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Tectonic regimes in the Baltic Shield during the last 1200 Ma - A review

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Gråbo, November, 1993

Keywords: Baltic shield, Tectonicregimes, Upper Proterozoic, Phanerozoic, Magmatism, Sedimentation, Erosion, Metamorphism, Continental drift, Stress regimes.

ABSTRACT

This report is a review about tectonic regimes in the Baltic (Fennoscandian) Shield from the Sveconorwegian (1.2 Ga ago) to the present. It also covers what is known about palaeostress during this period, which was chosen to include both orogenic and anorogenic events. A summary is given in table form, and a litho-stratigraphic map of Baltica including adjacent sea areas is enclosed.

Plate movements are the ultimate reason for stress build-up in the crust. It is concluded that continental drift and rotation velocity have changed during the Earth's history. Periods of convergence and collision between continents are succeeded by periods of continental break-up. The different stress regimes, which prevailed during fracturing, produced specific fracture patterns on different scales. These fractures were reactivated during later favourable stress regimes. Within the next 100 000 years the stress situation of the Baltica crust will not change, except for the effects imposed by the growth and melting of an ice cover.

SAMMANFATTNING

Denna rapport innehåller en sammanställning över den Baltiska sköldens tektoniska regimer under de sista 1.2 miljarder åren. Denna tidsperiod valdes för att inkludera både anorogena och orogena skeden. Sammanställningen omfattar även uppgifter om de bergspänningar som rått under denna tid med utgångspunkt bl.a. från gångars och sprickors riktningar. En tabell summerar den geologiska utvecklingen under perioden, och en karta visar Baltiska sköldens litostratigrafi inkluderande omgivande havsområden.

Plattrörelser är det yttersta skälet till spänningsuppbyggnad i jordskorpan. Det kan konstateras att kontinenternas drifthastigheter och rotationer har varit olika under olika skeden. Perioder av konvergens och kollision mellan kontinenter följs av uppsprickning och uppdelning av desamma. Differentialspänningar ger upphov till sprickor i den övre jordskorpan. Dessa sprickor har specifika mönster under olika spänningsregimer. Klart är dock att sprickor (i olika skala) oftast reaktiveras vid nya påkänningar. Under de kommande 100 000 åren kommer ej den plattektoniska situationen att förändras så att spänningsbilden nämnvärt påverkas i den Baltiska skölden. Den övre krustan kommer dock att starkt påverkas av en landis under samma tidsintervall.

PREFACE

This report comprises a review about tectonic regimes of the Baltic Shield since the break-up of the Proterozoic super-continent – the initiation of the Sveconorwegian-Grenvillian period – to present, a time span of more than 1.2 Ga. Our intention is to give a condensed version of the present knowledge about the tectonic evolution of the shield. The literature reviewed is covered up to mid-1993 and comprises what we have found to be key-publications. We are aware of the impossibility to be able to review all published information into this report.

This work has not been possible without keen support from numerous colleagues. We will especially mention the following persons: Mats Andersson, Johan Berglund, Kerstin Berndtsson, Lennart Björklund, Svetlana Bogdanova, Göran Bylund, Sven Dahlgren, Lars O. Ericsson, Kjell Flodberg, Kjell-Olof Häger, Lars Karis, Kristina Kling, Gustaf Lind, Inger Lundqvist, Thomas Lundqvist, Robert Maddock, Raimond Munier, Lennart Samuelsson, Veli Suominen and Ove Stephansson.

Sven Åke Larson *Eva-Lena Tullborg*

CONTENTS

1 INTRODUCTION

The purpose of this report is to present the current knowledge about the history of palaeo-tectonic regimes in the Baltic (Fennoscandian) shield. The review is focused on tectonics and palaeostress regimes in the Baltic shield (Baltica) during the last 1.2 Ga, i.e. from the onset of the Sveconorwegian period to present (Figure 1-1) (with less attention to the Skåne province and the Caledonides). This time period was chosen to include both orogenic and anorogenic events. We have used some time-definable objects like fractures, dykes and faulted markers, created during specific stress regimes and have also estimated the thickness of sedimentary covers. A summary of the tectono-metamorphic, magmatic and sedimentary events in Sweden is shown in Appendix 1. A litho-stratigraphic map of Baltica, Appendix 2, is also enclosed.

Orogene	Era	Period	Age (Ma)
	Cenozoicum	Quaternary	1.6
Alpinian	Cenozoicum	Tertiary	65
	Mesozoicum	Cretaceous	140
	Mesozoicum	Jurassic	205
	Mesozoicum	Triassic	250
	Palaeozoicum	Permian	290
Variscian	Palaeozoicum	Carboniferous	355
	Palaeozoicum	Devonian	410
Caledonian	Palaeozoicum	Silurian	437
	Palaeozoicum	Ordovician	510
	Palaeozoicum	Cambrian	570
	Late Proterozoicum	Vendian	700
	Late Proterozoicum	Riphean	900
Sveconorwegian	Mid Proterozoicum	Riphean	1250
	Mid Proterozoicum	Riphean	1600

Figure 1-1. The geological time scale considered in the review.

1.1 SHIELDS AND THE STRESS FIELD

A **shield**, is an area of exposed Precambrian rocks which has not been reworked by Phanerozoic orogenic events. Southern Sweden is part of the Baltic shield which at its southern end terminates against a major fault zone, the Tornquist-Teisseyre Zone. Southernmost Sweden (Skåne) is not included in the shield concept, as the Precambrian platform here is covered by extensive Phanerozoic sedimentary rocks which have been tectonized.

The cause of the stress field in the Earth's crust is multifold. Main factors controlling this are plate movements (e.g. Skordas et al., 1991), depth within the crust, thickness of "external load" (sedimentary cover, ice sheet etc.) and for the local stress field also other factors (topography, fracturing, and other local anomalies). The cause of the current seismic activity in Baltica is presently debated. Ridge push and glacial rebound are considered to be the main factors (Slunga, 1989; Skordas, 1992; Muir-Wood, 1993).

For most of the stable shields, it has generally been possible to show that the present, vertical, principle stress is less than the minimum, horizontal, principal stress down to a depth of approximately 200 to 500 metres (Figure 1-2; Hoek & Brown, 1977; Jamison & Crook, 1978; Wallroth, 1992). Below this level the stress-gradient situation is more ambiguous, but generally the vertical load is larger than the smallest of the horizontal principal stresses. It is not known how long this type of stress situation has been valid for southern Baltica. However, the present tectonic regime with sea floor spreading and ridge push in the Atlantic ocean has prevailed during the last 65 Ma. The fracture pattern of Precambrian areas is the result of a long history of repeated deformation. From this follows that the fracturing in Baltica is referred to the Archean, the Proterozoic, the Phanerozoic or even is a result of neotectonic movements.

As most papers reviewed do not consider displacements along fractures this information usually is missing here. However, most extensional opening of fractures can be assumed to give information about the direction of the principal stresses (Appendix 1).

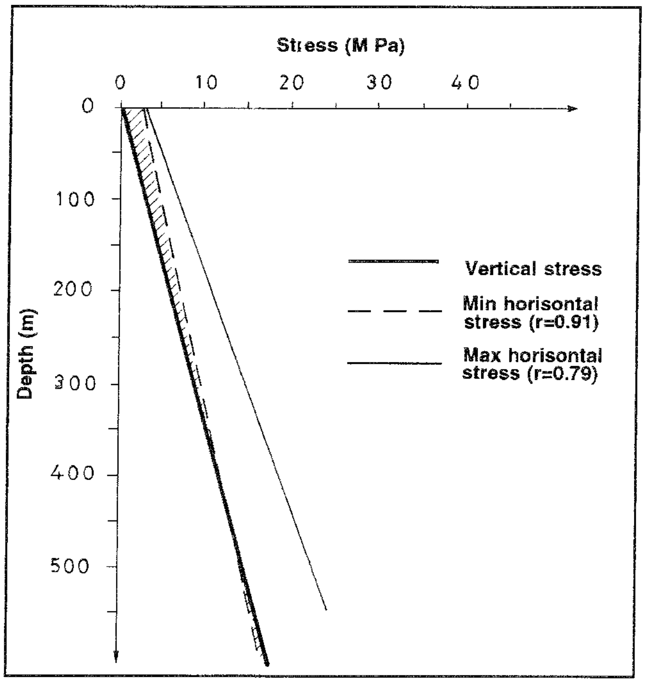

Figure 1-2. Regression analyses of maximum and minimum horizontal stress versus depth for hydraulic measurements in Sweden. Data from Stephansson et al., 1986. Vertical stress gradient according to Jamison & Cook, 1978.

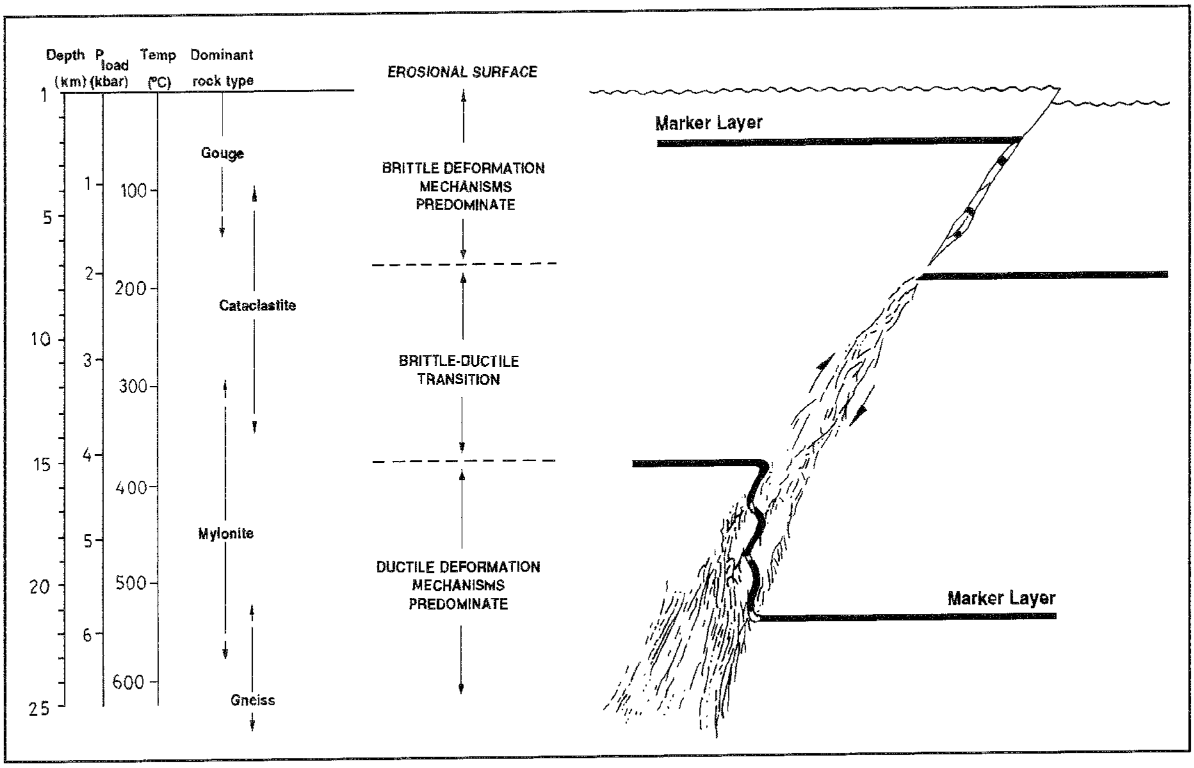

Figure 1-3. *Regimes of deformation versus depth (modified from Colvine et al., 1988).*

High absolute stress and high stress gradients may create stress release resulting in brittle or ductile deformation depending on P-T conditions. Thus, shallow level deformation will result in fracturing while deep level deformation will give folding, flow and recrystallisation of the rock. At intermediate depths brittle-ductile deformation will be the mark of stress release (Figs. 1-3 and 1-4).

1.2 OROGENIC AND ANOROGENIC PERIODS

During the Earth's history orogenic and anorogenic periods have replaced each other. **Orogenic periods** are characterized by collision tectonics mainly resulting in compression but also in extension of the crust. The onset of orogenic periods is typically rifting and dyking. Most dyke swarms occupy a failed-arm environment and form during early spreading. Intracratonic volcanic and subvolcanic feeders form as fringes along passive margins of the spreading zone (Figure 1-5) or deep within the plate where failed-arm dyke magma is trapped in preexisting rift areas (Fahrig, 1987).

The tectonic pattern resulting from convergence of lithospheric plates is complicated. In Figure 1-6, a typical configuration of displacements during a collision is illustrated including thrusting and strike-slip movements, a pattern found in a.o. the Himalayas.

So called ensialic orogenesis was formed in the Precambrian and was developed intercontinentally by rifting, volcanism, trough sedimentation and succeeding compression and deformation (Kröner, 1981).

The Pre-Sveconorwegian history of the Baltic shield will not be considered in this report. However, several orogenies have been identified during this early period of the shield.

About 1250-900 million years ago southwestern Baltica was influenced by the Sveconorwegian / Grenvillian orogeny which was succeeded by a more than 400 million years long anoro-

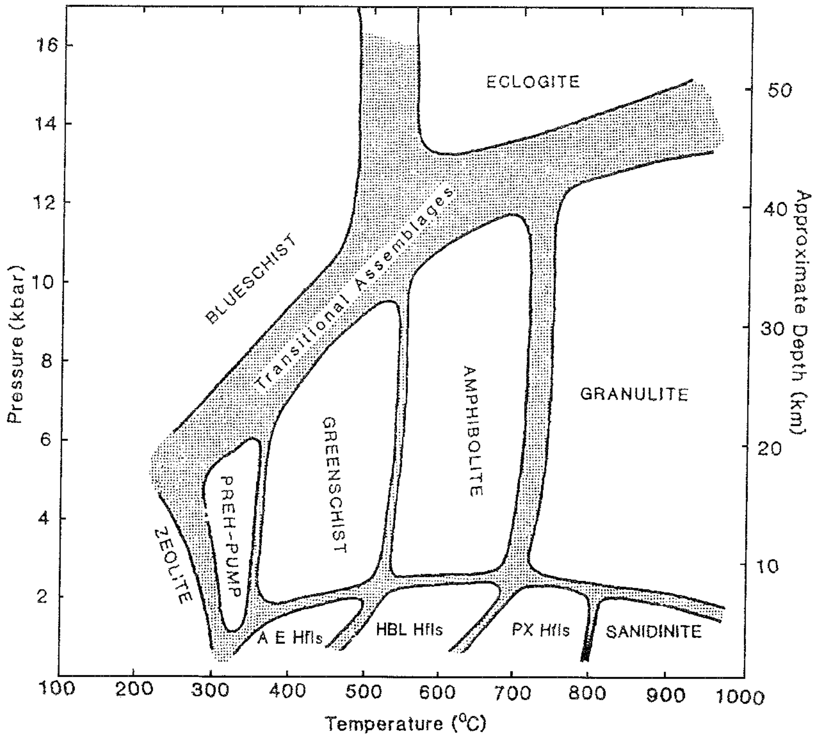

Figure 1-4. *Pressure-temperature diagram showing the field of the various metamorphic facies. Hfls=Hornfels, AE=albite-epidote, HBL=hornblende, PX=pyroxene, PREH-PUMP=prehnite-pumpellyite (Yardley, 1989).*

genic period. The subsequent Caledonian orogeny, which culminated at about 400 million years ago, severely influenced the western margin of Baltica by deformation and docking of new crust. Also the Variscian and Alpine orogenies, about 300 and 100 million years ago respectively, influenced the southernmost parts of the Fennoscandian shield.

The **anorogenic periods** succeeding the orogeneses are characterized by erosion, sedimentation and moderate igneous activity. Extensive erosion or load of sediments will give changes of the principle vertical stress resulting in uplift or depression of the crust.

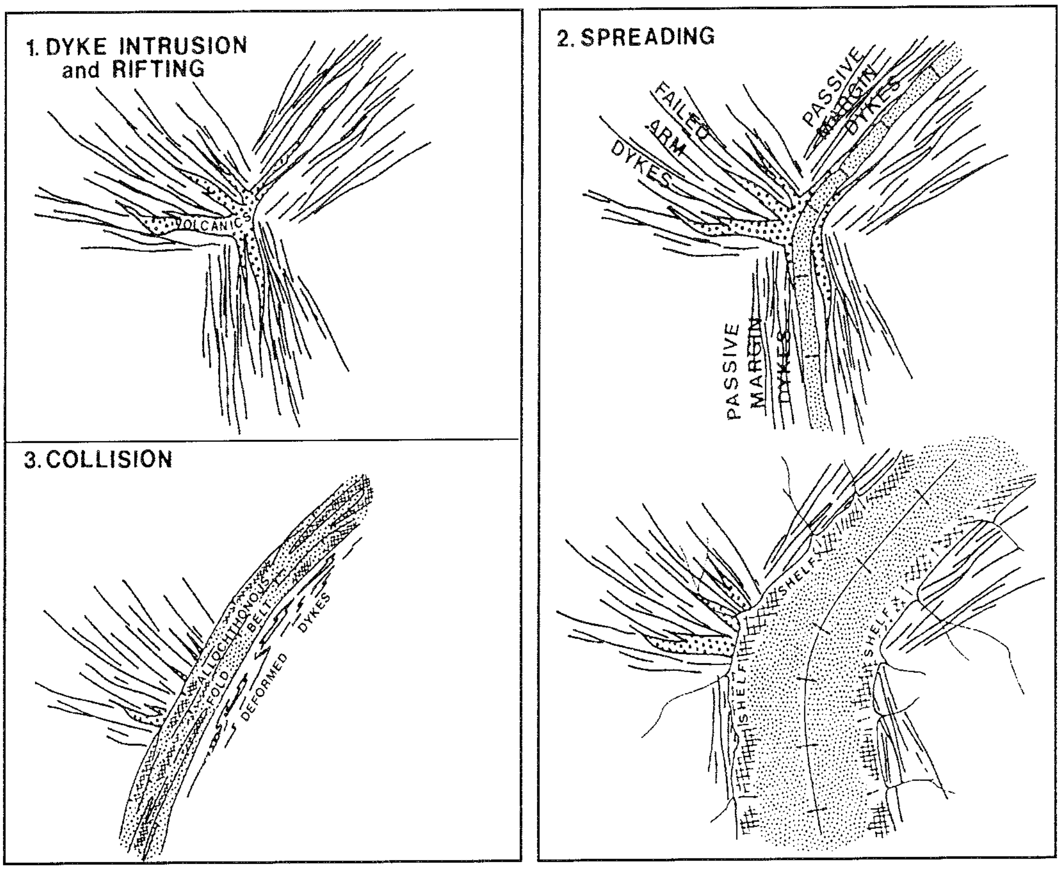

Figure 1-5. *Development of mafic continental dyke swarms by a three-stage plate tectonic cycle (from Fahrig, 1987).*

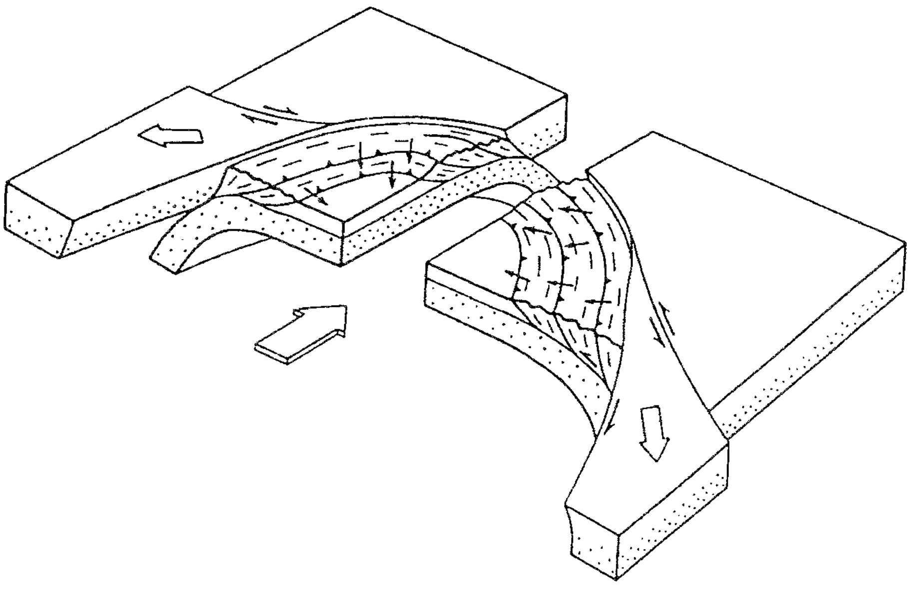

Figure 1-6. *Ideal block diagram showing the possible relationships and compability between crustal nappe displacement and lithospheric plate convergence (from Matte, 1991).*

2 THE SVECONORWEGIAN PERIOD, 1250 – 900 Ma AGO

The Sveconorwegian orogeny mostly affected the SW parts of Baltica resulting in plutonism and deformations. Tensional regimes are in the entire Baltica indicated by dolerite swarms of different ages (Figure 2-2).

2.1 INITIAL RIFTING AND MAGMATISM

The period started with rifting during the brake-up of Baltica from Laurentia (e.g. Poorter, 1981; Pesonen et al., 1989; Gower, 1990) (Figure 2-1a). At this time large areas were covered by Jotnian sandstones of continental type, in some areas with an assumed thickness of more than 2 km. In the Bothnian sea ca. 1 km of Jotnian sediments are still preserved. These sediments were originally deposited into a Jotnian graben which was the initiation of the Bothnian Basin (cf Figure 4-1).

The initial phase of rifting is in central Sweden as well as in SW Finland represented by the so called post-Jotnian dolerites (ca. 1270-1250 Ma) (cf. Figure 2-2). These were mostly intruded

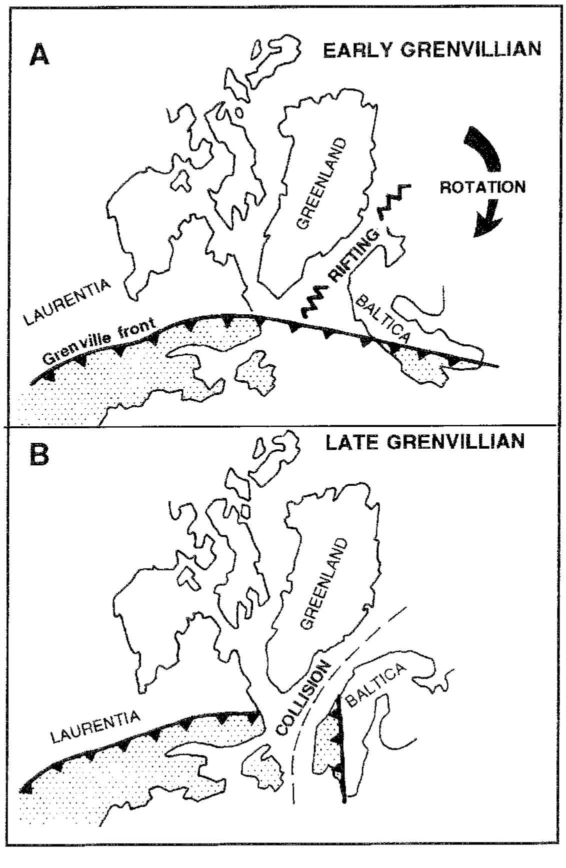

Figure 2-1. Early Grenvillian/Sveconorwegian break-up of Baltica/Laurentia (from Gorbatschev et al., 1987).

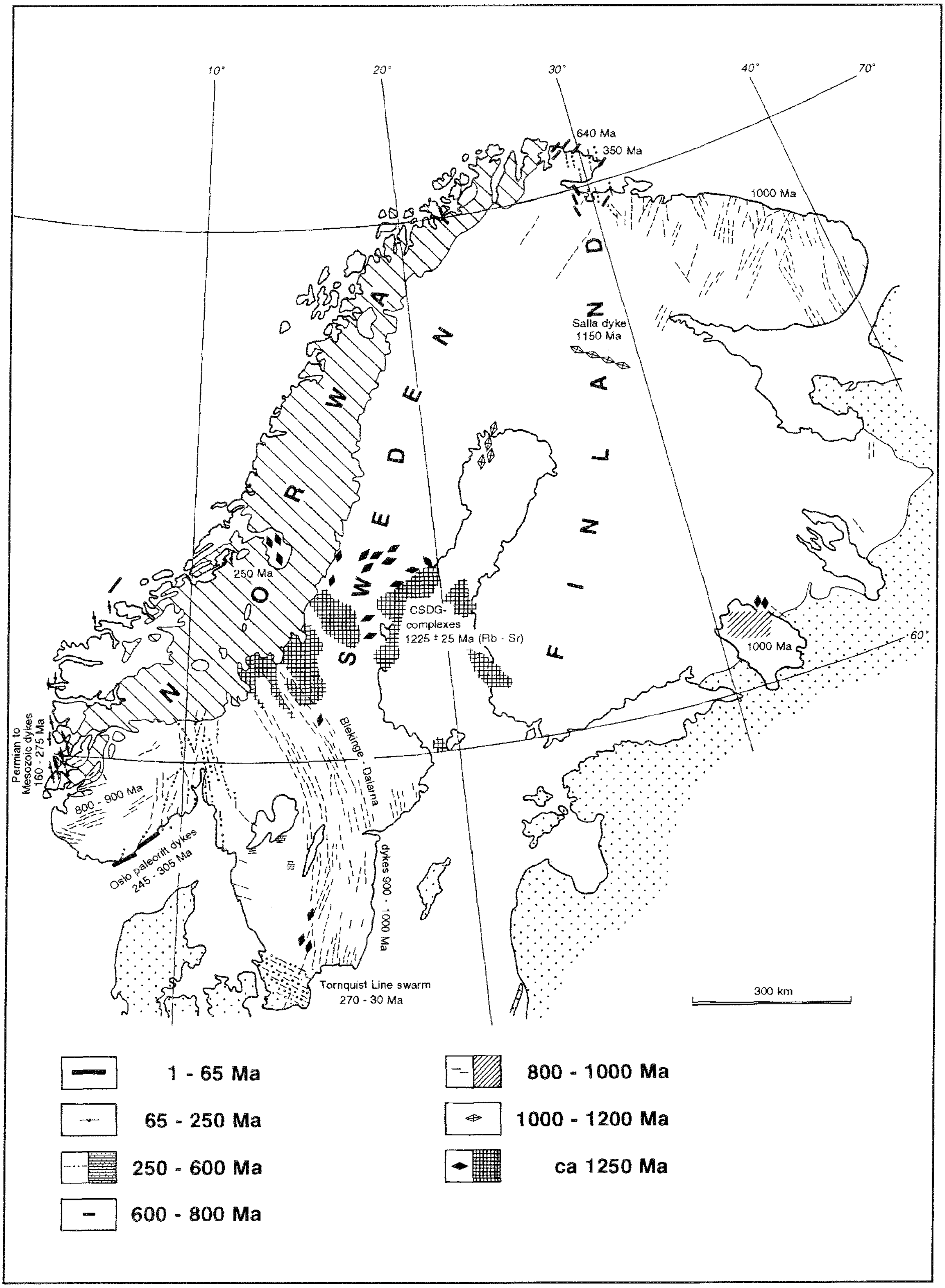

Figure 2-2. *General map of the mafic dyke swarms from 1250 Ma to present in the Baltic Shield; modified from Gorbatschev et al., 1987. Hatched/striped/checked areas (symbols to the right in the legend boxes) represent sills and sheets.*

as sheet-like bodies in some cases as lopoliths (Larson, 1980; Suominen, 1991). In Scandinavia these rocks have been termed the "Central Scandinavian Dolerite group" (Gorbatschev et al., 1979). The dolerites were in some areas emplaced into Jotnian sandstones as sills. The sheet-like shape of the intrusions is also found when intruding the granitoids of the region (Lundqvist et al., 1990). Geophysical evidence for several, sub-horizontal dolerite sheets of supposed similar ages recorded at several kilometres depth beneath the Siljan impact, was also reported by Juhlin (1990). The dolerite sheets suggest a stress field with horizontal components larger than the vertical. This is different from the stress situation recorded during the same time or slightly later (ca. 1180 Ma ago according to Johansson & Johansson, 1990) for south-central Sweden, where the difference between the two horizontal, principle stresses (sigma H – sigma h) was large and a vertical, N-S trending, dyke swarm was emplaced.

