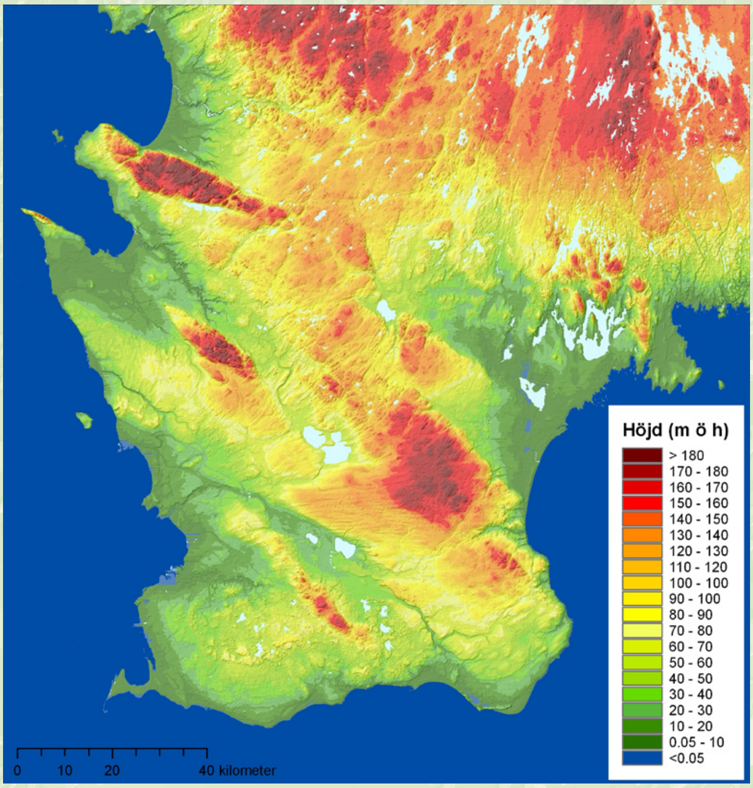
Sveriges geologiska undersökning

Tectonic evolution and geological framework of Scania

A review of interpretations and geological models



Mikael Erlström

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Mikael Erlström*

*SGU, Kiliansgatan 10, 223 50 LUND
mikael.erlstrom@sgu.se

CONTENT

APPENDIX 1.

Definitions of some of the main structural elements

1 INTRODUCTION

This report gives a comprehensive review of the present knowledge concerning the tectonic evolution of Scania and adjacent areas on the southwestern margin of the Fennoscandian Shield during the last c. 500 Ma. Special attention is given to the structural setting and manner in which the different tectonic stages evolved and how this could relate to the present situation concerning the orientation of rock stresses in Scania.

The information given is mainly based on results from performed bedrock mapping, research projects and geophysical investigations during the last decades. Many of the results have previously been presented in various publications however a comprehensive description has so far been missing. This report aims to fill this gap.

2 TECTONIC EVOLUTION AND GEOLOGICAL FRAMEWORK OF SCANIA

2.1 *Introduction - background*

The tectonic pattern and structure of the Precambrian basement in Scania and southwestern part of Scandinavia is a complex mixture of Precambrian inherited tectonic signatures and younger tectonic events. The later most commonly overprint and shadow the older structures. Combinations of principal stress regimes, fault reactivations and wrench tectonics have given the area a complex tectonic signature.

The description that follows is, thus, intended to comprehensively describe the Phanerozoic tectonic evolution of Scania and the southwestern part of the Fennoscandian Shield. The aim is to display and exemplify the tectonic complexity of the area and the difficulty in transferring regional tectonic events to the local geological scale.

Our knowledge of the geological history of the southern part of the Fennoscandian Shield (Figs 1 & 2) has improved greatly over the last two decades. This is mainly due to new geophysical data, primarily deep seismic surveys, which, combined with mapping and drilling, provide valuable new information (e.g. the EUGENO-s working group 1988, the BABEL Working group 1991 and the European Geotravese Project 1992).

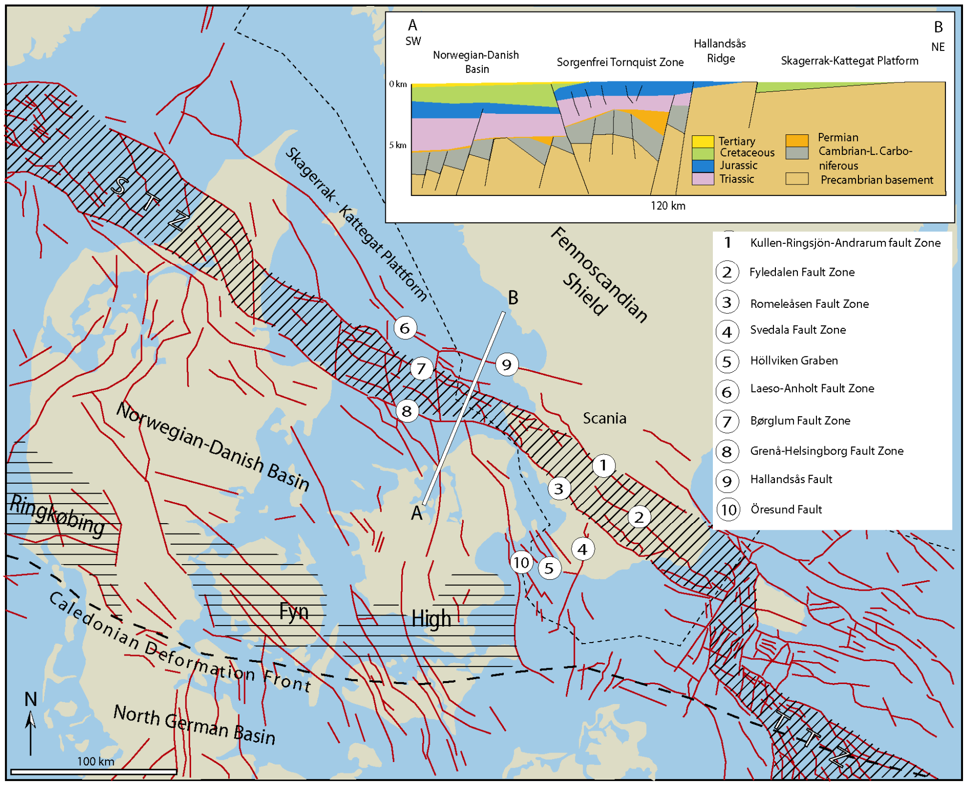

Fig. 1. Map showing main structural elements at the top pre-Zechstein surface of south-western Scandinavia with inset profile A–B.

However, new data are being repeatedly added to the geological model (e.g. Fig. 2). Most verifies much of what has already been presented in existing models. But there are also data that fall outside the traditional model thus creating a need to modify that model. In particular, recent publications by Marek (2000), Vejbaek & Andersen (2002), Mogensen & Korstgård (2003), Babuska & Plomerova (2004), Ziegler (2005), Nielsen et al. (2005) and Japsen et al. (2002, 2007) have contributed with data and interpretations that explicitly describe, as do many other key papers (e.g. Sorgenfrei & Buch 1964, Baartman & Christensen 1975, Bergström et al. 1982, Pegrum 1984, Liboriussen et al. 1987, Michelsen & Nielsen 1991, Berthelsen 1992, Michelsen & Nielsen 1993, Thomas et al. 1993, Thybo et al. 1994, Mogensen 1994, Zielshuis & Nolet 1994, Mogensen & Jensen 1994, Christensen & Korsgård 1994, Vejbaek et al. 1994, Mogensen 1995, Vejbaek 1997, Erlström et al. 1997, 2004, Berthelsen 1998, Lie & Andersson 1998) the complexity involved in interpreting the tectonic evolution of the area. This must be carefully considered when transferring regional stress fields and effects into the Scanian mosaic of faulted bedrock units.

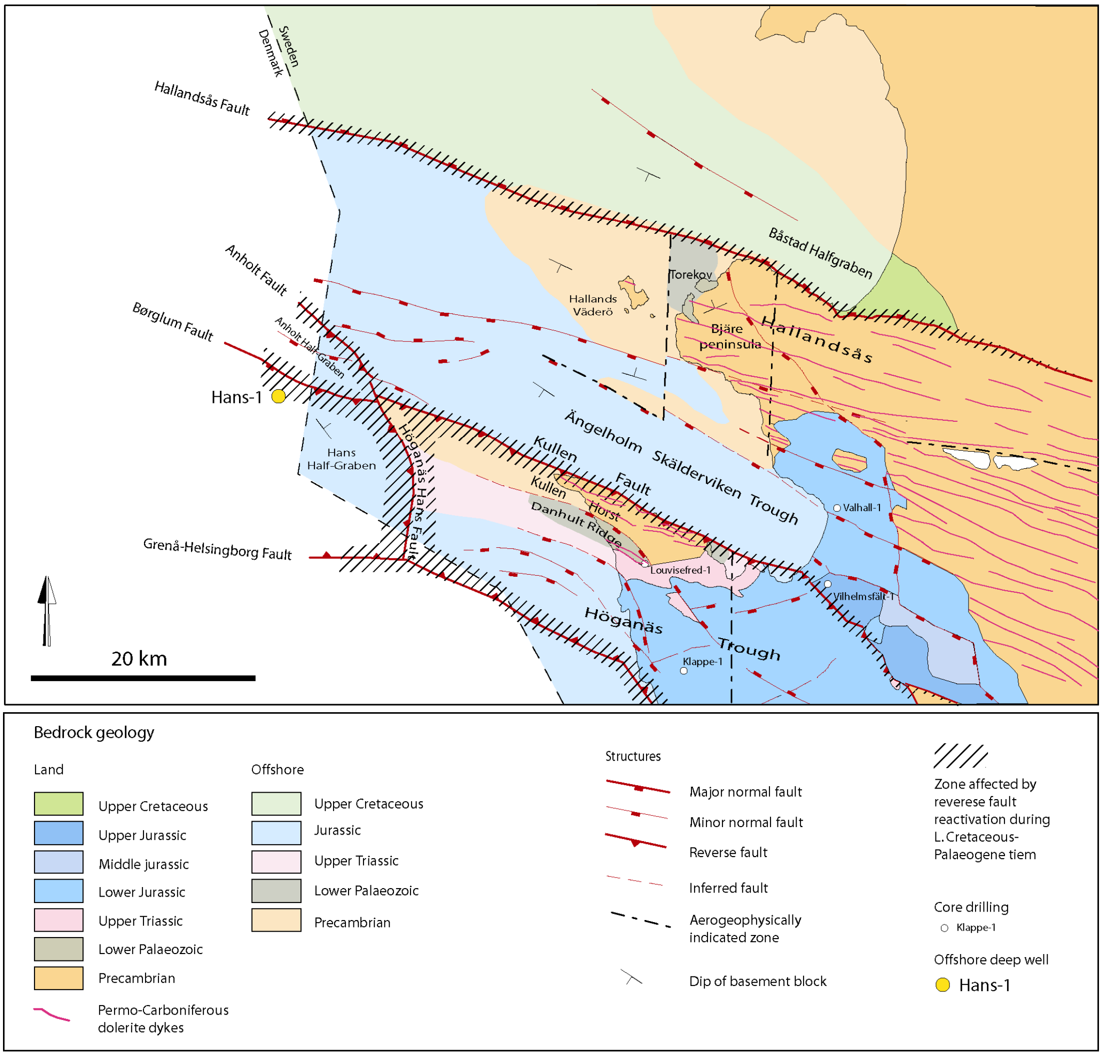

Fig. 2. Main structural elements in the Hallandsås-Kullen-Southern Kattegat area.

