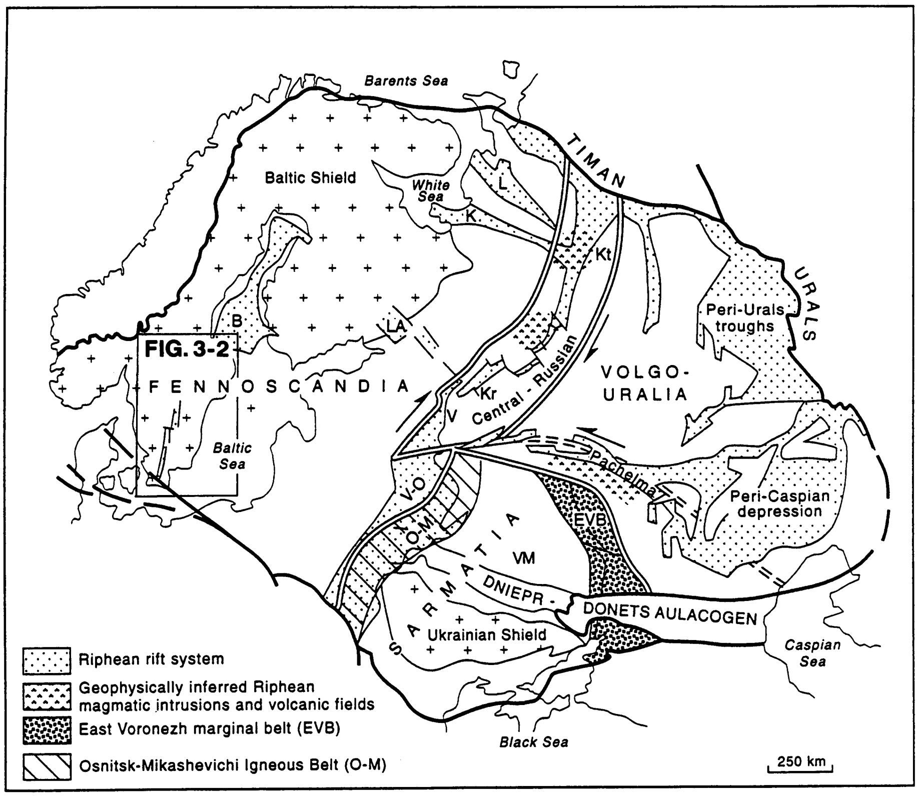


Fig. 3-1

Overview map of the main subdivisions of the Precambrian basement of the East European Craton (from Bogdanova et al 1996). Box shows the location of Fig. 3-2, the geological map of southern Sweden, which lies completely within the Fennoscandian part of the EEC.

Uralia - which show quite different histories (Gorbatschev & Bogdonova 1993, Bogdanova et al. 1996) and which seem to have amalgamated into a single craton at quite a late stage (Elming et al., in Oskarshamn 1996). Onshore Sweden and the Baltic Sea lie completely within the Fennoscandian part of the East European Craton.

The geology of the exposed part of Fennoscandia in SE Sweden was the subject of many scientific presentations at the 1996 Oskarshamn and 1997 Vilnius EUROBRIDGE workshops, and was studied in detail after the Oskarshamn meeting on a series of field trips (Beunk 1996, Mansfeld & Sundblad 1996, Wikström 1996, Zellman & Kornfält 1996). Ongoing work was also summarized in many papers presented in the Precambrian section of the Swedish Geological Society Jubilee Meeting, during late 1996, and published in the jubilee issue of GFF. In this chapter, we summarize some of the results of this ongoing research, and attempt to integrate them into the general geology of southern Sweden, as outlined in recent SGU compilations, particularly the geology volume of the National Atlas of Sweden (Fredén 1994) and the Geological Map of Sweden (Stephens et al. 1994) . Fig. 3-2 shows the southern part of the latter, with numbers indicating the main lithologies of the Svecokarelain Domain and its cover sediments, discussed in the following.

3.2 FORMATION OF THE SVECOKARELIAN CRUST

There is general agreement that, in the whole of southern Sweden, the Baltic Shield is constructed of continental crust which was formed and/or reworked during the Svecokarelian and Gothian orogenies (Fredén 1994, cf. Mansfeld, in Vilnius 1997). Formation of new continental crust took place during the late Palaeoproterozoic (>1900-ca.1850 Ma, see Table 3-1) in southeastern Sweden (part of the Svecokarelian orogeny), continued until at least 1770 Ma in the extreme southeast, and took place during the time interval 1700-1590 Ma in southwestern Sweden (part of the Gothian orogeny). In southwestern Sweden, the Gothian crust was reworked during the Sveconorwegian orogeny, in the time period 1100-900 Ma (Table 3-1). This means that southern Sweden can be subdivided into an eastern domain, which has not been affected by this late Mesoproterozoic event, referred to here as the Svecokarelian Domain, and a western domain, which was affected by late Mesoproterozoic high-grade metamorphism, ductile deformation and magmatism, the Sveconorwegian Domain (Fig. 3-2, cf. Fig. 2-1). These domains are separated by a zone which marks the eastern limit of Sveconorwegian influence, represented by the so-called "Protogine Zone" (e.g. Andréasson & Rodhe 1992, Bylund & Pisarevsky, in Oskarshamn 1996) from Lake Vättern southwards, and by a broad zone of heterogeneous overprinting to the east of the traditionally defined "Protogine Zone", to the north (e.g. Wahlgren et al. 1994, Wahlgren & Stephens 1996). This zone is now referred to as the Sveconorwegian Frontal Deformation Zone (SFDZ on Fig. 3-2, see also Fig. 2-1) and has a general N-S trend.

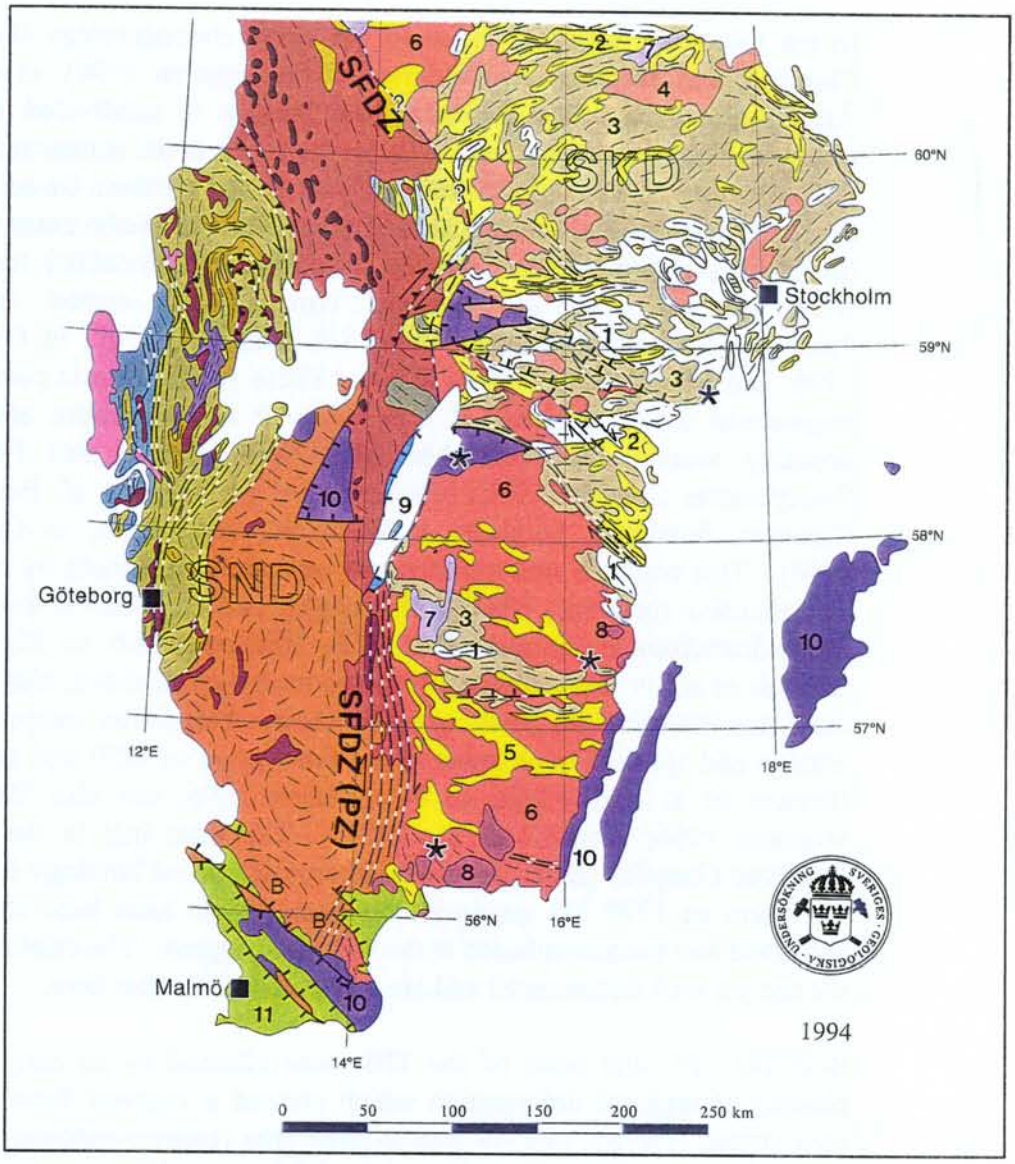


Fig. 3-2

*Geological map of the bedrock of southern Sweden (Stephens et al. 1994). Colour key: **1-3**: medium to high grade metamorphic rocks of the Svecokarelian Domain (SKD), partly migmatitic, derived from **1**-sedimentary protolith, **2**-volcanic protolith, **3**-calc-alkaline granitoids and subordinate gabbro protolith, age range ca.1900-1850 Ma; **4** - younger granites and pegmatites in central Sweden, ca.1850-1750 Ma; **5-6**: rocks of the Trans-Scandinavian Igneous Belt (TIB), **5**-felsic and intermediate volcanic rocks with some conglomerates and sandstones, **6**-granitoids and subordinate mafic intrusions, ca.1850-1690 Ma; **7** - Jotnian sandstone, conglomerate, siltstone,shale and basalt, ca. 1690-1250 Ma; **8** - anorogenic granite, syenite, gabbro and anorthosite, ca. 1580-1400 Ma; **9** - Visingsö Group (Neoproterozoic sandstone, breccia, siltstone and shale); **10** - Lower Palaeozoic sandstone, shale and limestone; **11** - Triassic to Tertiary rocks. SND = Sveconorwegian Domain, to the west of SFDZ (PZ) = Sveconorwegian Frontal Deformation Zone (Protogine Zone).*