Extensive sheet like mafic dykes of a possible similar age also occur in the Lake Ladoga and to the west of Lake Onega (Gorbatschev et al., 1987) in Russia but also in northern Sweden.

In southwest Sweden, scattered, Early Sveconorwegian granitoids intruded around 1200 million years ago (e.g. Zeck & Wallin, 1980; Welin et al., 1981 & 1982; Skjernaa & Pedersen, 1982). In the provinces of Skåne and Småland, plutonism is recorded at about 1200 to 1230 million years ago (Jarl, 1992; Johansson, 1990). Early Sveconorwegian NW thrusting and intrusions of coarse grained granites are also known from S. Norway (Starmer, 1993).

Subsequent erosion of the crust resulted in sedimentation, as recorded within the Dal Group (Heybrook, 1950). The age of the Dal Group is restricted to the 1200 – 900 Ma interval. The sedimentation was of marine type and connected to basic volcanism.

Contemporaneous basaltic and rhyolitic volcanic rocks with a preliminary U-Pb age of about 1200 Ma, interbedded with sediments are known from Telemark (Bandak Group) in Norway and reflects E-W back-arc tension related to subduction further west (Starmer, 1993), but also gabbroic intrusions were emplaced there at 1145 Ma and formed dyke and sill complexes (Sven Dahlgren, Oslo, pers.com. 1990).

In the Bamble sector of SE Norway an Early-Sveconorwegian orogenic phase of deformation and granitic intrusions were concentrated at the interface to the Telemark gneiss Complex. A phase of crustal extension in SE Norway was localized to the Bamble Shear Belt where much basic magma was intruded at 1200 to 1100 Ma (Starmer, 1990). Quartz filled, tensional fractures created during a NW-SE directed compression was reported by Larsson (1938) from the Bohus granite at the Swedish-Norwegian border. These fractures preceeds a "Pre-Caledonian" mylonitic phase.

In central Sweden the post-Jotnian dolerite sheets are cut by an E-W trending dyke swarm (Lundqvist et al, 1990; Lundqvist, 1991) which probably is of Sveconorwegian age and could be of the same age as the NW-striking Salla dolerites in northern Finland which intruded at 1150 Ma (Lauerma in Gorbatschev et al., 1987).

2.2 ROTATION AND SHEARING

Succeeding the Laurentia-Baltica brake up, the rotation of Baltica in relation to Laurentia certainly created a complicated stress regime (concerning E. Canada and the clockwise rotation of the Grenvillian stress field, see Figure 2-3).

In Baltica several Sveconorwegian shear zones have been identified like e.g. the Protogine Zone and the Mylonite zone (cf. Figure 2-5) which are two of the most prominent zones in Sweden. In southern Norway (e.g. Starmer, 1990) and Sweden (e.g. Samuelsson, 1977; Larson et al., 1990) these trend in a roughly N-S direction. Larson et al. (1990) concluded that the Protogine Zone is a long lived zone of crustal weakness, probably with an Early Proterozoic precursor (cf. also Berglund et al., 1992 and Andréasson & Rhode, 1992). The complexity of the zone in the region west of Lake Vättern, S. Sweden is shown in Figure 2-4.

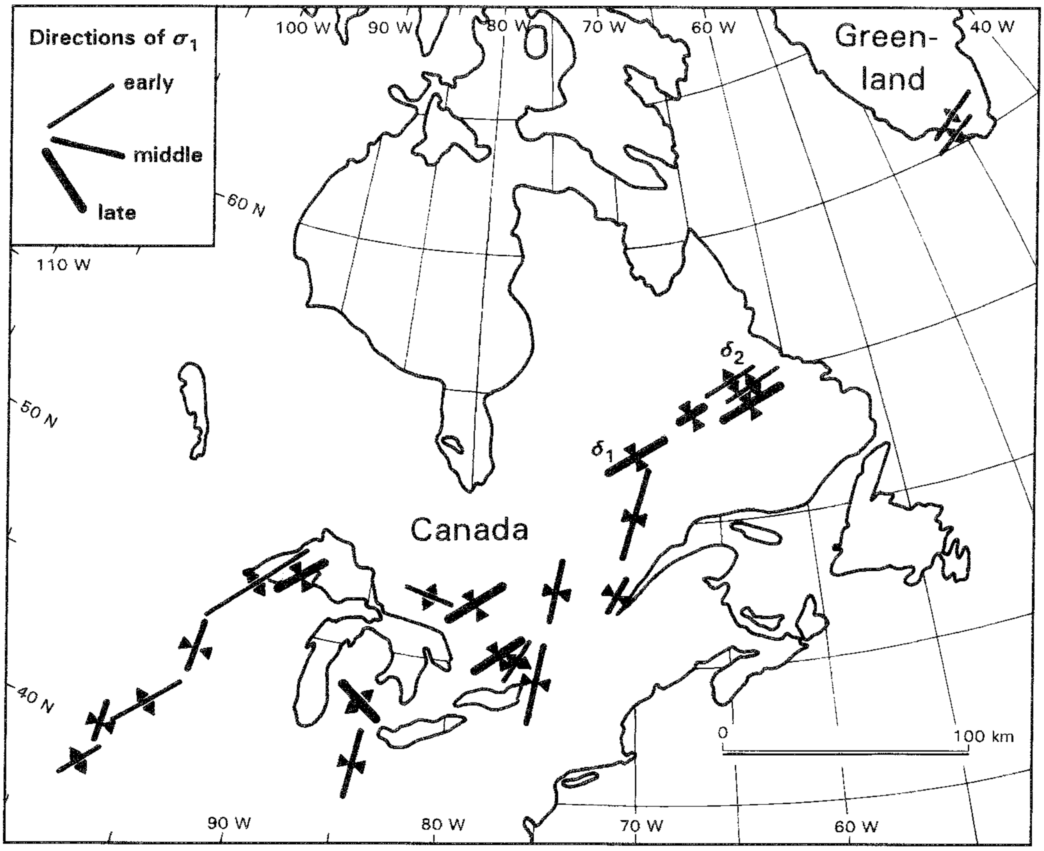

Figure 2-3. *Changes in the assumed stress field of the eastern Canadian Shield between approximately 1300 ("early") to 950 ("late") Ma ago. Arrows towards line indicate the direction of sigma 1 and away from line the direction of sigma 3. (From Baer, 1981).*

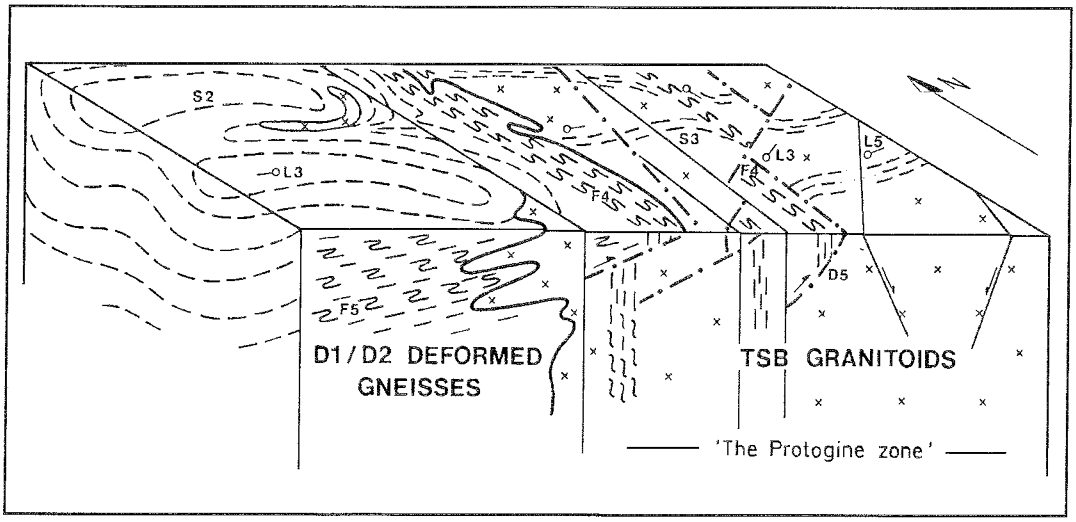

Figure 2-4. *Block diagram of Protogine Zone structures trending N-S affecting older E-W trending structures in the area SW of Lake Vättern. (From Larson et al., 1990).*

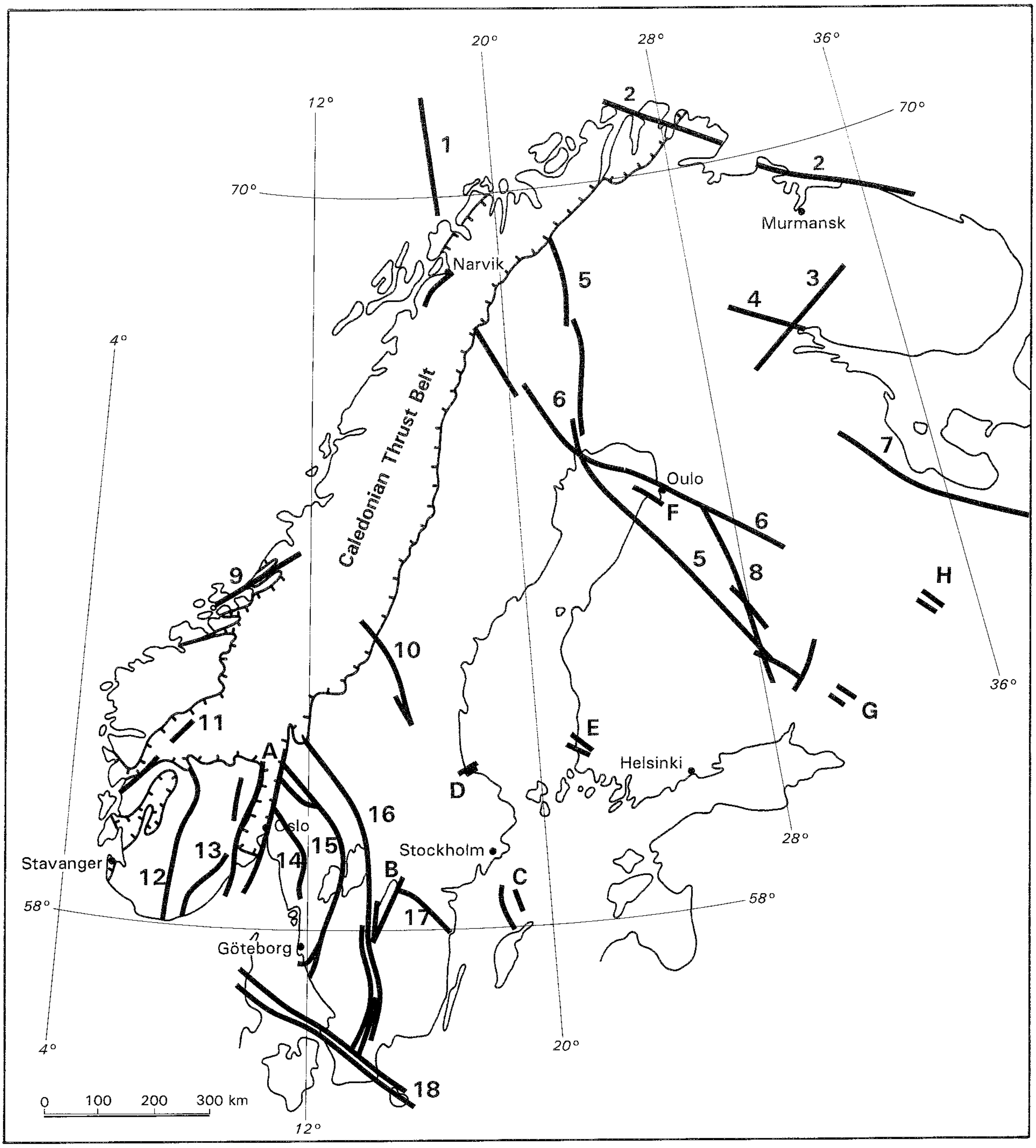

Figure 2-5. *Some prominent tectonic zones (1-18) and grabens (A-H) in the Baltic shield.*

Shear/fault zones: 1=Senja; 2=Trollfjord-Komagelva; 3=Kontozero Zone / Graben; 4=Kandalaksha; 5=Ladoga-Bothnian Bay; 6=Senja-Oulunjoki; 7=Vetrenny; 8=Muhos-Karelian Isthmus; 9=Möre-Tröndelag; 10=Kårböle-Ljusnan; 11=Laerdal-Gjende; 12=Mandal-Ustaoset; 13=Kristiansand-Porsgrund/Meheia-Ådal; 14=Dalsland Boundary; 15=Mylonite Zone; 16=Protogine Zone; 17=Västervik; 18=Tornquist.

Grabens: A=Oslo; B=Lake Vättern; C=Landsort; D=Gävle; E=Satakunta; F=Muho; G=Ladoga, H=Onega.

The definition of the Protogine zone has been debated. Berglund et al. (1992) suggested the name "The Transscandinavian Shear Zone" for the Sveconorwegian shearing along the zone to be separated from other movements, e.g. the younger tectonic events connected to the Lake Vättern Graben formation. The Sveconorwegian shearing affected among others syenites (Larson et al. 1990) of an age of 1205 million years (Jarl, 1992). Parallel to this shearing gently, westward dipping mylonites have been observed. These have also been considered as the result of Sveconorwegian deformation (Larson et al., 1990). To the east of the Protogine Zone in southern Sweden Talbot (1990) only recorded PreSveconorwegian mylonites. This area is considered to be east of the Sveconowegian front as a.o. K-Ar ages of whole rock samples and biotites are ca. 1200 to 1400 Ma (Åberg, 1978; Jarl, 1992).

East of Lake Vänern, Wahlgren (1988) mapped a N-S trending foliation in the Protogine Zone (gently eastwards dipping in the western part and steeply in the eastern part) considered to be of Sveconorwegian age, with "the western-side-up" kind of kinematics. Thus, different styles of Sveconorwegian deformation are found along the zone.

The ductile N-S trending fabric along the Protogine Zone is overlain by the about 700 million years old Visingsö sediments (Lars Karis, Uppsala, pers. com., 1992). This supports the assumption of Gavelin (1912) whom assumed the age of the foliation along the Protogine Zone to be older than the Visingsö Formation.

2.3 DOCKING, THRUSTING AND EXTENSION

A new docking of Laurentia to Baltica took place at about 1100 to 1000 Ma ago causing a compressional stress regime (Figure 2-1b). Hoffman (1992) suggested an alternative reconstruction of the Sveconorwegian collision event to be a docking also to the Amazonia (Figure 3-1). This collision resulted in eastward thrusting in SW Sweden (e.g. Park et al., 1990) with thickening of the crust (Gorbatschev et al., 1987; Larson et al., 1990), and succeeding peak of the Sveconorwegian orogeny (cf. Daly et al., 1983). The thickening of the crust in SW Sweden resulted in increased vertical load. It is suggested that succeeding, extensional tectonics of this thickened crust resulted in subhorizontal folding (Larson et al., 1990). A strong metamorphic event in the Eastern Segment (see enclosed map sheet) of the Southwest Scandinavian Domain is recorded at c. 950 Ma by Larson et al. (1993).

In Halland and Småland Johansson et al. (1991) discovered a granulite facies mineral paragenesis formed during a metamorphic event at about 900 Ma. This paragenesis required pressures corresponding to a depth of c. 35-40 kilometres to be formed. However, Page et al. (1993) reports on $^{40}Ar/^{39}Ar$ hornblende ages of 931+/-3 to 1007+/-3 Ma from the same region. The reason for this discrepancy is not yet known. Within and north of the Mylonite Zone $^{40}Ar/^{39}Ar$ hornblende ages of 911+/-3 to 917+/-4 Ma are recorded, indicating tectonic activity at this time within the Mylonite Zone.

A minimum age of 904+/-13 Ma of the last ductile deformation within the Mylonite Zone is given by the age of an E-W cross cutting lamprophyre (Wahlgren & Kähr, 1977). An almost concordant U-Pb titanite age from a mafic lens in the southern part of the Mylonite Zone yielded c. 930 Ma (Johansson & Johansson, 1993).

Thrusting in the Glaskogen Nappe in Värmland (Gorbatschev, 1988) has been dated by the Rb-Sr method to be 962 +-19 Ma (Wahlgren et al., 1981). Sveconorwegian thrusting is also found along the Protogine Zone (cf. Figure 2-3) and is probably also the case in the Almesåkra group, ca. 30 km east of the Protogine Zone (Th. Lundqvist, 1991). According to Talbot (1990), Sveconorwegian local thrusting is found as far east as in the Ävrö area on the Swedish east coast.

The Sveconorwegian in S. Norway was a major crustal reworking event which produced large volumes of granite and caused large scale deformation. The N-S trending structures in

Telemark were produced in response to major compressional tectonics causing westward thrusting of the Kongsberg and Bamble Blocks (cf. Starmer, 1985 and 1993) on the Telemark Domain (Dahlgren, pers. com. 1990).

The "Sveconorwegian Front" has its N-S extension in southern Sweden. The detailed site of this is debated and is dependant on its definition. However, the regional, Sveconorwegian, ductile deformation and heating approximately ends up at the "Protogine Zone" but, as reviewed above, the Sveconorwegian thrusting is found far east of the zone.

2.4 FINAL DYKING AND BLOCK MOVEMENTS

Concerning temperature imprint, fractures filled with prehnite (indicating prehnite-pumpellyite grade) are typical for the Sveconorwegian period in SE Sweden (Wiman, 1930; Wickman et al., 1983; Larson & Tullborg, 1984; Tullborg 1988 & 1989; cf. also Nyström, 1982), but to the west of the Protogine Zone amphibolite-granulite mineral parageneses are found (cf. also Tucker and Krogh, 1990). Tirén (1991) measured a preference for a NNE-SSW direction of these fractures at Finnsjön indicating a maximum compression in the same direction (Munier & Tirén, 1989). Later infillings of laumontite succeeded the prehnite infillings only within major fracture zones. This shows that the ca. 1.1 Ga old prehnite filled fractures (Wickman et al., 1983) were later opened by less penetrative low temperature fluids.

A new phase of dyking and plutonism also took place in the Late Sveconorwegian. Thus, dolerites of an age of c. 1000 Ma appears in N-S and NE trending dykes and sheets in the Kola Peninsula, Russia but also in a N-S trending swarm from the Kola province to Lake Onega (Sinitsyn 1963, Gorbatschev et al., 1987). Late Sveconorwegian deformation and magmatism (ca 1050-950 Ma) are recorded from Telemark and Bamble sectors in Norway (Starmer, 1990). In south central Sweden a N-S trending dyke swarm was intruded east of the Protogine Zone at about 900 Ma and is possible to trace from the Blekinge province in the south to the Dalarna province in the north (Johansson & Johansson, 1990). This dyke swarm indicates a strong E-W tensional stress regime.

The ending of the Sveconorwegian period in SW Sweden and SE Norway, is a.o. manifested by the emplacement of the Bohus-Blomskog-Idefjord granite at 910 Ma (Eliasson & Schöberg, 1991). Granitoids of similar age were also emplaced in many places in southern Norway. A moho off set of 8 kilometres connected to and east of the "Bohus-Flå granite Belt" was recorded from seismic investigations and is interpreted as due to deep crustal underthrusting (Andersson et al., 1993).

In southern Norway and adjoining parts of Sweden c. E-W trending mafic dyke swarms represent a (final?) Sveconorwegian fracturing (Gorbatschev et al., 1987).

The Sveconorwegian terrane of southern Scandinavia displays different structural and metamorphic imprints in different parts. The metamorphic grade varies from granulite to greenschist/prehnite-pumpellyite and structural trends are shown to change over short distances. In some places these breakes are recognized as shear zones.

K-Ar datings from SW Baltica show Late Sveconorwegian ages (Welin & Blomqvist, 1966) and in SW Sweden it is known that also recrystallization of magnetite took place. In SE Sweden K-Ar biotite ages are approximately 1400 Ma (Åberg, 1978). This indicates an uplift of SW Sweden in relation to eastern Sweden. In the province of Värmland, Jarl (1992) found that the segment between the Mylonite Zone and the Protogine Zone represents a deeper crustal level than surrounding segments (cf. also Welin & Blomquist, 1966). Thus, these regions with rocks representing different depths juxtaposed, have suffered large scale, Late Proterozoic normal and thrust faulting.

In summary:

* The Sveconorwegian period comprises the Laurentia-Baltica break up, subsequent clockwise rotation of Baltica, and a new docking to Laurentia(?). These movements created a number of stress regimes, inter alia represented by dikes and shear zones.
* A number of shear zones in SW Scandinavia were active during the Sveconorwegian. One of the most prominent is the Protogine Zone which was active during several different stress regimes (compression and extension) which resulted in shearing, thrusting and dyking.
* The Sveconorwegian orogeny in terms of deformation and thermal metamorphism mainly affected SW Sweden and southern Norway.
* Several dyke swarms e.g. the Blekinge-Dalarna dolerites and the dolerites on the Kola Peninsula indicate extensive rifting in Late Sveconorwegian time.
* Large scale block faulting have taken place in the Late Sveconorwegian and/or the Late Riphean.

3 THE LATE PROTEROZOIC PERIOD, 900 – 570 Ma AGO

Relatively little has been published about this period (Late Riphean – Vendian) concerning Scandinavia, where it is characterized by uplift involving faulting with large vertical displacements, erosion, sedimentation and rifting. Palaeomagnetic data indicate a rapid rotation velocity of more than 0.6 degrees/million year for the period 850 Ma to 600 Ma.

3.1 RIFTING AND GRABEN FORMATION

It has generally been accepted that the Northeuropean lithosphere was attached to the Northamerican lithosphere after the Sveconorwegian orogen (e.g. Gower, 1990). However, a recent palaeoreconstruction by Hoffman (1992) gives attention to an alternative position of Baltica at this time (Figure 3-1).

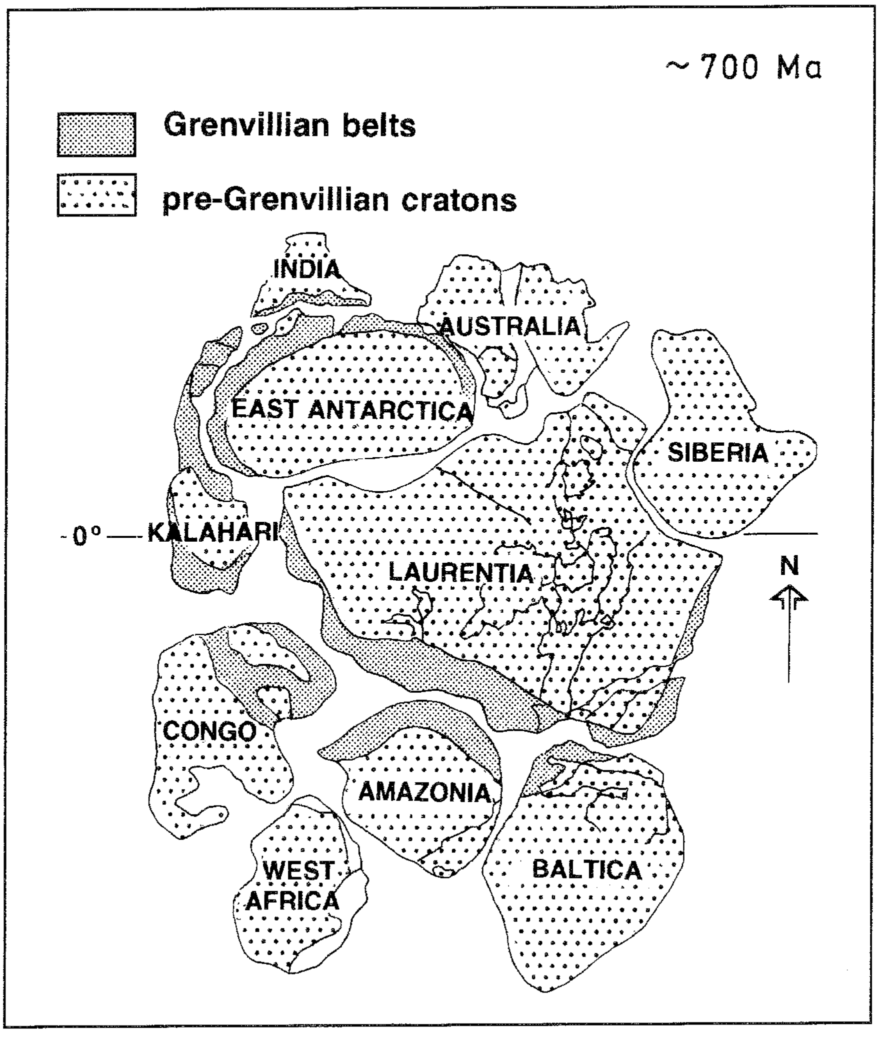

Figure 3-1. Reconstruction of continents c. 700 Ma ago (from Hoffman, 1992).