2.2 *Tectonic evolution*

Phanerozoic break-up of the south-western margin of the Fennoscandian Shield, including Scania, has created a complex crustal transition zone between the stable shield and the tectonically active Phanerozoic continental Europe (Liboriussen et al. 1987, EUGENO working group 1988). Scania is thus sutured by structural elements reflecting several periods of tectonic activity (see map and definitions in Appendix 1). The dominant fault trend is NW–SE, extending from the North Sea, through Scania into Poland. However, NNE–SSW, and N–S fault orientations are also common. The fault geometry has resulted in a heterogeneous block-faulted terrane with great variation in characteristics of individual blocks.

The Phanerozoic tectonic history includes phases of compression as well as extension (rifting). Most of these movements were associated with the evolution of the Tornquist Zone, which constitutes the most important structure that crosses the south-western part of the Fennoscandian Shield. Wrench faulting and strike-slip movement have been characteristic features along the main faults incorporated in the Tornquist Zone (Mogensen 1994, Berthelsen 1992) yielding a complex block geometry due to the existence of restraining and releasing bends and N–S oriented extension faults.

The main tectonic phases during the Phanerozoic are generally well established in the models (cf. Figs 3–5), since they can be verified in the characteristics of the preserved bedrock. However, there are gaps in the database for certain time intervals because pre-existing strata have been more or less completely removed by erosion during later tectonic events. This is particularly the case for the Devonian, Early Carboniferous and parts of the Permian and the Neogene periods.

The Phanerozoic tectonic evolution can be divided into the following main stages:

- Cambrian–Carboniferous evolution including Caledonian deformation
- Late Carboniferous–Early Permian rifting - Variscan orogeny
- Late Permian–Early Jurassic subsidence, rifting and block faulting
- Jurassic block faulting–volcanism - Kimmerian orogeny
- Late Cretaceous–Paleogene inversion - Alpine orogeny
- Neogene uplift and faulting

2.2.1 Cambrian–Carboniferous evolution including Caledonian deformation

The geological history described here begins when Baltica evolved as an independent plate, as it broke loose from Gondwana in the Early Ordovician. Baltica drifted towards Laurentia and a third terrane, i.e. East Avalonia joined in the Caledonian collision forming Laurasia (Fig. 4). The final stages of the Caledonian collision and closure of the Iapetus Ocean and Tornquist Sea occurred approximately 440–400 Ma ago. The oblique junction between the plates yielded a stress field resulting in predominantly dextral strike-slip displacements (Meissner et al. 1994).

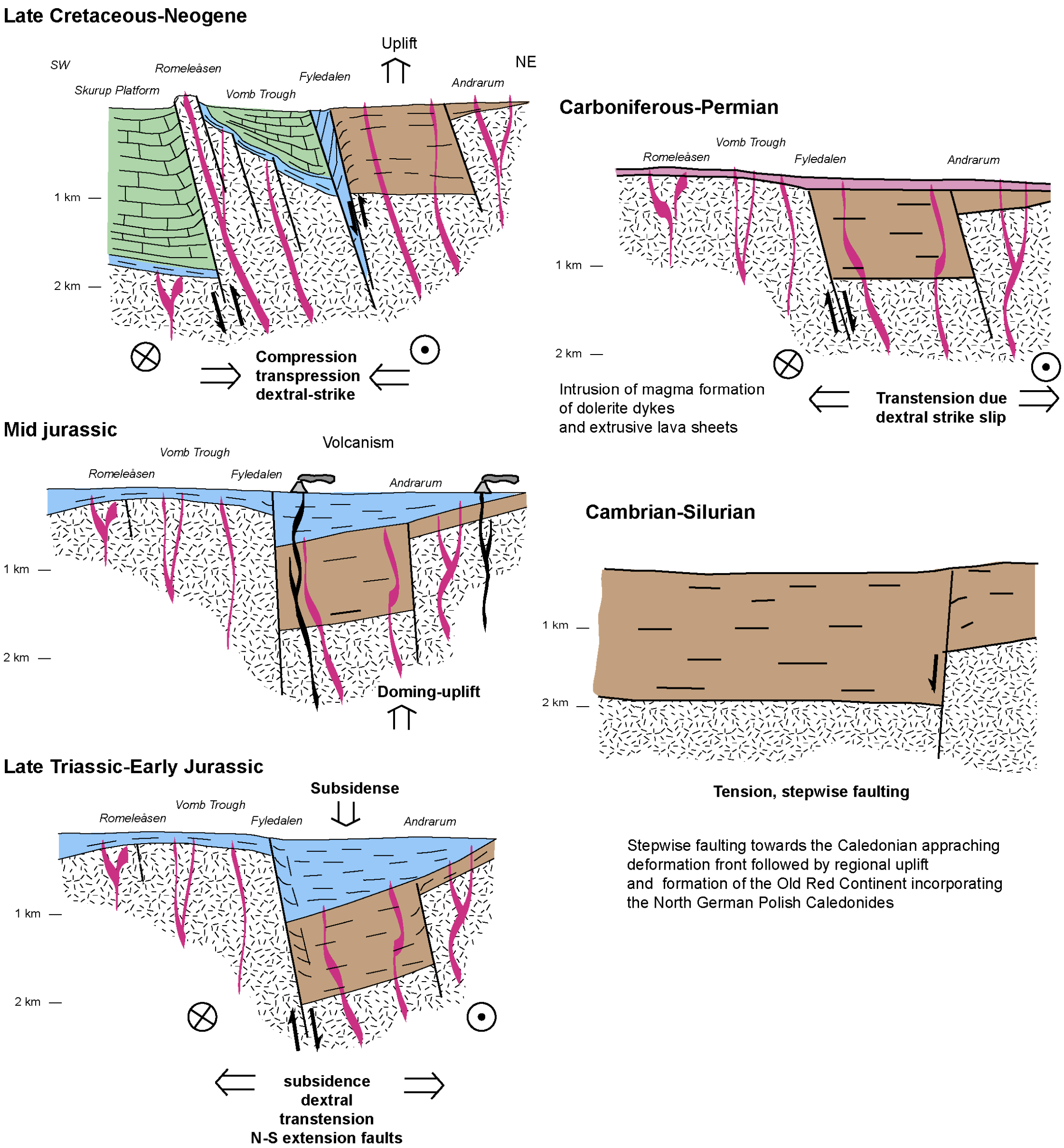

Fig. 3. Schematic reconstruction of the structural evolution of the Sorgenfrei-Tornquist Zone in south-eastern part of Scania (from Erlström et al. 2004).

The central part of Baltica acted as a rigid craton and was more or less unaffected by these movements. Between the Trans European Fault Zone (cf. Appendix 1) in northern Germany and the Skagerrak-Kattegat Platform, the crust has acted as a buffer zone between the Precambrian Shield to the north east and younger geological provinces to the south and south west (Berthelsen 1992). The mechanisms of the main Early – Middle Palaeozoic faulting in the area are related to intra-plate reactions due to movements involved in the plate junction of Laurentia, Baltica and Avalonia, i.e. the Caledonian orogeny and the subsequent agglomeration of Laurasia. Southern Scandinavia was gradually transformed into a foreland basin to the Caledonian orogenic belt and underwent rapid subsidence. Early Palaeozoic stepwise faulting towards the south is indicated in Scania along the main faults that were to be involved in the subsequent formation of the Sorgenfrei-Tornquist Zone (Erlström &

Guy-Ohlson 1999, Erlström & Sivhed 2001). Early Palaeozoic movements occurred particularly along the Kullen–Ringsjön–Andrarum Fault Zone.

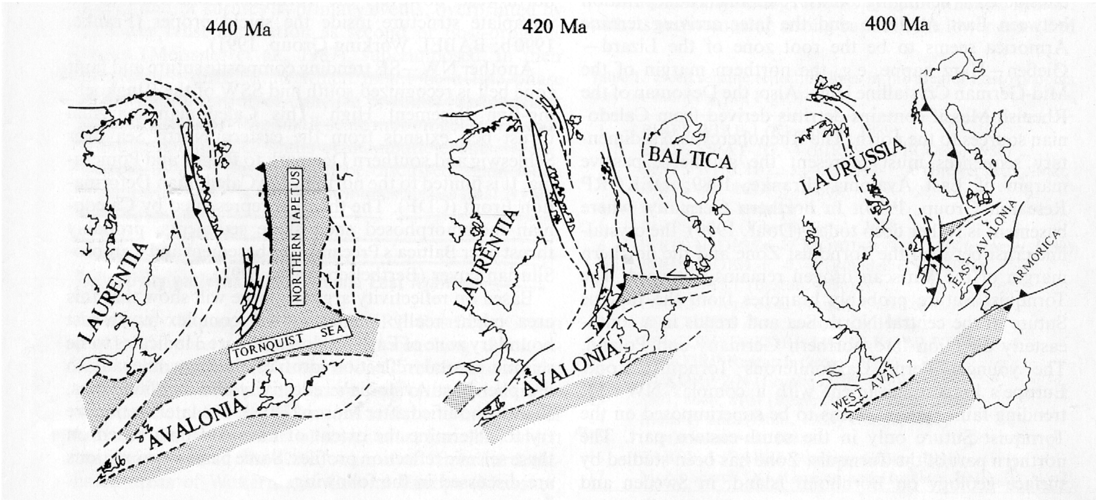

Fig. 4. Final closure of the Iapetus Ocean and the junction of Laurentia, Avalonia and Baltica during the Caledonian orogeny. (from Meissner et al. 1993).

Volcanic events in southern Scandinavia during Silurian times have been inferred from extrusive rocks in Silurian strata by e.g. the EUGENO-s working group (1988) and by Michelsen & Nielsen (1993).

The North Polish Caledonides and the associated Caledonian Deformation Front, (cf. Appendix 1) involving metamorphosed and thrusted strata was evolving south of Scania. Uplift brought an end to the sedimentation on the Fennoscandian Shield and much of the Danish-Scanian area was incorporated in the so-called Old Red Continent. This resulted in a period of erosion, which is seen as a Devonian to Early Carboniferous regional hiatus in the area (Michelsen & Nielsen 1993, Erlström et al. 1997) and little is thus known about the tectonic situation during the interval.

The Late Carboniferous–Early Permian succession includes Carboniferous volcanoclastic rocks conformably overlying a thick sequence of Lower Palaeozoic fine-grained strata, mainly shales. Deposition of these units took place in a subsiding foreland basin in front of the Caledonian orogenic belt. All the pre-rift strata are parallel and conformable, indicating a uniform regional subsidence.

However, the Cambrian–Early Permian sequence experienced deep erosion during later tectonic events, particularly in connection with peneplanation and formation of the base Zechstein unconformity. This has resulted in a patchy and generally incomplete representation of strata in down-faulted half grabens in south-western Baltica.

The Upper Carboniferous volcanoclastics are roughly contemporaneous with the volcanic activity in the Oslo Graben (Michelsen & Nielsen 1993) and with the extensive occurrence of northwest–southeast striking dolerite dykes in Scania. These deposits were formed 250–290 Ma ago as precursors to the Early Permian rifting and the development of the Sorgenfrei-Tornquist Zone.