In the following, we shall focus on the older, *Svecokarelian Domain* (cf. Claesson, and Stephens & Wahlgren, in Oskarshamn 1996), in which the Äspö region lies. The Svecokarelian Domain is subdivided into three petrographically dissimilar belts. The northern belt is the southermost part of the rock complex which forms most of central and northern Sweden (Fig. 3-2). It consists of the metamorphosed equivalents of sedimentary, volcanic (mainly felsic) and intrusive (mainly granodioritic to tonalitic) rocks which were accreted onto the Archean core of the craton during the Palaeoproterozoic accretionary phase (cf. Bibikova et al., in Oskarshamn 1996, and Mansfeld, in Vilnius 1997). These rocks were in part intensely migmatized during a phase of high T/low P metamorphism and anatexis probably around 1850-1800 Ma ago. We refer to this belt as the *Svecofennian Complex* (SFC, lithologies 1-4 on Fig. 3-2, cf. Beunk et al., Claesson, Sundblad, Stephens & Wahlgren, and others, in Oskarshamn 1996). This complex was intruded and covered in the south by the plutons and extrusive rocks in a NNW-SSE trending swathe, which is known as the *Trans-Scandinavian Igneous Belt* (TIB, lithologies 5-6 on Fig. 3-2, see Ahrendt et al., in Oskarshamn 1996, and others cited above; also known as the Trans-Scandinavian granite-porphyry belt). This shows various phases of granitic and syenitic magmatism in the time range ca.1850 and ca.1770 Ma (Brewer et al. and others, in Oskarshamn 1996, see also Wahlgren & Stephens 1996, Kornfält et al. 1997). The third belt is the *Blekinge-Bornhom Complex* (BBC, dashed southermost part of lithology 6 on Fig. 3-2), where ca 1770 Ma granitoids dominate which have been subsequently deformed and metamorphosed in the Gothian orogeny. The relations in BBC are not yet well documented and are not discussed further here.

Both the SFC and parts of the TIB were affected by an early phase (or phases) of regional deformation which created a regional foliation which now strikes NW-SE to E-W over a large area (tectono-metamorphic phase D_1, Table 3-1). This was followed by folding and heterogeneous shearing under variable metamorphic conditions, whilst the presently exposed rocks were still at depths of 15-20 km (tectono-metamorphic phase D_2, Table 3-1). During D_2 , an anastomosing system of steeply-dipping ductile shear zones was created, with a general NW-SE strike and an important component of dextral strike- slip movement (Fig. 3-2). The lineation patterns associated with these shear zones are complicated and suggest varying ages and kinematics. TIB rocks are in part affected by and in part synchronous with the D_2 structures (Stephens & Wahlgren, in Oskarshamn 1996), indicating a complex interplay of magmatic and tectono-metamorphic processes. The period of "D_1/TIB magmatism/migmatization/D_2" between ca.1850 and ca.1750 Ma can be taken to represent the *Svecokarelian orogeny* (Table 3-1). The formation of the crust in the region covered by the seismic profiles described in Chapter 2 mainly occurred during this event, except in the extreme southeast (BBC, see above), where Gothian events are recorded (see Claesson, in Oskarshamn 1996). The region was then "cratonized" (i.e. transformed from a highly mobile crustal welt, with abundant magmatism, to a rigid, immobile basement complex) during the early Mesoproterozoic, during a period of anorogenic magmatism, which accompanied the main phase of uplift and erosion which created the base Jotnian unconformity (see below). Subsequently, the rocks we see today at the surface have remained continuously within the brittle regime (Tullborg et al., in Oskarshamn 1996, cf. Larson & Tullborg 1993).

It should perhaps be emphasized that the use of the term "orogeny" in connection with the Svecokarelian event may be misleading if it is thought of in terms of Phanerozoic collisional tectonics, particularly with respect to the late Svecokarelian. As indicated above, it is characterized by partial melting, igneous intrusion, volcanism and ductile deformation over a very large area of previously accreted crust, covering the main part of the present Fennoscandian craton. In the Äspö region, the present erosion level represents a depth of 15-20 km, at which magmatic and anatectic processes dominated. Above this semi-molten layer came a solid and unstable crust, possibly only a few kilometres in thickness. Characteristic of TIB is the presence of contemporaneous near-surface rocks (sediments, rhyolites, porphyries, etc.) - including evidence for contemporaneous surface processes (uplift, erosion, sedimentation, e.g. in the Vetlanda and Västervik areas visited during the Oskarshamn workshop, see Mansfeld & Sundblad 1996, Wikström 1996, and Ahrendt et al., Mansfeld, Beunk et al. and others, in Oskarshamn 1996) - all engulfed in the granitoid magmatites (Fig. 3-3b). A further characteristic is the system of essentially coeval ductile shear zones, with complex movement patterns. This presents us with the picture of crowds of small crustal rafts continually breaking up and jossling each other (local uplift, tilting, thrusting, etc.), and often foundering as "mega-xenoliths" into the underlying magmatic morasse. The continual addition of molten material from below must have caused spreading and lateral extrusion of the upper crust in some areas, coeval with convergence and minor collision in others, implying a complex pattern of contractional and extensional tectonics. The semi-molten layer must have had almost zero strength and hence could not have supported any large-scale gravitational perturbations (crustal roots, large areas of high topography, density inversions) for any length of time. This picture, derived directly from the field relations, has implications for the interpretation of the deeper structure of the present Baltic crust (Chapter 4).

Table 3-1: Skeleton timetable for the tectonic evolution of the Baltic Shield in southern Sweden

Epoch	Time (Ma)	Svecokarelian Domain SKD (= Äspö region)	Sveconorwegian Domain SND
		glacial loading and rebound	
	2		
		?fault reactivation	
	150		
Phanerozoic		Vättern 2 faulting (?domal uplift - block faulting west and north of Vättern, tilting of U_3 to east)	
	300		
		Devonian molasse in foreland basin (**Caledonian orogeny** to south and west)	
	400		
		lower Paleozoic sediments on base Cambrian unconformity U_3	
	570		
Neo-Proterozoic		Vättern 1 faulting Visingsö sediments on base Visingsö unconformity U_2	
	900		
		Blekinge-Dalarna dykes	**Sveconorwegian orogeny**
	1100		
Meso-Proterozoic		anorogenic magmatism (Götemar and related intrusions, post-Jotnian dykes) ?Jotnian sediments on base Jotnian unconformity U_1	anorogenic magmatism (numerous phases)
	1500		
		"anorogenic" magmatism (Rapakivi intrusions and pre-Jotnian mafic dykes)	**Gothian orogeny**
	1600		
		late Svecokarelian orogeny: tect.-metm. phase D_2 ,ductile shearing , main TIB magmatism 1810-1770 Ma	?Gothian orogeny
	1800		
Paleo-Proterozoic		**early Svecokarelian orogeny**: tect.-metm. phase D_1, regional foliation, start of TIB magmatism	
	1850		
		formation of new continental crust	
	>1900		

3.3 POST-CRATONIZATION HISTORY

After the exceptional mobility of the late Palaeoproterozoic, the Svecokarelian Domain in the Äspö region stabilized, becoming cratonic in the early Mesoproterozoic and remaining so ever since (Nikishin et al. 1996, cf. Table 3-1). At first, magmatism continued in the form of the intrusion of the rapakivi granites and related bodies, centred mainly outside the Äspö region (cf. Elo & Korja 1993, Puura & Flodén, in Oskarshamn 1996, Puura & Flodén 1996, Claesson & Kresten 1997), together with systems of dykes and sills (cf. Larsson & Tullborg 1993). Conditions were "anorogenic" throughout the Mesoproterozoic (Gorbatschev 1996), although this intracratonic magmatism could have been genetically related to continued orogeny in what was later to become the Sveconorwegian domain (Gothian orogeny, cf. Åhäll et al. 1996). The Mesoproterozoic was also a period of uplift and erosion, during which the TIB intrsuive rocks and anorogenic intrusions (e.g. Götemar granite) in the Äspö region were unroofed approximately to the extent that we see today. This unroofing history, and subsequent periods of renewed subsidence and uplift/erosion has been followed using fission track dating and other methods (Tullborg et al. 1996). In the field, it is represented by remnants of three major unconformities, which will be used in the following to outline the post-cratonization history.

A pictorial summary of the time relations in the Äspö region as they have been observed in the field is given in Figure 3-3. The earliest post-cratonization events are represented by dykes and faults which are truncated by the earliest recognizable **unconformity U_1** , which is overlain by Jotnian sediments. The evidence for these sub-Jotnian events is rather tenuous, since U_1 can only be identified where Jotnian sediments are preserved. These sediments are rare and poorly exposed (e.g. Almesåkra area in the Äspö region, Rodhe 1987). However, early Mesoproterozoic dykes have been discovered by dating (e.g. 1565 Ma dyke immediately west of Almesåkra, Ask 1996), and a sub-Jotnian set of NW-SE trending faults has been argued for in earlier studies (Asklund 1923, Martin 1939). Dykes and sills are also found which intrude the Jotnian sediments and most of the dykes in southern Sweden are probably post-Jotnian in age (e.g. Åhäll & Connelly 1996).