It is stated (e.g. Lindström et al., 1991) that a short time after the emplacement of the Bohus granite c. 900 Ma ago, the new crust was stretched, thinned and immense layers of sediments (erosion products from the "Sveconorwegian mountains") were emplaced in the basin created between Laurentia (Northamerican/ Greenland plate) and Baltica (Northeuropean plate) (cf. Figure 3-2).

Also within Baltica were several grabens formed. One of these is the Vättern Graben which probably was formed during the Late Riphean due to a roughly E-W tensional regime (cf. Figure 3-2). Sediments in S. Sweden, from the Late Proterozoic period, are recognised as the Visingsö Group (Collini, 1951). They are considered to be about 800-700 Ma (Late Riphean) according to unpublished data by E. Welin (referred to in Kumpulainen & Nystuen, 1985; c.f. also Bonhomme & Welin, 1984) and Late Riphean to Early Vendian according to micropaleontological data (Vidal, 1979 and references therein) and include three sub-units. The maximum thickness of the Visingsö sedimentary rocks is about 1000 metres (e.g. Vidal, 1984) and they probably covered most parts of S. Sweden. Presently they are found within or connected to the Vättern Graben. It is also probable that several fracture zones parallel to the Vättern Graben were active or possibly even initiated at this time.

A N-S trending rift system filled with Vendian sediments was also recorded by Lassen et al. (1993) in the southern part of the Baltic Sea, and was speculated to be a southern continuation of the Vättern graben structure.

In SE Norway the Vangsås Formation in the Lake Mjösa region was deposited in a tectonically active basin contemporaneous with the deposition of the Visingsö Group (Vidal, 1985).

Ulmishek (1991) argues about a N-S trending graben structure ("the Central Baltic Rift") in the central part of the Baltic Sea filled with Upper Proterozoic sediments.

NW trending basins were formed at the same time SW of Åland, in Lake Ladoga, in Russia and S of Oulu in Finland (the "Muhos Formation") (Flodén, 1992). The earliest unit of the Muhos Group is interpreted to be of Middle to Late Riphean age and the youngest unit to be of Lower Cambrian age (Wannäs, 1989). Vendian sediments are also found in the Finnish Bay off shore Tallinn and eastwards to Lake Ladoga (Puura, 1993).

In northern Norway and Sweden approximately contemporaneous sediments to the Visingsö Group are marine clastic rocks and alluvial to fluvial clastic sediments deposited in basins and other depressions (Kumpulainen & Nystuen, 1985). These deposits became allochtonous, parautochtonous or autochtonous in relation to the Caledonide orogen. Three periods of deposition are distinguished; a Late Riphean-Early Vendian sedimentation, a Varanger sedimentation and a Late Vendian-Cambrian sedimentation.

In northern Norway and northwestern Russia the Varanger Peninsula and Fiskare Peninsula respectively are covered by Riphean-Vendian sediments. On northern Varanger Peninsula these sediments are up to 15 km thick. The Varanger Peninsula is cut by the WNW-ESE trending Trollfjord-Komagelva Fault Zone which is a dextral strike slip shear zone displaced approximately 250 km during the protracted Caledonian orogeny (Siedlecka & Roberts, 1992). This zone was later reactivated and was active up into the Cenozoic (e.g. Gabrielsen, 1984; Gabrielsen & Faerseth, 1989; Lippard & Roberts, 1987) or possibly into post-glacial time (Olesen et al., 1992). The Tanafjord-Varangerfjord Sedimentary Basin has a tectonic development similar to that of the Muhos Basin (Wannäs, 1989). Also on the southern coast of the Kola Peninsula sediments of similar ages are found (Nalvikin, 1976; Wannäs, 1989).

In the Caledonides the Torneträsk Formation in N. Sweden and the Gärdsjön Formation, W. central Sweden were deposited during Late Vendian (Thelander, 1982; Vidal, 1985; Wannäs, 1989).

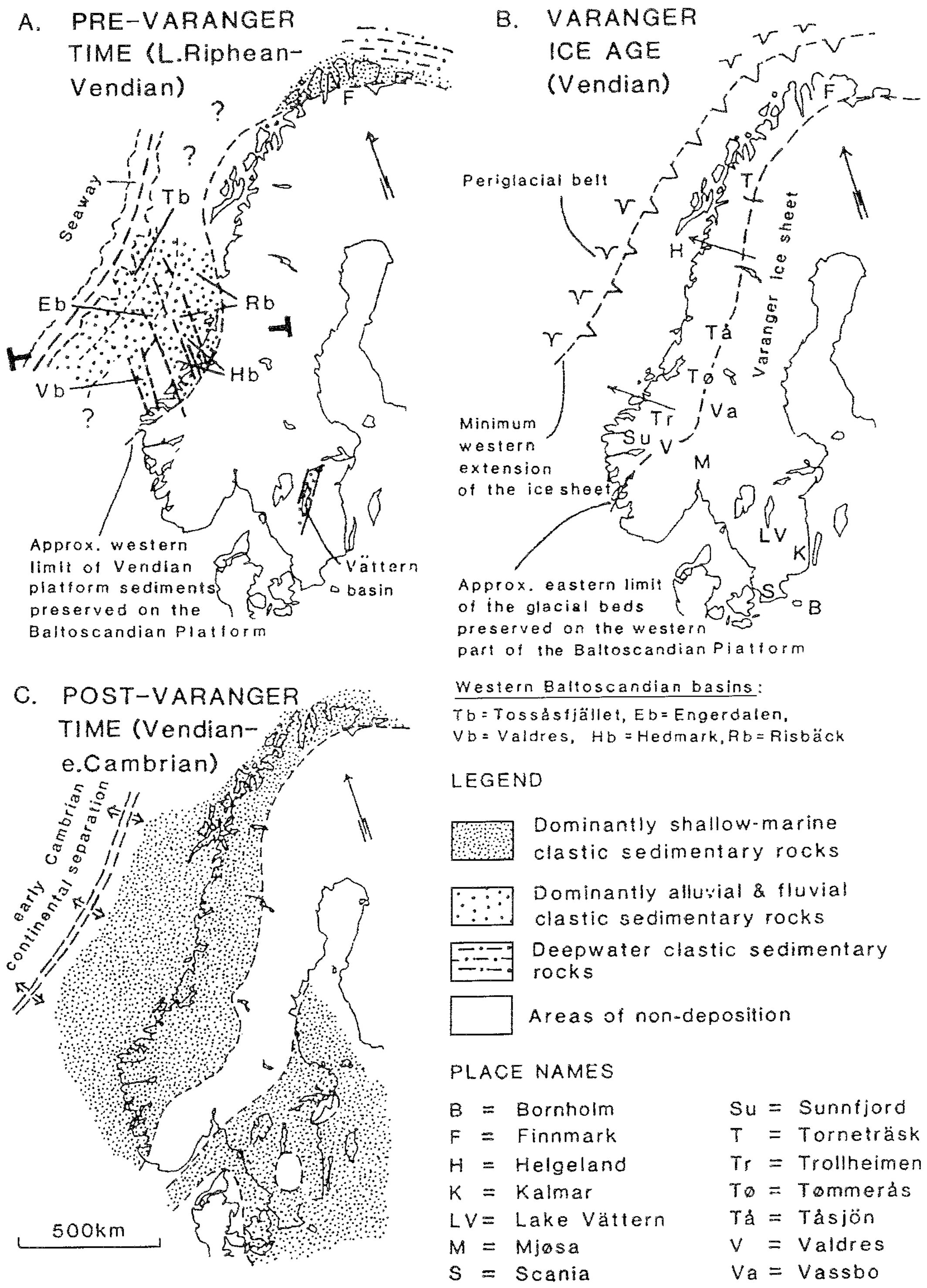

Figure 3-2. *The Late Riphean – Early Cambrian palaeographic evolution in western Baltica. (From Kumpulainen & Nystuen, 1985).*

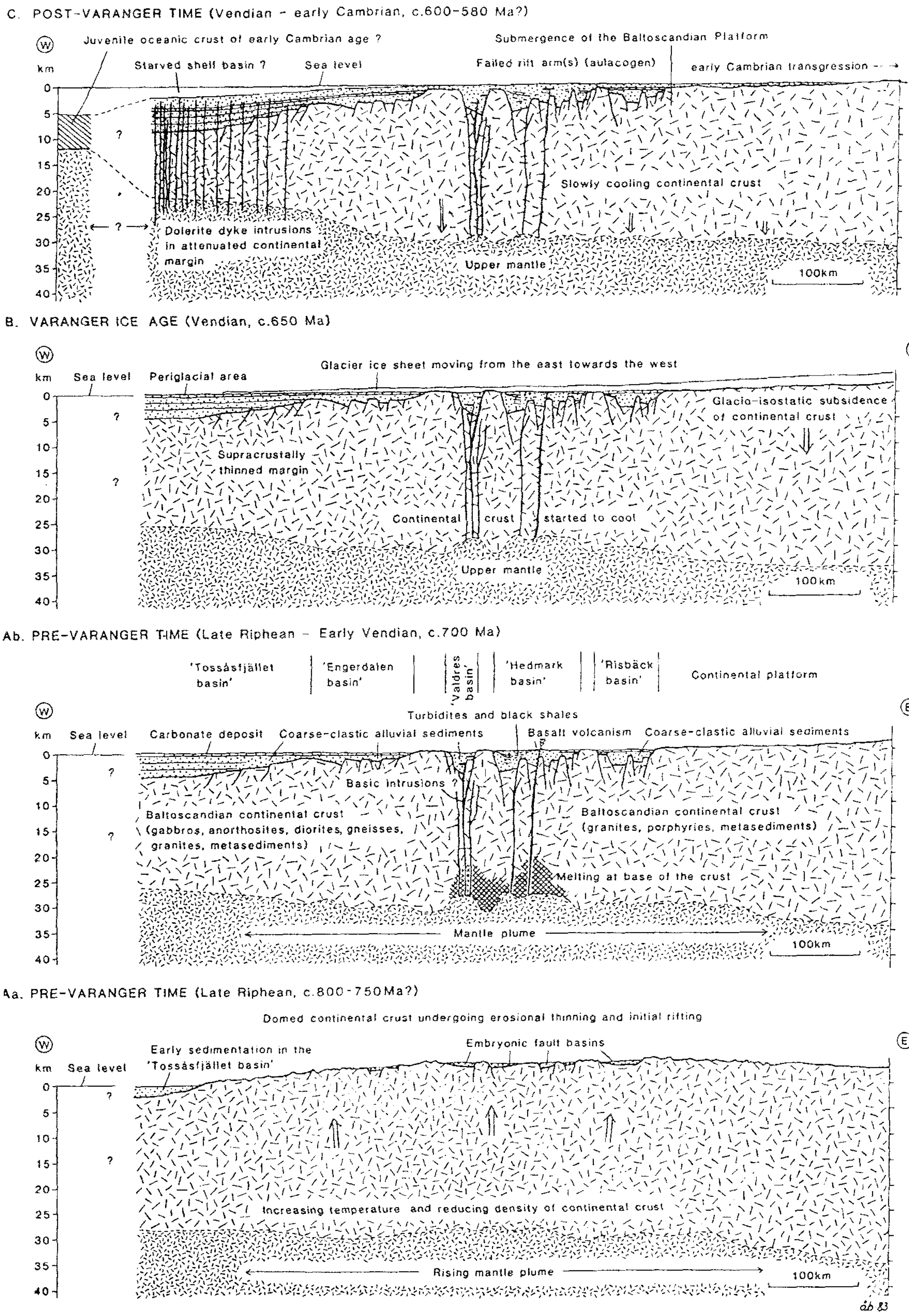

Figure 3-3. *Conceptual diagrams of the Late Riphean to Early Cambrian evolution in western Baltoscandia. The location of the section is shown in Figure 3-2A. (From Kumpulainen & Nystuen, 1985).*

3.2 MAGMATISM

Fractures formed west of the present Scandies were filled with basic lava (Figure 3-3). This event corresponds to the opening of the Iapetus Ocean and is represented by the widespread Ottfjället dolerite dykes in the Scandinavian Caledonides. They have been dated to ca. 650-750 Ma by Beckinsale et al., (1975), Claesson & Roddick (1983) and Krill (1983). During the Vendian also most of Norway (except for the southern parts) and probably at least parts of Sweden were glaciated; the so called Varanger glaciation (e.g. Kumpulainen & Nystuen, 1985). This is in consistence with palaeomagnetic data indicating a position close to the south pole (Smethurst, 1992).

The alkaline complex at Alnön intruded 584+/-13 Ma ago (P. Kresten, pers.com. 1992) bringing upper mantel material to the surface (Kresten in Lundqvist et al., 1990). A close genetic relationship between continental rifting and alkaline magmatism has been demonstrated for the Mesozoic and Tertiary times (e.g. Bailey, 1974). This is obviously also the case for the initial rifting during the opening of the Iapetus ocean and alkaline magmatism in Scandinavia and especially in North America and Greenland (Doig, 1970; Scott, 1981) (cf. Figure 3-4). The geographical position of the Alnön complex corresponds to the intersection of several fracture zones striking NW and NNE. These zones are probably remnants of an aborted rift situation (P. Kresten, pers.com., 1992). As erosion and uplift continued during this

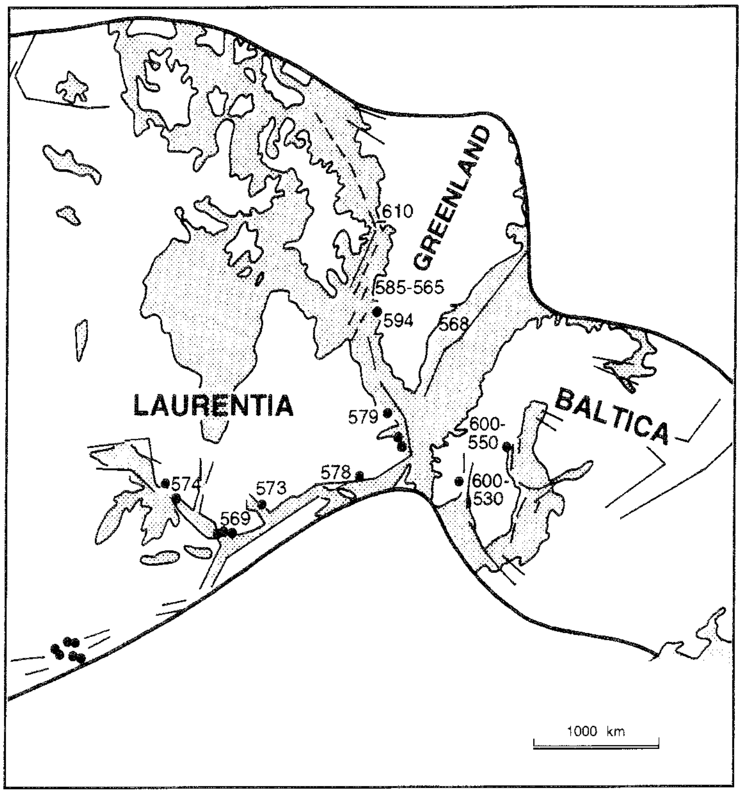

Figure 3-4. The distribution of latest Precambrian to Early Cambrian alkali granites and syenites, carbonatites, kimberlites, potassic lamprophyres and alnöites. The extensive alkaline magmatism preceded the continental breakup at the base of the Cambrian. Note that some of these alkaline rifted zones have been the sites of later continental separation (Labrador-Davis Strait), or rifting and magmatism without separation (Oslo Graben), or have remained dormant (Superior-Hudson's Bay lineament and the Gulf of Bothnia). Radiometric ages are shown. (From Piper, 1985).

period in parts of central and northern Sweden, the present surface corresponds to a level where the magma chambers are exposed.

SW of the Oslo district in Norway contemporaneous alkaline volcanic activity took place at Fen, a for-runner to the Permian Oslo rift.

3.3 UPLIFT AND PENEPLANATION

Sphene, fission track ages of c. 680 Ma were recorded from surface samples in the Dalsland Province of SW Sweden (Zeck et al., 1988). This means that from this time to the completion of the sub-Cambrian peneplain c. 100 Ma later the uplift was c. 7 km. Zeck et al. (1988) also concluded that at least 7 km of supracrustals or "Grenvillian" thrust sheets were placed on top of a "sub-Grenvillian peneplain" and were subsequently removed.

The ending of the period is characterized by peneplanation (the sub-Cambrian peneplain) in southern Sweden. It is assumed that conditions suitable for surface oxidation due to percolation of oxidising groundwater prevailed when the peneplain was exposed (before the Cambrian sedimentation started). As this level roughly corresponds to the present surface, it is possible that some of the surface related oxidation observed today is Late Proterozoic. This was e.g. considered for the Fe-oxyhydroxide fracture fillings found in a study of the Finnsjön area, SE Sweden (Tirén, 1991).

In summary:

* The entire period is characterized by rifting.
* The break up of Laurentia/Greenland from Baltica took place and rifting within Baltica resulted in formation of e.g. the Vättern Graben and Muho Graben.
* Sedimentation of Late Riphean-Vendian sediments, of alluvial to shallow marine type, took place within and outboard Baltica.
* The Varanger ice had its culmination in northwestern Scandinavia during the Vendian.
* At the end of the period rifting and alkaline volcanism took place at different sites in Laurentia, Greenland and Baltica.
* The Sub-Cambrian peneplain was complete and sedimentation of shallow marine clastic sedimentary rocks started.

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4 THE CAMBRIAN TO SILURIAN PERIOD, 570 – 410 Ma AGO

The Cambro-Silurian period is characterized by marine sedimentation, convergent Laurentia-Baltica plate movements, and at the end of the period the closure of the Iapetus ocean and formation of the Caledonides.

4.1 CAMBRIAN FRACTURING

Fractures filled with sandstone ("sandstone dykes") suggested to belong to the Lower Cambrian are found in the southwestern part of Sweden (Mattsson, 1962; Samuelsson, 1975; Martinsson, 1968). Thin section studies have shown that the host rock adjacent to the fractures is either weathered or fresh, which means that some of the fractures filled with Cambrian sediments are created shortly before or synchronously with the infilling, i.e. the stress field during the Early Cambrian favoured new fracturing but also opening of older WNW fractures in SW Sweden.

Fractures with Palaeozoic fillings are also known from the east coast of Sweden and from the island of Åland (Bergman & Lindberg, 1979). An older set of the fractures on the Swedish east coast are mostly trending in NE and a later set of fractures in E-W (Sundius, 1938; Nordenskjöld, 1944; cf. also Talbot 1990). Based on examination of fossils in the sandstone dykes at Åland an Upper Cambrian age (Martinsson, 1968) is suggested for these. However, Bergman and Lindberg (1979) conclude that the main tectonic events took place during the Lower

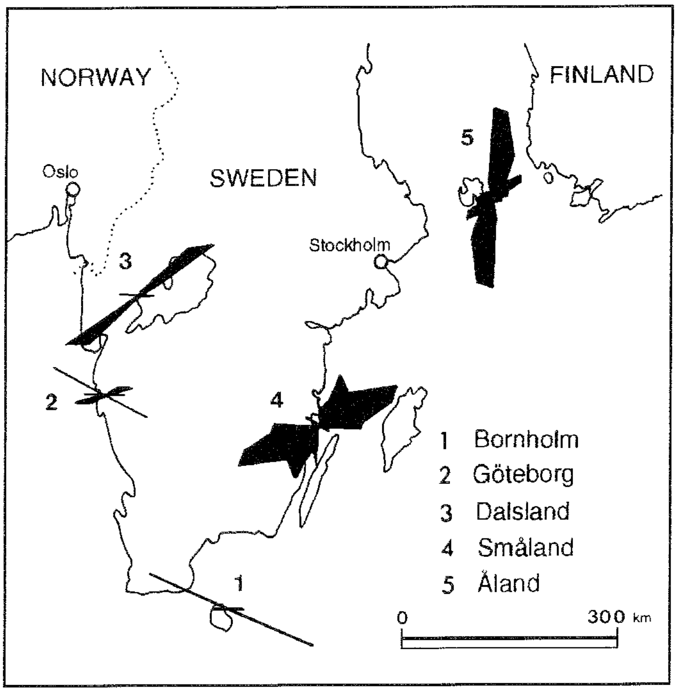

Figure 4-1. The orientation of clastic dykes in the Precambrian basement in five different areas. 1. Bornholm, Mattson (1962) n=?, 2. Göteborg, Samuelsson (1975) n=131, 3. Dalsland, Mattson (1959) n=19, 4. Småland, Nordenskjöld (1944) n=145, 5. Åland, n=317. (From Bergman, 1981).

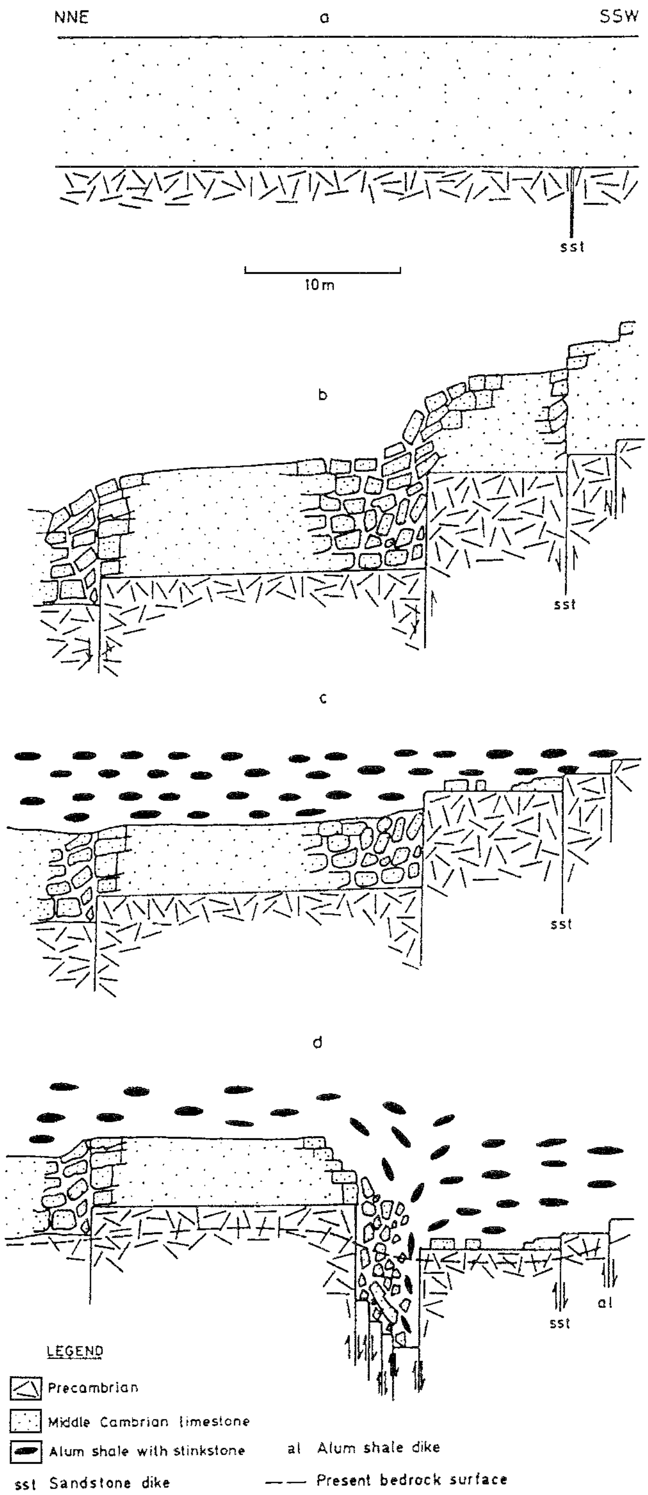

Figure 4-2. *Sketch of different stages in the development of the Cambrian breccia at Kungälv. (a) Middle Cambrian, (b) Late Middle Cambrian to Early Upper Cambrian, (c) Upper Cambrian, (d) late Upper Cambrian or slightly later. (From Samuelsson, 1975).*

Cambrian and Lower Ordovician. An older set of Lower Cambrian dykes strike between 40-160 degrees, while a younger set of Upper Cambrian dykes strike 0-20 degrees. The sandstone filled fractures on the Swedish east coast have not been dated. It is possible that the difference in orientation of the sandstone dykes (Figure 4-1) is due to differences in the stress field during the Lower and Upper Cambrian.

Repeated fracturing during the Cambrian has obviously occurred. This is also shown by the brecciation of Middle Cambrian limestone and alum shale in a fracture zone west of the Göta Älv Zone at Kungälv, SW Sweden (Figure 4-2; Samuelsson, 1975).

4.2 THE EARLY PALAEOZOIC COVER

The Cambro-Silurian sediments which formed a cover on the sub-Cambrian peneplain are preserved in the province of Skåne, but also on the islands of Gotland and Öland, in the Baltic sea, and in the mountains of the Västergötland province. In the Baltic sea, south of Gotland, a Cambro-Silurian sediment thickness of c. 1000 metres is recorded (Ahlberg, 1986). In the province of Östergötland and Närke fault controlled depressions are filled with sedimentary rocks from this period. Further north the Siljan impact is filled with a rim of tectonically disturbed Cambro-Silurian sedimentary rocks. Along the Caledonian front Cambro-Silurian autochthonous and parautochthonous rocks crop out.

In Norway the Oslo and Skagerrak grabens contain Cambro-Silurian sedimentary rocks. Small remnants are also found in western Finland.

In the Bothnian Sea (Figure 4-3), ENE of Hudiksvall in Sweden, a maximum thickness of 375 metres is recorded for Cambro-Ordovician sediments (Winterhalter, 1972). The Cambro-Silurian stratigraphy is uncomplete (Figure 4-4) due to transgressions and regressions of the sea (Figure 4-5).

All this indicate an original cover of Cambro-Silurian rocks of considerable extent and thickness.

4.3 PLATE MOVEMENTS AND THE CLOSURE OF IAPETUS

It is known that during the Late Cambrian a new phase of interaction between Laurentia (Northamerican and Greenland plate) and Baltica (Northeuropean plate) took place by converging movements and compression of the crust (Figure 4-7). In Figure 4-6, a palaeo-reconstruction of continents at ca. 500 Ma ago is shown.