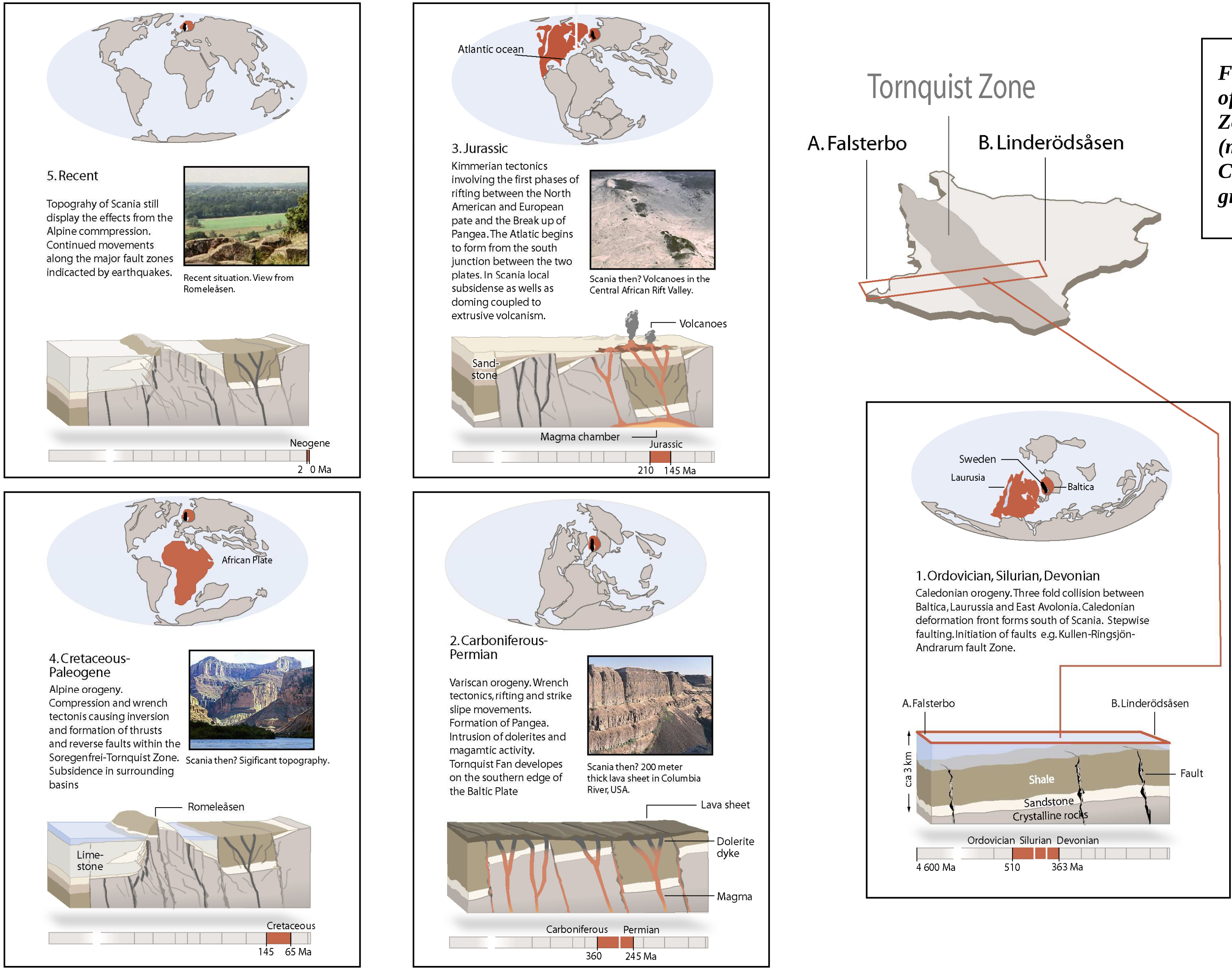

Fig. 5. Schematic evolution of the Romeleåsen Fault Zone in Central Scania. (modified illustration from Christoffer Rhen Sydsvenska grafikerna).

2.2.2 *Late Carboniferous–Early Permian rifting–Variscan orogeny*

Late Palaeozoic stress fields in northern Europe were related to the oblique collision between Gondwana and Laurasia, resulting in the assemblage of the supercontinent Pangea, i.e. the Variscan orogeny. The Sorgenfrei-Tornquist Zone is interpreted as originating from Variscan (Carboniferous–Permian) shear stresses due to the dextral translation between Europe and Africa (Vejbaek 1985, Ziegler 1990). The zone was part of a splay of faults and fault zones known as the “Tornquist Fan” (cf. Appendix 1), which developed during the Late Carboniferous to Early Permian (250–300 Ma) over the Danish Scanian and western Baltic area (Berthelsen 1992).

During the Permian–Triassic, Europe was bounded by the active rift zones of the Arctic-North Atlantic and the Tethys, which led to unstable tensional regimes in north-western Europe. The Early Permian included extension in the Oslo Graben and oblique dextral shear stresses in the Sorgenfrei-Tornquist Zone (Figs 6 & 11). This led to zones of uplift and subsidence accompanied by restraining and releasing bends along the Sorgenfrei-Tornquist Zone in the Kattegat (Mogensen 1994, 1995, Erlström & Sivhed 2001).

The Lower Palaeozoic sequence was locally down-faulted and more or less protected against denudation in half-grabens. This pattern can be followed eastwards into Scania. Here the Colonus Shale Trough displays the same pattern (Mogensen 1994, Erlström & Sivhed 2001). Local depocentres formed along releasing fault bends and north–south oriented extension faults. These received large amounts of clastics derived from extensive erosion of the footwall blocks; thus, large amounts of Lower Palaeozoic strata were removed to the north east. Much of the material was deposited as alluvial fans which filled the basins when the subsidence ended in the Mid Permian.

Similar release caused by transtension along the Öresund and Svedala Faults resulted in the down-throw of Lower Palaeozoic strata in the Höllviken Graben. In the southern Kattegat area, two extensional subsiding half-grabens developed along the Anholt and Børglum faults (Erlström & Sivhed 2001). Lower Permian Rotliegendes deposits are preserved in the subsiding half-graben adjacent to the Børglum Fault, which has an extensional component in its easterly part where it bends to the south joining up with the Grenå-Helsingborg Fault. The estimated lateral displacement along the fault is 4 km. Similar faults to the west give a total right-lateral displacement for the Kattegat part of the Sorgenfrei-Tornquist Zone in the order of 20 km (Mogensen 1994). The main dextral strike-slip movements occurred along the Børglum and Grenå-Helsingborg faults.

2.2.3 *Late Permian–Early Jurassic subsidence, rifting and block faulting*

The Late Permian–Early Jurassic was a period characterised by regional subsidence, rifting and block faulting. During the Mid to Late Permian the Sorgenfrei-Tornquist Zone and the Skagerrak-Kattegat Platform began to act as a marginal zone to the subsiding Norwegian–Danish Basin that was evolving to the south west.

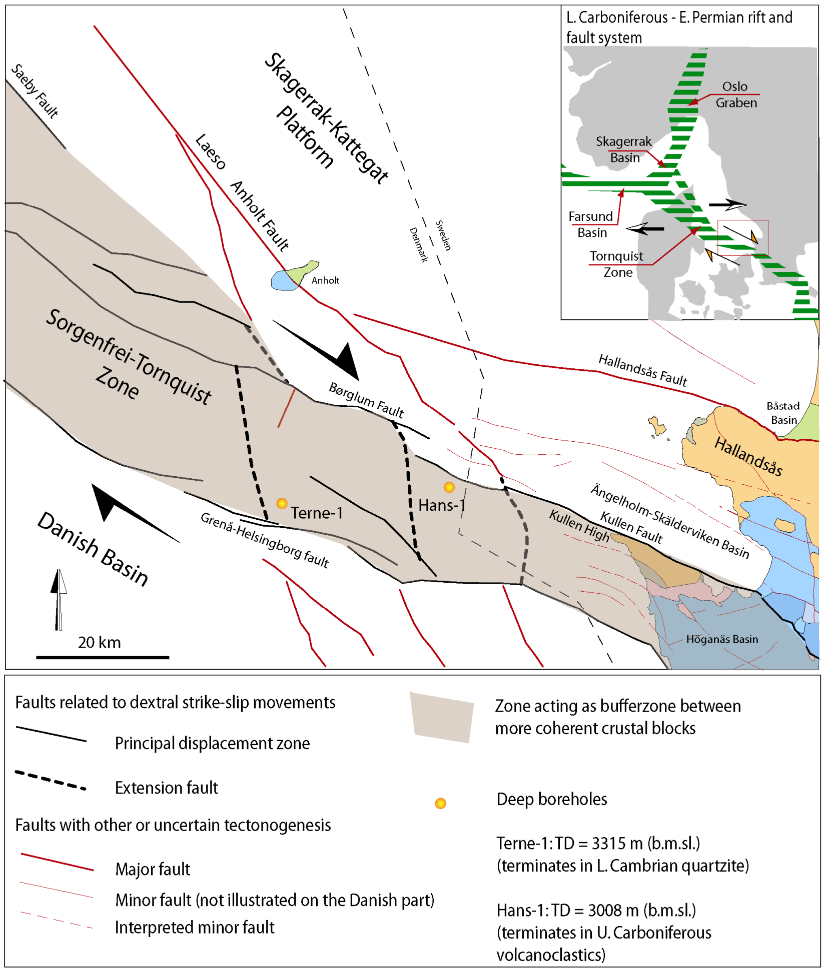

Fig. 6. L. Carboniferous and Early Permian rifting and formation of N-S trending extension faults. (from Erlström & Sivhed 2001).

The Triassic tectonic realm in north Germany, Denmark and the Tornquist Zone was characterised by rifting in N–S striking zones. Three major rift zones Horn Graben, Glückstadt and Brunswick Gifhorn, formed in the North German Basin (Frisch & Kockel 1998). In Scania E–W tension resulted in NE–SW extensional faults, e.g. the Svedala Fault and Öresund Fault (Erlström et al. 1997, Sivhed et al. 1999).

Much of the Late Triassic deposition in Scania took place in releasing bends (pull-apart basins) in the Sorgenfrei-Tornquist Zone (Mogensen 1995), and the phase of dextral transtensional stresses continued intermittently into the Jurassic (Mogensen 1995). The Jurassic stress field was associated with the break-up of Pangea and led to dextral strike-slip fault reactivation, resulting in differential subsidence in the Late Jurassic, often referred as the Kimmerian tectonic phase (Norling et al. 1993). This Kimmerian rifting phase resulted in the formation of transtensional faults as well as reactivation of Permian fault systems in e.g. the Sorgenfrei-Tornquist Zone (Vejbæk 1990, Mogensen 1994, Michelsen 1997).

2.2.4 Jurassic block faulting – volcanism - Kimmerian orogeny

The Mid-Jurassic featured localised tectonic uplift coupled with magmatic intrusions, which led to intensive volcanism in central Scania and removal of pre-existing strata.

The stepwise decrease in the thickness of the Lower Jurassic sequence east of the Anholt and Kullen faults is an indication of Early to Mid-Jurassic tectonic activity (mid-Kimmerian tectonics), coupled with tectonic uplift and erosion of the area north of the fault (Norling & Bergström 1987, Ziegler 1988, 1990, Mogensen 1995). There are also indications that the volcanic activity was mainly located in junctions between NE–SW and NW–SE directed fault systems (Wikman & Bergström 1987, Erlström et al. 1999).

2.2.5 Late Cretaceous-Paleogene inversion–Alpine-Laramide orogeny

The differential subsidence continued into the Early Cretaceous, with restricted fault activity (Mogensen 1995).