The second major unconformity, **unconformity U_2** , occurs at the base of the Visingsö sedimentary sequence, which is Neoproterozoic in age (Vidal & Moczydlowska 1995) and which post-dates the latest phase of mylonitization along the Sveconorwegian Frontal Deformation Zone (Wikström & Karis 1993). U_2 is also only clearly identifiable where it is marked by overlying Visingsö beds, as within the Vättern rift and in two small areas outside the rift zone. As indicated on Fig. 3-3, the first phase of faulting in the Vättern rift (Vättern 1, Månsson 1996) was coeval with the middle unit of the Visingsö formation, post-dating U_2 and the deposition of lower Visingsö unit, the latter having covered a much wider area. Fissures containing Visingsö shale (lower unit) have also been reported below the sub-Cambrian

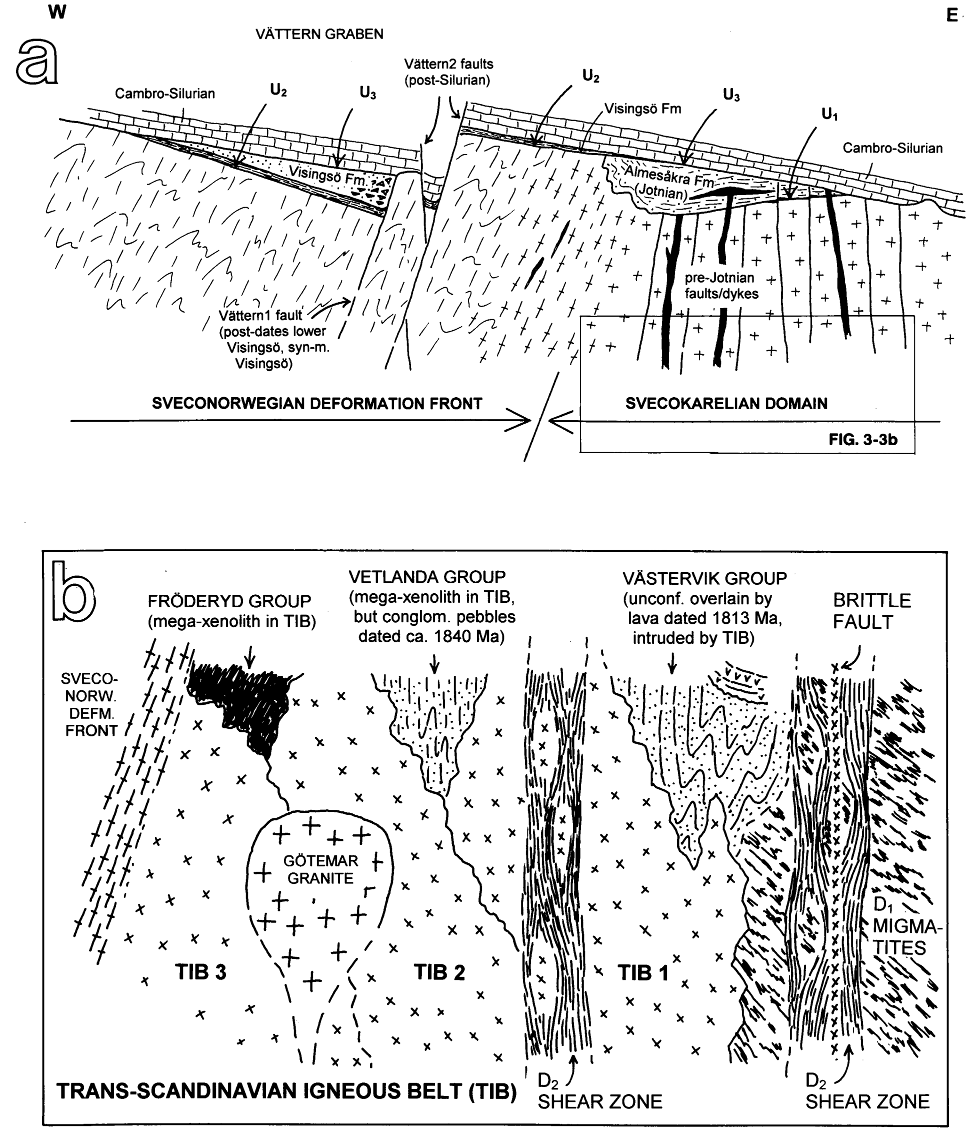


Fig. 3-3

Pictorial summary of post-cratonization events in the Svecofennian domain of SE Sweden, based on sketches made on the field trips during the Oskarshamn workshop (cf. Beunk 1996, Mansfeld & Sundblad 1996, Wikström 1996) and in the Vättern area (cf. Martin 1939 and Månsson 1996). Not to scale. (a) The post-cratonization history is defined by remants of three unconformities, of Mesoproterozoic (U_1), Neoproterozoic (U_2) and latest Precambrian age (U_3), lying close to the present day Earth surface. (b) The pre-cratonization history of the Äspö region is represented by a complex sequence of Palaeoproterozoic magmatic and metamorphic events in the Svecokarelian basement (see inset in (a), dykes and faults omitted), dominated by the intrusion sequence of the Trans-Scandinavian Igneous Belt (TIB 1-3).

unconformity (Martin 1939), indicating that this follows the sub-Visingsö erosional surface in places. Important in this respect is the evidence pointing towards considerable overburden and/or high heat flow at this time, corresponding to a "normal" depth of burial of 8 km (Tullborg et al., in Oskarshamn 1996). Obviously, the Visingsö formation was only the basal formation of a considerable sedimentary pile and by no means confined to the present Vättern rift, as it is usually shown (e.g. in Vidal & Moczydlowska 1995). Faulting which post-dates Jotnian and pre-dates Palaeozoic sedimentary rocks is known from the Baltic Sea area (Flodén et al., in Oskarshamn 1996, see also Flodén 1980) and may be correlatable with the first phase of faulting in the Vättern rift system.

Unconformity U_3, the base Cambrian or sub-Cambrian unconformity is developed over large parts of southern Sweden as a dominant morphological feature (Fredén 1994, Lidmar-Bergström 1996). In several areas, it is marked by an overlying sequence of lower Paleozoic sedimentary rocks within down-faulted blocks (Fig. 3-4), in others by small outliers of Cambrian sandstone, in still others by sandstone-filled fissures which indicate its presence just above the present surface (e.g. Larsson & Tullborg 1993). Offshore, U_3 is clearly identifiable on the numerous shallow reflection-seismic sections (Flodén 1980). Geomorphological studies have shown that it determines the present-day topography, and that its changing level can be used to map post-Cambrian faults and flexures to a remarkable degree of detail (Lidmar-Bergström 1996 and numerous earlier papers). This mapping shows a clear subdivision of the shield in SE Sweden into two tectonic regimes. The northwestern regime (Fig. 3-4) is characterized by a complex pattern of variously tilted blocks, including the structures formed during the second phase of faulting in the Vättern rift (Vättern 2, Månsson 1996). The southeastern regime, within which the Äspö region lies, is characterized by a regionally flat U_3 surface with a very low dip towards the east (0.2° according to Flodén 1980, or gradient 1:230 as constructed from information in Fredén 1994).

This remarkable U_3 peneplain, with its occasional monadnocks (e.g. Blå Jumfrun, offshore Oskarshamn), shows practically no signs of faulting or flexuring in the southeastern regime, either onshore or offshore, a fact which is well demonstrated offshore by the simple shape and consistent younging direction of the submarine outcrop pattern (see Flodén 1980, Ahlberg 1986). The few faults which have been identified have throws measured in tens of metres, at the most. The peneplain rises to a top height of 300-350 m a.s.l. at the transition to the northwestern regime, just to the east of lake Vättern . Crossing the transition zone westwards and northwards, it suddenly drops, and comes to lie 500 m or more below the top height in some of the fault blocks. Single faults within the block faulted zone have throws of several hundred metres or more, in contrast to the maximum tens of metres typical for the Äspö region and the central Baltic Sea. Also, in the downfaulted

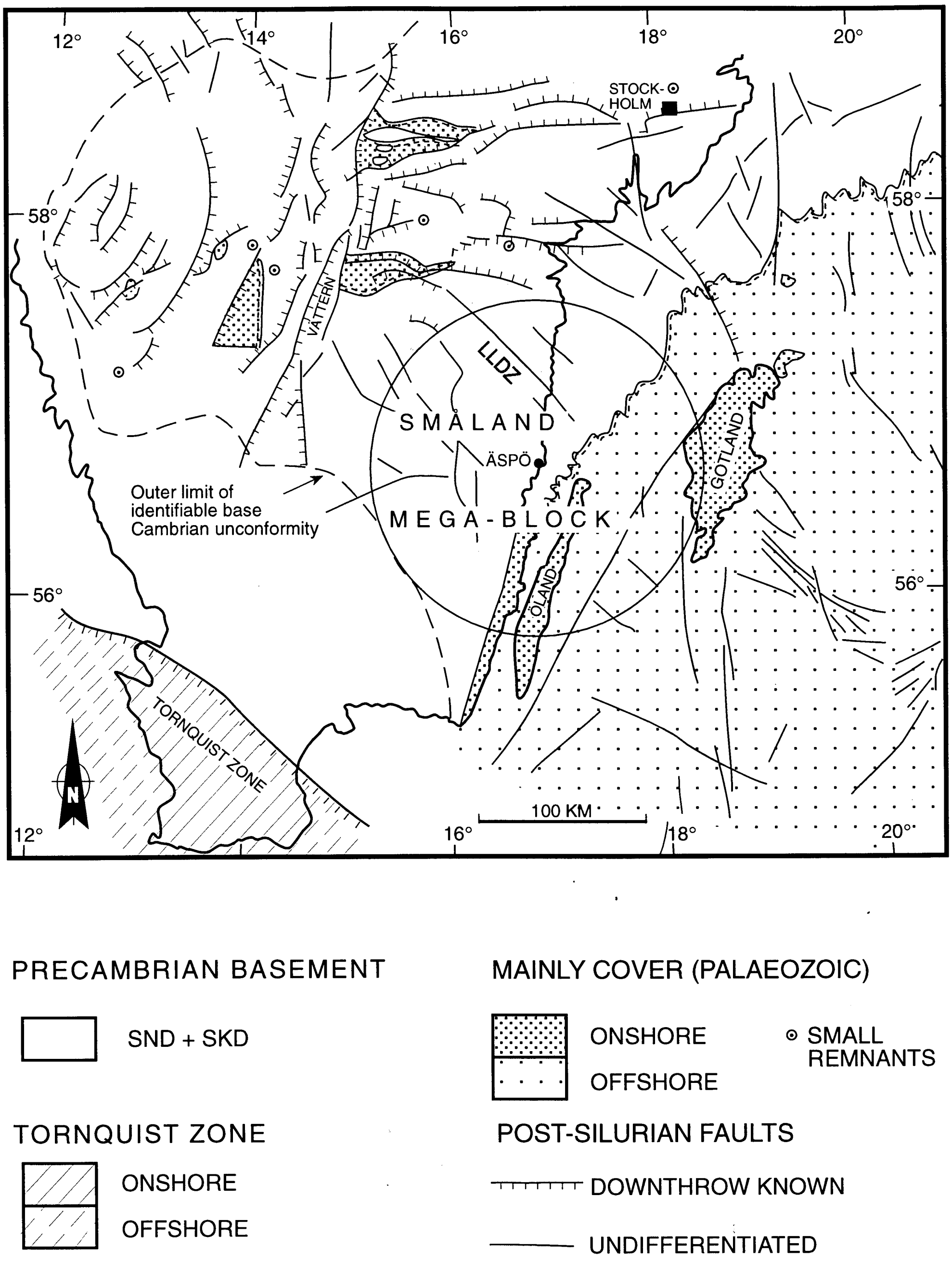


Fig. 3-4

Map of the faulting which affects the sub-Cambrian unconformity in southern Sweden and the central Baltic Sea (after Fredén 1994 and Lidmar-Bergström 1996). In some cases, the faults truncate the whole lower Palaeozoic succession, and since there is otherwise no evidence for syn-sedimentary faulting, all faults are regarded as post-Silurian in age (see text). The increased post-Silurian faulting to the west and north of the lake Vättern marks the northwestern boundary of the Småland mega-block, a crustal segment which has been little affected by Phanerozoic tectonics. The southern boundary of the block is marked by the Tornquist Zone (Caledonian orogeny, Mesozoic-Tertiary faulting). Its boundary to the east of Gotland is unknown due to deep burial. The Äspö region (circle, see Fig. 2-1) lies wholly within the Småland mega-block. LLDZ = Loftahammar-Linköping Deformation Zone blocks of the northwestern regime, a tendency to a westward dip can be discerned (Lidmar-Bergström 1988), which becomes a constant westward dip in the Kattegat (Fredén 1994). The northwestern regime is marked by sharp and straight or curvilinear topographic features and is coincident with a zone of earthquake activity - in contrast to the wide and open topographic features and lack of seismicity in the southeastern regime (Tirén & Beckholmen 1992).