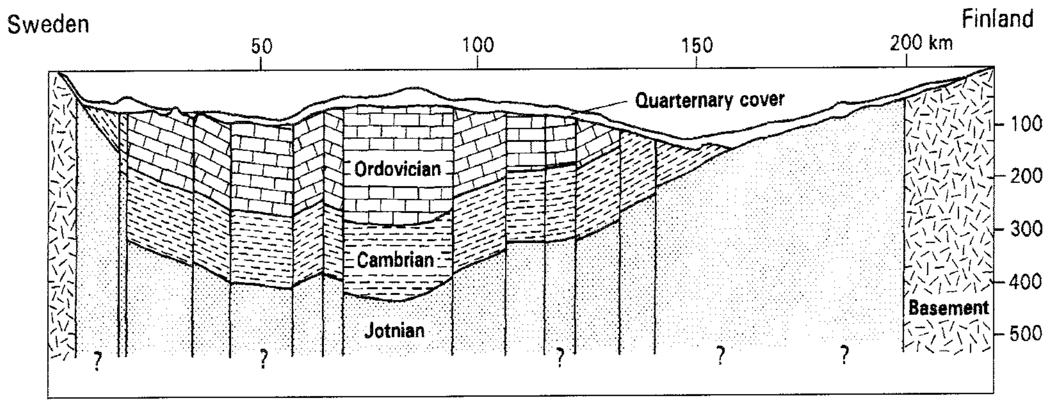

Figure 4-3. *E-W section through the Bothnian Sea Basin showing Post-Ordovician faulting (modified from Axberg, 1980).*

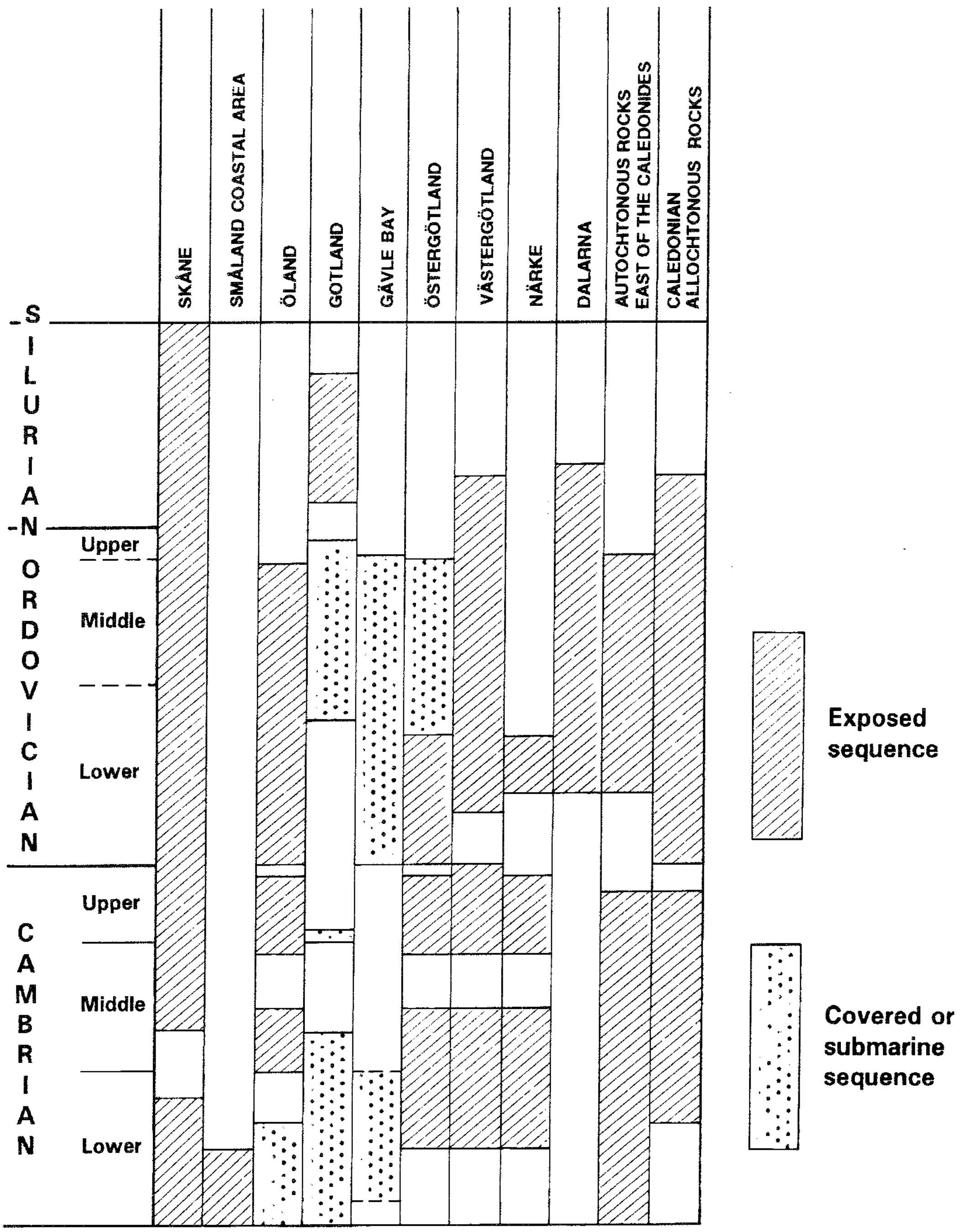

Figure 4-4. Overview of the Cambro-Silurian of Sweden. Ruled area = outcropping formation. Dots = covered by younger rocks or submarine formation (from Bengtsson, 1976).

During this period of time the deformations recorded are most likely the result of a collision due to westward subduction within the Iapetus (e.g. Hossack and Cooper, 1986), between Baltica and a micro-continent or an island-arc (e.g. Gee, 1988; Stephens, 1988). Early orogenic movements are referred to the Finnmarkian phase and are traced in the Finnmark province of northern Norway, where also gabbros and alkaline rocks intruded the Kalak Thrust Sheet (Sturt et al., 1975). During the Early Ordovician collision of Laurentia with arc complexes through eastwards subduction caused deformation and metamorphism as recorded in several outboard terranes (Stephens, 1988). Obduction of oceanic thrust sheets onto Baltica

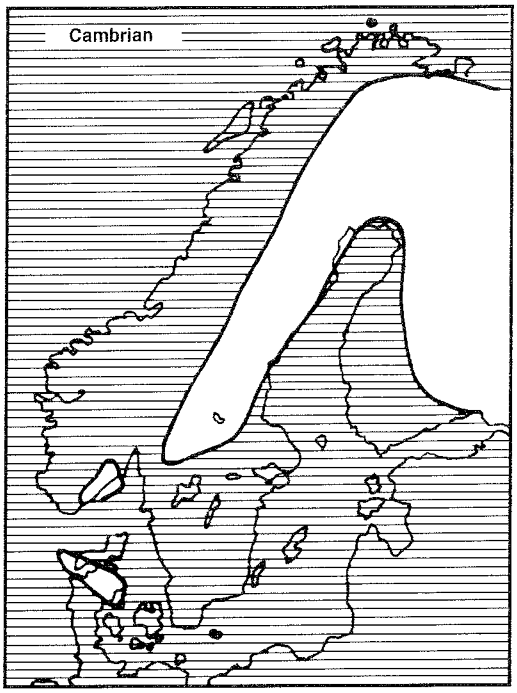

Figure 4-5. *Maximum extension of marine Cambrian sediments (compiled from Bengtsson, 1976).*

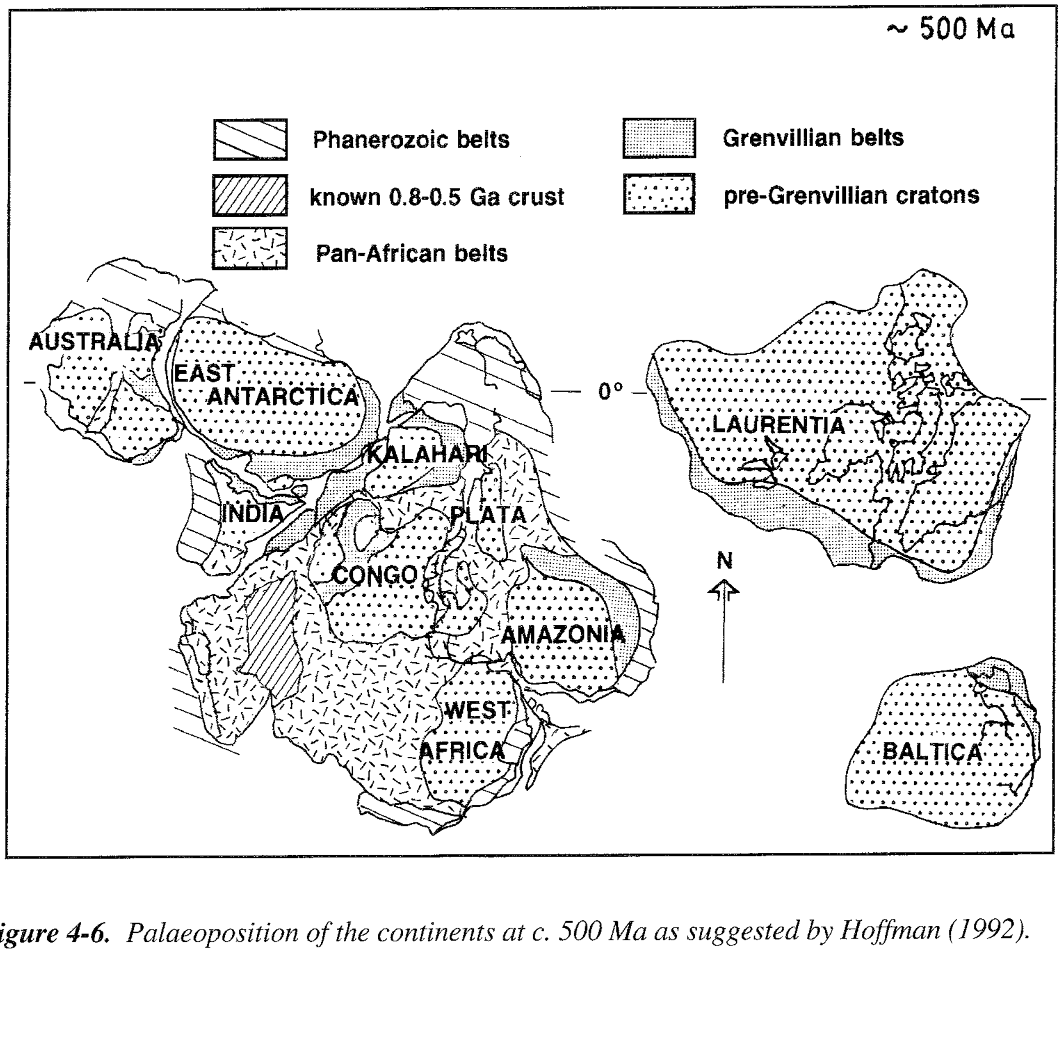

Figure 4-6. *Palaeoposition of the continents at c. 500 Ma as suggested by Hoffman (1992).*

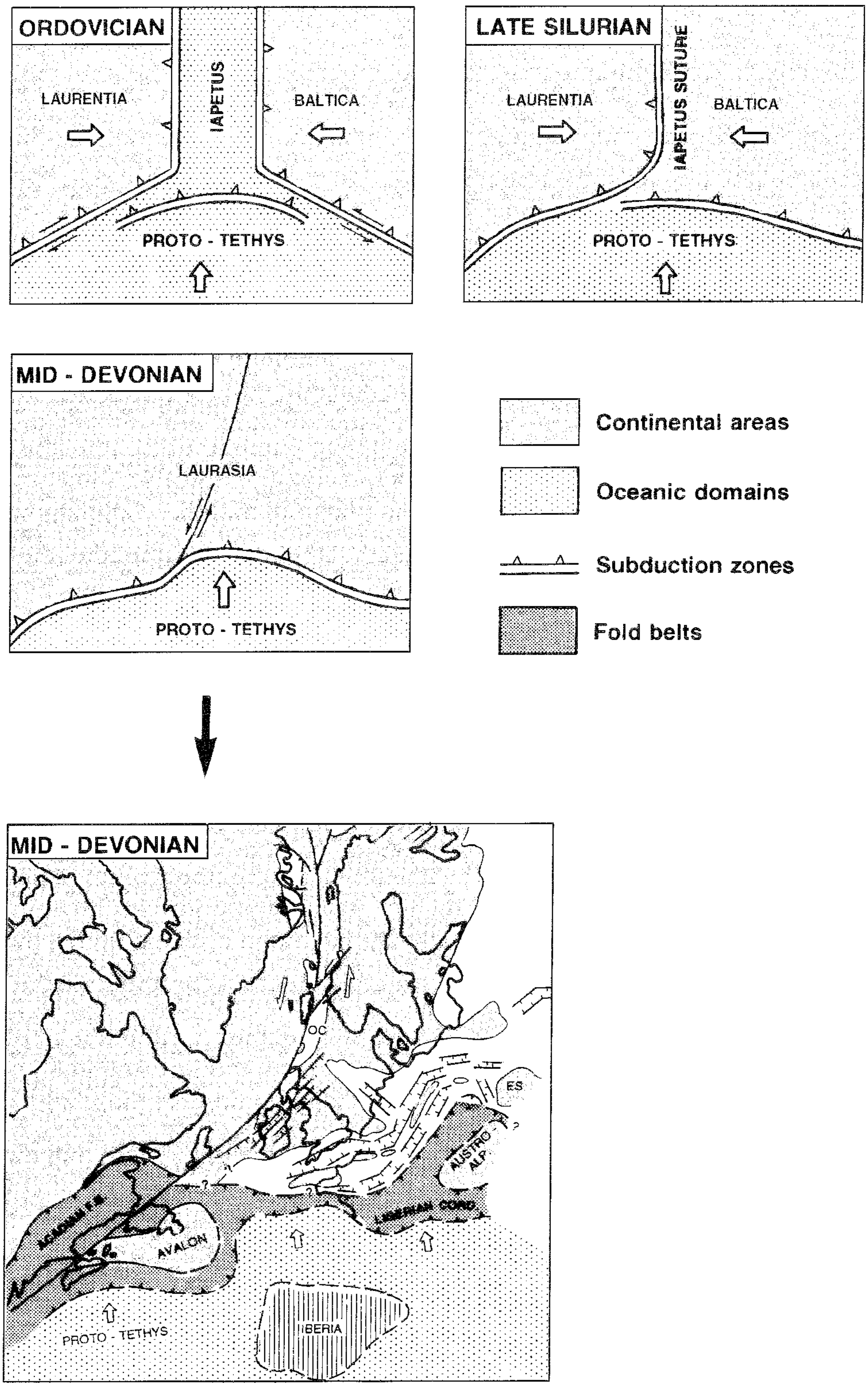

Figure 4-7. *Change of plate configurations in the Arctic-North Atlantic realm during Ordovician to Devonian time and tentative Middle Devonian tectonic framework of Arctic-North Atlantic realm.*
Light grey = continental cratons and intrabasinal highs; dark grey = active foldbelts; white = sedimentary basins; stippled = oceanic domains, hatched = microcontinents; OC = Orcadian Basin; ES = East Silesian Massif. (From Ziegler, 1985).

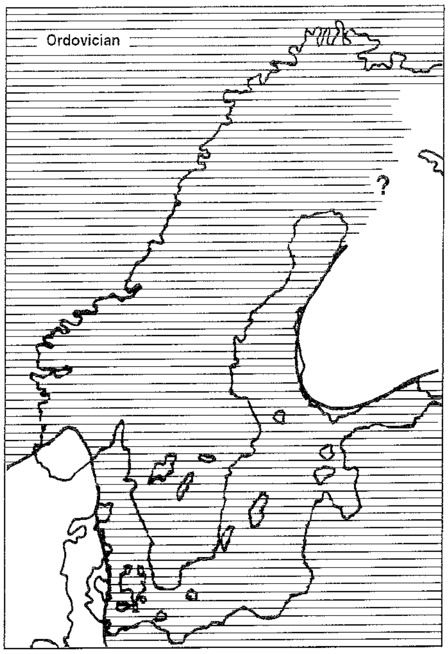

Figure 4-8. *The approximate maximum extension of the Ordovician marine sediments (compiled from Bengtsson, 1976).*

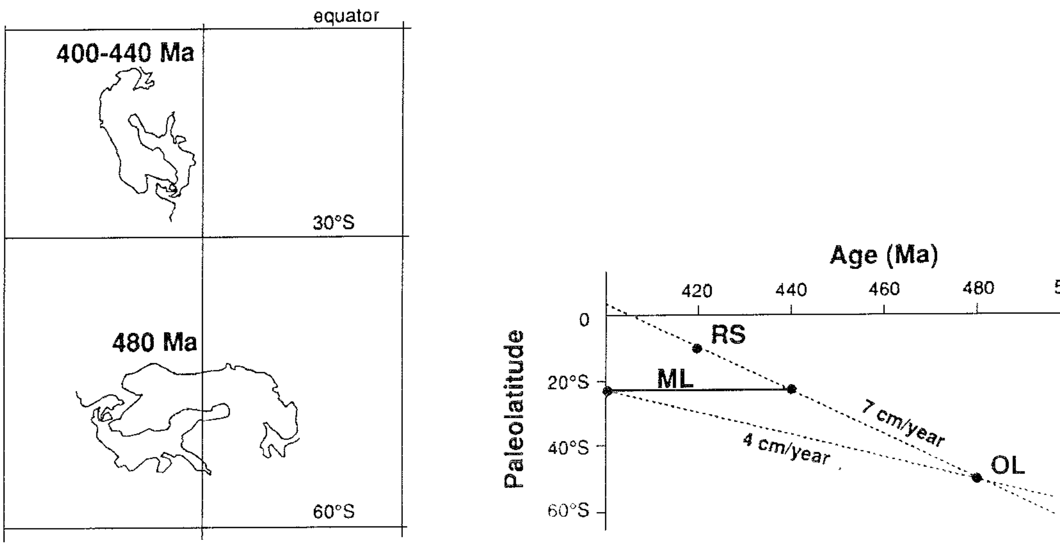

Figure 4-9. *Palaeogeographic reconstruction of Baltica during the Lower Palaeozoic, and corresponding palaeolatitude evolution with time (OL="Ortoceras limestone", ML=Mjösa Limestone, RS=Ringerike Sandstone). Due to uncertainty for the ML pole, drift can be estimated to be within 4 to 7 cm/yr. (From Perroud et al., 1992).*

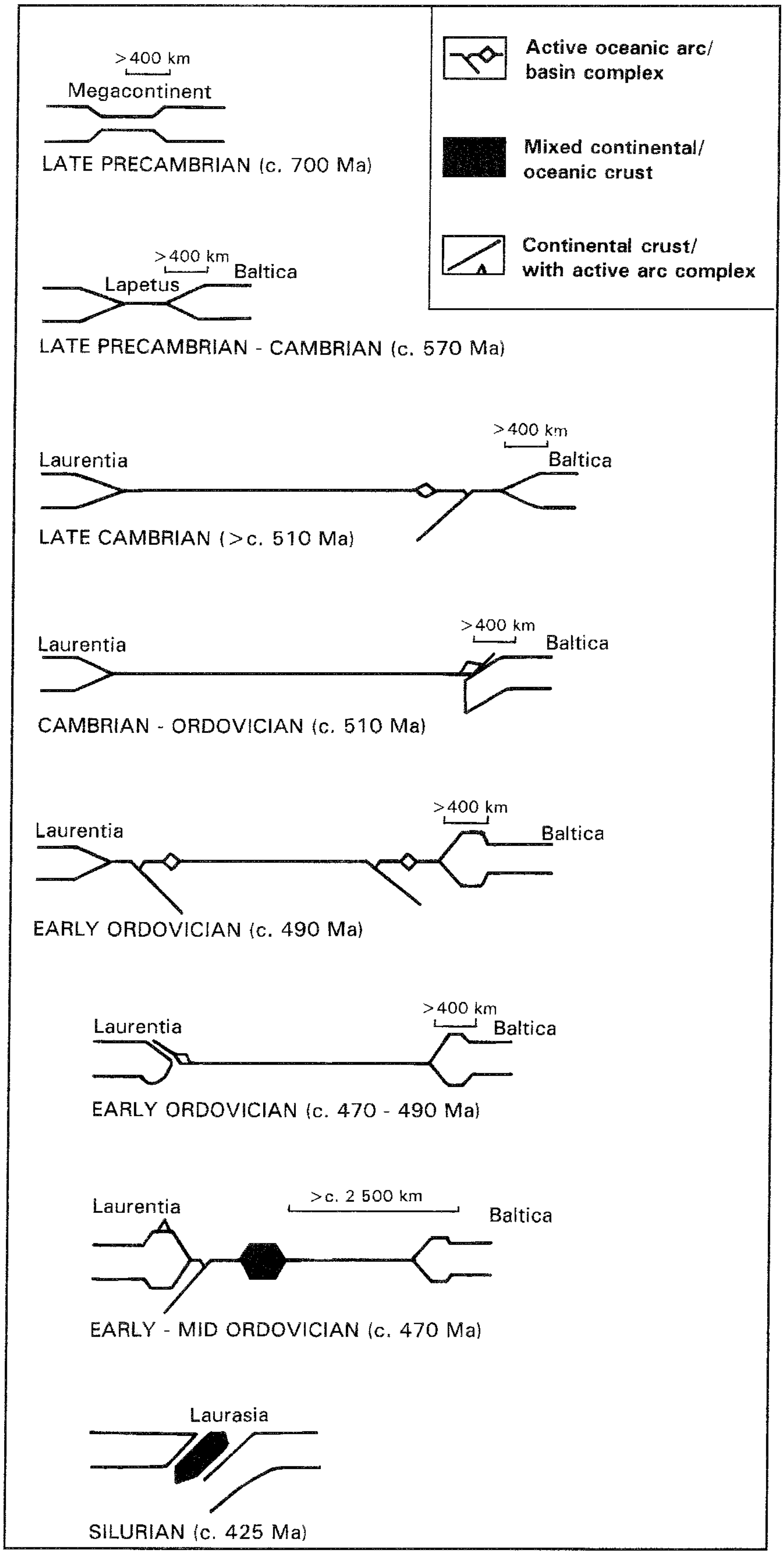

Figure 4-10. *Laurentia/Baltica plate tectonics during the time span 700 to 425 Ma. (Modified from Stephens, 1988).*

by A-subduction of Baltica beneath an island arc took place during Mid-Ordovician (Hossack and Cooper, 1986).

Sea sediments were deposited into the tropical Iapetus ocean during the upper Ordovician and Silurian (cf. also the Silurian reef limestone at Gotland), with a common fauna for Laurentia and Baltica. The "Ordovician Sea" covered a larger area of Baltica than the "Cambrian Sea". The approximate maximum extent of the Ordovician sediments is shown in Figure 4-8. By time the Iapetus Ocean was narrow enough to allow a common fauna. The two plates were approaching each other very fast which created extensive compression of the crust. New palaeomagnetic data (Perroud et al., 1992) from Ordovician limestones in Scandinavia indicate a clockwise rotation of 110^0 and a northward drift rate of 4-7 cm/year during the time period 480 to 420 Ma (Figure 4-9).

Faulting and volcanism characterize the margin of the Baltic shield during the Middle Ordovician and onwards resulting in bentonite horizons with local gaps in the platform sediment succession (Bruton et al., 1985). Silurian bentonite horizons mapped in Baltica as well as Laurentia indicate a destructive plate margin setting along the Baltica-Laurentia margin (Bergström et al., 1992). Baltica was subducted beneath exotic terranes including Laurentia. Several exotic terranes were subsequently docked to Baltica and are now recognised in the nappes of the Scandinavian Caledonides (Stephens, 1988).

The collision between Greenland/Laurentia and Baltica gave rise to a westward subduction and prominent eastward thrusting (the Scandian phase of deformati). A shortening of 400 to 500 kilometres is calculated (Gee, 1975, 1978; Hossack and Cooper, 1986). The different phases of the complex Caledonian orogeny is illustrated in Figure 4-10. This model, presented by Stephens (1988), includes westward as well as eastward subduction of which the latter (westward Ordovician subduction) is questioned by Hossak & Cooper (1986).

The degree of basement involvement in the thrusting is presently debated (e.g. Palm et al., 1991; Dyrelius and Palm, 1993). That the nappes were displaced to a position farther to the east than what can be seen today has been stressed by Hossack and Cooper (1986). Caledonian reactivation of preexisting zones in the shield have most probably taken place, e.g. the Caledonian reactivation of the Kårböle-Ljusnan Zone (Sjöström & Bergman, 1993).

In southern Baltica a fore deep to the central European Caledonides was formed due to the collision of Avalonia and Baltica. This forced the southwestern part of the Skåne province in Sweden to subside during the Late Silurian (Norling & Bergström, 1987).

By the end of the Silurian the so called Old Red Sandstone terrestrial facies covered Scandinavia (Bassett, 1985).

4.4 ORDOVICIAN-SILURIAN FORE LAND DEFORMATION

Data reported by Milnes & Gee (1991) from northwest Öland show that minor amounts of post-Cambrian deformation have taken place there and that 90 % of the fractures show no lateral displacements. The rest of the fractures can be discriminated into one set of dextrally displaced, NW trending fractures and another set of sinistrally displaced, NNE-ENE trending fractures. The displacements are maximum 5 cm.

Talbot (1990) reports oblique shearing from NW Öland and NE trending, dextral, strike-slip shearing near Borgholm in Öland which later inverted to sinistral shearing during oxidizing conditions.

In summary:

* During the Late Cambrian there was a switch from divergence to convergence of North-america / Greenland in relation to Baltica. Deformation and magmatism took place in northernmost Norway (the Finnmarkian phase).
* During the Ordovician, fast plate movement and rotation of Baltica took place as well as volcanic activity and faulting along the western plate margin.
* The collision between Baltica and Northamerica/Greenland during the Silurian resulted in extensive eastward thrusting (the Scandian phase) to complete the formation of the Scandinavian Caledonides.
* In Baltica the Lower Palaeozoic marine sedimentation was changed to terrestrial conditions in the Late Silurian.

5 THE DEVONIAN TO PERMIAN PERIOD, 410 - 250 Ma AGO

During the Early Devonian the collision between Laurentia/Greenland and Baltica was completed, the Iapetus ocean was closed, and the Caledonian mountain range was formed along the zone of collision (cf. Figure 5-1). The crust of the Iapetus ocean was thrusted c. 500 kilometres eastwards onto the Baltica basement. The thrust front is assumed to has been situated more than c. 100 kilometres to the east of the present Caledonian border (Hossack & Cooper, 1986). Post-collisional tectonics including uplift and denudation of the Caledonian mountains characterize the Devonian. The Carboniferous-Permian is characterized by rifting and related magmatism, including the formation of the Oslo Graben.

5.1 DEVONIAN POST-COLLISIONAL TECTONICS AND MAGMATISM

A large scale sinistral strike-slip displacement of c. 2000 km took place along a main fault running along the Caledonian-Appalachian Fold Belt in the Early Devonian (Figure 4-7). However, strike-slip movements along the fault continued into the Carboniferous (Ziegler, 1988). Some other zones of weakness was affected during the same period in Scandinavia.