In the Late Cretaceous, the fault-controlled subsidence within the Sorgenfrei-Tornquist Zone came to an end and the Jurassic–Lower Cretaceous depocentre became inverted during the Late Cretaceous and Early Paleogene. This resulted from a change in the regional stress orientations to a predominantly compressive regime, associated with Alpine deformation in northern Europe and the opening of the North Atlantic. This deformation is often referred to as the sub-Hercynian phase, which was most pronounced during the Santonian–Campanian (Ziegler 1990). Although tectonic activity in the Alpine foreland decreased during the Maastrichtian, fault activity is indicated in south-western Scania at this time. Here, coarse clastics were deposited during upper middle Maastrichtian times, adjacent to the Romeleåsen and Svedala faults indicating a reactivation of these faults during Late Cretaceous times (Erlström 1990, Sivhed et al. 1999).

The inversion regained its force in northern Europe during the late Paleocene–Eocene (50–55 Ma), particularly in the southeastern part of the Tornquist Zone, i.e. the Polish Trough. Vejbaek & Andersen (2002) have identified a later inversion sub-phase during the early Oligocene (33 Ma). These events are referred to as effects from the Laramide and Pyrenean tectonic phases (Norling & Bergström 1987, Ziegler 1990, Vejbaek & Andersen 2002).

Compression and crustal shortening were accommodated by reactivation of the main faults incorporated in the Sorgenfrei-Tornquist Zone (Fig. 7). The inversion was caused by right lateral transpression along this zone. The compression from the south resulted in a dextral strike-slip motion along the main faults in the Kattegat area. This resulted in an oblique reverse activation of the Børglum Fault. The absence of major inversion features along the Anholt Fault implies that compression was accommodated along the fault by dextral strike-slip displacement (Kape 1997).

The inverted uplifted area was bordered to the north and south by subsiding basins where sedimentation continued through the Late Cretaceous–Early Paleogene. Contemporaneously with the inversion, thick Santonian–Campanian clastic deposits were formed on the southern side of the uplifted zone, i.e. the south-eastward continuation of the Grenå-Helsingborg Fault (Erlström 1990, Sivhed et al. 1999).

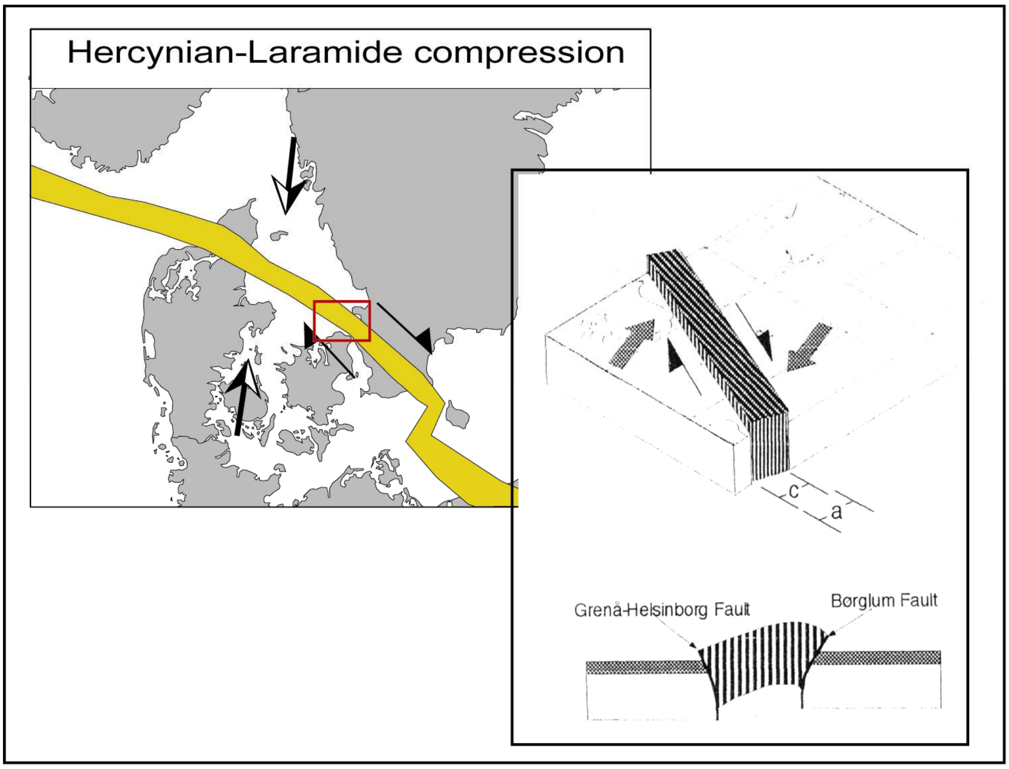

Fig. 7. Schematic illustration of the Hercynian-Laramide transpression and inversion of the Sorgenfrei-Tornquist Zone.

Compression and uplift were more intense in the Scania-Bornholm area, where more than 2–3 km of uplift occurred, resulting in deep erosion of uplifted strata within the Sorgenfrei-Tornquist Zone (Berthelsen 1992). A general view (cf. Ziegler 1992, Mogensen & Jensen 1994) is that the inversion began in the Turonian in the south east and prograded to the north west, with a corresponding decrease in the intensity of deformation in the same direction (Mogensen & Jensen 1994, Michelsen 1997).

2.2.6 *Neogene uplift and faulting*

A major regional unconformity separates the Quaternary sequence from the Mesozoic succession and also from the Precambrian crystalline basement within the Skagerrak-Kattegat Platform, the Sorgenfrei-Tornquist Zone (Jensen & Michelsen 1992, Michelsen 1997, Japsen 1997, Japsen & Bidstrup 1999) and the Norwegian-Danish Basin. This unconformity is a result of the extensive Neogene uplift and erosion that has affected the continental margins around the North Atlantic. Based on basin modelling and well data, Japsen & Bidstrup (1999) estimated that the missing sequence was 1.0–1.2 km thick in the Skagerrak-Kattegat area. Japsen et al. (2007) identified three main phases of uplift, i.e. 33 Ma, 24 Ma and 4 Ma, which causal mechanism is interpreted to lie in the deep crust where the thickness of the crust and lithosphere change substantially over a short distance. This is particularly the case along the north-eastern margins of the Norwegian-Danish Basin bordering the crystalline Fennoscandian terrane.

The reactivation of faults and folding of the Scanian bedrock during the post-Eocene period are verified in SW Scania. Here the preservations of Eocene strata against the N–S striking Svedala and NNW–SSE striking Vellinge Fault indicate post-Eocene fault activity (Sivhed et al. 1999). Vejbaek & Andersen (2002) consider that folding of strata in the Öresund area indicates post-Danian inversion and compression. Miocene faulting has also been verified in Denmark (Rasmussen 2004). The latest movements along the faults, which cut through the Paleogene strata are probably related to the Neogene uplift phases.

2.2.7 Opening of the North Atlantic and Neogene evolution

During the early Eocene, c. 55 Ma, the onset of sea-floor spreading started in the Arctic-North Atlantic region. Push forces and wrench faulting in the prolongation of the Iceland ridge and the Charlie Gibbs fracture zone are thought to extend far beyond into the southwestern part of the agglomerated northwest Europe continental terrane. At the same time crustal shortening in the central Alps continued which still induced forces on the Alpine foreland (Ziegler 2005), particularly in the central North Sea. The stress pattern evolving during Neogene time is a combination of N–S directed forces from the south (collision between the African and European plates) and the NW–SE stresses from the opening of the North Atlantic. In North Germany the stress field clearly shows that the interactions between these regimens yield a bimodal data set (Roth & Fleckenstein 2001), where both N–S and NW–SE directions are present. Roth & Fleckenstein (2001) suggest that the predominance of N–S stresses in parts of North Germany is the result of stress release of the NW–SE component by strike-slip motion along major regional fault zones such as the Trans European Fault Zone. Hence, stress release along similar NW–SE directed strike slip regimes, such as the Tornquist Zone, in the Alpine Foreland is probably a cause of local similar variations in the stress field orientations.

2.2.8 Recent fault movements

GPS measurements have provided valuable new information on the present crustal movements in Scania (Pan et al. 2001). These reveal significant movements, which add information on the heterogeneous structure of Scania where the direction and magnitude of the lateral displacement of individual rock blocks varies greatly (Fig. 8). As an example the GPS station at Stavershult, on the Hallandsås, moves in a NNE direction in comparison to the reference station at Onsala located on the Fennoscandian shield.

Several earthquake epicentres in the southern Kattegat area seem to correlate with the main faults in the Sorgenfrei-Tornquist Zone, including the N–S extension faults (Fig. 9, Erlström & Sivhed 2001). It is not yet possible to verify the exact depth of the earthquakes. However, there appears to be good reason to believe they are associated with recent fault activity (Reynir Böðvarsson, Uppsala University, dep. of Geophysics, pers. comm.).
Submarine bubbling reefs (Jensen et al. 1992) located along the main faults delimiting the Sorgenfrei-Tornquist Zone also indicate recent movements along the major fault zones in the Kattegat area.

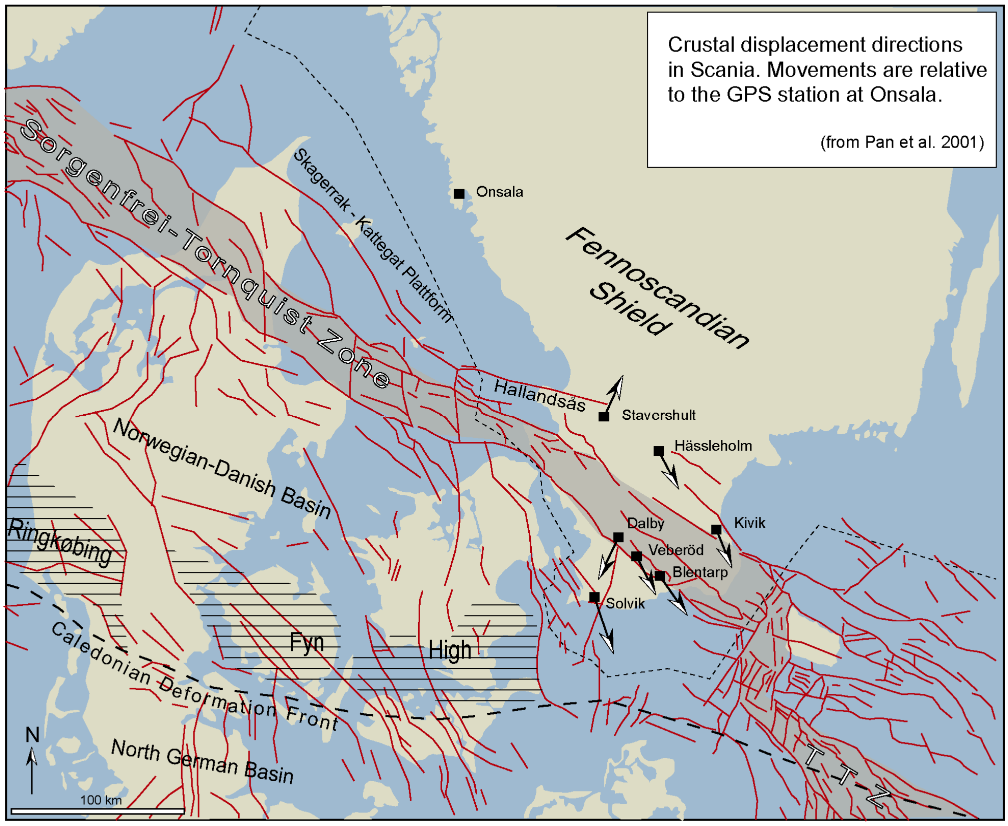

Fig. 8. Crustal displacement directions in Scania (from Pan et al. 2001).