The lack of significant post-Silurian faulting in the southeastern regime can be used to define a crustal segment which has remained stable and internally undeformed since late Precambrian times, the **Småland mega-block** (Fig. 3-4. The northwestern corner of the mega-block is outlined by the increased faulting in the northwestern regime. To the south, the boundary is marked by the Tornquist Zone, with its intensive Mesozoic to Tertiary faulting superimposed at depth on the margin of the buried Caledonian (early Palaeozoic) orogen of Poland and northern Germany (cf. Franke 1993, Meissner et al. 1994, Thomas & Deeks, 1994, Erlström et al. 1997). To the east, the margin of the Småland mega-block is unclear because of the thick cover of Phanerozoic sedimentary rocks of the East European platform. From the lack of deformation in the Ordovician and Silurian sequences of Öland and Gotland, however, it certainly extends east of these islands.

The zone of irregular block faulting to the west and north of the Småland mega-block is obviously a major element in the tectonics of southern Sweden. Although the main marker horizon is the base Cambrian unconformity, there is no evidence for widespread syn-sedimentary faulting in the Cambro-Silurian sequences, indicating that the faulting is post-Silurian in age. The main fault pattern (normal faults of multiple orientation) suggests multi-directional extension, as could be expected across the top of a broad domal flexure (outlined by the sub-Cambrian unconformity, see above). The slight eastward tilt of U_3 on top of the Småland mega-block would then be coeval with dome formation, and a maximum age for the doming event would be given by the first major unconformity in post-Silurian times. The available compilations of stratigraphic relations in the southern Baltic Sea, north of the Tornquist zone, indicate that the first major post-Silurian unconformity is base Permian (cf. Sliaupa & Lazauskiene, in Vilnius 1997), followed and itself truncated by base Cretaceous (e.g. Ahlberg 1986, Fredén 1994). This suggests a late Carboniferous or younger age for the slight tilting of the Småland mega-block and the faulting along its northwestern margin (Vättern 2, Fig. 3-3a, see Månsson 1996). It supports earlier speculations of a connection between the Vättern rifting and the major Permian episode of rifting to the west (Oslo graben, see Martin 1939, Månsson 1996), and is confirmed by fission track data indicating uplift of southern Sweden in late Paleozoic and Mesozoic times (Tullborg et al., in Oskarshamn 1996, cf. Tullborg et al. 1996). The available data indicates that subsidence, rather than doming, occurred during the Devonian, when an overburden of 3000-4000m of molasse-type deposits derived from the Caledonian mountain chains is postulated above the presently exposed

Palaeozoic sedimentary rocks (Tullborg et al. 1995). A pronounced Caledonian foreland basin, since completely removed by uplift/erosion, is indicated, since the Devonian in the eastern Baltic Sea has a thickness of only 700-800 m (Flodén 1980, Sliaupa & Lazauskiene, in Vilnius 1997).

3.4 REACTIVATION OF PRECAMBRIAN SHEAR ZONES

Of particular interest for the search for radioactive waste disposal sites in Sweden is the question of the geometry, orientation and mechanical significance of shear zones (narrow, regionally extensive zones of intense ductile deformation characterized by the occurrence of mylonitic rocks) in the Baltic Shield basement, and their propensity for acting as zones of weakness during later phases of brittle deformation. Based on the above summaries of the regional aspects of ductile and brittle deformation in the Äspö region (Chapter 3.2 and 3.3, respectively), this question can be brought into focus.

3.4.1 Ductile shear zones

Recently, major steeply dipping zones of intense ductile deformation have been described from different parts of the Svecokarelian Domain (e.g. Sjöström & Bergman 1995, Stephens & Wahlgren 1995, Talbot & Sokoutis 1995, Högdahl et al. 1998, see also Berthelsen & Marker 1986). At the Oskarshamn workshop, the occurrence of a major set of NW-SE striking, subvertical zones of mylonites and mylonitic gneisses in the northern part of the Äspö region was reported (Stephens & Wahlgren, and Beunk et al., in Oskarshamn 1996, cf. Figs. 15 and 16b). One of these, the Loftahammar-Linköping Deformation Zone (LLDZ), with the country rocks on each side, was studied in the field (Buenk 1996, Wikström 1996). As noted above, the shearing and mylonitization occurred during a regional ductile event of late Svecokarelian age (tectono-metamorphic phase D2, see Table 3-1). This has been recognized throughout south-central Sweden and in much of the Äspö region. The relatively young, penetrative deformation and metamorphism in the Blekinge region in southeasternmost Sweden may belong to the same phase (Stephens & Wahlgren 1996), or to an early phase of the Gothian orogeny (Table 3-1, cf. Windley, in Blundell et al. 1992). In the Äspö region, the shear zones seem to form an anastomosing network, with individual zones several hundred metres thick and bundles of such zones reaching 20 km in width (for instance LLDZ, Stephens & Wahlgren, in Oskarshamn 1996). Shearing initiated coeval with the TIB magmatism and continued after the intrusion of the TIB plutons (Mansfeld & Sundblad 1996, Stephens & Wahlgren, in Oskarshamn 1996). The movement on the shear zones is complex and variable, but there is clear evidence for dominantly dextral, strike-slip, transpressive deformation with evidence for a considerable dip-slip component of displacement, generally "south-side-up". Metamorphism during shearing, at the present exposure level, occurred under amphibolite and greeschist facies conditions (Stephens & Wahlgren 1996). Strain estimates suggest several 10s of kilometres of dextral displacement, at least 50 km in the case of the LLDZ (Beunk 1996).

Both the TIB magmatism and the D_2 shearing post-date the early Svecokarelian D_1 tectono-metamorphic event and related structures (migmatitic heterogeneities, isoclinal folds, regional foliation S_1, see Table 3-1). This transition marks a radical change in orogenic conditions. The early Svecokarelian processes have been interpreted as subduction-related, reworking the material accumulated during the main phase of continental accretion. The late Svecokarelian has also been thought of as subduction-related (e.g. Andersson 1991), but the special characteristics of the D2 relationships (see above and Chapter 3.2) are more reminiscent of the European Variscides (cf. Rey et al. 1997). They suggest a regime developed in response to the decoupling and sinking of lithospheric mantle and upwelling of asthenosphere, causing partial melting and magma production to occur far up into the crust (e.g.Stephens & Wahlgren 1995, 1996). Continued shortening in a N-S direction would then be accomodated by "lateral extrusion" (Stephens & Wahlgren, in Oskarshamn 1996) or "tectonic escape of continental lithospheric segments" (Beunk 1996) rather than thrust-determined crustal-thickening tectonics. A corollary of this concept is that the presently exposed subvertical shear zones do not continue to great depth, but rather that the movements at depth were accomodated by distributed strain within the largely molten or semi-molten substrate (see Chapter 3.2).

3.4.2 Brittle reactivation

There is good evidence that strongly sheared zones of the types described above act as zones of weakness and stress guides during later deformation in the brittle regime, for instance, during the post-cratonization development (Chapter 3.3). For instance, brittle faulting has been described as being concentrated along the high-strain core of the ductile LLDZ, and fault-slip analysis of slickenside surfaces at one locality indicate an extensional regime with *sigma3* in a NE-SW direction, albeit of unknown age (Beunk 1996). Comparison with recent fault compilations (Lidmar-Bergström, in Fredén 1994, Lidmar-Bergström 1996, cf. Fig. 3-4) suggests that the morphology along the LLDZ trace is partly due to fracturing along the shear zone and shows that the LLDZ trace broadly connects, at its northwest end, with post-Silurian fault zones, within and/or along the margin of the Motala half-graben (cf. also Beunk 1996). However, exactly in the Motala area, the main, EW-striking marginal fault of the half-graben is reported as *not* being controlled by pre-existing structures (Månsson 1996), being a splay off the essentially NS-striking Vättern 2 fault system, which in turn is mainly localized by the reactivation of ductile shear zones marking the Sveconorwegian Frontal Deformation Zone ("Protogine Zone" to the south). In general, the controversy surrounding the significance of the brittle deformation associated with the Protogine Zone (cf. Andréasson & Rodhe 1990, 1992, 1994, Larson et al. 1990, Månsson 1996, Wikström & Karis 1993) turns around the dating of the fracturing, which is certainly itself poly-phasal (see Chapter 3.3), rather than the basic concept that it largely follows and is localized by pre-existing mylonitic zones in the basement (in this case, Sveconorwegian in age, rather than the late Svecokarelian shear zones of interest in the Äspö region).