The Möre-Tröndelag Fault Zone, W. Norway, was a sinistral transtensional zone during the Devonian (Séranne, 1992). The fault zone has probably an older history as a compressional strike-slip zone and was also reactivated (Figure 5-2) in the Late Proterozoic (Buckovics et al., 1984; Séranne, 1992) and the Mesozoic (Fossen, 1989; Böe & Bjerkelid, 1989; Grönlie & Roberts, 1989; Torsvik et al., 1989). At Vestlandet, SW Norway, Devonian sediments were folded, during a stress regime compatible with the postulated, complex wrench faulting which followed the final Iapetus Ocean closure and the Baltica – Laurentia collision (Steel et al., 1985; cf. also Séranne, 1992).

An extensive post-collisional extension of the Caledonian orogen in Scandinavia is demonstrated by Fossen & Rykkelid (1992) (cf. also McClay et al., 1986). This is traced 200 km to the west off shore Norway and into the Caledonides, and is manifested as low-angle detachments. The deformation involved substantial backsliding of the orogenic wedge in the western parts of the entire Scandinavian Caledonides and westdipping, extensional shear zones in the basement in the southwestern part. The extensional deformation is considered to be due to rapid change from convergent to divergent plate motions.

Alkaline magmatism is widespread in the Kola Province of northwest Russia and in northeast Finland at 380-310 Ma and is contemporaneous with the extensive rifting of the East European Craton. The magmatism includes intrusions of nepheline-syenites as well as ultrabasites and carbonatites of which the former are restricted to the Kontozero Graben area (Kramm et al., 1993).

5.2 UPPER PALAEOZOIC SEDIMENTS

The Caledonian mountains were uplifted and denudaded. An uplift rate of 0.1 mm/year was calculated by Andriessen & Bos (1986) for the period 390 Ma to 306 Ma ago. The sediments were deposited a.o. on the foreland to the east of the Caledonides which formed part of the so called Old Red-continent (Figure 5-1). About 5000 metres of crustal material was removed

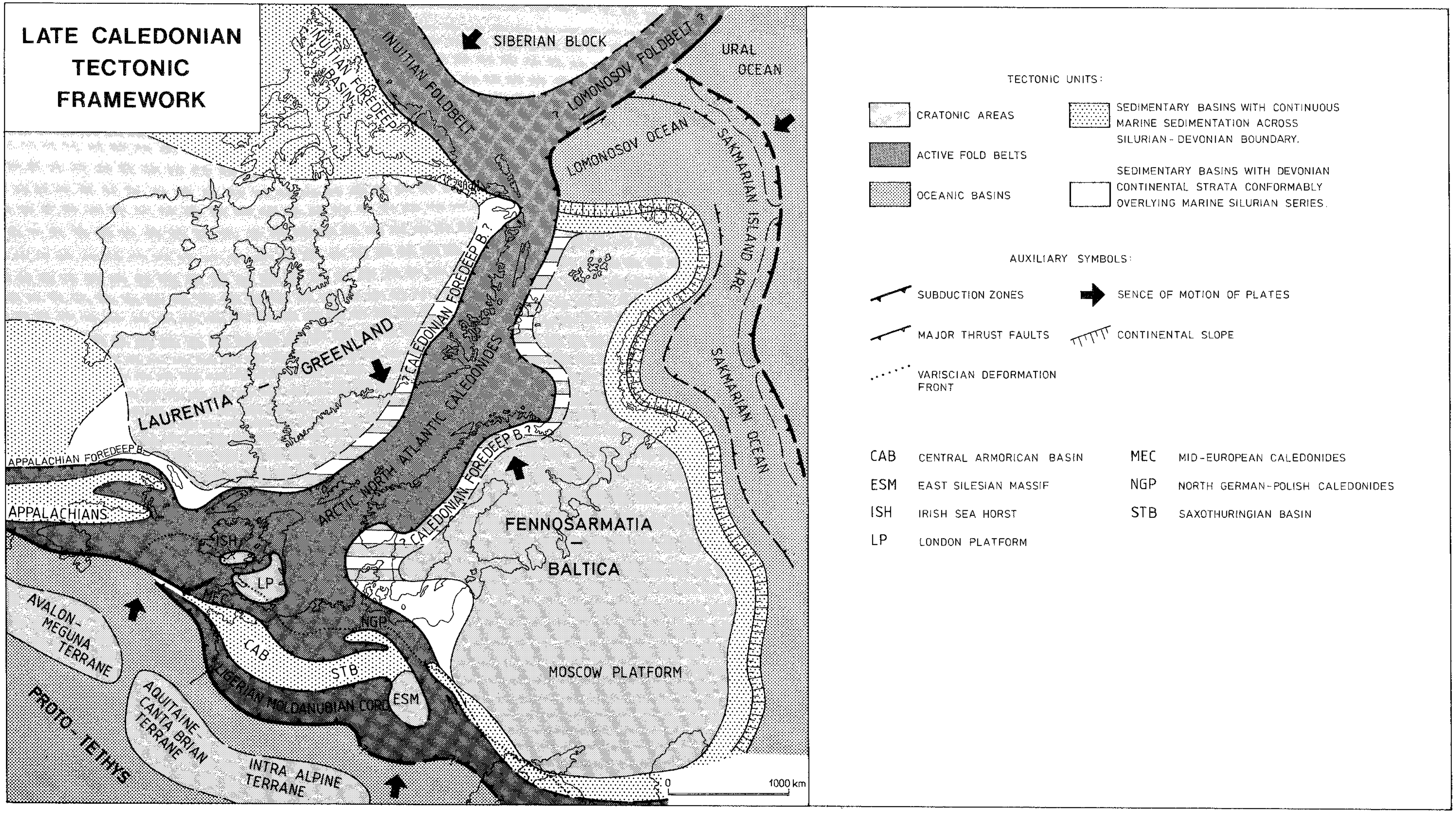

Figure 5-1. *Late Caledonian tectonic framework according to Ziegler (1988).*

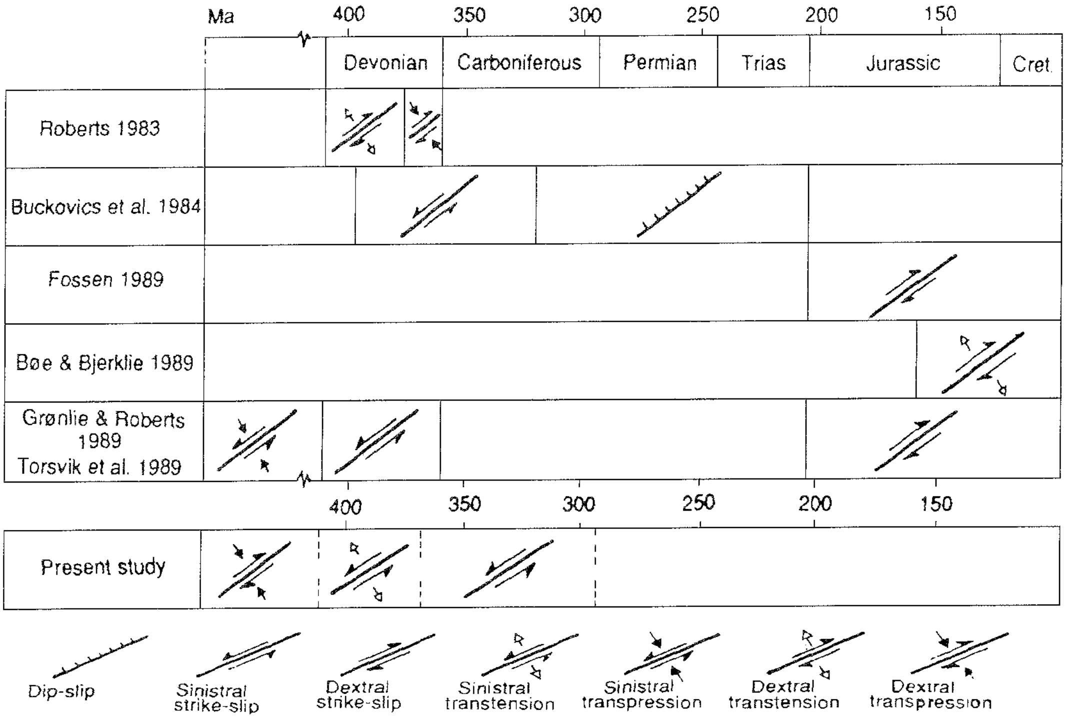

Figure 5-2. *Summary of different hypotheses of movements of the Möre-Tröndelag Fault Zone.*

during the first 80 Ma of erosion. Only scattered remnants are left of the Old Red sediments. The most prominent are the occurrences in the Permian Oslo Graben and at Vestlandet in Norway. At Vestlandet locally the thickness of sediments is several 1000 of metres. In the Baltic Sea, Devonian sedimentary rocks are preserved along the coast of Lithuania.

Fission track dating on apatite in the province of Dalsland indicates a Palaeozoic cover of 2 – 3 km (Zeck et al., 1988). However, a review of earlier published data from other parts of Sweden concerning conodont alteration indices (CAI), fission track annealing (also including data from Andriessen & Bos, 1986), stable carbon and oxygen isotopes, vitrinite reflectance and illite/smectite ratios indicate temperatures high enough to allow for a thick Palaeozoic cover in the rest of Sweden (Tullborg et al., in manuscript and references in Figure 5-3). In Figure 5-3 estimated temperatures are shown for different "thermometers". The temperatures give evidence for an extensive Silurian-Devonian sedimentary cover with a thickness of 3+/-1 kilometers, geographically corresponding to a foredeep basin to the Scandinavian Caledonides (cf. Figure 5-1). If this foredeep extended into Finland or not is yet not solved as data is lacking from this region. However, the available data on fission tracks from S. Finland (Lehtovaara, 1976) indicate a thinner Phanerozoic cover there. The loading of the sedimentary cover influenced the stress situation dramatically in the uppermost part of the crust during the Upper Palaeozoic and probably also the Lower Mesozoic.

It is suggested by Lidmar-Bergström (1991) that places where the Sub-Cambrian peneplain is preserved (i.e. the provinces of Västergötland, Östergötland and eastern Småland), were still protected by Palaeozoic sediments during the Mesozoic deep weathering phase. Samuelsson (1975) reports a number of "clay veins" from the Swedish west-coast. These show a preferential orientation of WNW-ESE with vertical to subvertical dip, i.e. they parallel and in some places re-open the Cambrian sandstone dykes. It can be noted that a breccia of Upper Cambrian age at Kungälv, W Sweden, is post-dated by clay alteration along WNW-ESE fractures (which must have been formed after the diagenesis of the breccia). According to Samuelsson (1975) the appearance and the mineralogy of the clay veins suggests a formation

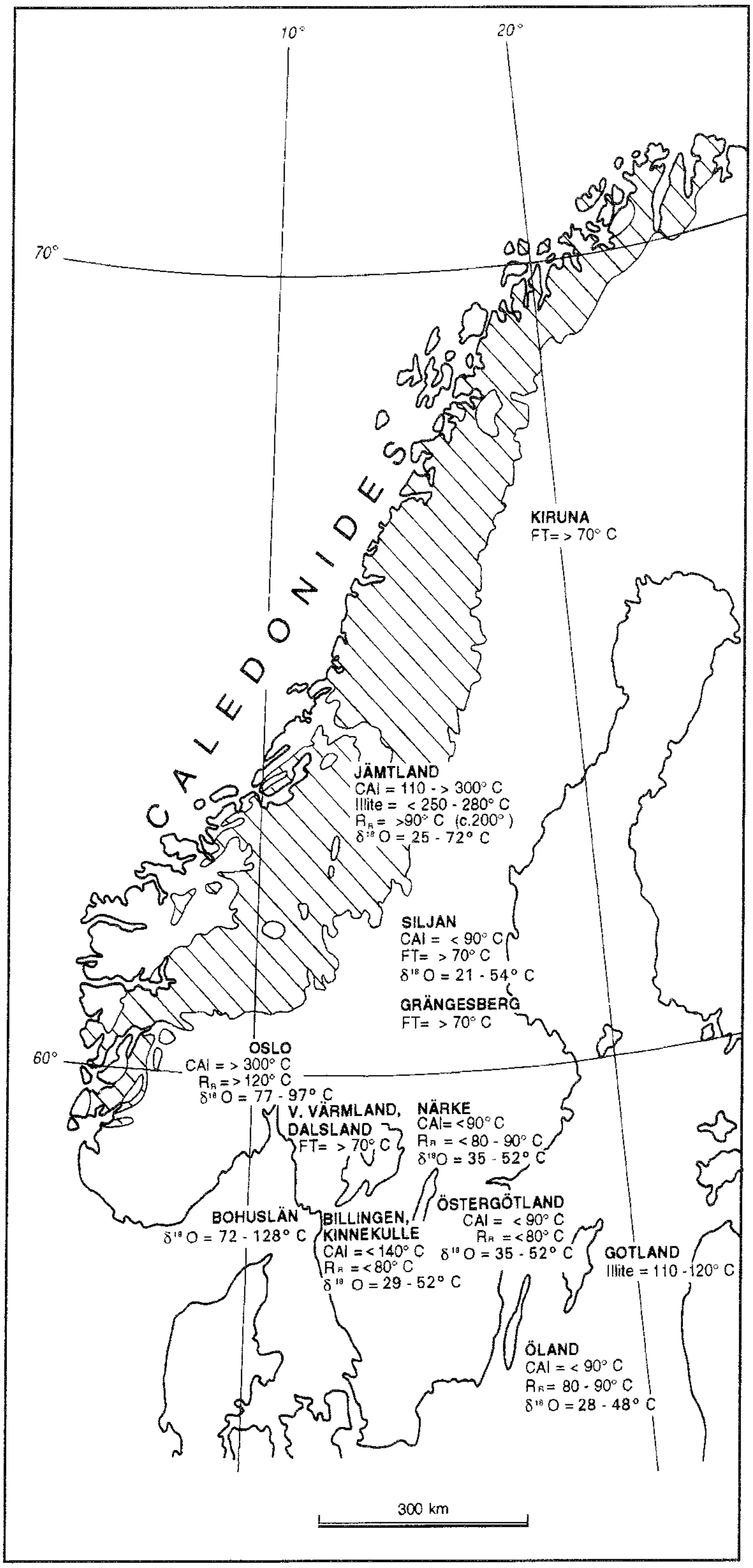

Figure 5-3. *Calculated maximum palaeo-temperatures in Post-Ordovician time used in estimations of the thickness of the sedimentary cover. CAI: colour alteration index (Bergström, 1980), V.R.: vitrinite reflectance (Buchardt et al., 1986; Kisch, 1980), F.T.: fission track (Koark et al., 1978, Zeck et al., 1988, Hansen et al., 1989; Andriessen & Verschure, 1991),* ^{18}O: *temperatures estimated from oxygen isotope ratios in carbonates (Tullborg et al., in manuscript), Illite: illite crystallinity and illite/smectite ratios (Kisch, 1980; Push & Karnland 1988; Snäll, 1988).*

during slightly hydrothermal conditions rather than by superficial weathering. A thick sedimentary cover during the Devonian to early Mesozoic time, should have caused temperature conditions favourable for clay-alteration, e.g. formation of montmorillonite/illite (cf. Push & Karnland, 1988), and in places possibly also chlorite.

A thick late Palaeozoic cover is consistent with K-Ar datings on mixed-layer clay minerals from a NNW trending, gently W dipping gouge seam at Äspö, SE Sweden (Maddock et al., in manuscript) which gave a range of ages from 368 Ma to 335 Ma.

It can be assumed that reducing conditions prevailed in the bedrock beneath the cover rocks. The reducing conditions are demonstrated by the occurrence of sulphide minerals precipitated in fractures of the Cambrian sandstone filled fractures, for example pyrite observed by Samuelsson (1975) on the swedish west coast and galena in Åland (Bergman & Lindberg, 1979) and Kråkemåla on the SE coast of Sweden (Sundblad, 1991). Occurrences of asphaltite and thucholite, indicative of reducing conditions, in fractures suggested to be of Palaeozoic age have been discussed by Welin (1966) (samples from mines in central Sweden) and Åberg et al. (1985) (samples from the Västervik area in Sweden).

During Early Carboniferous shallow marine conditions prevailed to the east of Baltica (Moscow platform) but to the west Baltica-Greenland-Laurentia formed a continuous landmass (Figure 5-1). The Carboniferous period was characterized by the Hercynian – Variscian orogeny which a.o. affected parts of south central Europe (Matte, 1991). In the Oslo Graben remnants of the Carboniferous Knabberud limestone is found. This limestone is considered to be connected with the Moscow basin sediments (Bergström et al., 1985). The original distribution of Carboniferous sediments in southern Scandinavia is unknown.

At the end of the Palaeozoic the final completion of the supercontinent Pangea took place (Figure 5-4). Thus, the Hercynian folding can be traced across several continents. Also the Ural mountains in Russia was formed during this period.

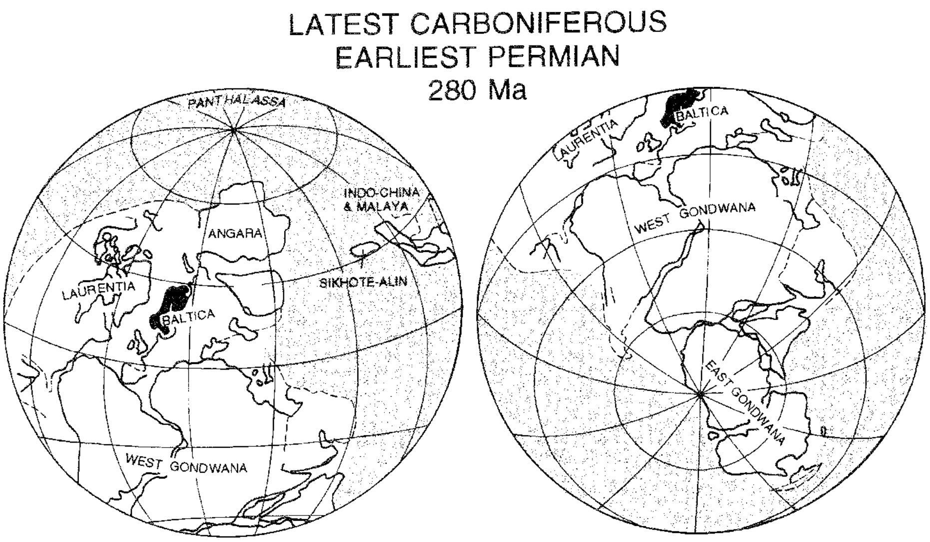

Figure 5-4. *Palaeoposition of the continents 280 Ma ago (from Irwing, 1983).*

5.3 THE PERMIAN RIFTING AND VOLCANISM

The transition between the Carboniferous and the Permian is manifested as a dramatic period in southern Scandinavia. Both extensive volcanism and rifting characterize this period. In Scandinavia it is best demonstrated in the Oslo Graben area where extrusive rocks formed during the time interval 300 to 240 Ma ago (Sundvoll et al., 1990). During this period also dykes were formed which can be traced on both sides of the Oslo Rift (Figure 2-2). These roughly N-S trending dykes are porphyries, dolerites and lamprophyries, and can be found from the Oslo area in the north to Göteborg on the Swedish west coast (Samuelsson, 1971) in the south. The dykes intruded preexisting structures (Ljungner, 1927) but also forced new fractures to open (Samuelsson, 1971). To the west the Central- and Midland Valley Grabens in Great Britain are considered contemporaneous with the Oslo Graben formation. Extensive basaltic volcanism also prevailed in central Europe (Figure 5-5).

The main graben formation along the Oslo Rift (Figure 5-6) took place in the interval 295-275 Ma, and propagated from south to north. The rift is considered to have been a zone of weakness already in the Sveconorwegian (Figure 5-7; Swensson, 1990). There are also several important Precambrian shear zones which terminates against the Oslo Rift. It is suggested that Precambrian shear zones east and west of the Oslo Rift were reactivated during the Oslo Rift event (e.g. Ramberg & Larsen, 1978; Starmer, 1985) and that stress release along the fault zones may have brought hot lithosphere above solidus causing episodic melting (Sundvoll et al., 1990).

Also the dolerite sills outcropping on the tops of the hills in the Västergötland province, Sweden, are suggested to be Early Permian (290 Ma) according to K-Ar dating (Priem et al., 1968). The Särna alkaline complex in the Dalarna province, dated to 281 Ma (Bylund & Patchett, 1977), is regarded as the "continuation" of the Permian Oslo Rift volcanism.

An alkaline bimodal volcanism of the central North Sea is similar and contemporaneous to that in the Oslo Graben (Dixon et al., 1981).

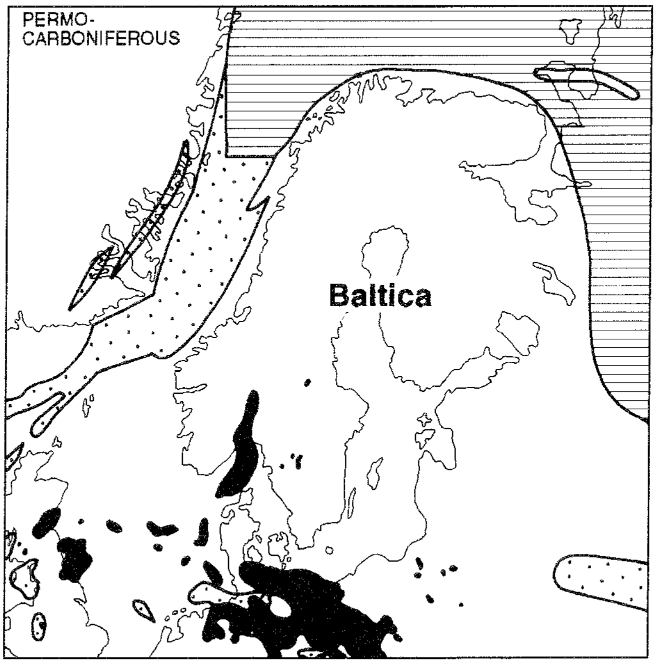

Figure 5-5. Depositional environment during the Carboniferous-Permian (Ziegler, 1988). White: cratonic area; Black: lavas, mainly basalts; Stippled: Mainly continental clastics; Ruled: shallow marine sediments and evaporites.

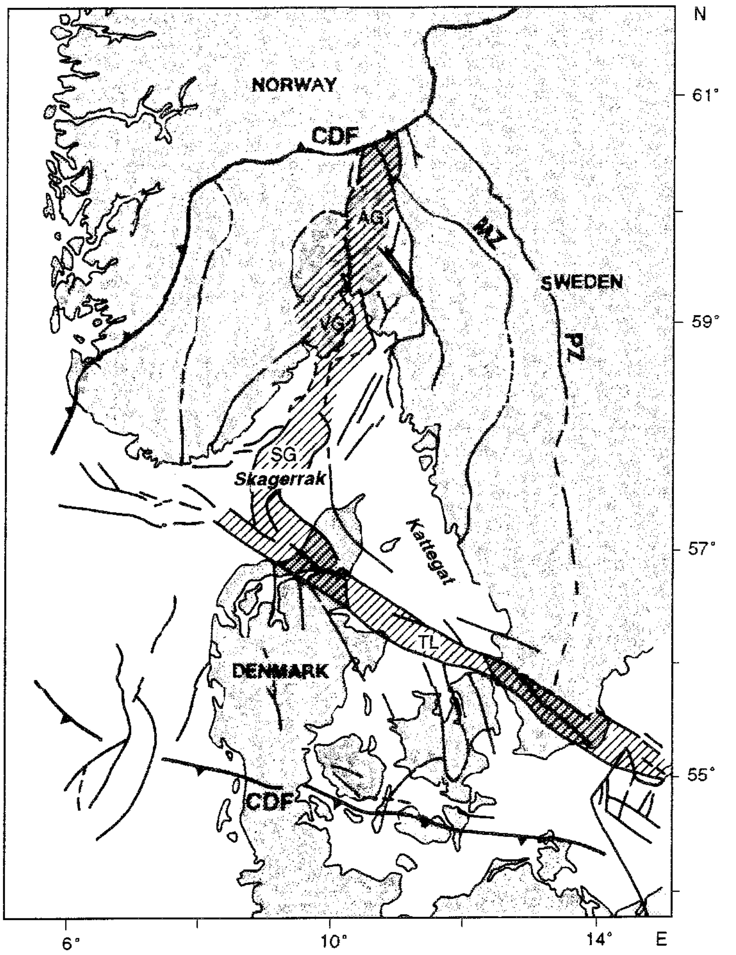

Figure 5-6. Regional structural map of SW Baltica: Hatching marks the Oslo Rift and Tornquist Zone. CDF: Caledonian Deformation Front; PZ: Protogine Zone; MZ: Mylonite Zone; TL: Tornquist-Teisseyre Line, AG: Akerhus Graben; VG: Vestfold Graben; SG: Skagerrak Graben. (Modified from Ro et al., 1990).

Except for the Oslo rift related volcanism most of the volcanic activity in Scandinavia during this period is concentrated to the Tornquist Zone in southernmost Sweden. Today the Tornquist Zone separates the Baltic shield from the Alpinian foreland to the south. This tectonic zone probably has a Pre-Cambrian precursor but most of the movements along the zone are of Variscian age (i.e. late Devonian to Permian). Wrench deformations associated with the development of the Oslo Graben induced a swarm of NW-SE trending dolerite dykes (Ziegler, 1982) intruded at about 300 Ma ago (Rb-Sr dating by Klingspor, 1976). However, the Tornquist Zone was repeatedly reactivated during the Mesozoic and thus cuts the southern part of the Oslo Rift (Skagerrak Graben) in the North Sea (Figure 5-6).

When estimating ages of post-Silurian faulting in south Sweden several authors refer to Permo-Carboniferous events, aware of the magmatism and tectonics connected to e.g. the Oslo Rift formation. The faults suggested to be Permian are N-S to NNE trending, but also W-E trending, vertical or normal faults are observed (cf. Ahlin, 1987). One obvious example of faulting a.o. affecting Early-Permian dolerites are the NNE and NW trending, steep, normal faults along the Palaeozoic hills in the Västergötland province of south Sweden (Figure 5-9).