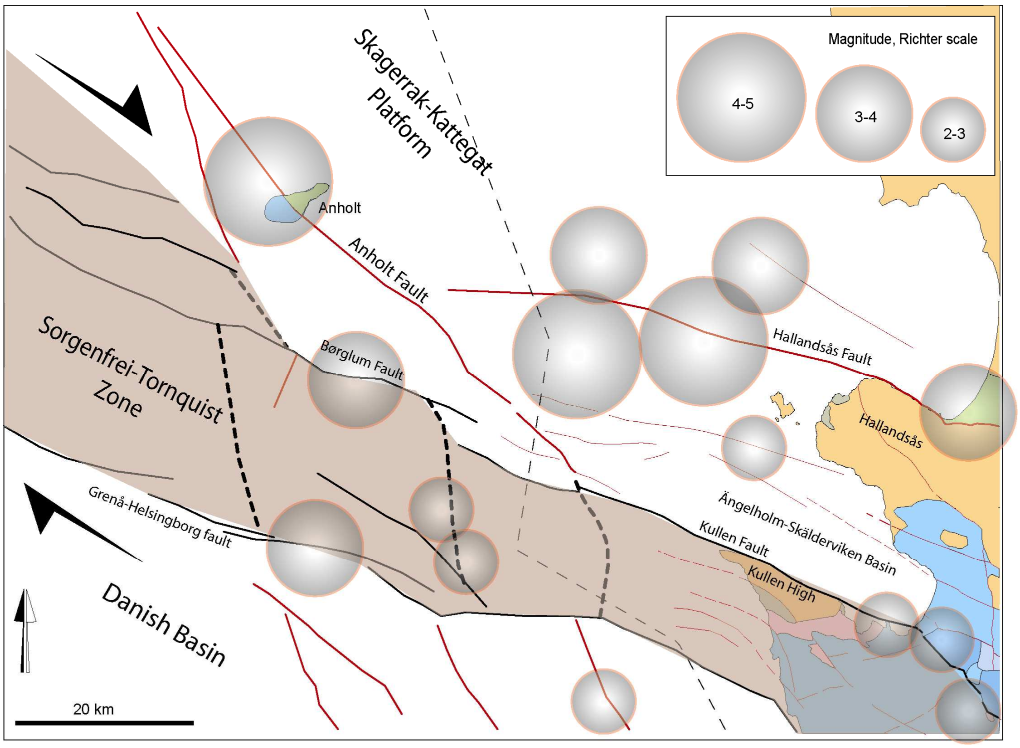

Fig. 9. Earthquake epicentres in the Southern Kattegat area, based on earthquake statistics between 1900 and 1996.

2.2.9 Glacial isostatic rebound

Post-glacial rebound (sometimes called continental rebound, isostatic rebound, isostatic adjustment or post-ice-age isostatic recovery) is the rise of land masses that were depressed by the huge weight of ice sheets during the last glacial period, through a process known as isostatic depression. Today much of Southern Sweden including Scania and the Hallandsås display very small or negative amounts of rebound (Fig. 10).

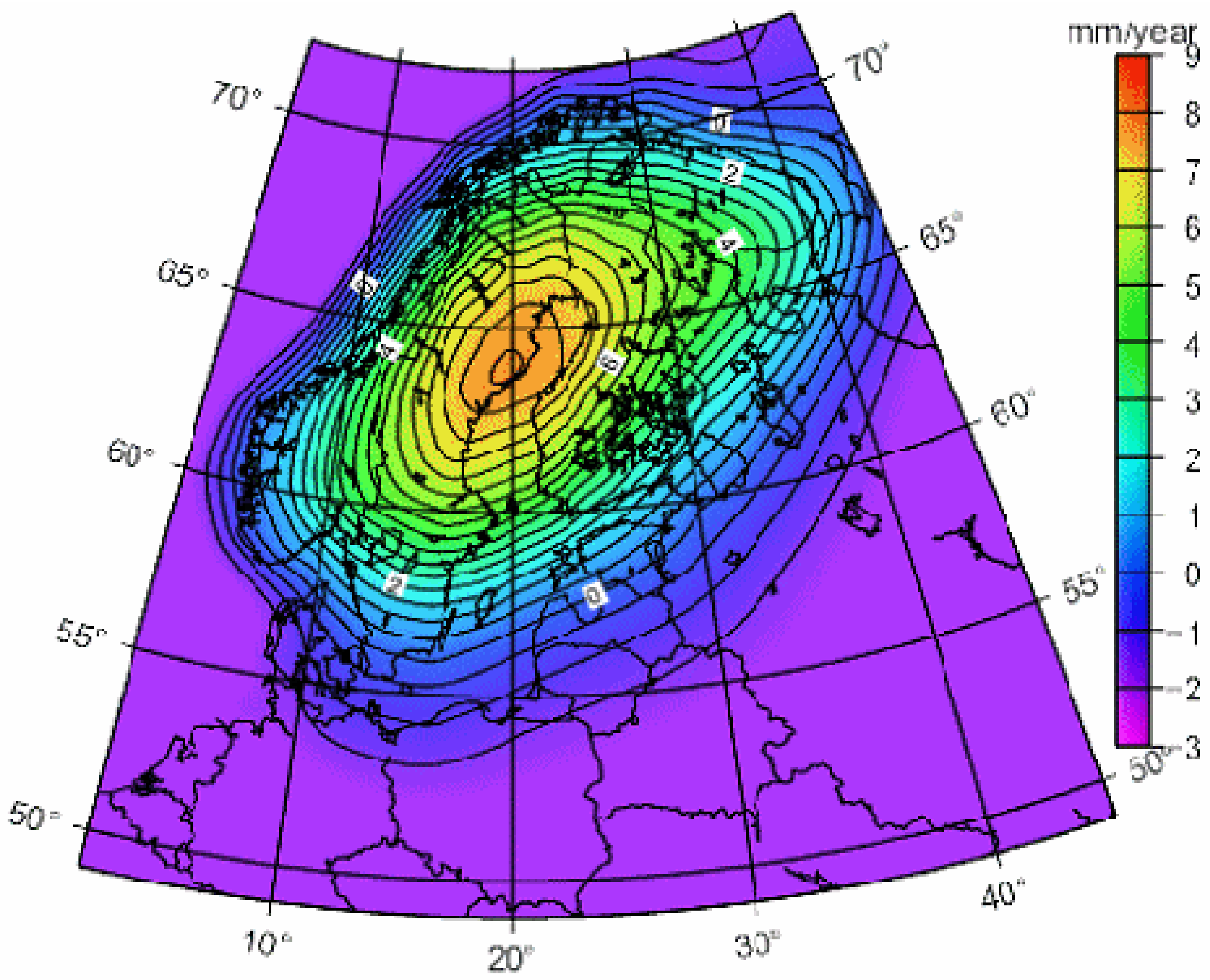

Fig. 10. Present glacial rebound in Northern Europe (data from Nation Land Survey of Sweden).

2.3 *Compilation of main tectonic events*

Table 1 below presents a comprehensive summary of main tectonic events and their effects on the Scanian bedrock.

Table 1. Compilation of main tectonic events and their characteristics.

Chronological period	**Event characteristics**	**Effects in Scania**
Late Cambrian 495–505 Ma	Tension due to increasing sediment load on the southern margin of the Fennoscandian Shield.	Normal faults initiated, e.g. Kullen- Ringsjön-Andrarum Fault Zone.
Ordovician–Silurian 495–420 Ma	Increasing subsidence and tension in front of the approaching Caledonian Deformation Front. Volcanic extrusions. Caledonian deformation. Compression, thrusting south of Scania.	Normal faulting, subsidence tension. Uplift.
Late Silurian–Early Carboniferous 420–325 Ma	North German Polish Caledonides. Erosion.	Effects uncertain.
Late Carboniferous–Early Permian 325–280 Ma	The Permo–Carboniferous Variscan tectonics resulted in wrench faulting and the Palaeozoic sequence was down faulted as tilted block units. Principal rifting, continental scale dextral shear, uplift, magmatic intrusion, multidirectional array of transtensional pull-apart basins, mantel plumes. Variscan orogen.	Tension, intrusion of dolerite dykes, formation of the Tornquist Zone, N–S extension due to strike slip movements.
Middle Permian–Late Permian 280–250 Ma	Thermal subsidence. Unconformity.	Erosion, peneplanation.

Table 1 (cont.). **Compilation of main tectonic events and their characteristics.**

Chronological period	**Event characteristics**	**Effects in Scania**
Triassic 250–205 Ma	Localised subsidence and rifting, particularly along N–S oriented faults. Dextral transtensional stresses. The stress field was associated with the break-up of Pangea and led to dextral strike-slip fault reactivation.	Much of the Late Triassic deposition in Scania took place in releasing bends (pull-apart basins) in the Sorgenfrei-Tornquist Zone. During the Triassic much of pre-existing Palaeozoic strata were eroded on the Skurup Platform and Linderödsåsen Ridge. Reactivation of N–S oriented faults such as the Svedala Fault Zone.
Jurassic 205–150 Ma	Differential subsidence, often referred as the Kimmerian tectonic phase (Norling et al. 1993). Regional Middle Jurassic doming began c. 190 Ma and continued into the Early Cretaceous c. 125 Ma. Volcanism in the Middle Jurassic.	During Lower Jurassic fairly uniform conditions prevailed in Scania. The Middle Jurassic involved a doming and uplift of central Scania coupled with intense volcanism. Basaltic, volcanic activity was concentrated to the central parts of Scania.
Late Cretaceous 100–65 Ma	Alpine deformation with the Hercynian inversion phase. N–S compression and dextral relaxation in the Tornquist Zone, reactivation of faults and inversion.	Formation of thrust and reverse faults zones overprinting previous normal faults. Releasing as well as restraining bends causing formation of positive “push up” and negative flower structures. Subsidence of adjacent sedimentary Basins, e.g. SW Scania, Hanö Bay Basin.

Table 1 (cont.). **Compilation of main tectonic events and their characteristics.**

Chronological period	**Event characteristics**	**Effects in Scania**
Paleogene–Neogene 65 Ma–present *Eocene c. 55 Ma*	Laramide and Pyrenean inversion phases in the Alpine foreland (c. 55 and 33 Ma). The opening of the North Atlantic started in the Early Eocene. Spreading along the Mid-Atlantic ridge induced an overall change in the stress pattern from NE–SW to NW–SE. Differential spreading along the ridge caused formation of transform and wrench faults, which affected the stress patterns over large parts of the northwest European crust.	Continued inversion of Sorgenfrei-Tornquist Zone. Movements along the faults belonging to the Tornquist Fan. Less than 50 Ma ago movements occurred in the Svedala Fault. The movements have normal extension character, which is remarkable, since the North Atlantic opened up at the same time and the general stress situation changed to NW–SE. A probable explanation is the complex tectonic construction of the Tornquist Fan and where strike-slip movements gave rise to normal extension faults between different lateral fault zones with differing amounts of movements.
Miocene–Oligocene *33–4 Ma* *Pliocene-Quaternary* *4 Ma–recent*	Regional uplift of the Danish Basin and the south-western part of Scandinavia. Reactivation of Permo-Carboniferous shear systems in Germany. Stress patterns deviating from the general Neogene NW–SE trend and strike-slip movements are evident in North Germany. Sinistral shear in the Rhine Graben (Pliocene c 4 Ma). These effects are thought to been caused by a combination of tectonic push from African Plate and spreading along the Mid-Atlantic ridge.	Two main phases of uplift, erosion and minor fault reactivation during Oligocene–Miocene c.33–24 Ma, and 4 Ma (Japsen et al. 2007). Formation of the South Småland peneplane (Japsen et al. 2007). Differential crustal movements in Scania (Pan et al. 2001). Fault activation in Kattegat (Jensen et al. 1992, Lykke-Andersen 1987). Recent earthquake activity in the southern Kattegat along Læsø-Anholt-Børglum and the Hallandsås faults. Strike-slip movements.