It is important to emphasize, that localization of brittle deformation along pre-existing ductile shear zones in crystalline complexes is (1) a tendency, not a necessity, and (2) not the only determinant. Reactivation depends on the shear zone having a favourable orientation with respect to the potentially reactivating stress field, and on the presence or absence of other features, notably regionally sub-planar lithological heterogeneities, which provide weaker and/or more favourably orientated stress guides. A corollary of this is that the location of brittle deformation preferentially along pre-existing zones of anisotropy and/or heterogeneity makes it difficult to draw quick conclusions about the orientation of the reactivating stress field. Hence the complex pattern of the inferred post-Silurian faulting to the west and north of the Småland mega-block (Fig. 3-4) could be interpreted as due to a complicated stress pattern (e.g. doming, as suggested in Chapter 3.3), or to a complex pattern of pre-existing structures, or to the superimposition of fractures of different ages. Probably it is due to a combination of all three.

3.5 SUMMARY

The above outline of the regional tectonic framework of the Äspö region based on surface geological observations (as presented at the Oskarshamn and Vilnius workshops, and based on recent SGU compilations) was not intended as an exhaustive review. The aim was to give some background for the interpretation of crustal structure and evolution, discussed in the next chapter. The main result is that the Äspö region lies within a major crustal unit, the Småland mega-block, within which the effects of three main phases of tectonic activity can be distinguished:

Palaeoproterozoic - accretionary phase and Svecokarelian orogeny (formation of the crust, synorogenic magmatism, ductile shearing)
Mesoproterozoic - cratonization phase (crustal consolidation, anorogenic magmatism, uplift/erosion)
Neoproterozoic and Phanerozoic - post-cratonization phase (oscillating uplift/erosion/subsidence, brittle deformation)

The distinction of the Småland mega-block is based on the apparent lack of regionally significant Neoproterozoic and Phanerozoic effects ("regionally significant" as opposed to the ubiquitous local fracturing, which is not considered in this report). Hence, it is clear that, as far as the mega-block and the Äspö region are concerned, the deep seismic images outlined in

Chapter 2 are going to reflect Palaeoproterozoic crust-forming processes, dominated by magmatic underplating which continued into the Mesoproterozoic cratonization phase. With the low degree of resolution attainable in deep seismic surveys, no effects of younger age are likely to be distinguishable, with the exception, perhaps, of the Sveconorwegian Frontal Deformation Zone, as indicated in Section 2.3.4. These points will be taken up in more detail in the following discussion.

4. DISCUSSION

The present report has outlined the large-scale features of the Earth's crust of the Äspö region, which lies within a crustal segment we have called the Småland mega-block. The view is regional in the context of its application to predictive modelling for radioactive waste disposal (the 100 km scale referred to as "global" by Stephansson 1987), i.e. its aim is to help to define the boundary conditions for the local (sometimes called "regional") and far-field rock mechanical models (at the 10 km and 1 km scales, respectively, Stephansson 1987). The main question in this discussion is thus: what parameters can be defined at the regional (100 km) scale which may be relevant for problems of large-scale rock mechanics, based on the data reviewed in Chapters 2 and 3. With regard to this question, it is clear that our study is complimentary to a whole series of earlier works commissioned by SKB, as mentioned previously. These present more detailed treatments of some of the problems touched on here, as indicated below. In the following, however, we confine ourselves to argued interpretations based on the large-scale geophysical and geological features of the crust described above, and their possible significance for the problem at hand.

From the brief summaries of the geophysical and geological data in Chapters 2 and 3, it is clear that the Äspö region lies within a crustal segment which shows a characteristic long-term/large-scale tectonic evolution. In the following, we concentrate on defining relationships within this unit, the Småland mega-block, and discuss first the interpretation of the seismic data in terms of bulk rock composition and deep structure (Chapters 4.1 and 4.2). This leads to a discussion of ideas on crustal evolution (Chapter 4.3), combining the geophysical and geological data and interpretations with general ideas on Precambrian crust-forming processes. The geological model for the Småland mega-block which emerges is then compared with data relevant to large-scale rock mechanics ("bedrock stability"), i.e. the present thermal and mechanical conditions which, together with crustal composition and structure, govern the long-term rheology and flexural rigidity of the crust (Chapter 4.4).

4.1 CRUSTAL COMPOSITION

The ranges of variation of velocity structure and depth to Moho of the Småland mega-block (Table 2-1) are compatible with the global averages for Precambrian shields and platforms (e.g. Meissner 1986, Holbrook et al. 1992). The upper crust (Vp 5.8-6.3 km/s, thickness 8-18 km) can be interpeted as mainly granitic in composition, both from

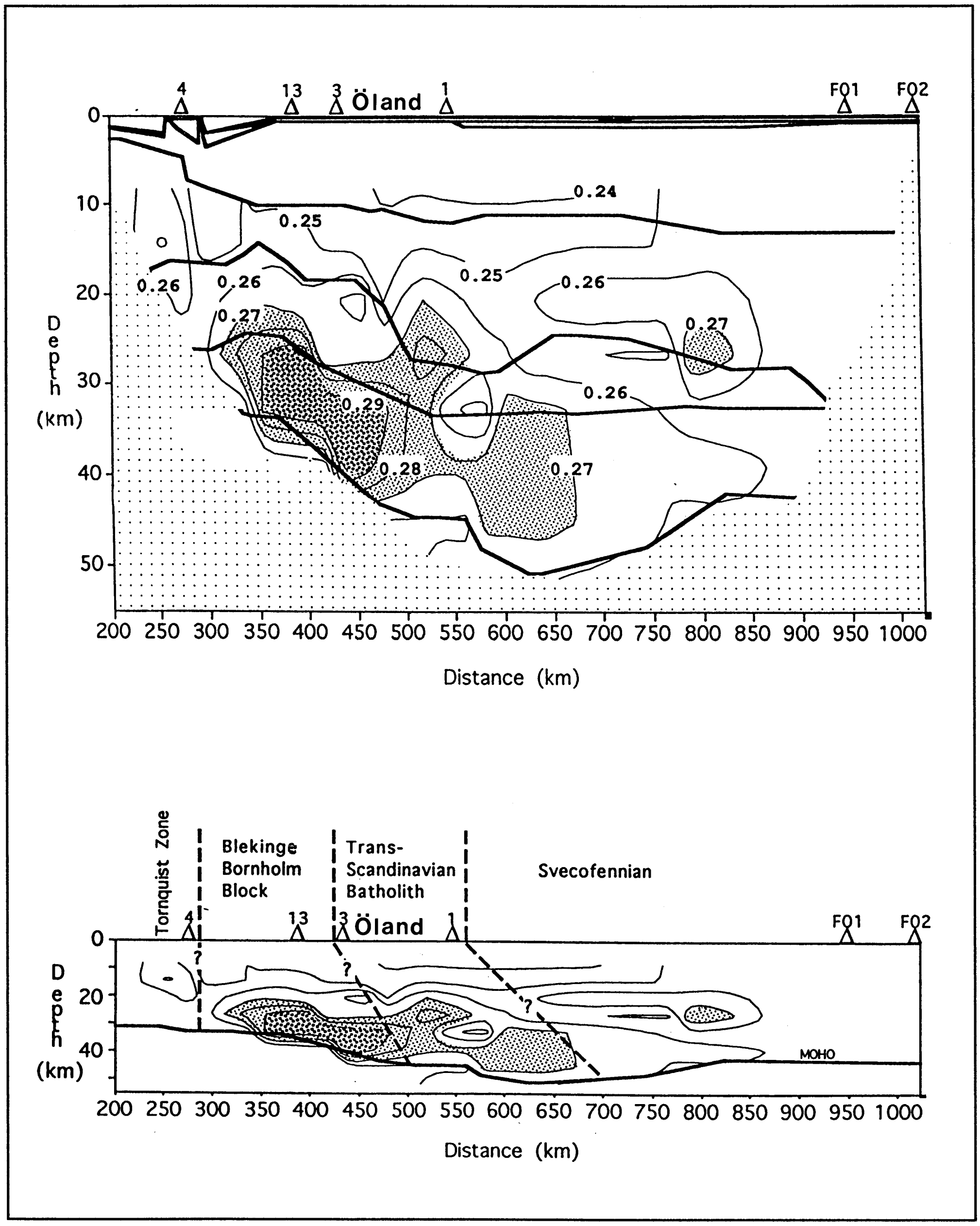


Fig. 4-1

BABEL A-B DSS profiles (cf. Fig. 2-8) processed to show variations in Poisson's ratio calculated from the P- and S-wave velocity structures (from Barth & Klemperer 1996). Below, a possible interpretation in terms of surface geology (Barth & Klemperer 1996, but compare Fig. 4-2 and discussion in text) surface geology and general geophysical and petrophysical data. The middle and lower crust (Vp 6.3-7.5 km/s) falls in the fields of "gabbro/ meta-gabbro/ amphibolite" and "anorthosite/ mafic granulite/ amphibolite/ felsic and intermediate garnet granulite" with respect to seismic velocity (Holbrook et al. 1992). In addition, it has been suggested that the high-velocity lowermost crust (Vp 7.1-7.5 km/s), which according to gravity modelling should have a density in excess of 3.2 g/cm^3 (Blundell, in Blundell et al. 1992), could be composed of eclogite (Henkel et al. 1990, Balling 1995).

The data from the Småland mega-block indicate considerable lateral variations in Vp (Table 2-1), suggesting strong lateral compositional variations, as expected from surface geology and as has been indicated in mapped or reconstructued lower crust analogues (e.g. Smithson & Brown 1977, Percival 1986). This is reflected in the Vp velocity contours on several profiles discussed in Chapter 2, and is expressed strikingly in some structural models (e.g. Clowes et al. 1987). Lateral heterogeneity has been confirmed by the recent reprocessing of the BABEL A-B data (Barth & Klemperer 1996), which included a Vs velocity model of the profile shown in Fig. 2-8. Combining the Vp and Vs data allowed the variations in Poisson's ratio to be mapped along the BABEL line (Fig. 4-1). The low Poisson's ratio in the upper crust (< 0.25) is consistent with high-silica crustal material, as indicated above (Holbrook et al. 1992). The lower and middle crust shows strong lateral variations and a prominent region of high Vp and high Poisson's ratio at the base of the crust below Öland, which suggests a concentration of gabbro or mafic granulite (Barth & Klemperer 1996). In general, then, the Vp velocity models discussed in Chapter 2, and the additional indications from Vs, together with global comparisons, suggest a compositional model consisting of a quartz-rich upper crust (granitic, down to 10-20 km depth) and a quartz-poor, feldspar-rich, middle and lower crust (intermediate-mafic, between 10-20 km depth and the Moho at 40-50 km) for the Småland mega-block. This has important consequences for the long-term rheology of the crust in this area (see below).