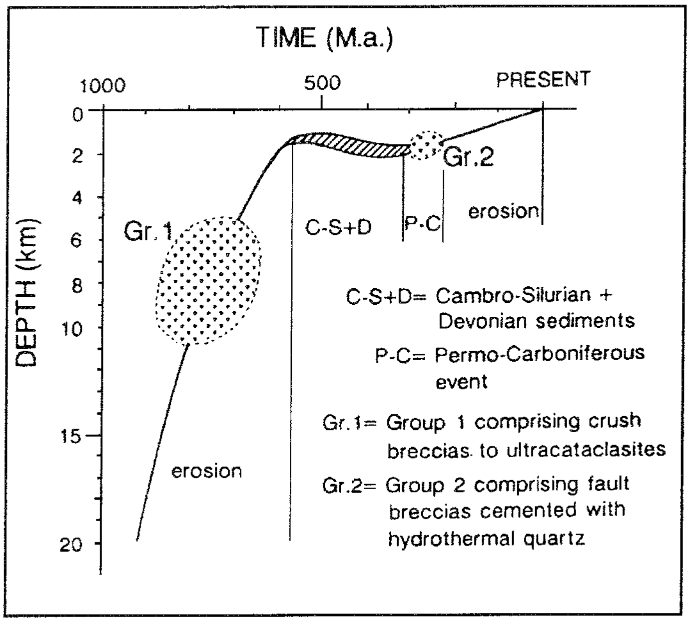

Figure 5-7. *Time versus depth path for the brecciation zone along the Oslo fjord. Two groups of breccias (Gr.1 and Gr.2) are recognised, the first of Precambrian age. The ruled area represents a period of subsidence and deposition of Cambro-Silurian sediments. (From Swensson, 1990).*

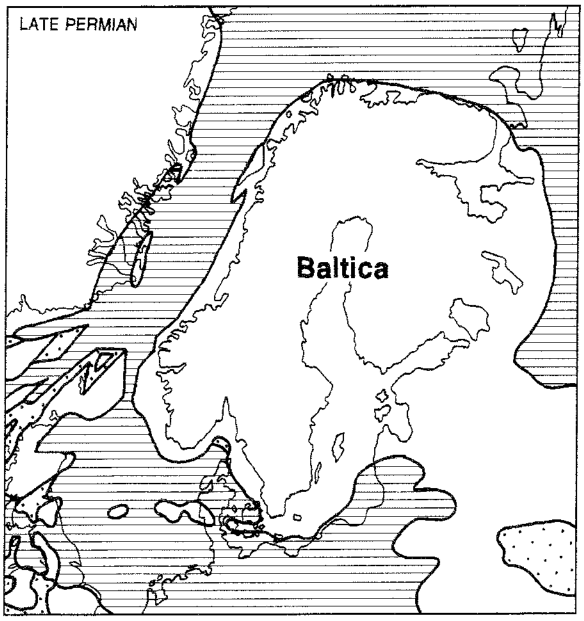

Figure 5-8. *Late Permian depositional environment according to Ziegler (1988). White: cratonic area; Stippled: continental clastics; Ruled: shallow marine sediments and evaporites.*

Post-Silurian faults also include the NNE trending faulting roughly separating Ordovician-Silurian sediments between Öland and Gotland and N-S trending faults north of the Polish coast (Ahlberg, 1986). The normal faulting indicates tensional regimes.

Figure 5-8 illustrates the shallow marine environment surrounding Baltica during the Late Permian (including evaporite basins at the southern border) which corresponds to the initial phase of the Pangea break-up.

In summary:

* The Caledonian orogeny in Baltica was completed during the Devonian and is characterized by eastward thrusting, but also normal faulting, basin formation and strike slip movements.
* Sediments covered the foreland to the Scandinavian Caledonides for more than 100 million years with thicknesses up to 2-4 kilometres.
* The Hercynian-Variscian orogeny affected central Europe and caused movements which a.o. trigged dyke injection along the Tornquist Zone.
* The Carbonian-Permian transition is characterized by volcanism and rifting, e.g. in the Oslo Graben and formation of sills and dykes in SW Sweden and along the Fennoscandian border zone (the Tornquist Zone).

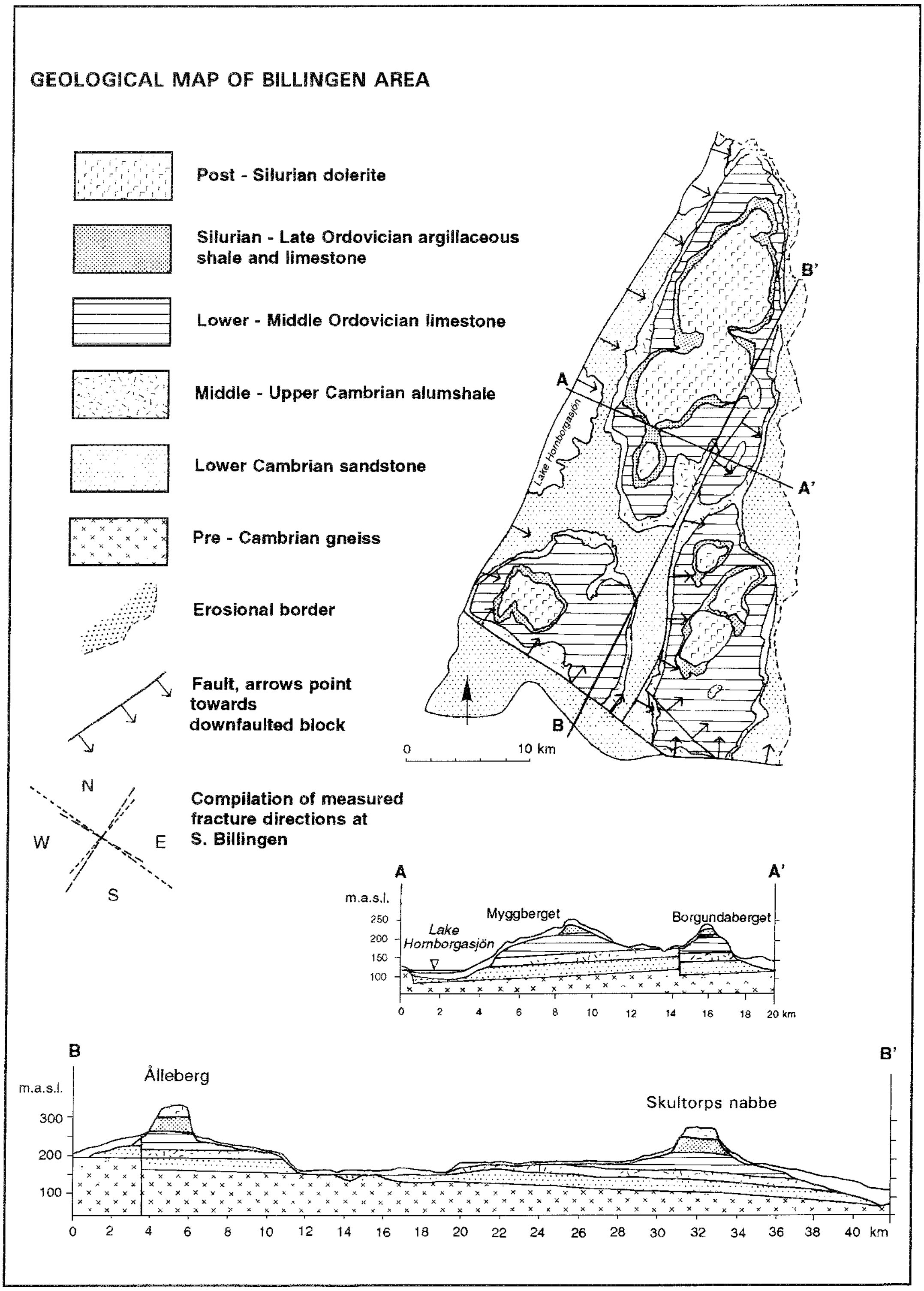

Figure 5-9. Geological map of the Billingen area south central Sweden, showing preferred orientations of fractures affecting the Palaeozoic rocks. (Modified from Hörnsten et al., 1977).

6 THE TRIASSIC TO CRETACEOUS PERIOD, 250 – 65 Ma AGO

This period is characterized by rifting of Pangea and inversion tectonics along the Fenno-scandian border zone (the Tornquist zone). In Late Cretaceous the initiation of the Alpine orogeny took place.

6.1 THE PANGEA BREAK-UP

The tensional forces which initiated the Carbono-Permian rifting in Europe was succeeded during the Mesozoic by extension transecting the Variscian fold belt and its European foreland causing the Pangea break-up. The Norwegian – Greenland sea rift propagated southwards to meet a westward propagation of the Tethys Rift system (Ziegler, 1988). (Figure 6-1 illustrates the land-sea distribution during the Middle Triassic). In this way the Central Atlantic opened by sea-floor spreading initiating separation of Gondwana from Laurasia during the Middle Jurassic. A plate reconstruction for a.o. the Early to Middle Jurassic, with the propagation of the Tethys Sea is shown in Figure 6-3 (cf. the land-sea distribution during the Middle Jurassic in Figure 6-2).

During the Late Jurassic to Mid-Cretaceous the spreading in the Central-Atlantic and Thetys regions continued as well as the extension in the North-Atlantic region. (Figure 6-3).

6.2 TECTONICS OF THE TORNQUIST ZONE

During Middle and Late Jurassic NE-SW trending grabens and troughs became inactive while NW-SE striking wrench systems came into evidence, reflecting changes in the regional stress system affecting northwest Europe (Ziegler, 1988).

During the Triassic to Early Cretaceous sinistral transtension influenced the Tornquist Zone but during Late Cretaceous and initial Tertiary, dextral transpression prevailed (Norling & Bergström, 1987). In the Hanö Bay area two tectonic phases are distinguished (Wannäs & Flodén, 1993); an Early Kimmerian subsidence reactivating older faults and a Late Cretaceous, which is the main subsidence phase of the Hanö Bay Halfgraben. Sinistral strike slip movements in the order of 2-3 km are reported along the NE-SW trending Bornholm Gat Tectonic Zone during Late Cretaceous. In summary both right- and left lateral strike slip movements with a net right lateral displacement of some 350 kilometres have affected the Tornquist Zone (Kumpas, 1984; Figure 6-4).

In northernmost Skåne, basalts were extruded during the Jurassic to Cretaceous period and can nowadays be traced as volcanic necks.

6.3 REGRESSION AND TRANSGRESSION

A Mesozoic denudation surface (Figure 6-5) was reconstructed for southern Sweden by Lidmar-Bergström (1991). An elevation of the southernmost part of Sweden must have taken place in pre-Cretaceous time. This allowed Palaeozoic sediments to be eroded and deep weathering, characteristic of the warm climate prevailing during the Mesozoic, of the basement to take place before the sedimentation during the Cretaceous. The warm climate also

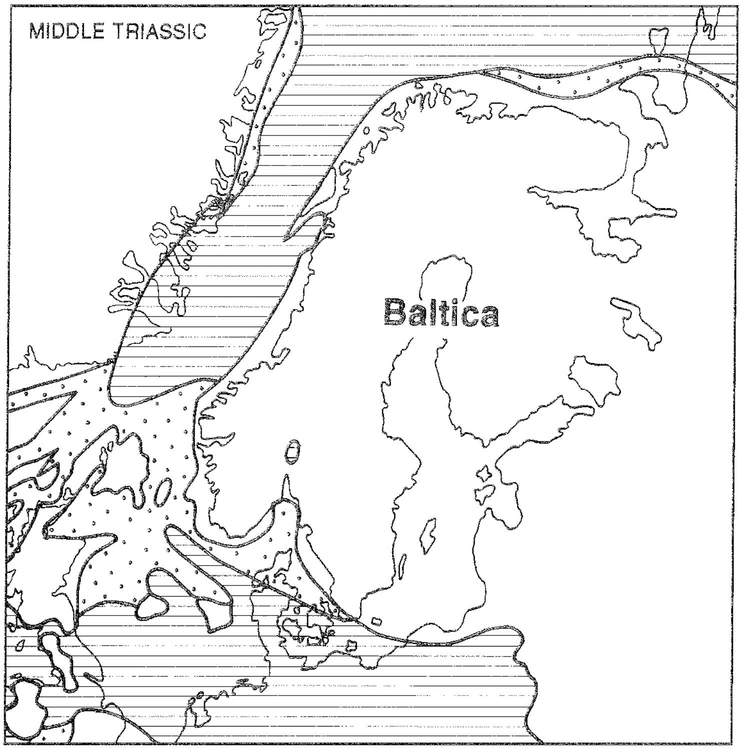

Figure 6-1. Middle Triassic depositional environment according to Ziegler (1988). White: cratonic area; Stippled: continental clastics; Ruled: shallow marine sediments and evaporites.

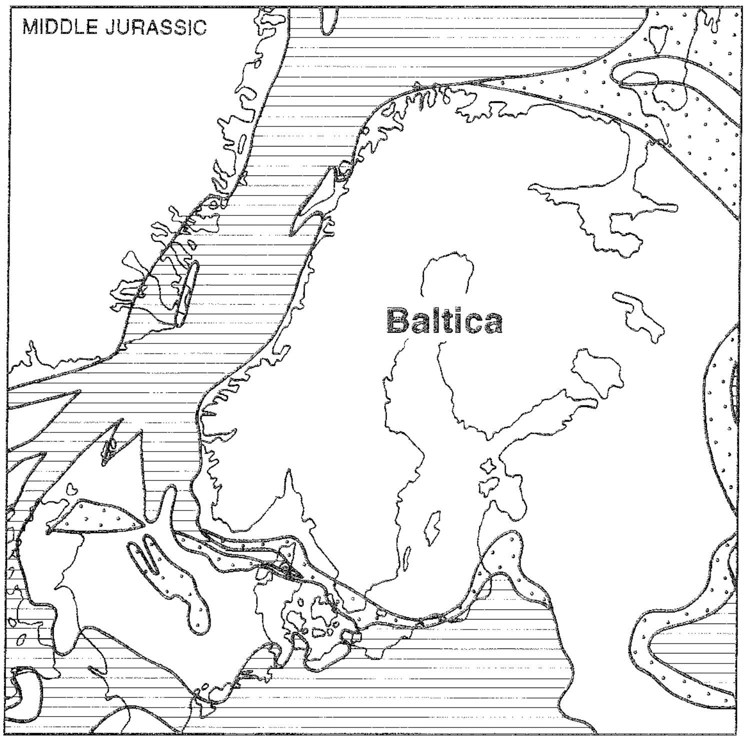

Figure 6-2. Middle Jurrasic depositional environment according to Ziegler (1988). White: cratonic area; Stippled: continental clastics; Ruled: shallow marine sediments and evaporites.

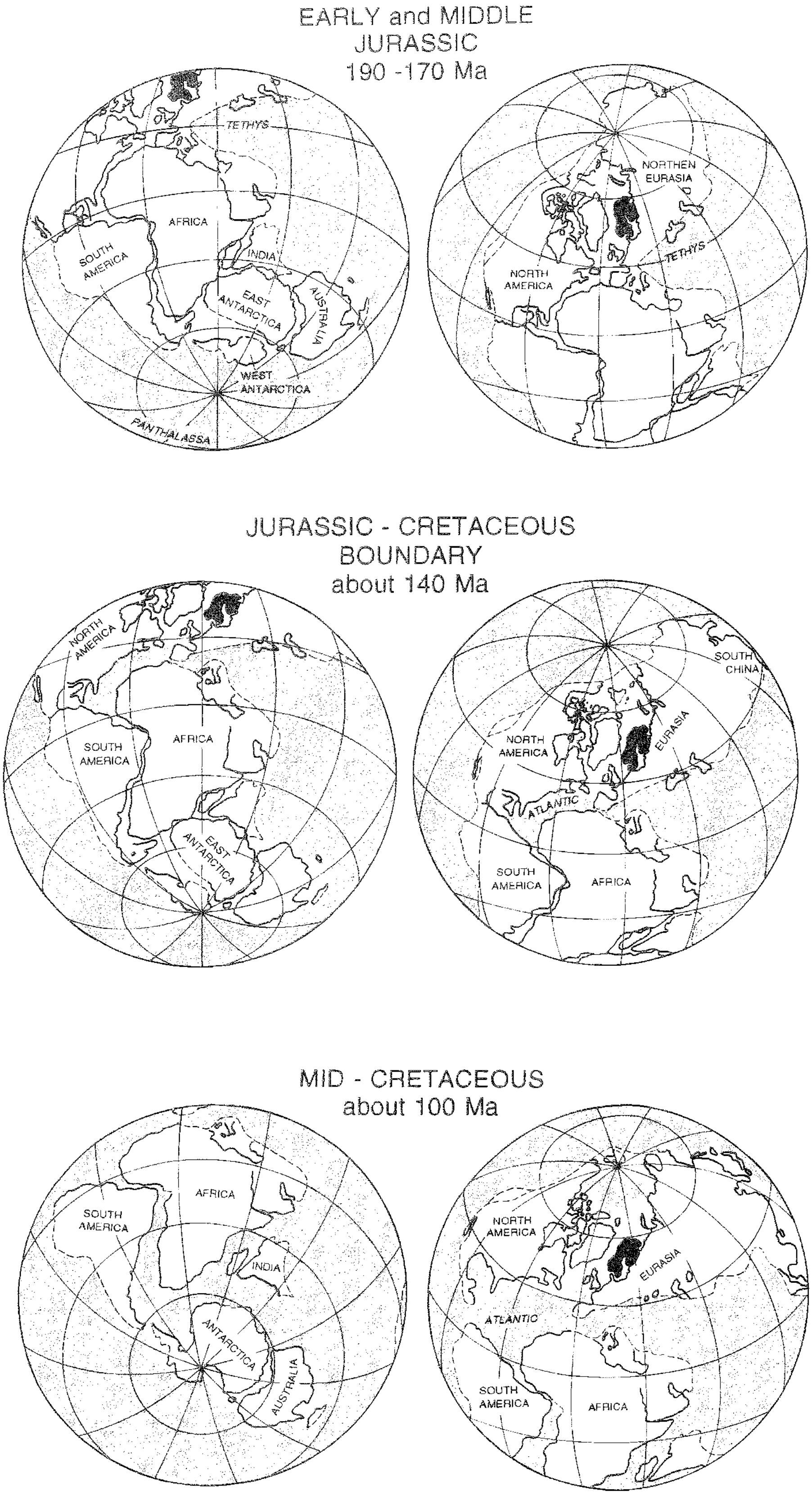

Figure 6-3. *Palaeoposition of plates during the Mesozoic (Irwing, 1983).*

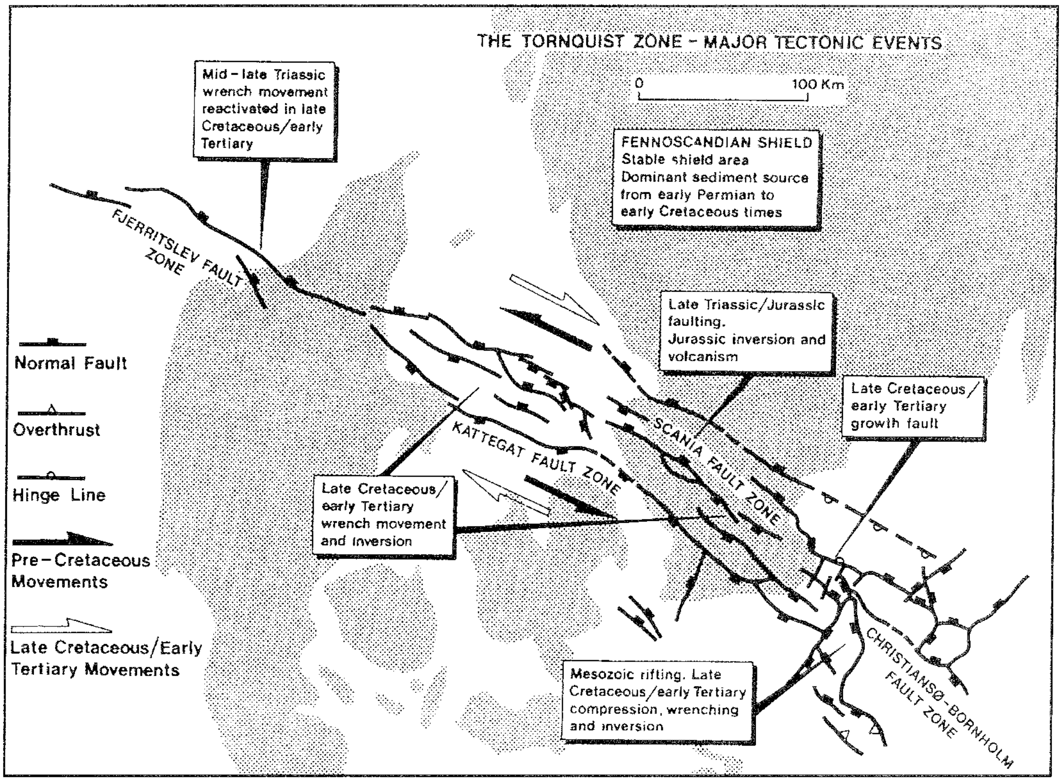

Figure 6-4. *Major tectonic events of the Tornquist Zone. (From Kumpas, 1984).*

favoured the formation of kaoline at the surface and probably also along near-surface fractures where meteoric water was transported.

The Triassic and Early Jurassic periods were characterized by continental conditions in Baltica, while the Cretaceous was characterized by transgression in southern Baltica allowing sedimentation of limestones in the near-shore, shallow sea (Figure 6-6). The only remanents of Mesozoic sediments in Sweden are today found in the southernmost parts. The ending of the Mesozoicum is contemporaneous with the initiation of the central european Alpine Orogeny.

In summary:

* The Mesozoicum is characterized by rifting along the Laurentia-Baltica border (the Norwegian-Greenland Sea Rift) and rifting and subsequent sea-floor spreading along the Gondwana-Laurasia border.
* The effects of the crustal separation between Gondwana and Laurasia are only evident outboard the Baltic shield. In Sweden especially the Tornquist Zone was reactivated by extension during the Triassic and Jurassic and compression during the Cretaceous.
* In Baltica continental conditions, erosion and deep weathering characterize the Mesozoic except for the marine sedimentation in the southernmost part during the Late Cretaceous.

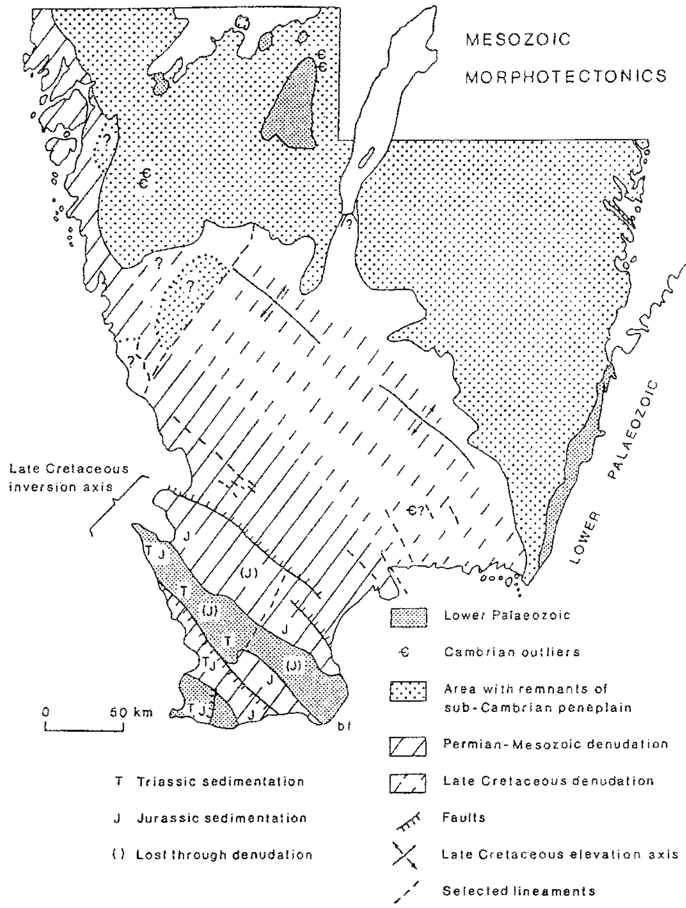

Figure 6-5. *Mesozoic morphotectonics of southern Sweden. (From Lidmar-Bergström, 1991).*

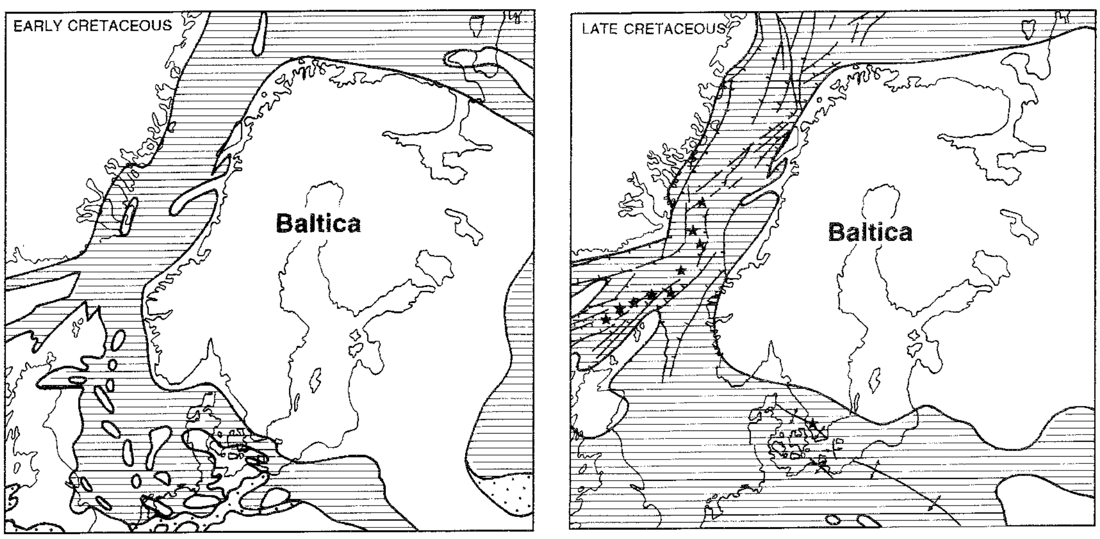

Figure 6-6. *Cretaceous depositional environment according to Ziegler (1988). White: cratonic area; Stippled: continental clastics; Ruled: shallow marine sediments; Stars: anorogenic volcanic activities.*

7 THE TERTIARY TO QUATERNARY PERIOD, 65 Ma TO PRESENT

The period is characterized by the North Atlantic sea floor spreading and related tectonism in Baltica. The last part of the period contains repeated glaciations.