3 TECTONIC SIGNATURE

The many phases of deformation acting on the Scanian bedrock have generated a wide range of structures, which reflect the tectonic history described above.

Many of the older phases of deformation are hidden or obliterated by the Hercynian–Laramide dextral transpression due to N–S compression in the Alpine foreland. These phases involved inversion tectonics and rearrangement of the Tornquist Zone. Basins and grabens, developed during the Permian–Triassic rifting, were elevated and subjected to intense erosion. At the same time subsidence and formation of new basins took place on both sides of the Tornquist Zone, e.g. SW Scania, Hanö Bay Basin and the Båstad-Southern Kattegat area.

Even though the Alpine deformation overprints much of the previous phases of deformation there are still geological evidences that explicitly verify the older deformation phases. A common feature in the Scanian tectonic signature is the reactivation of weakness zones such as the main faults incorporated in the Tornquist Zone. The main fault trend in Scania is NW–SE. But there is also a significant pattern of faults running more or less perpendicular to this direction, i.e. NE–SW, NNE–SSW and N–S. Many of these have been repeatedly active since their formation during Permian–Triassic times.

Thus, the zones of weakness established as early as the Palaeozoic seems to be long lived since new events of deformation and stresses in the lithosphere are often released along the pre-existing zones.

There are also indications that some of the old fault zones in the Kattegat area correlate with recent earthquakes, i.e. there are ongoing movements along these ancient zones of weakness. Thus, the recent movements follow pre-existing fault lines. The repetitive nature of tectonic movements in the established faults is typical for the whole region.

3.1 *Inversion tectonics*

During much of the Triassic–Jurassic the Tornquist Zone acted as a rift induced graben (Erlström et al. 1997, Erlström et al. 2004). The bordering faults, e.g. Kullen–Ringsjön–Andrarum and the Romeleåsen fault zones were formed as normal extension faults. Hercynian and Laramide compression and transpression resulted in reverse reactivation of the faults and uplift of the Tornquist Zone. Older rock units were thrusted upon younger ones, in Scania particularly along the Fyledalen and Romeleåsen fault zones. Often a new fault trace was cut adjacent to the south west of these pre-existing normal faults. These thrusts are evidenced e.g. at Fårarp in the Fyledalen Fault Zone (Fig. 11) and in the deep borings outside Lund in the Romeleåsen Fault Zone (Erlström 2002) (Fig. 12).

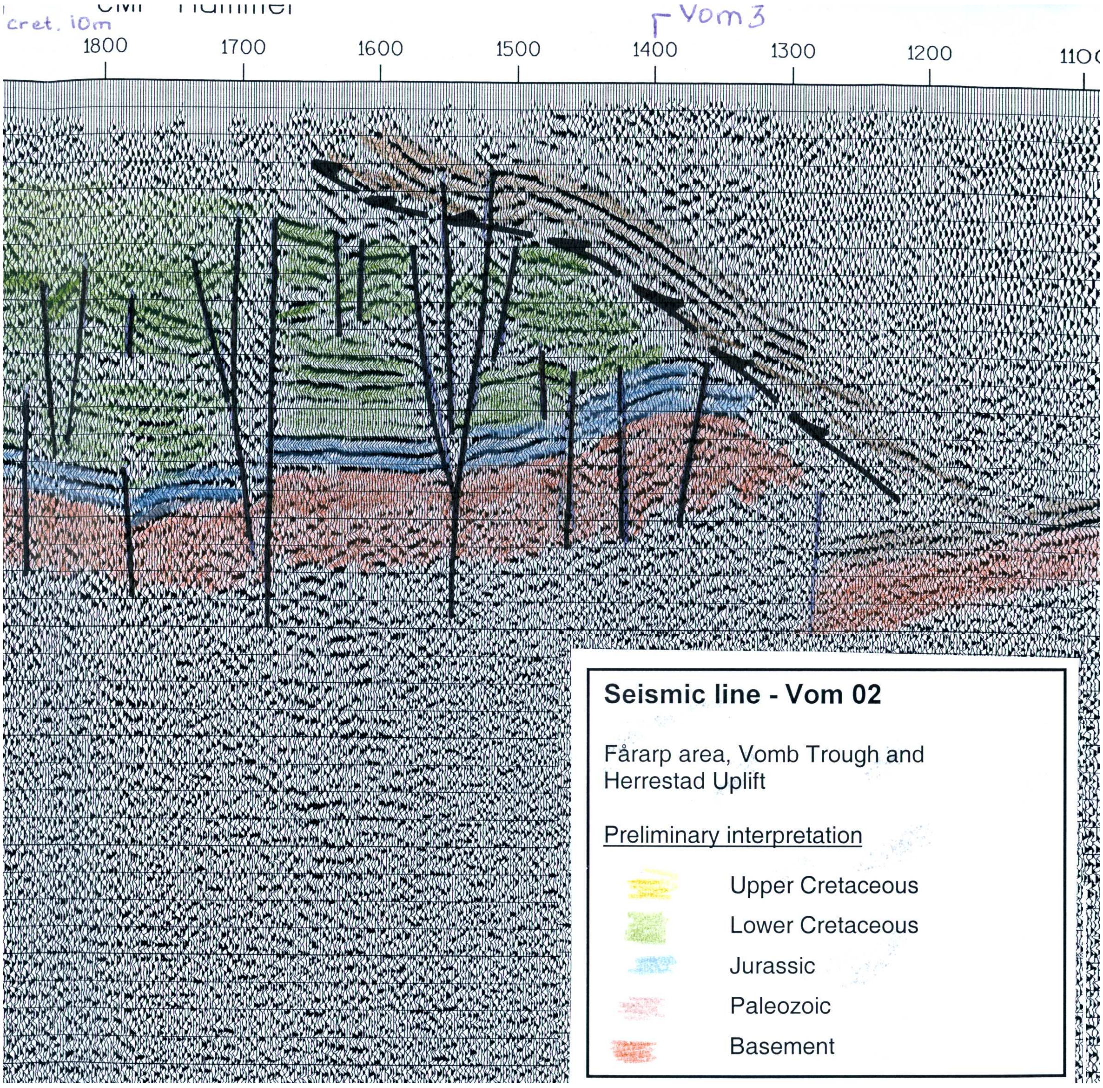

Fig. 11. Major thrusting of Palaeozoic rock units up over Mesozoic strata along the Fyledalen Fault Zone at Fårarp in south-eastern Scania. The basement (red) on the right- hand side of the seismogram lies at a depth of approximately 600 m. The seismogram displays a section approximately 2 km long

The model of thrusting and reactivation of faults is debated and it has by Thomas & Deeks (1994) and Marek (2000) been suggested that the inversion (thrusting) is associated with deep-seated listric faults that transfer compression shear and stress from the lower to upper crust. In addition Marek (2000) presents a model that includes rotation of individual blocks. He also postulates that as early as the Jurassic the Sorgenfrei-Tornquist Zone in the Kattegat area evolved as a pop-up structure during Kimmerian inversion phases.

Inversion and thrusting along the Læsø-Hallandsås Fault is additional to the Børglum, Helsingborg-Grenå, Romeleåsen, Fyledalen and Kullen–Ringsjön–Andrarum faults zones presented by Marek (2000) and Vejbaek et al. (1994).

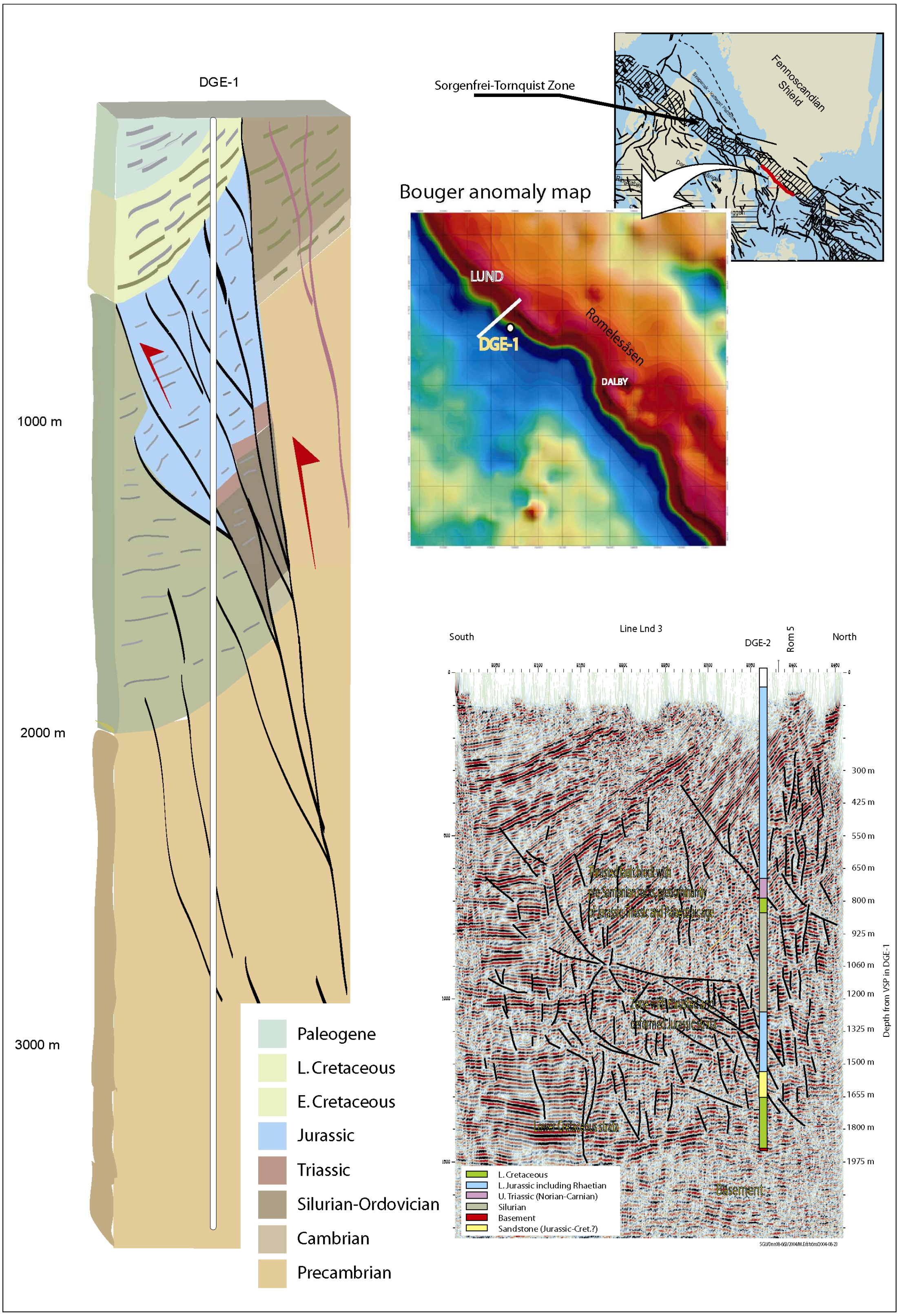

Fig. 12. Schematic illustration of the highly complex thrusting along the Romeleåsen Fault Zone, which constitutes the south-eastern border of the inverted Sorgenfrei-Tornquist Zone.