4.2 CRUSTAL STRUCTURE

Structural relations within the Earth's crust and upper mantle are best imaged by near-vertical reflection seismic profiling. For the Småland mega-block, the BABEL-B CDP experiment in the Baltic Sea is particularly important, since it provides the only available reflection seismic profile crossing the whole crustal segment (see Chapter 2.4 and Fig. 2-11). In addition to the original interpretation (BABEL Working Group 1993b), several models have been proposed to explain the seismic structure revealed by this survey, especially across the southern margin of the Småland mega-block, i.e. the Tornquist Zone, which forms the southern margin of the Baltic Shield and East European Platform facing Phanerozoic Europe (Meissner et al. 1994, Thomas & Deeks 1994, Abramovitch et al. 1997, Erlström et al. 1997). Of these, only Abramovitch et al. (1997) focus specifically on the

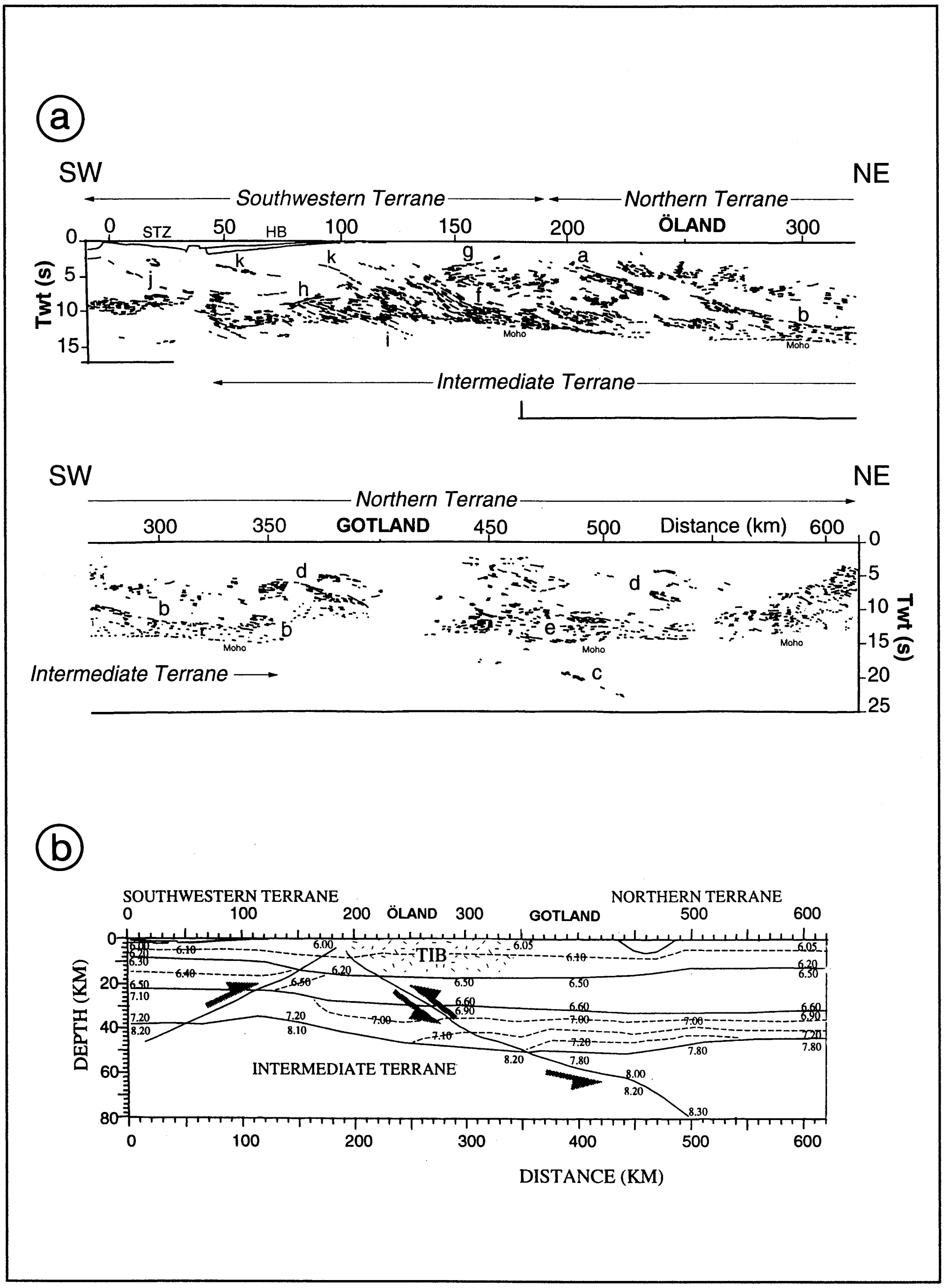


Fig. 4-2

The seismic structure of the Småland mega-block along the BABEL A-B profiles, as interpreted by Abramovitz et al. (1997). (a) Line drawing of the most prominent reflectors on the CDP profile (for the detaied reflective structure, see Fig. 2-11). (b) Interpretation of the CDP profile in terms of Proterozoic terranes and their bounding shear zones or sutures, superimposed on the DSS velocity structure (see Fig. 2-8). According to this interpretation, the movement on the northern suture is Svecokarelian, that on the southern suture Gothian in age (see Fig. 4-3) reflective structure of the crust to the north of the Tornquist Zone, so their interpretation is outlined below.

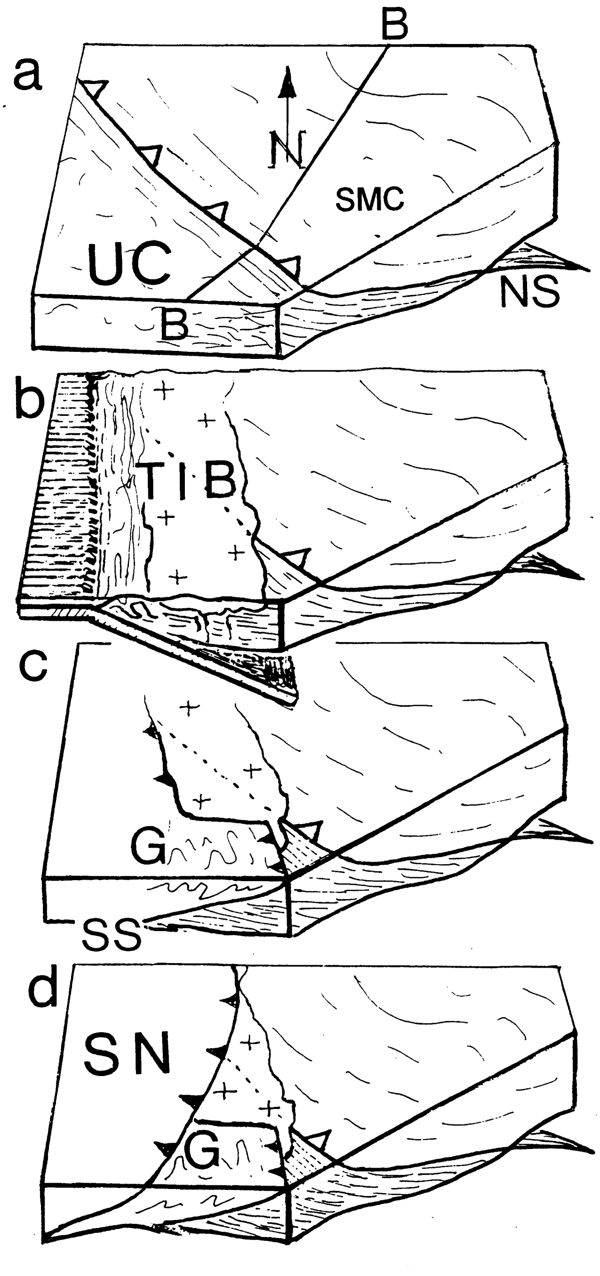
As noted earlier (Chapter 2.4), in the analysis of Abramovitz et al. (1997) the crust of the Småland mega-block is subdivided into three “seismic terranes” (Fig. 4-2). The Intermediate Terrane, which is nowhere exposed at the surface, is characterized by high reflectivity and a prominent N-dipping seismic fabric which parallels a well marked N-dipping reflective zone, marking the upper surface of the Intermediate Terrane to the north (zone a - b-b-b-c on Fig. 4-2a). This zone is thought to represent a major shear zone or suture (the Northern Suture), separating the Intermediate Terrane from the overlying Northern Terrane (cf. Fig. 4-2b), which is much less reflective and shows a more nebulous seismic structure. The Northern Terrane corresponds at the surface to the Svecokarelian Domain described above (Chapter 3.1) and the Northern Suture is interpreted as an early Svecokarelian collision zone (see below, see also Midgley & Blundell 1997). A similar shear zone or suture (zone g-h on Fig. 4-2a) is distinguished to the south, dipping southwest and marking the transition from the Intermediate Terrane and the overlying Southwestern Terrane (at the surface represented by the Blekinge meta-igneous rocks, showing Gothian-age deformation and metamorphism). The hidden Intermediate Terrane corresponds in its northern part to the zone of high Poison’s ratio, noted above (Abramovitz et al. 1997, Barth & Klemperer 1996, compare Figs. 4-1 and 4-2).

The other works which make use of the BABEL data mainly treat the structure of the region to the south of the Småland block, the Tornquist Zone, often in conjunction with other deep and shallow seismic data (Fig. 2-1). The emphasis is on Phanerozoic tectonics, either in terms of Caledonian collision between Baltica and eastern Avalonia (e.g. Meissner et al. 1994, see also Berthelsen, in Blundell et al. 1992, Franke 1993, Makris & Wang 1994, MONA LISA Working Group 1997), and/or superimposed Mesozoic rifting and Tertiary inversion (e.g. Thomas & Deeks 1994, Erlström et al. 1997). A discussion of these interpretations lies outside the scope of this study. However, one aspect needs mention. Many of these works propose that Phanerozoic movements at the surface are partly transmitted northwards as deep ductile shearing in the lower crust (e.g. Thomas & Deeks 1994, MONA LISA Working Group 1997). This opens for the question of Phanerozoic effects at deep levels in the Småland mega-block, and for more general questions of integrating surface/geological and subsurface/geophysical data in terms of crustal evolution.