7.1 THE BIRTH OF THE NORTH ATLANTIC

The break-up of the North Atlantic is considered to have taken place in Early Tertiary time. The Thulean volcanism (60-50 Ma) which is associated with the crustal separation between Greenland and Eurasia in the North Atlantic region, is unique concerning areal extension (of which the easternmost parts are shown in Figure 7-1). In Figure 7-2, a global plate reconstruction is shown for Eocene. The volcanism continued along the Mid-Atlantic Ridge and Iceland was initially formed during the Middle Tertiary. Transform faults were created in the oceanic crust of the North Atlantic. Some of these, the Jan Mayen Transform Fault and Iceland Transform Fault, have been considered to continue into zones of weakness on land (Talbot & Slunga, 1989). Muir Wood (1993) doubted this and argued that the differences in rheology between the shield and its surrounding should not allow for such a continuation.

Several NW trending fracture zones at the northern coast of Norway were formed/activated during the Tertiary, e.g. the Senja Fracture Zone which continues on land into the probably older Bothnian-Senja Fracture Zone (Henkel, 1989). From dislocations in magnetic patterns both sinistral and dextral displacements up to 45 km have been suggested in these fracture zones.

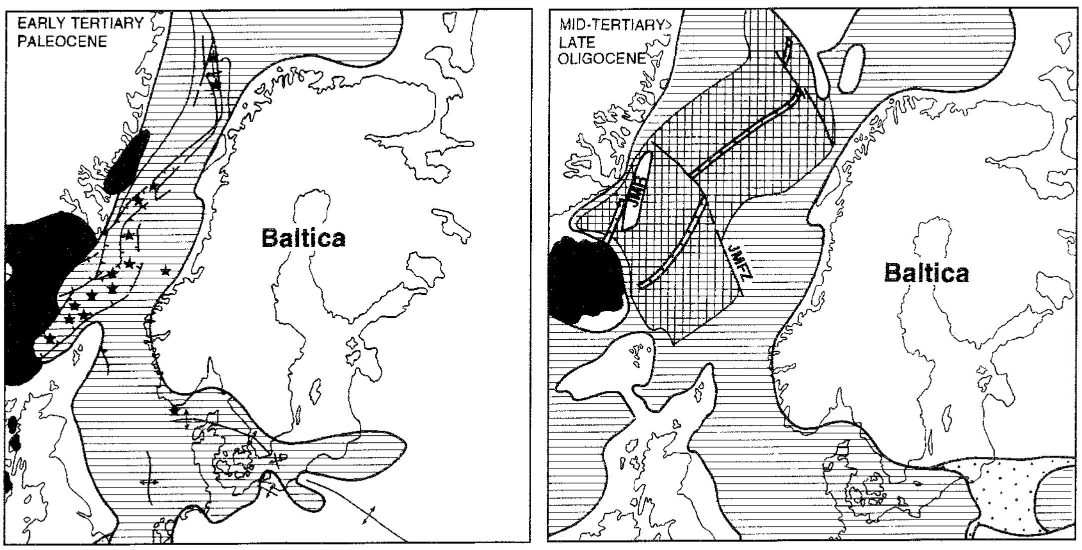

Figure 7-1. Depositional environment during Early and Middle Tertiary respectively. The Thulean volcanism and the birth of Proto-Iceland is shown in black. (From Ziegler, 1988.) White: cratonic area; Stippled: continental clastics; Ruled: shallow marine sediments; Black: Plateau basalts; Checked: Basins floored by Oceanic crust; Stars: anorogenic activities; JMFZ: Jan Mayen Fault Zone; JMR: Jan Mayen Rift.

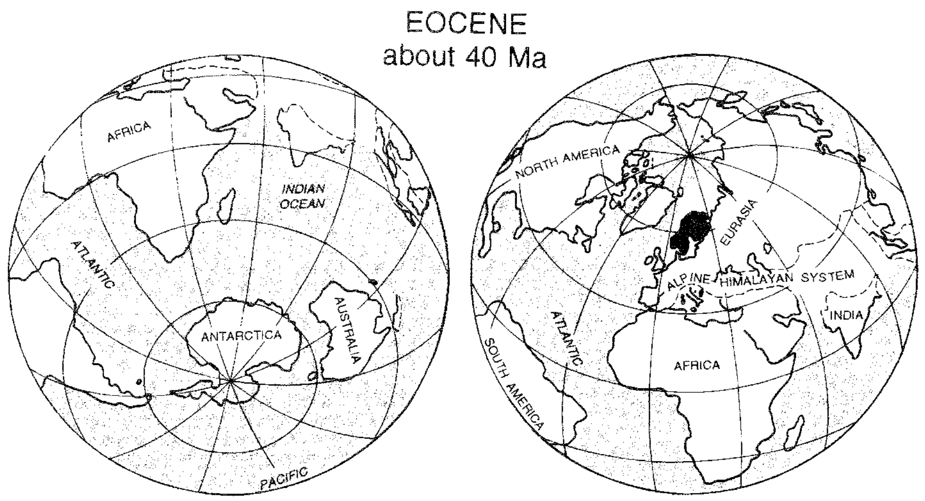

Figure 7-2. *The palaeoposition of continents during Eocene (after Irwing, 1983).*

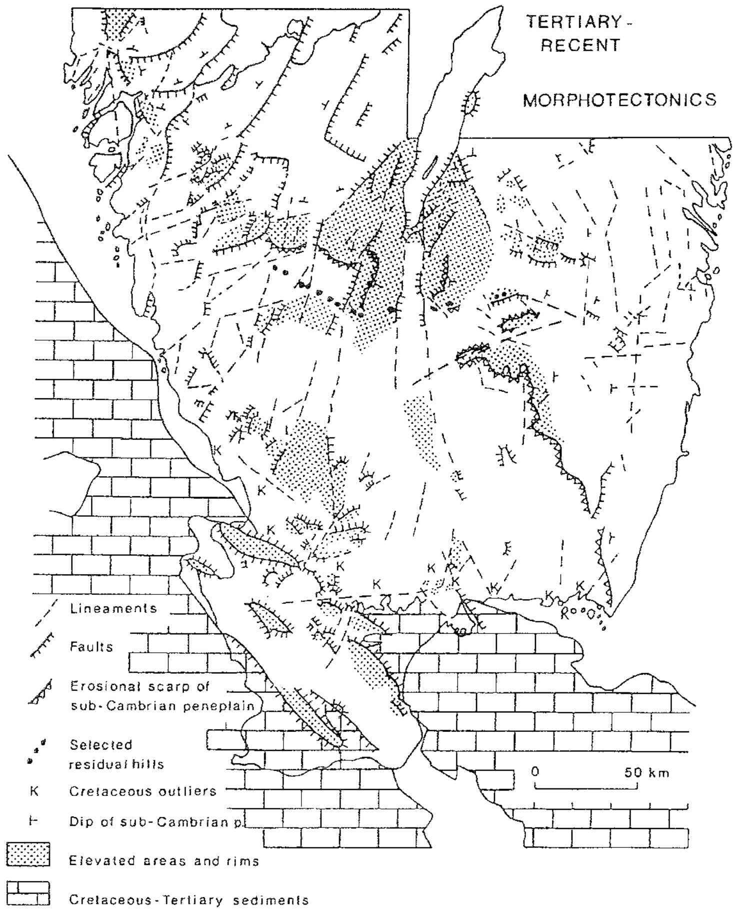

Figure 7-3. *Tertiary-recent morphotectonics of southern Sweden (from Lidmar-Bergström, 1991).*

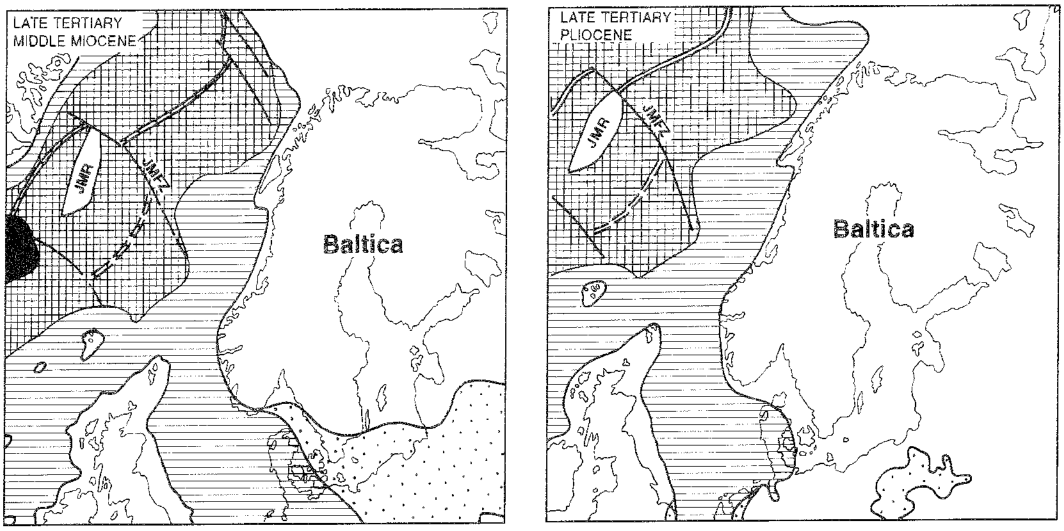

Figure 7-4. Late Tertiary depositional environment (after Ziegler, 1988). White: cratonic area; Stippled: continental clastics; Black: Plateau basalts; Ruled: marine sediments; Checked: basins floored by Oceanic crust. JMFZ: Jan Mayen Fault Zone; JMR: Jan Mayen Rift.

In southern Europe the Alpine folding culminated. Within the Tornquist Zone, Tertiary faulting is evident (e.g. Ahlberg, 1986) and according to Bergström (1984) a compressional stress regime prevailed in the zone during this period with dextral wrench faulting, resulting in inversion movements (Norling & Bergström, 1987).

In southern Baltica an uplift of southern Småland during Late Cretaceous to Early Tertiary resulted in denudation of the surface to a peneplain (Figure 7-3). Late Tertiary to recent tectonism have affected this peneplain with vertical displacements (Lidmar-Bergström, 1991). Indications of a very late (e.g Tertiary) formation of the Vänern basin was given by Ljungner (1927) and also advocated by Ahlbom et al. (1979; cf. also Ahlin, 1987). The Late Tertiary land – sea distribution and the widening of the N. Atlantic is shown in Figure 7-4.

7.2 QUATERNARY GLACIATION AND POST-GLACIAL TECTONICS

The climatic evolution during the Quaternary shows that repeated glaciation has taken place. It is known that three glaciations, Elster, Saale and Weichsel, have affected southern and central Sweden during the last 400 000 years (e.g. Lindström et al., 1991). These glaciations had probably several precursors in the Quaternary and late Tertiary, although not dated.

A maximum ice cover of c. 2 to 2.5 km is suggested for central Sweden during the last (Weichselian) culmination 20 000 to 18 000 years ago. The repeated loading/unloading of the bedrock are the most prominent changes in the stress field during the Quaternary (cf. Stephansson, 1989; Muller et al., 1992).

It is known that the rebound of the crust decreases exponentially with time after the release of the ice-load. Just after deglaciation, the uplift rate may exceed 0.1 m/year in the central parts of the glaciated area, while 10 000 years later it is in the order of 0.01 m/year (Ahlbom et al., 1991). Thus, late glacial/early post-glacial periods are regarded as "dramatic" periods when faulting due to changes of the stress can be expected. In shield areas the result will be changes of the major principle stress in the upper parts of the crust from vertical to horizontal.

In Norway neotectonics is strongly related to earthquake activity and is concentrated along some of the well known major fault zones and rifts (Bungum et al., 1990). Vertical movements in the order of several hundreds of metres could have taken place parallel to the SW coast of Norway during the Quaternary (Riis, 1992; cf. also Böe et al., 1992). On land, south of Stavanger, neotectonic faulting is suggested to have reactivated the Gannsfjord lineament (Fugelli & Riis, 1992).

A review of the seismotectonics of Sweden was published by Muir Wood (1993). Here he argues that all current seismicity of Sweden appears to be a respons to post-glacial rebound.

Post-glacial faulting in southern Sweden has been advocated by a.o. Mörner (1979, 1980). Nordenskjöld (1944) reports post-glacial movements from the Oskarshamn-Västervik area although only minor displacements are observed. Also Björk & Digerfeldt (1982) measure a Late Weichselian shore displacement at Hunneberg, S. Sweden which may be explained by post-glacial faulting.

The Kattegat basin is suggested to be a Quaternary feature (Lykke-Andersen, 1987) with faulting in the Tornquist Zone due to a compressional stress regime possibly of post-glacial age (G. Lind, Göteborg, pers. com. 1992). Wannäs and Flodén (1993) distinguished a subsidence of the Hanö Bay Halfgraben, "possibly in the order of 20-60 m during the Quaternary". All this indicate an ongoing tectonically active Tornquist Zone.

Also in northern Scandinavia post-glacial tectonics is well documented e.g. in the Pärvie and Lansjärv areas (Lagerbäck & Witschard, 1983; Lagerbäck, 1991 and references therein; Bäckblom & Stanfors, 1989) as well as in Finnmarka, Norway (Olesen, 1988). Most of these neotectonic zones trend in NNE to NE (Figure 7-5) and show "eastern block up" faulting in some places with a vertical displacement exceeding 25 metres (Lagerbäck & Witschard, 1983). Muir Wood (1993) graded neotectonic claims concerning Scandinavia into five classes of reliability. The first class of reliability was only given to observations from northern Norway and Sweden.

A combination of isostatic rebound and plate tectonics (ridge push) as reasons for neotectonic features has been discussed (Stephansson, 1989; Slunga, 1989), in contrast to the opinion stated by Muir-Wood (1993) about isostatic rebound as the main reason for neotectonism.

7.3 PRESENT STRESS AND SEISMOTECTONICS

The present orientation of rock stresses in Baltica is presented in the Fennoscandian Rock Stress Data Base – FRSDB (Stephansson et al., 1987). Methods used and quality of rock stress measurements have long been disputed (e.g. Stephansson et al., 1988). There is a tendency for the maximum horizontal stress to have a NW-SE direction in central Sweden and Finland for depths larger than 300 metres (Stephansson et al., 1987; Muller et al., 1992). This means that todays principle stress in S. Sweden allows approximately NW-SE trending fractures at depth to be dilated at Äspö on the SE coast (cf. Ericsson, 1988). From this follows that the hydraulic conductivity should be favoured along these fractures.

For northern Sweden a tendency of roughly N-S trending directions of the maximum horizontal stress is found (Stephansson et al., 1988). Measurements close to the Tornquist Zone show maximum horizontal stresses roughly perpendicular to the zone, indicating compression (Figure 7-6) in the upper part of the crust in consistence to the neotectonic features discovered in the Kattegat basin (pers. com. G. Lind, Göteborg). In Norway irregular distributions are found for the maximum horizontal stresses, but in the North Sea the directions varies between N70°-118°E (Clauss et al., 1988), with a preference to NW to NNW for borehole break-outs as stress indicator (Muller et al., 1992). The different stress fields of Europe (Figure 7-6) can be attributed to plate-driving forces acting on the plate boundaries and are locally modified by litospheric properties (Muller et al., 1992). Ongoing tectonic activity caused by e.g the plate

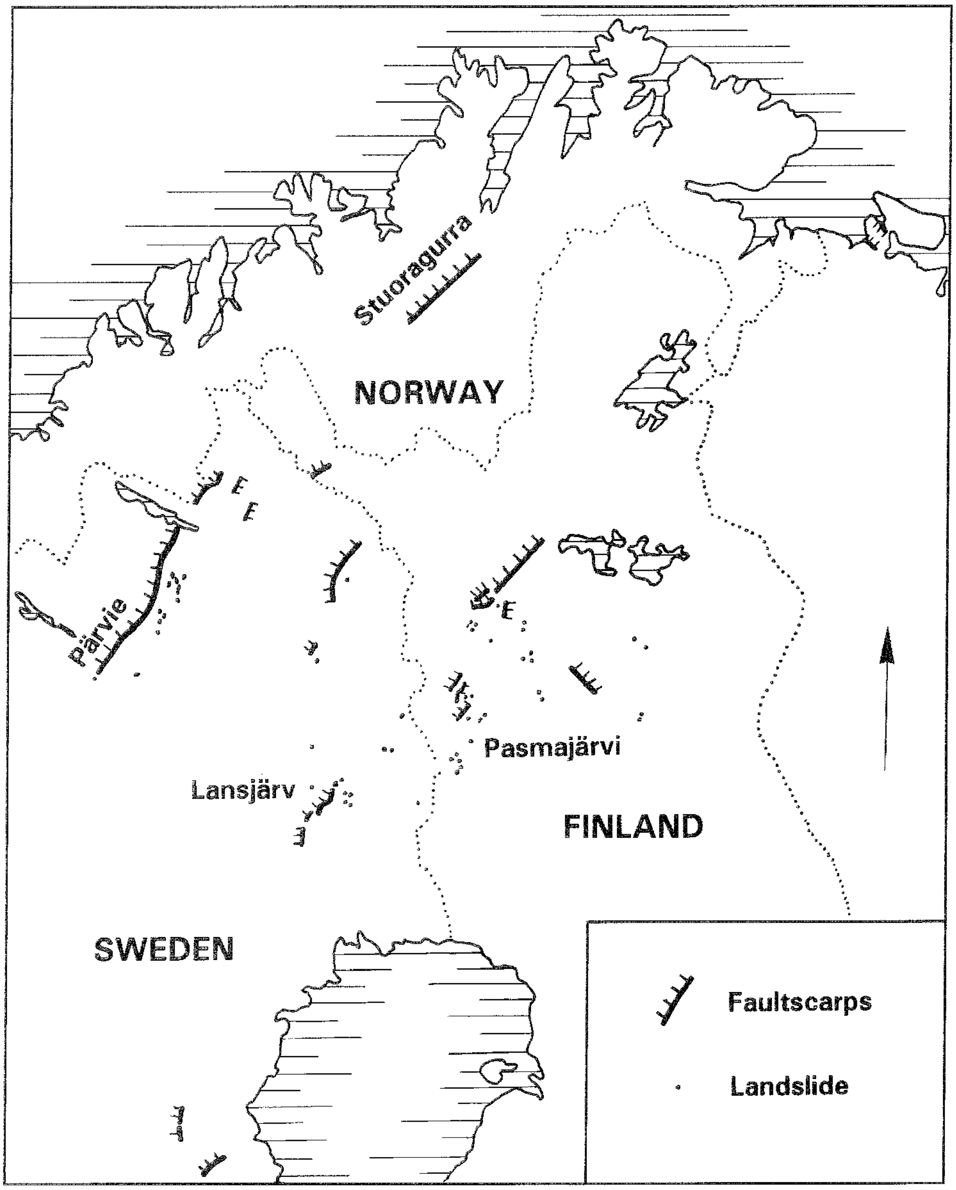

Figure 7-5. Landslides (dots) and Post-glacial faults in northern Baltica. (From Vourela, 1990).

movements and the land upheavel is manifested in seismic events and aseismic slip. In Sweden earthquakes have been registrated already from 1891. To supplement these, Wahlström (1990) published a catalogue of earthquakes in Sweden formed during the time interval 1375-1890.

Epicentral distribution of earthquakes with magnitude greater than 2.7 (M_L) in Baltica, during 1980 – 1989, is shown in Figure 7-7, showing a concentration of epicentres to the west coast of southern and central Norway. In Sweden there is a concentration of epicentres to the northern parts, the northern east coast and the Lake Vänern district.

Slunga (1989) showed that earthquakes are generated at locked parts of a fault where shear stress is concentrated due to creep (aseismic slip). He calculates that in mean about 20 km of aseismic slip preceeds an earthquake. The seismicity of the southern part of the Baltic shield has been studied by e.g. Slunga et al. (1984) (Figure 7-8). They conclude that approximately 80% of the earthquakes, recorded during a four year period, occurred at crustal depths between 19 to 7 km. The orientation of the horizontal stresses relaxed by the events show dominantly

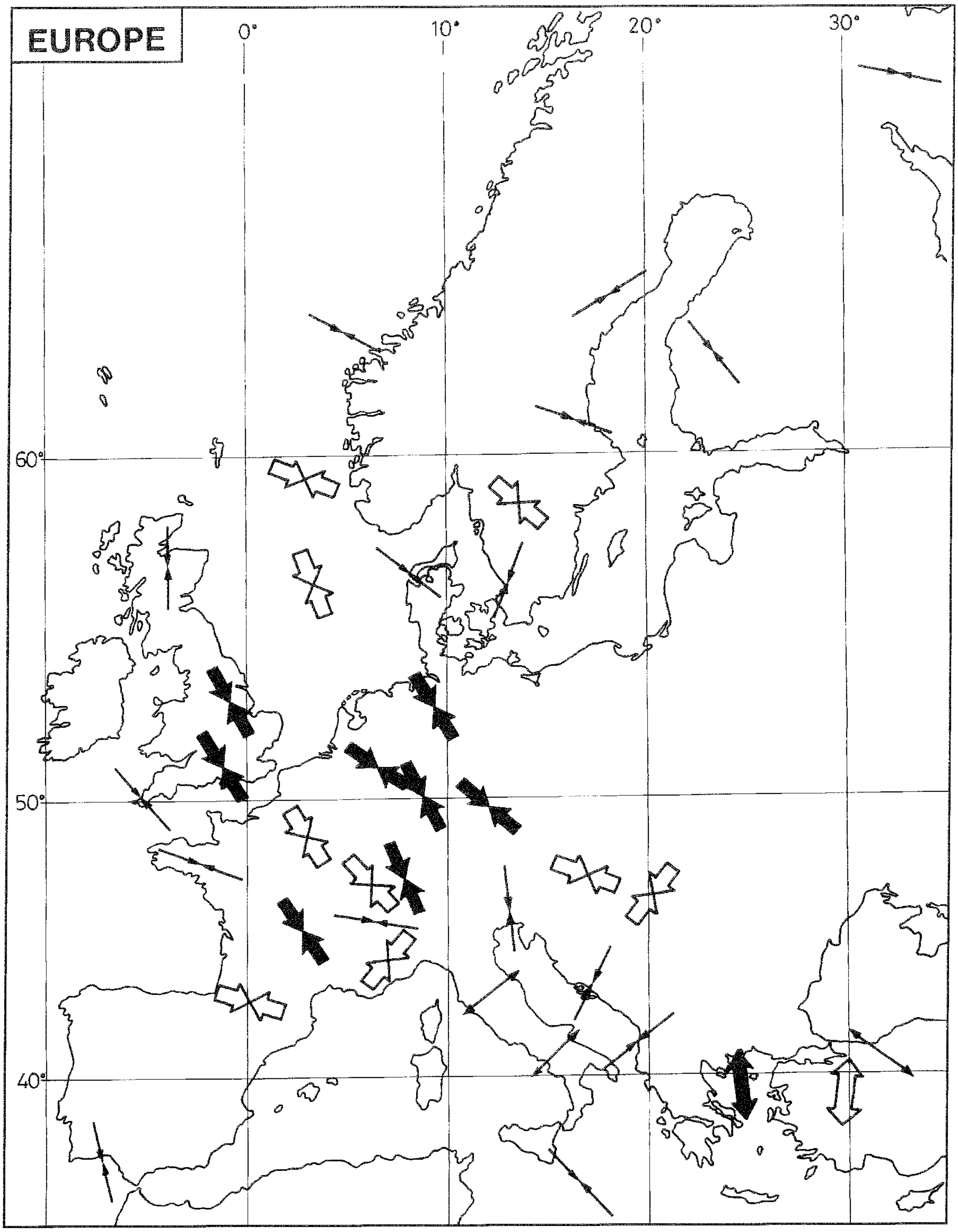

Figure 7-6. *Generalized stress map for Europe. Inward directed arrows indicate the maximum horizontal compression directions in regions of dominantly compressive stress regimes (either thrust or strike-slip faulting). Outward directed arrows indicate the least horizontal stress in the regions of extension. Thick arrows are shown for average stress directions which are based on numerous (>10) stress observations preferentially from different types of stress indicators with uniform orientations, open arrows are used for means based on 5 to 10 consistent orientations and thin arrows are for average directions based on less than 5 observations. (From Muller et al.,1992).*

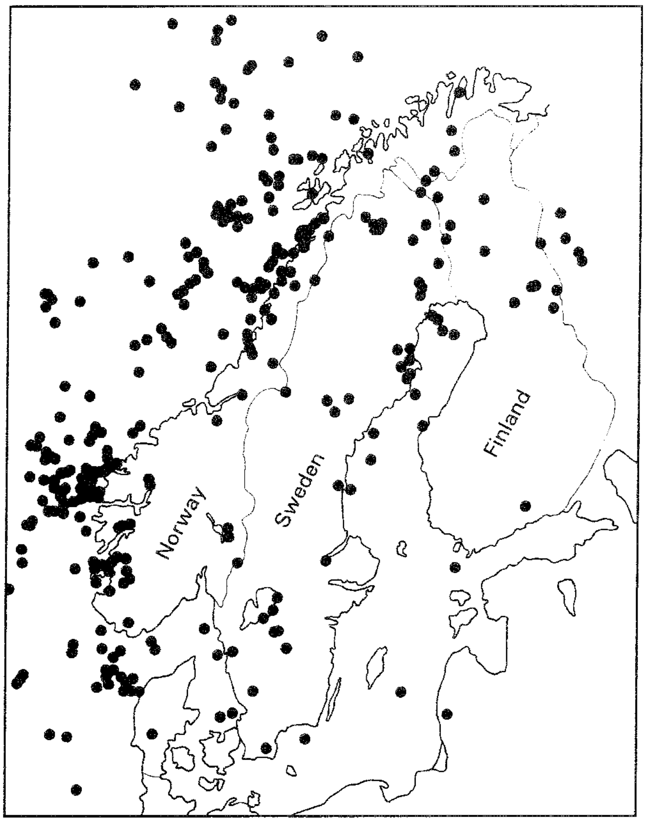

Figure 7-7. *Seismicity of Fennoscandia above the general threshold of magnitude 2.7 for the years 1980-1989 (after Ahjos & Uski in Muir-Wood, 1993).*

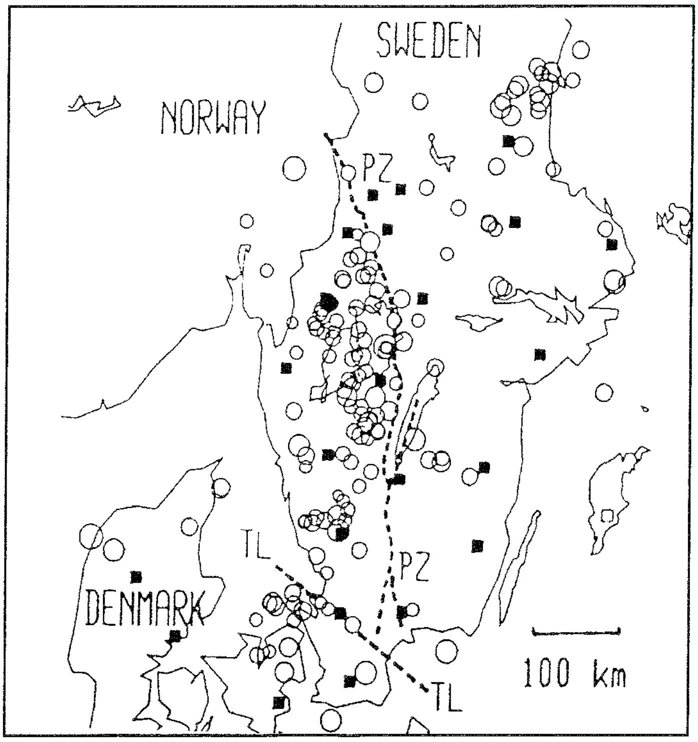

Figure 7-8. *Earthquakes recorded in Sweden and Denmark during a four year period. Squares mark the stations, circles mark the earthquakes. TL=Tornquist Zone, PZ=Protogine Zone (from Slunga et al., 1984).*

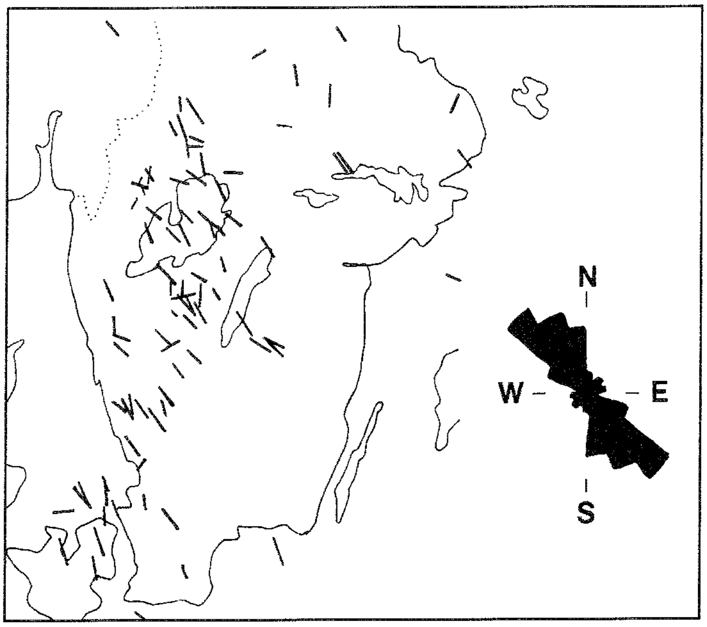

Figure 7-9. The orientation and relative size of the maximum horizontal compression given by the P- and T-axis of fault-plane solutions. The polar histogram gives the frequency distribution of these orientations of compression (from Slunga et al., 1984).

principal compression orientated in NW-SE (Figure 7-9). This is in accordance with rock stress measurements in southern Sweden (Stephansson, et al., 1987; Bjarnason, 1989) and in agreement with the present plate tectonic evolution in the North Atlantic (cf. Slunga, 1989). Most of the earthquakes recorded, occurred on existing zones of weakness extending up to the surface. From this Slunga et al. (1984) concluded that lineaments (faults) with large lateral extension also have a large vertical extension, probably through the brittle part of the crust. The sense of movement from the earthquakes is determined by the orientation of these faults. The reverse faulting takes place along pre-existing faults which typically trend NE-SW, the normal faulting along pre-existing faults trending NW-SE and the strike-slip faults either along N-S or E-W trending pre-existing faults. The Protogine Zone of south central Sweden has been shown to be the border between a more seismic west Sweden and a more aseismic east Sweden (Slunga et al., 1984).