3.2 *Strike-slip regime*

There are several observations of strike-slip influences on the Scanian bedrock. Work by Blundell et al. (1992), Thomas & Deeks (1994), Thybo et al. (1997), Mogensen (1994, 1995) and Erlström & Sivhed (2001) describe how dextral strike-slip movements were a significant component in the tectonic regime during both extension and compression phases centred around the Tornquist Zone. However, sinistral movements within the zone have also been proven by Sivhed (1991) (Fig. 13).

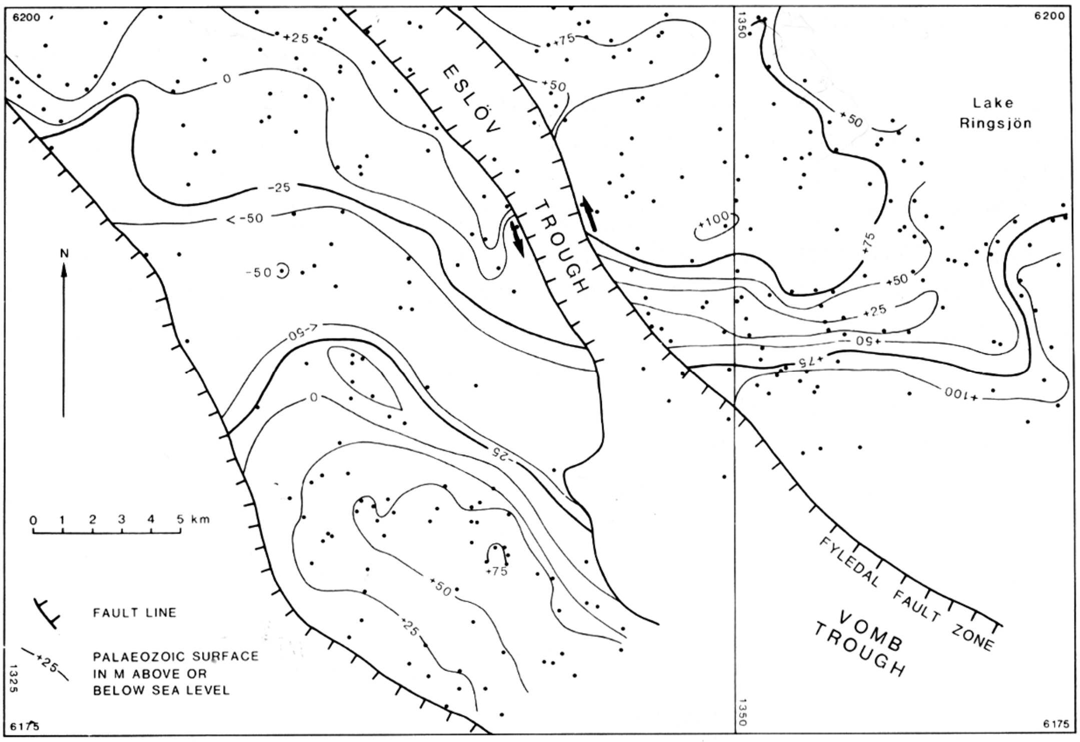

Fig. 13. A pre-Quaternary, post-Palaeozoic ravinement deformed by strike-slip faulting, Scania, southern Sweden (from Sivhed 1991).

A strike-slip regime is commonly associated with releasing or restraining conditions depending on how the fault trace bends (Fig. 14). This leads to a wide variation of stress conditions in such a setting. Push-up compression and relaxation structures are found in the Kattegat area (Fig. 15, Mogensen 1994, 1995) associated with bends in the major faults. Similar effects are found along the Romeleåsen Faults Zone at Dalby (Erlström 2002), in the Vomb Trough (Erlström et al. 2004) and in the Bornholm Gat prober (Deeks & Thomas 1995).

In addition strike-slip movements have generated a system of N–S and NNW–SSW trending extension faults, particularly during the Permian and Triassic, e.g. the Svedala Fault and faults in the southern Kattegat (Mogensen 1994, 1995, Erlström & Sivhed 2001). Geophysical data (aeromagnetic surveys) of Scania reveal the anomaly pattern where alongside the dominant NW–SE direction, NNE–SSW directions are a characteristic component. N–S trending anomalies are also seen in the data. These anomalies are probably related to extension faults formed in the strike-slip regime.

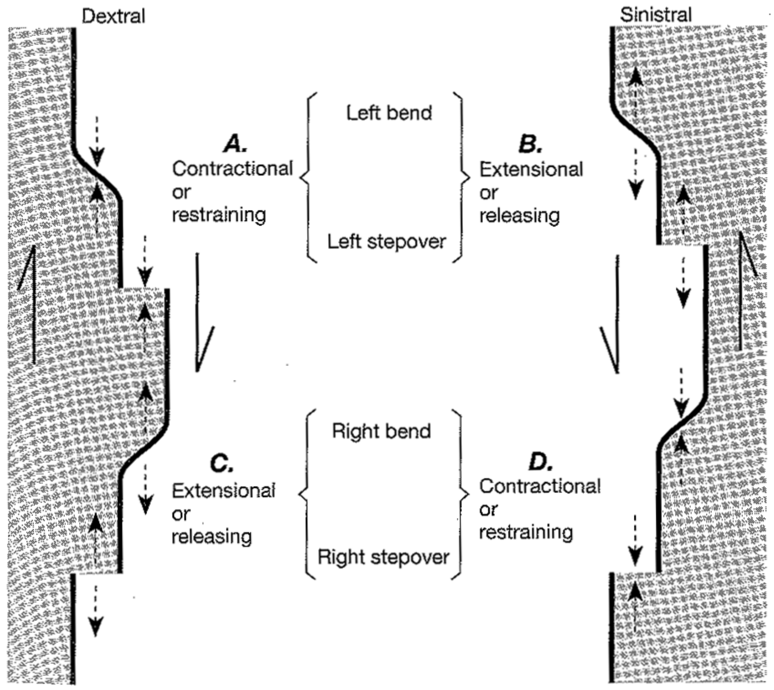

Fig. 14. Description of geometry and terminology of strike-slip step-overs and restraining bends (from R. J. Twiss and E. M. Moores: Structural Geology).

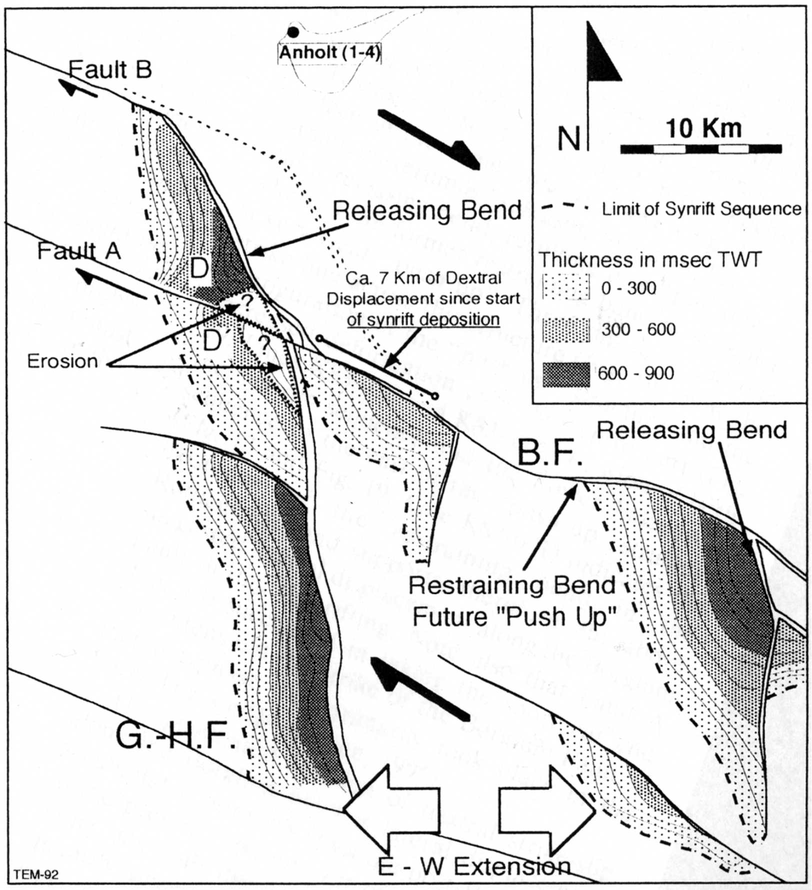

Fig. 15. Illustration of releasing and restraining bends along the Børglum and Grenå-Helsingborg fault zones in the southern Kattegat (from Mogensen 1994).

3.3 *Scanian mosaic of rock blocks*

The Scanian bedrock, particularly brittle rocks such as the Precambrian basement and Cambrian quartzite, displays a characteristic pattern of fractures and faults that divide the rock mass into numerous block units of different sizes. A rock mass quality inventory by Wikman et al. (1991) of the Romeleåsen ridge shows the high frequency of rock lineaments (mainly fracture zones weathered to varying degrees) cutting through the rock mass. The fracture orientation coincides with the different directions mentioned above. The mosaic of rock blocks separated by variably weathered zones makes it difficult to predict the prevailing rock stresses. Stress release along the delimiting weathered zones as well as rotation of rock blocks in the strike-slip regime are likely to occur.

3.4 *Geophysical and topographical signature*

The regional geophysical mapping of Scania clearly displays the major structures in Scania. The NW–SE trending major structures (dolerite dykes, faults, ridges) as well as presence of deep-lying high density rock bodies, e.g. gravity highs are revealed. The Scanian ridges (the term ridge should preferably be used instead of horst for the uplifted highs in Scania) appear clearly in the topographic relief map as units (Fig. 16). During the L. Cretaceous–Paleogene transpression at least, the ridges seem to have acted as individual units where the major stress release occurred along the bordering faults.

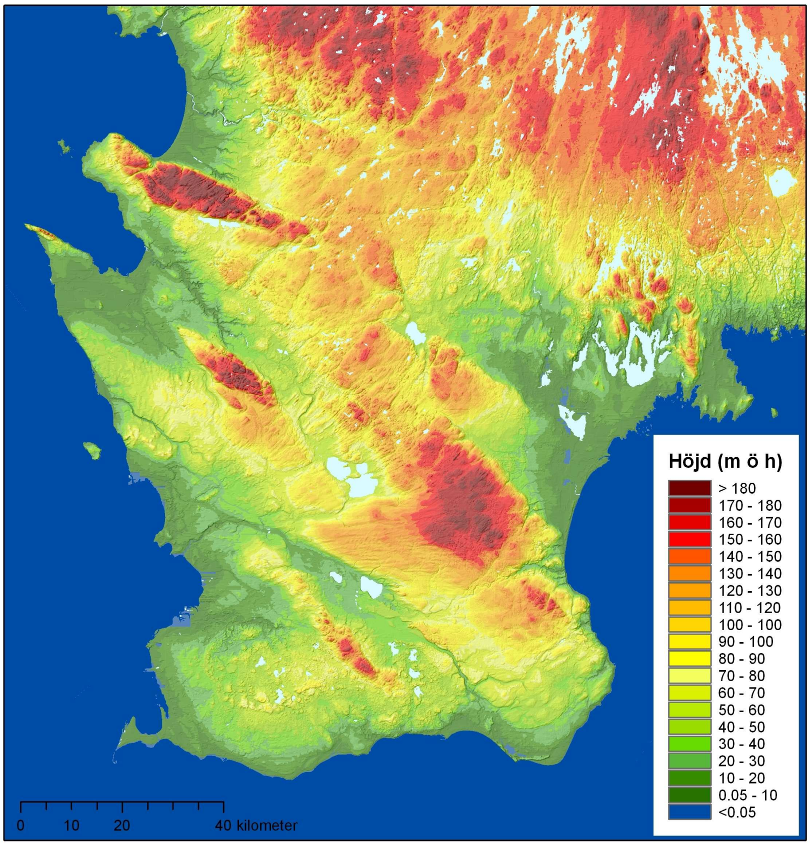

Fig. 15. Topographic relief map of Scania showing the main topographic elements such as the various ridges ("horsts").