4.3 CRUSTAL EVOLUTION

Comparison of the different interpretations of the BABEL profiles from the Baltic Sea, north of Hanö Bay, and the Bothnian Sea (i.e. through crust which is represented by Svecokarelian rocks at the surface), show that they are strongly influenced by the models of crustal evolution used to interpret them (e.g. BABEL Working Group 1990, Korja & Heikkinen 1995, Abramovitz et al. 1997, Nironen 1997). In addition, difficulties are often encountered in assigning a particular mode of formation to a specific reflection or group of reflections. Mooney & Meissner (1992) take, as an example of the multi-genetic origin of crustal reflectivity, a section of the BABEL line 3/4 from the Bothnian Sea to illustrate the different characteristics of reflections from "(1) lithologic/metamorphic layering, (2) shear zone, (3) igneous intrusions (sills), (4) crustal root: lithologic layering, (5) Moho: igneous/metamorphic layering" (op. cit., Figs. 2-4a and 2-15). Also, as Nelson (1991) points out, in cratonic crust, of which the Baltic shield is a typical example, structures are often outlined by subtle variations in reflectivity, rather than well-defined reflections, and are commonly obscured by diffractive patterns. He suggests that the vagueness of the patterns in cratonic crust is partly due to repeated underplating by basaltic magmas after the initial stabilization of the orogen, leading to widespread anatectic melting of the lower crust and voluminous dyke injection (cf. Elo & Korja 1993, Nironen 1997). With regard to the reflection seismic pattern: "Only the very largest orogenic structures are likely to be visible through this overprint ...." and " .... the crust would be expected to exhibit a complex pattern of reflectivity determined largely by the varying distribution of post-orogenic plutonic bodies ....."(Nelson, op. cit., p. 31-32). This, clearly, is applicable to the Baltic Shield, with its long history of orogenic and "anorogenic" magmatism, following the crust-forming, Svecokarelian orogeny (Chapter 3). The only prominent reflectors occur in the upper crust and represent large mafic sills (BABEL Working Group 1993a, Line et al. 1997, cf. Palm et al. 1991).

From the surface geology (Chapter 3), a model for the crustal evolution of the Småland mega-block would include late Palaeoproterozoic accretion and reworking in several orogenic phases, accompanied and followed by magmatic underplating, and, in the Mesoproterozoic, uplift and erosion of the stabilized orogenic welt to its present level. The accretionary period resulted, conceptually, in a collage of crustal blocks, originally magmatic with island-arc affinity, and intervening sedimentary basins, possibly including fragments of Archean crust and other terranes with a pre-orogenic deformational history (cf. Mansfeld 1996, Claesson, in Oskarshamn 1996). Further north, some conductive and reflective structures in the upper and middle crust within the Svecokarelian Domain have been interpreted as boundaries between accreted terranes, and the period is considered to be one of crustal thickening produced by the numerous accretional collisions (Korja et al. 1993). One of the latest accretionary events may have been the collisional accretion of the Intermediate Terrane and the formation of the Northern Suture, extending through the crust and into the upper mantle (Fig. 4-3, see Abramovitz et al. 1997). The later orogenic phases (early and late Svecokarelian) have been described in some detail above (Chapter 3.2). At high levels in the crust (present exposures represent a depth of 15-20 km), they are characterized in southern Sweden by anatectic and magmatitic processes, combined with deformation features indicative of shortening in a N-S direction. In northern Sweden, interpretations lean towards extensional collapse of the over-thickened and magmatically weaken crust (Korja &



ca. 1860 Ma
(Svecokarelian D_1)

ca. 1800 Ma
(Svecokarelian D_2,
TIB magmatism)

ca. 1600 Ma
(Gothian)

ca. 900 Ma
(Sveconorwegian)

Fig. 4-3

Conceptual model for the Precambrain evolution of the Småland mega-block and surrounding areas, based on the interpretation of the BABEL profiles shown on Figs. 2-11 and 4-2 (from Abramovitz et al. 1997). UC = "unknown continent" (Intermediate Terrane on Fig. 4-2), SMC = Svecofennian Migmatite Complex (Northern Terrane on Fig. 4-2), NS = Northern Suture (line a-b-b-b-?c on Fig 18), TIB = Trans-Scandinavian Igneous Belt, G = Gothian orogen (Southwestern Terrane on Fig. 4-2), SS = Southwestern Suture (line g-h on Fig. 4-1). B--B = line of BABEL profile. The Småland mega-block corresponds to the eastern half of these block diagrams, east of the Sveconorwegian Frontal Deformation Zone shown as a thrust boundary in block (d).

Heikinnen 1995). Generally, because of the widespread magmatism, it seems unlikely that upper crustal structures, such as the late Svecokarelian ductile shear zones, would continue as individual structures through whole crust at this stage. For instance, we agree with Ambramovitz et al. (1996) that it is unlikely that the Åseda shear zone, which occupied a prominent place in earlier discussions as being related to the supposed 10 km large displacement of the Moho below Öland (Guggisberg et al. 1991, BABEL Working Group 1993b), represents a major crustal structure, not only because of the "disappearance" of the Moho step during later reprocessing and in newer experiments (see Chapter 2), but also because of crustal conditions at the time.

Typical for the Svecokarelian orogeny in southern Sweden is its association with a type of magmatism which has been classified as "post-orogenic" or anorogenic", indicating a melt-dominated infrastructure at comparatively shallow depths (Chapters 3.2 and 3.4.1). This type of magamtism continued into the anorogenic period, which occupied the whole of the Mesoproterozoic. This was characterized by magmatic underplating at the base of, and igneous intrusion (small plutons, dykes, sills) into, a cooled and consolidated crust, making potential seismically reflecting zones from the accretionary and orogenic periods even more diffuse (cf. Furlong & Fountain 1986, Nelson 1991). The high-velocity lowermost crust at the base of the Småland mega-block could be interpreted as the remains of the mafic underplate, possible in the form of eclogite (cf. Henkel et al. 1990, Balling 1995). For instance, the so-called Intermediate Terrane of Abramovitz et al. (1997), which coincides approximately with the region of high Poisson ratio of Barth & Klemperer (1996, cf. Fig. 4-1), could be a this nature, and the prominent N-dipping reflectors could be of magmatic rather than deformational origin. In general, one can conclude that, at the present state of knowledge, all conceptual models for Fennoscandian crustal evolution (for instance, Fig. 4-3) must be treated with scepticism. Even so, the effort to understand deep processes in the early Earth is by no means unnecessary - without geologically argued conceptual models, the interpretation of deep seismic data becomes pure speculation.

The seismic data do not yield any information on the further evolution of the Småland mega-block, which seems to have remained stable and undeformed during the Sveconorwegian and Caledonian orogenies, along its western and southern edges respectively, and during Mesozoic to Tertiary movements around Fennoscandia in more recent times (Muir-Wood 1995). Although studies to the south often indicate northward penetrating movement zones in the lower crust related to these events (e.g. Thomas & Deeks 1994, MONA LISA Working Group 1997), the expected prominent subhorizontal reflectors under the Småland mega-block are lacking. In fact, if the interpretation of the Intermediate Terrane as showing a Svecokarelian internal structure (Abramovitz et al. 1997) is correct, a more definitive statement is possible. The reflectivity zones in the Intermediate Terrane (BABEL line A, see Fig. 2-11 and Fig. 4-2) are oblique to and partly cross the Moho over a distance of 100 km from Hanö Bay northwards, indicating a positive lack of appreciable, later, Moho-parallel, shearing or stretching, both at the Moho itself and in the lower crust.

4.4 CRUSTAL RHEOLOGY

With regard to the question of bedrock stability, now and over the next million years - the main focus from the point of view of radioactive waste disposal - discussions of data on, and interpretations of, crustal structure and evolution need to lead to a generally accepted geological model of the Earth's crust in the area of interest. We do not consider the model outlined above for the Småland mega-block to be conclusive, and we note the lack of concensus on major points. However, using the model can illustrate its importance in discussing crustal rheology. The present composition of the crust, together with an appreciation of large-scale patterns of crustal heterogeneity and anisotropy, forms the basis for reconstructing its thermal and mechanical state, which in turn determines predictions of its reaction to expected future, long-term (>10^4 years, Ranalli 1995) stress accumulations. These may be due to changes in plate motion, or as a result of glacial loading/unloading (cf. Muir-Wood 1993, 1995). As pointed out at the beginning of this chapter, this is the area of large-scale rock mechanics, and within this area we are dealing with modelling on the regional or so-called "global"scale (Stephansson 1987). Modelling itself lies outside the scope of this report; we merely add some final comments on crustal rheology based on the material reviewed.

As pointed out by Rey (1993), shield areas in general are characterized by a thick crust (around 45 km) of largely intermediate to mafic composition (lower two-thirds of crust) and a low surface heat flow (around 45 mW/m^2). Using the data of experimental rock deformation, extrapolating to geological strain rates (10^{-14}/s), and using a linearized geotherm, the strength/depth profile (also called the rheological profile or strength envelope, Ranalli 1997) for cratonic crust does not show any appreciable low strength levels in the crust or upper mantle down to at least 70 km (Fig. 4-4, see also Willett et al. 1985). In general terms, the crustal composition, dimensions and cratonic position of the Småland mega-block corresponds to these generalities. However, it is now recognized that SE Sweden shows a higher surface heat flow (50-60 mW/m^2 according to Sundberg 1995, 60-70 mW/m^2 according to Balling 1995). This leads to steeper estimates of the geothermal gradient than "typical" cratonic crust (Moho temperatures 700-800^{0}C, rather than 400-600^{0}C, cf. Blundell et al. 1992, Muir-Wood 1993, Balling 1995). Also, available seismological data indicate a maximum focal depth of earthquakes in SE Sweden of about 25 km (e.g. Muir-Wood 1993). This is often taken as an approximate measure of the base of the elastic/brittle part of the crustal strength/depth profile, at temperatures of 300-400^{0}C (e.g. Scholz 1990). Hence, a generally much weaker crust would be expected in SE Sweden, in comparison to a typical craton.