In summary:

* The sea-floor spreading of the North Atlantic region started at the beginning of the Tertiary.
* Repeated glaciations during the Late Tertiary and Quaternary have influenced the stress field of the upper crust by ice loading and rebound.
* Neotectonic faulting are known from northern Scandinavia but also from the Tornquist Zone in the south.
* The direction of maximum horizontal principle stress in the North Sea, southern Sweden and Finland is roughly NW-SE to WNW-ESE, (in agreement with the direction of ridge push forces), for depths more than 300 metres.
* Earthquake epicentres are clustered along the west coast of southern and central Norway, northern Sweden, the northeast coast of Sweden and also in the Lake Vänern district.

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8 GENERAL COMMENTS

Plate movements are the ultimate reason for stress build-up in the crust. Palaeopositions of the shields show that the continental drift velocity has changed during the Earths history (Figure 8-1). Since the Archean nuclei of Baltica was formed to the present, Baltica has changed its latitude from more than 60 degrees N to more than 60 degrees S and back again. The true velocity of the drift is uncertain but the latitudinal changes indicate velocities up to at least 25 cm/year during some time intervals (e.g. 1320-1300 Ma). Large differences in orientation is also recorded. For example a rotation velocity of about 2 degrees/ million year is found in the interval 480-420 Ma. This can be compared to the present rotation of stress tensors of the order of 7.5 degrees / 100 000 years of the East African rift (Bosworth et al., 1992). Rapid rotation should generate differential stress creating conditions for fracturing.

The present, fractured crust of Baltica contains imprints from different stress regimes during more than 2 Ga. When mapping fractures and fracture zones the resulting map will show different patterns depending on scale and methods used (e.g. Witschard, 1984; Ronge, 1988). Several studies of lineament and "rock blocks" have been carried out using different types of remote sensing (e.g Röshoff & Lagerlund, 1977; Tirén & Beckholmen 1989, 1990, 1991 and 1992). These studies give a picture of the existing vertical to steep zones of weakness in southern Sweden (Figure 8-2). Thus, different block patterns from the western and eastern part of southern Sweden have been recorded, where SE Sweden has got more orthogonal blocks and SW Sweden more lensoid blocks, representing "less distorted" and penetrative shearing respectively (Tirén and Bäckholmen, 1992). The demarcation line between these tectonic patterns are approximately that of the Protogine Zone.

Reactivation can be demonstrated in different scales. In global scale the peri-Atlantic orogenic zones have been shown to be reactivated in the way that older orogens have been overprinted by younger rifting and collisional events.

The Transscandinavian Igneous Belt, the Mylonite Zone, the Protogine Zone, the Sveconorwegian Front, the Vättern Graben, the dolerite swarms of 1500, 1200, and 900 Ma ages etc. all are roughly trending N-S and show that south central Swedish crust has been tectonically over printed along the same axis.

That reactivation of first order major shear zones is a common feature is e.g. evident from the Tornquist Zone (a good example of that both compressional and tensional forces can reactivate a single zone), the Mylonite Zone, the Protogine Zone, the Kårböle-Ljusnan Zone (Bergman & Sjöström, 1993; Gorbatschev 1993) and the Trollfjorden-Komagelva Fault Zone (Siedlecka & Roberts, 1992). Furthermore the Tornquist Zone and Trollfjorden-Komagelva Fault Zone have been shown to be post-glacially reactivated (Lykke-Anderssen, 1987; Wannäs & Flodén, in press; Olesen et al., 1992).

Munier (1993) argued that the ductile shear zones which were formed within the shield due to major reorganizations in the surrounding plate boundaries, later were fragmented as brittle fracture zones, which mostly have been reactivated ever since.

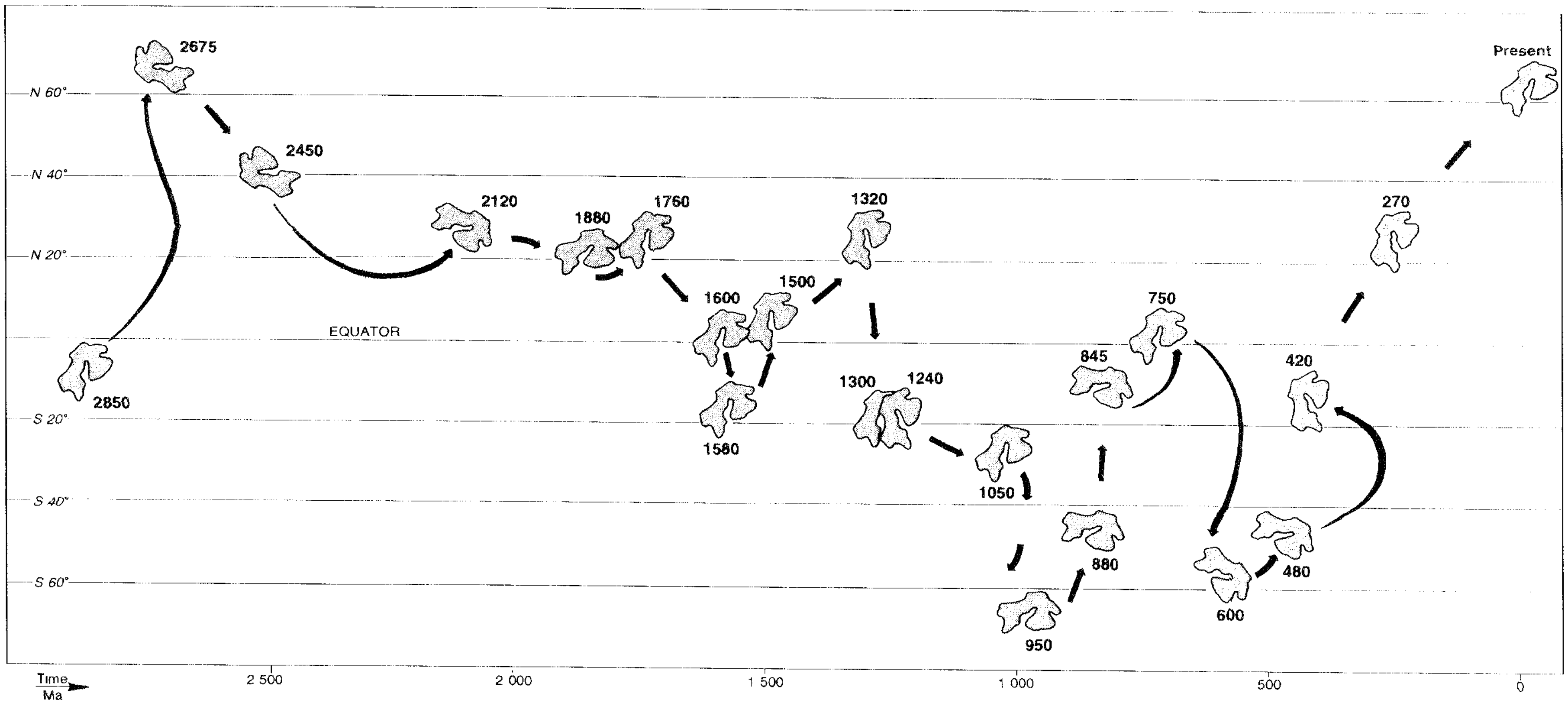

Figure 8-1. *The drift history of Baltica. The configuration of Baltica shown was not established until the Mid-Proterozoic. (After Elming et al., 1992; Perroud et al., 1992; Pesonen et al., 1989 and 1991; Smethurst, 1992).*

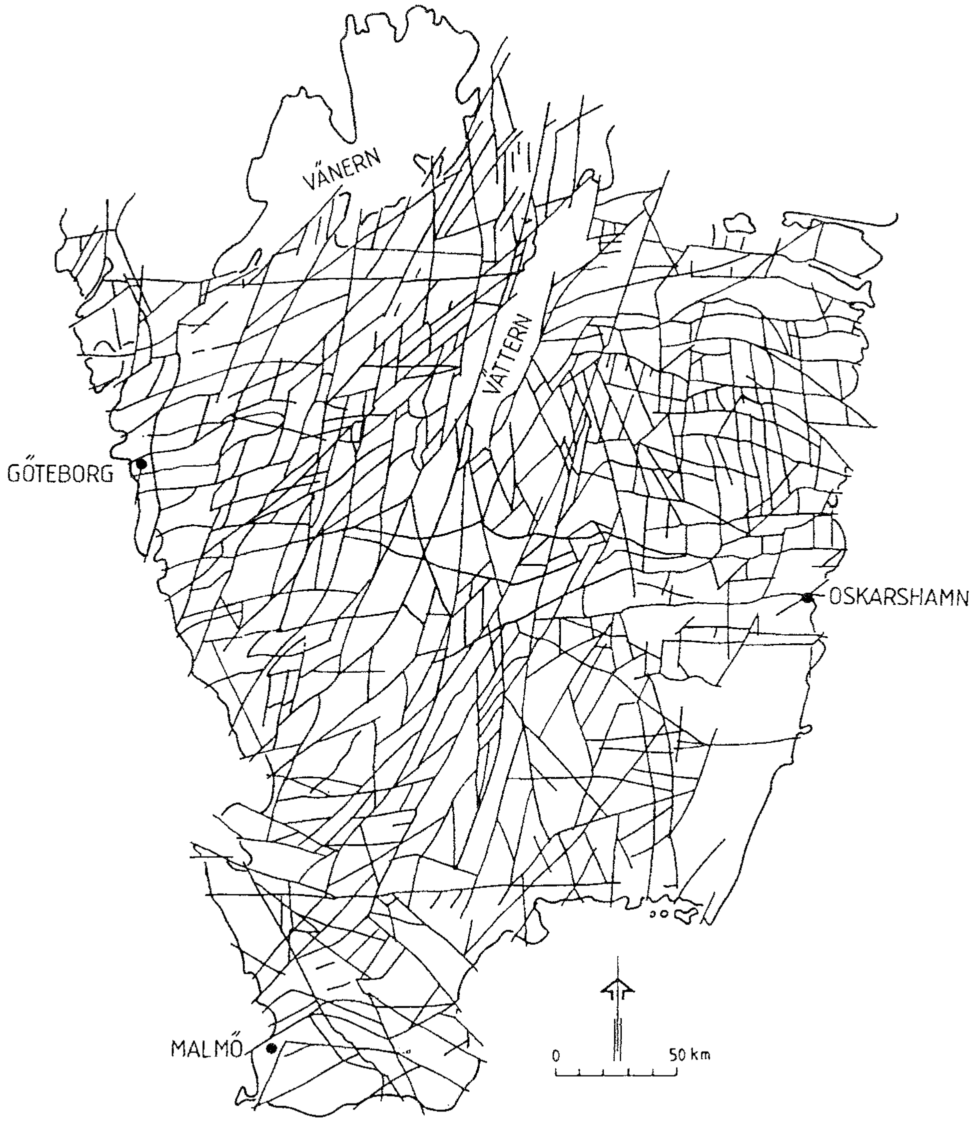

Figure 8-2. Regional rock blocks of southern Sweden (Tirén & Beckholmen, 1992).

9 THE NEXT 100 000 YEARS

As has been shown in earlier chapters the present surface in Baltica exhibits a fracture pattern and other hetrogenities formed and developed during a time period of many hundreds of million years. Although specific patterns are recorded from different areas within the Baltic shield most fracture directions are represented within each of them. The experience shows that deformed/fractured rocks will generally be deformed by subsequent events along preexistent anisotropies. Active stress during the next 100 000 years will thus most probably reactivate older zones and fractures of weakness within the crust. This means that fractures with strikes corresponding to the maximum principle stress will expand and thus have higher preference for e.g. water circulation than others.

The present situation of passive respons to the Mid-Atlantic ocean floor spreading as an anorogenic period of the Baltic shield history will not change substantially within the closest future and will thus also prevail within the next 100 000 years.

What we certainly have to consider is, however, a future ice cover (Ahlbom et al., 1991; Björck & Svensson, 1992) which will influence the stress situation of the upper crust within this time period.

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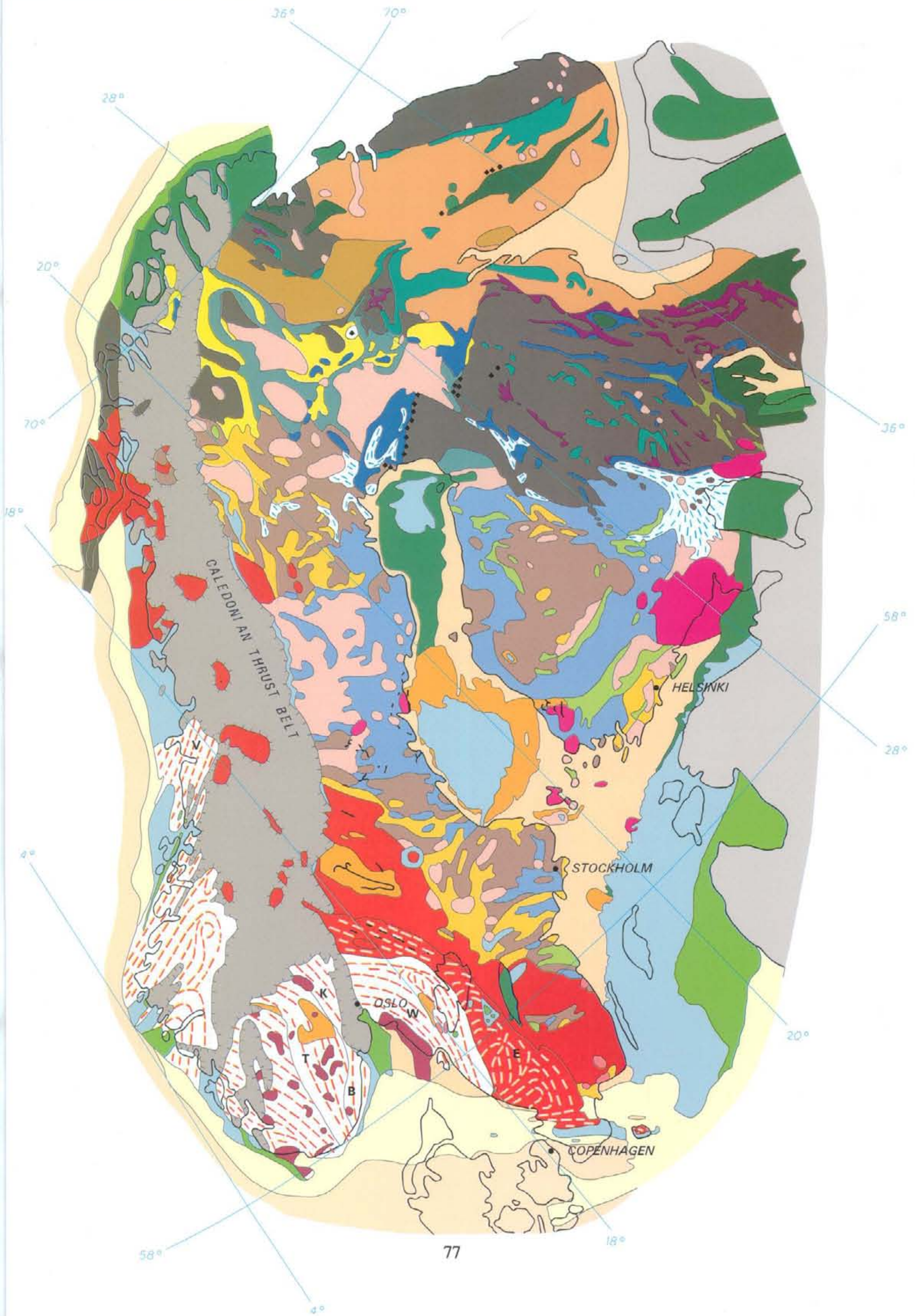
Appendix 1

A summary of the tectono-metamorphic, magmatic and sedimentary events in Sweden.

PERIOD (Ma)	MAGMATISM (Ma)	SEDIMENTATION / EROSION (Ma)	TECTONICS Normal-, thrust-, or strike slip-faulting	METAMORPHISM	CONTINENTAL DRIFT
		Repeated glaciation. Peneplanation of S Sweden.	Neotectonic features in N Scandinavia and Kattegat Basin. Faulting in the Tornquist Zone. Formation of the Vänern Basin. Uplift.	Surface conditions.	The Alpine Orogeny. Ocean floor spreading and formation of the N Atlantic.
65	Basalt necks in Skåne.	Marine sedimentation in S Sweden. Erosion of the shield.	Dextral transpression in the Tornquist Zone. Sinistral transtension in the Tornquist Zone. Uplift of S Sweden. Horsts and grabens (Tornquist Zone).	Low temperature (<70°C).	Pangea starts to break up.
250	Särna alkaline intrusion (281). Dolerite sills in Västergötland (290-250). Dyking along the Oslo Rift-swedish west coast (300-240). Dolerite swarm in Skåne (~300).	Continental sedimentation.	Uplift, blockfaulting and rifting (Oslo, Tornquist Zone). Sinistral strike-slip between *Greenland and Baltica*. Siljan impact. Thrusting.	Burial metamorphism (sulphide mineralization, asphaltite etc)(>80°C).	Super continent Pangea. Variscian-Hercynian Orogeny. The Caledonian Orogeny. Collision Laurentia-Baltica.
410		Marine sedimentation (510-410). Shallow marine sedimentation (570-510) <200 m thickness.	Subsidence of Skåne. Tornquist Zone activity. Fracturing in Åland and E Sweden. Fracturing in SW Sweden and Åland.	Low temperature (<50°C).	Rotation and rapid drift of Baltica (480-400). Converging Laurentia-Baltica. Diverging Laurentia- Baltica.
570	Alnö-Fen alkaline intrusions (610-530). Ottfjäll dolerite swarm (750-650).	The Sub-Cambrian peneplain. Glaciation in parts of Baltica (650-600). Continental-shallow marine sedimentation of Visingsö type of sediments e.g. in S Sweden-Bothnian Bay, ~1 km thickness (700-800).	Rifting W of Baltica and intracontinental (aborted) rift, Vättern Graben. Rifting-uplift.	Oxidizing (surface) condition. Low grade (~200-250°C in Dalsland) and in the Svecofennian Province. Intermediate grade in SW Sweden.	Rotation of Baltica. Iapetus Ocean opening (break up of Laurentia-Baltica). Stretching of the crust "Laurentia-Baltica".
900	N-S Trending dolerites, SE Sweden (~900) Bohus-Blomskog granite and pegmatite. SW Sweden (~910). Volcanics in Dalsland (~1100-1000). N-S dolerites in S central Sweden(~1180). Syenites and granites in W and S Sweden (~1200-1150). Dolerite lopoliths in central Sweden (~1250).	Continental sedimentation of Almesåkra sediments, 1 km thickness? (~1000?). Marine sedimentation of Dalgroup sediments, ≤3 km thickness (~1100-1000). Continental sedimentation of Jotnian sandstones, shales and conglomerates in central Sweden-Bothnian Sea ≥1 km thickness (≥1250).	Extension. Thrusting. Shearing e.g. in the Protogine Zone. Rifting Baltica-Laurentia.	Amphibolite-granulite paragenesis in SW Sweden, corresponding to a depth of up to 35 km, (lower in the province of Dalsland) and probably zeolite in N Sweden. Pumpellyite-prehnite in SE and central Sweden.	The Sveconorwegian Orogeny. Collision Laurentia-Baltica. Rotation of Baltica. Separation of Baltica from Laurentia.
1250					



Generalized, lithostratigraphic map of the Baltic shield and adjacent sea areas.

Appendix 2

Complied by S.Å. Larsson & E-L Tullborg 1993, mainly from Gaal and Gorbatschev, 1989; Berthelsen, 1989; Simonen 1990; Håkansson and Pedersen, 1992; Sigmond 1993 and Bogdanova, pers. com, 1994

Phanerozoic and Upper Proterozoic Cover

- Phanerozoic sedimentary cover, unspec.
- Tertiary
- Triassic-Cretacerous
- Devonian-Permian
- Caledonian thrusts, unspec.
- Cambrian-Silurian
- Late Proterozoic cover and aulacogens

Post-Svecofennian, Proterozoic Rocks

- Granites, subordinately anorthosites (1.0-0.9 Ga)
- Dolerite sills and "hyperite" gabbros (1.5-1.4 Ga) and Central Scandinavian Dolerite Group (1.25 Ga)
- Jotnian (in part sub-Jotnian or post Jotnian) sediments (1.4-1.1 Ga)
- Granites (1.4-1.2 Ga)
- Rapakivi granites (1.7-1.54 Ga)
- Gneisses and granites (1.75-1.4 Ga) of the Southwest Scandinavian Domain; V-Vestranden; T-Telemark; B-Bamble; K-Kongsberg; W-Western Segment; E-Eastern Segment.

Transscandinavian Igneous Belt and Svecofennian Domain

- Transscandinavian Granite-Porphyry Belt (1.84-1.65 Ga)
- Late Svecofennian granitoids (1.83-1.77 Ga)
- Early Svecofennian granitoids (1.9-1.86 Ga)
- Svecofennian metapelites and metapsammites (1.9-1.87 Ga)
- Svecofennian felsic to intermediary volcanic rocks (1.9-1.87 Ga)
- Svecofennian internediary to mafic volcanic rocks (1.9-1.87 Ga)
- Kalevian metasediments (2.0-1.9 Ga)
- Lapland Granulite Belt (2.0-1.9 Ga)

Early Proterozoic Cover of the Archaean Domain

- Karelian mafic and ultramafic effusive rocks (2.3-1.9 Ga)
- Terrestrial metasediments and tholeiites of the Jatulian Group and the Sumi-Sariola Group (2.5-2.1 Ga)
- Layered mafic intrusive complexes (2.45 Ga)

Archaean Domain

- Lapponian sedimentary rocks (in part Early Proterozoic)
- Lapponian volcanic rocks (in part Early Proterozoic)
- Metavolcanic units with tholeiitic and komatiitic rocks (2.9-2.7 Ga)
- Metavolcanic units with calc-alkaline volcanism (2.9-2.7 Ga)
- Metasedimentary units, chiefly metapelites, subordinately quartzites and conglomerates
- Belomorian and Kola Peninsula gneisses
- Granitoides, migmatites, grey gneisses (2.7-2.6 Ga, subordinately 3.1-2.9 Ga)

Unspecified

- Crystalline rocks

List of SKB reports

Annual Reports

1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
TR 80-26
The KBS Annual Report 1980
KBS Technical Reports 80-01 – 80-25
Summaries
Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
KBS Technical Reports 81-01 – 81-16
Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
TR 83-77
The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
Summaries
Stockholm, June 1984

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
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Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
Stockholm, May 1986

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

1991
TR 91-64
SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, April 1992

1992
TR 92-46
SKB Annual Report 1992
Including Summaries of Technical Reports Issued during 1992
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List of SKB Technical Reports 1994

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[1] Vibrometric Oy, Helsinki, Finland
[2] Section for Solid Earth Physics, Department of Geophysics, Uppsala University, Sweden
[3] Conterra AB, Uppsala, Sweden
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[2] SKB, Sweden
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