4 CONCLUDING REMARKS CONCERNING THE GEOLOGICAL SETTING OF SCANIA

As shown in previous chapters the tectonic evolution of Scania has resulted in a high complexity of faults, fractures, and rock blocks. Phases of extension as well as compression have been accompanied by shear and lateral displacement (strike-slip faulting) along the major faults incorporated in the Tornquist Fan. This unique structural framework has therefore to be carefully considered when transferring regional stress patterns into such a complex geological setting.

It is well known that the orientation and magnitude of the regional stress field is strongly influenced by the physical properties of the lithosphere and major tectonic structures. From figure 17A it is clear that the stress pattern is not homogenous in north Europe but instead display a wide scatter. In southwestern Sweden, the Sorgenfrei-Tornquist Zone and the Danish Basin there is a significant lateral difference in lithospheric thickness as well as integrity of the crust. Tectonic effects from the evolution of the Tornquist Fan have resulted in a geological setting that most likely causes the stress field in the area (cf. Fig. 17B). In addition the described Phanerozoic tectonic phases have most likely induced lateral differences in the viscoelastic properties of the mantle and/or lower crust over the south-eastern edge of the Fennoscandian Shield. Since most of the regional stresses are transmitted in the lower crust this would also effect the situation in the area.

Reactivations of faults and repeated strike-slip displacements have been characteristic features in the tectonic history of Scania. Shear and releasing as well as restraining bends, and extension faults have in addition to above mentioned facts resulted in local stress fields differing from the regional one.

Today there are several indications that there are ongoing movements along the major faults associated with the Sorgenfrei-Tornquist Zone. The present fault movements are likely following the existing weakness zones in the crust. Shear and presence of fault bends (releasing or restraining) can locally result in rotation of stresses from NW–SE to N–S. A similar situation with stresses deviating from the regional field is found in Germany. This is by Roth & Fleckenstein (2001) explained as a result of strike-slip motion along an active fault, which releases the stress component parallel to it so that only perpendicular components (orientated NE in this case) remain.

It has also, in different tectonic models, been put forward that the Sorgenfrei-Tornquist Zone is associated with deep-seated listric faults that could favour the transfer of stresses related to the Eurasian-African plate convergence.

It is by the above stated comments obvious that locally deviating stress orientations and magnitudes in such a unique and complex geological setting such as the Tornquist Zone and Scania have several geological explanations.

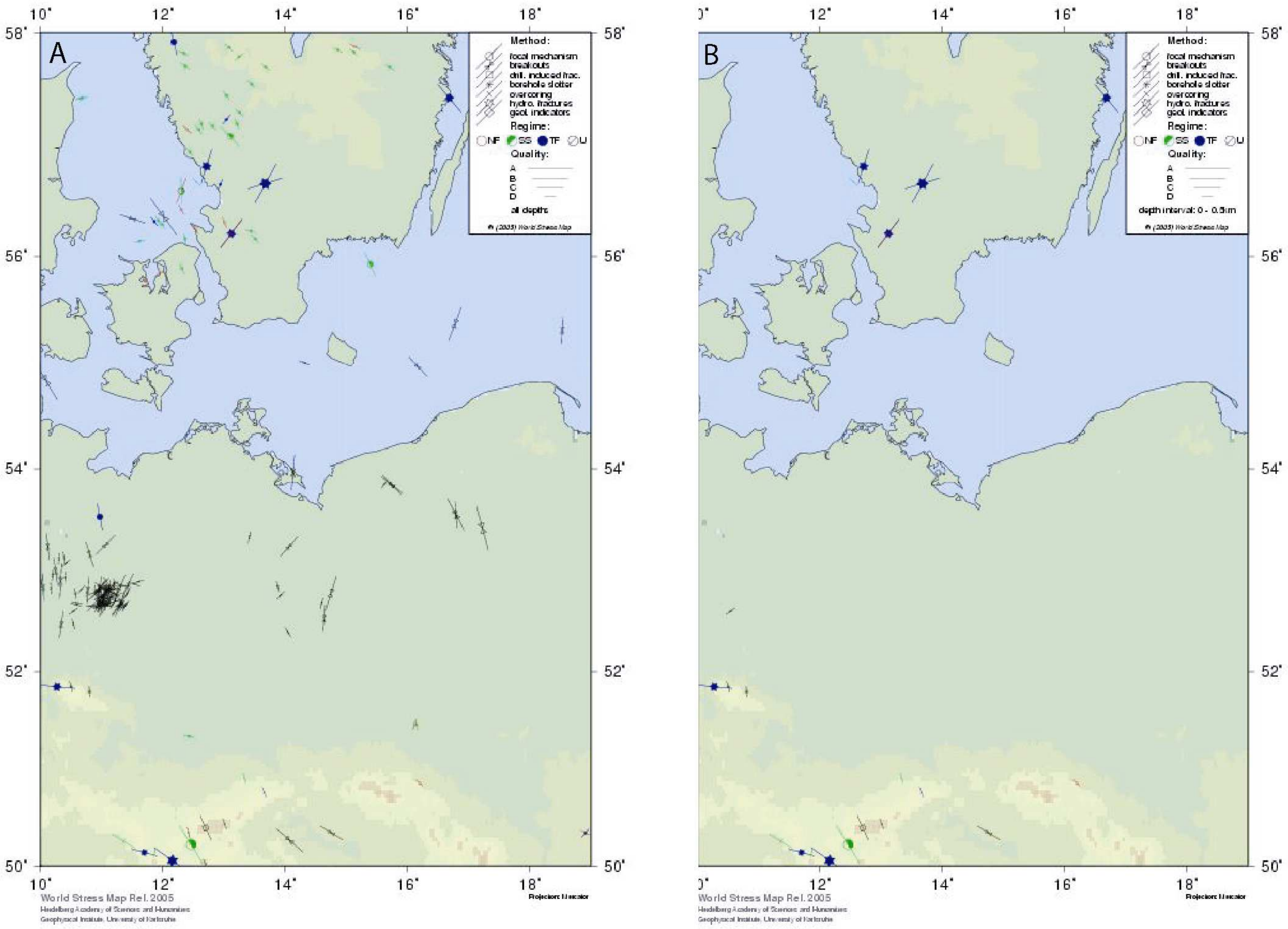

Fig. 17. Rock stress data derived from World Stress Map (Reinecker et al. 2005). Information based on: earthquake focal mechanism data, borehole breakout data, hydraulic fracturing data, overcoring data, geological fault-slip data and volcanic vent alignment). Data is also ranked according to quality. A: Map of rock stress data from Southern Sweden, Denmark, Poland and Germany. Including all existing data with no respect to depth B: Rock stresses in the uppermost 500 m of the crust.

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APPENDIX 1. Definitions of some of the main structural elements.

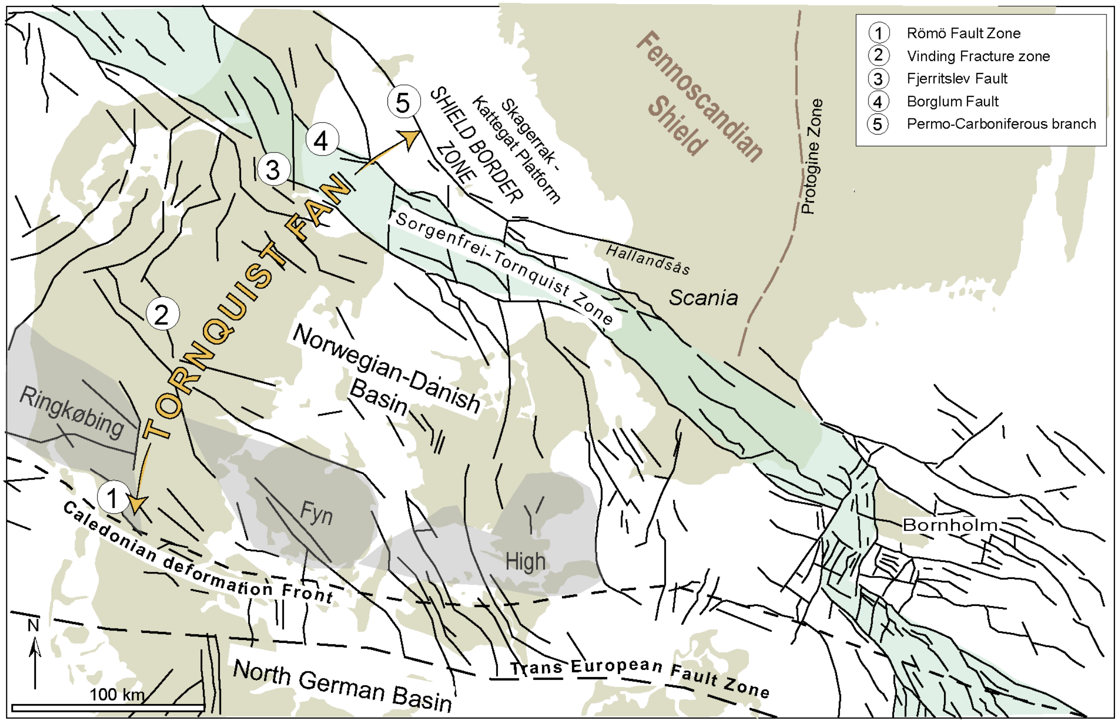

Fig. A1. Map of main structural components.

Caledonian Deformation Front
The northernmost extension of deformed and thrusted strata involved in the Caledonian orogeny.

Fennoscandian Shield
Synonymous with the Baltic Shield. A large area of Precambrian rocks that are exposed (or near surface). The oldest parts being in the range of 3 000 Ma while the youngest provinces in the south-west are between 900 and 1200 Ma old.

Norwegian-Danish Basin
A term introduced by Michelsen (1978). Describes the deep basin area between the Sorgenfrei-Tornquist Zone and the Rinkøbing-Fyn High. Characterised by rapid Triassic subsidence and thick sedimentary deposits (mainly Triassic and Jurassic) on top of the Fennoscandian Precambrian basement.

Rinkøbing-Fyn High
A series of elevated basement highs, separated from each other by grabens. Developed during Late Palaeozoic time. Precambrian rocks overlain by Triassic strata.

Shield Border Zone
The name first appeared in Berthelsen (1992) where it is defined as the Permo-Carboniferous splay of faults that cuts through the Skagerrak-Kattegat Platform.

Skagerrak-Kattegat Platform
Described as the area next to the Fennoscandian Shield that is covered by a relatively thin sequence of Mesozoic and Paleogene strata.

Sorgenfrei-Tornquist Zone
Defined by EUGENO-s working group (1988). Involves the Danish-Scanian part of the Tornquist Zone and is characterised by Alpine-Laramide inversion tectonics.

Tornquist Fan
Introduced by Thybo and Berthelsen (1991). A term used to describe the splay of faults transecting the south-western margin of the Fennoscandian Shield, between the Skagerrak-Kattegat Platform and the Caledonian Deformation front.

Trans European Fault Zone
Defined by Berthelsen (1984). Forms the tentative border between the Precambrian rocks of southern Scandinavia and younger domains to the south. Is considered the Avalonia-Baltica suture.