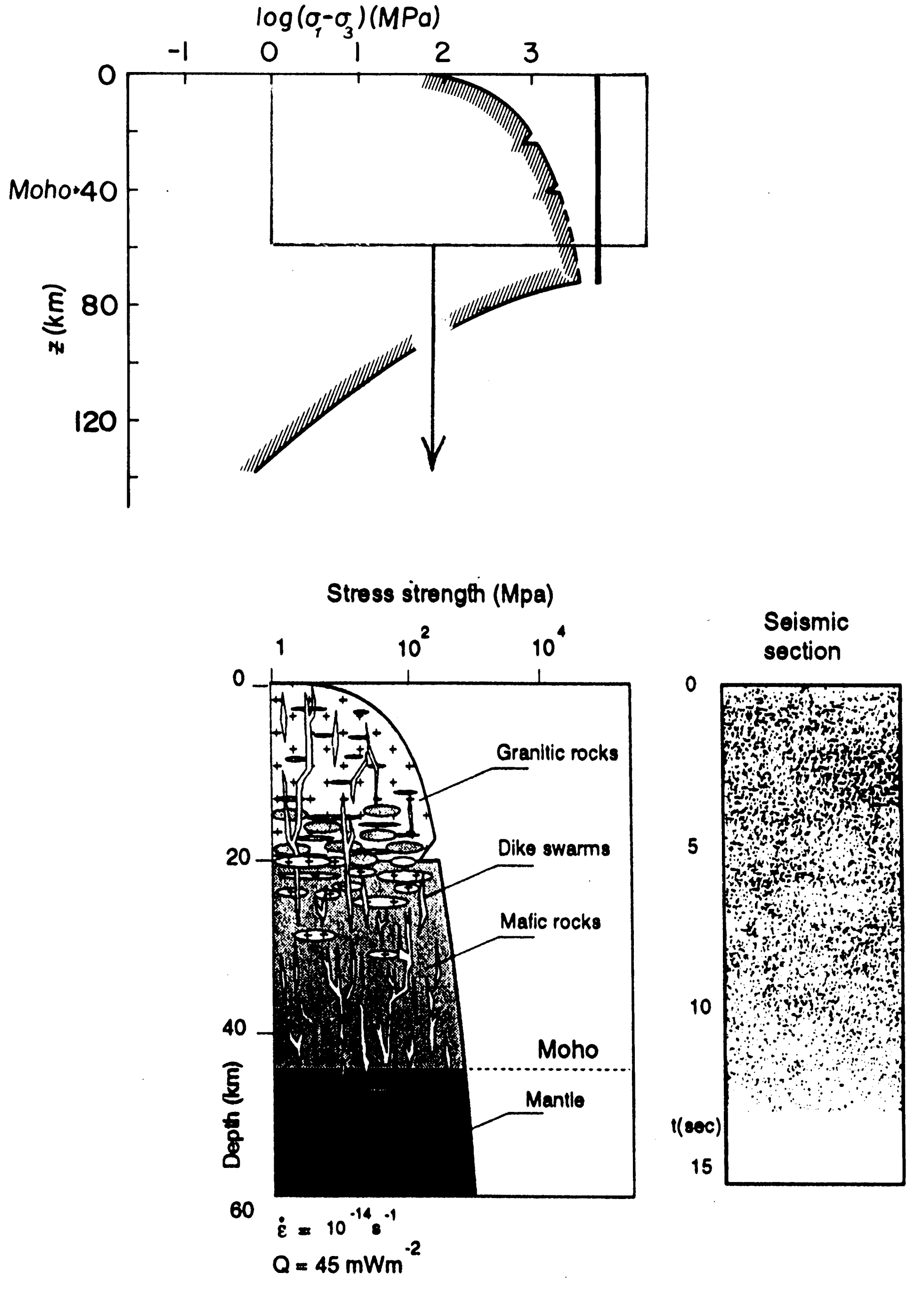


Fig. 4-4

Generic rheological profile for cold cratonic continental crust (from Ranalli 1997), constructed for a strain rate 10^{-14}*/sec, using a "cold" geotherm (corresponding to a surface heat flow of 40 mW/m*^{2} *) and a layered crust (felsic over intermediate/mafic). The thick vertical line shows the extent of brittle deformation. The box shows the area covered by the sketchs of petrographic and seismic characteristics of typical cratonic crust (from Rey 1993). Note the presence of a strong, brittle upper mantle and the lack of a weak zone in the lower crust (for discussion, see text)..*

This difference can be illustrated with reference to the EGT synthesis along the FENNOLORA line (Blundell et al. 1992). Fig. 4-5 shows the difference in crustal rheology between the northern and central parts of the Baltic Shield (FENNOLORA shotpoints G and E), which correspond to "typical" cratonic crust with low heat flow, and the southern part of the Baltic Shield (FENNOLORA shotpoint C, on the northern edge of the Småland mega-block). It should be noted that the low-strength lower crust shown for the northern and central Baltic is based on extrapolation of the experimental data to strain rates of 10^{-16}/s. A profile with high strength throughout is indicated by the occurrence of seismicity down to Moho level (Muir-Wood 1993), indicating a strength envelope similar to that shown on Fig. 4-4 (constructed for strain rates two orders of magnitude faster, see above). Although the heat flow and seismic data are still poor, an obvious conclusion of this preliminary discussion of crustal rheology is that any modelling of the tectonic effects of future ice ages will have to take into account this significant difference in long-term crustal strength between southern and central/northern Sweden.

Along the EUROBRIDGE main profile in Lithuania, significant lateral variations in the shape of the rheological profiles have also been described (Stephenson et al., in Vilnius 1997). The profile in western Lithuania, where the heat flow (65-95 mW/m^2) is much higher than in the east, shows similar characteristics to that of the Småland mega-block. Further east, the heat flow seems to fall to 30-45 mW/m^2 (although the data base here is weak). Assuming that relatively high heat flows (70-80 mW/m^2) can be taken as typical for the EUROBRIDGE main profile between Lithuania and SE Sweden, the data base is becoming sufficiently good to allow large-scale rock mechanical modelling of a NW-SE profile through the Småland mega-block, as has been proposed for northern Sweden (Stephansson 1987). The compositon, structure and rheology of the lithosphere can be argued from a relatively tight observational network, as outlined in this report. The seismo-tectonics, uplift patterns and state of stress have been described in considerable detail (Muir-Wood 1993, Björck & Svensson 1992, Juhlin et al. in press), and show that a NW-SE profile would be parallel to the present axis of maximum compressive stress. Although considerable uncertainties still exist (strength properties of fault zones, shear stiffness of fractured upper crust, depth limit of hydromechanical effects, pressure-dependence of frictional failure, strain softening v. strain hardening at depth, etc.), the present state of knowledge would suffice for preliminary, exploratory calculations and sensitivity studies.

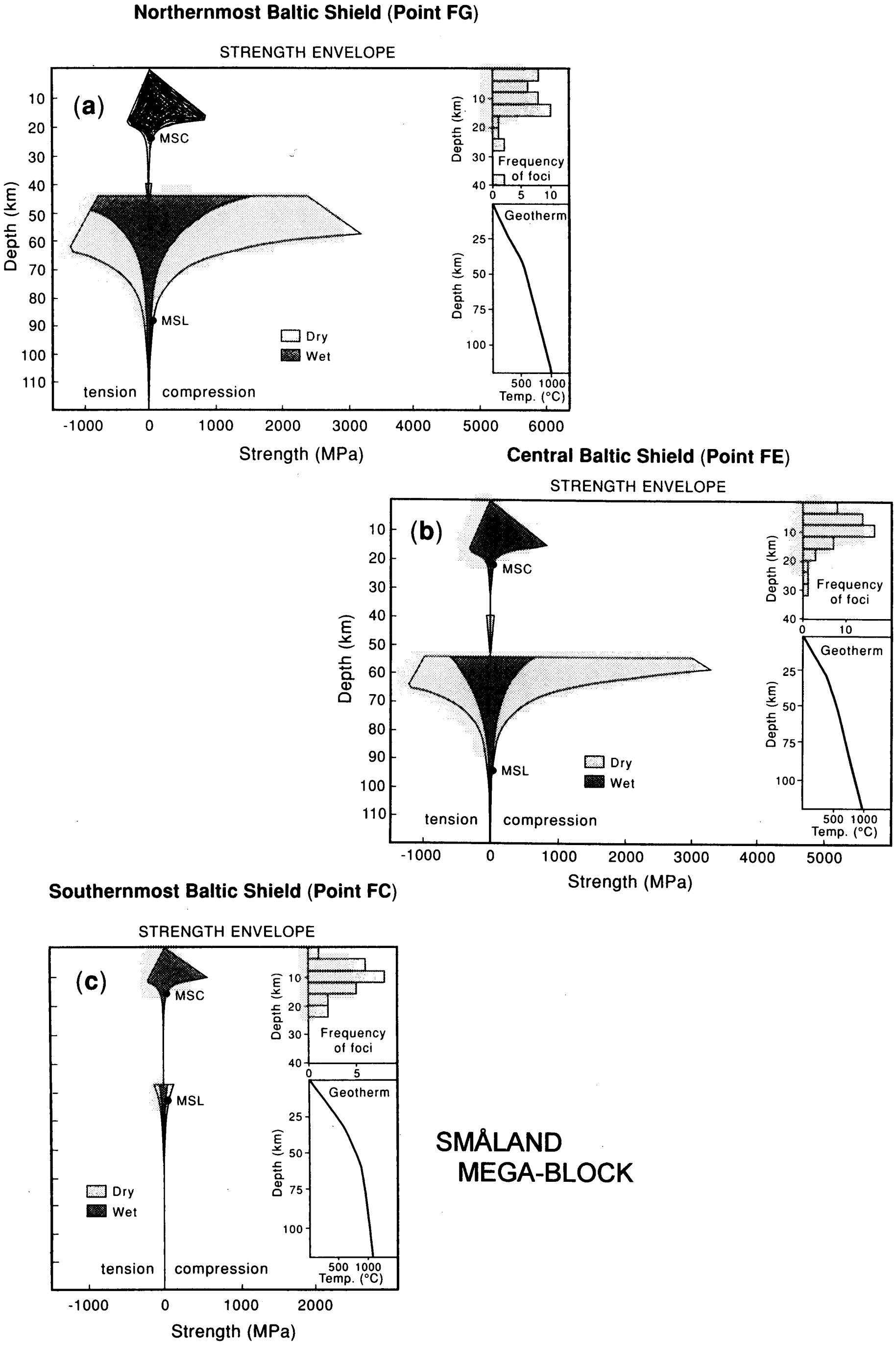


Fig. 4-5

Rheological profiles based on data from the FENNOLORA profile (a) from te northern part (shotpoint G), (b) from the central part (shotpoint E) and (c) from the southern part (shotpoint C, cf. Fig. 2-10) of the Baltic Shield in Sweden, using a quartz/diabase/olivine layer model and a strain rate of 10^{-16}/s (Banda & Cloetingh, in Blundell et al. 1992). FENNOLORA shotpoint C lies within the Småland mega-block and shows a markedly different rheological profile to those further north, for instance, a much weaker upper mantle (for explanation, see text).

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