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Cover: View of Kullen and Skälderviken Bay from Torekov. Photo M. Erlström.

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ABSTRACT

The geological framework of the southern part of the Kattegat includes the regionally important Sorgenfrei-Tornquist Zone, around which regional stresses in the crust have been released since the Late Palaeozoic. The zone evolved as an intra-cratonic fault zone as a result of stresses induced on the south-western margin of Baltica during the formation of Pangaea. Stratigraphic information from deep wells and high-resolution seismic surveys have made it possible to reconstruct the structural evolution and fault geometry of a key area of the south-western part of Baltica. Faulting during the Late Palaeozoic Variscan orogeny significantly weakened this area. Thick Rotliegendes clastics were deposited in rapidly subsiding half-grabens as a result of rifting and transtension in a dextral strike-slip regime along the major faults of the Sorgenfrei-Tornquist Zone. These deposits disconformably overlie a 3.5–4.0 km thick sequence of Cambrian, Ordovician, Silurian, and Carboniferous strata. Lower Palaeozoic strata underlying the syn-rift sequence provide valuable information on the original thickness of the pre-rift deposits on the margins of Baltica. The syn-rift sequence has a thickness of up to 2.5 km in the southern Kattegat. Wells and geophysical data verify that the rifting was accompanied by volcanism. Aeromagnetic and Bouguer gravity data indicate highly magnetic and dense rock bodies which probably correspond to intrusive magmatic rocks in the crust and basaltic layers in the Carboniferous–Permian succession. In Scania, the aerogeophysical data indicate the existence of north–south directed zones which are interpreted as Late Palaeozoic extension faults. This indicates that the structural style of syn-rift sedimentation in Scania was similar to that in the southern Kattegat. The Scanian deposits, however, were removed by erosion during Late Cretaceous–Palaeogene inversion and uplift. The Triassic–Early Jurassic is characterised by post-rift subsidence and the Kattegat evolved as a marginal part of the Norwegian-Danish Basin, where a thick Triassic succession was deposited. During the Late Triassic–Middle Jurassic the area experienced fault-controlled differential subsidence inside the Sorgenfrei-Tornquist Zone, leading to great variability in sediment thickness and stratigraphical detail. Most of the Quaternary subcrop in the study area is composed of Jurassic strata. The well-constrained onshore geology of Scania is correlated with offshore data for the southern Kattegat. The offshore continuations of faults and rock units are displayed, as are the extensions of the Precambrian Hallandsås and Kullen horsts. The Late Cretaceous to Palaeogene inversion is clearly verified by reverse reactivation of the major faults along the Sorgenfrei-Tornquist Zone.

Key words: Kattegat, seismostratigraphy, structural evolution, strike-slip, extension, rifting, inversion, Sorgenfrei-Tornquist Zone.

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INTRODUCTION

Reconstruction of the Phanerozoic structural evolution of the south-western part of the Baltica plate is largely based on subsurface data from deep wells and geophysical investigations (cf. EUGENO-S 1988, BABEL Working Group 1991, 1993, Berthelsen 1992). High-resolution commercial reflection seismic surveys, performed during the 1970s and 1980s in the search for hydrocarbons in Swedish and Danish waters, have yielded a substantial database relating to the sedimentary succession overlying the Precambrian basement on the south-western part of the plate. A relatively dense network of reflection seismic surveys covers the Danish part of the Skagerrak-Kattegat (Figs. 1–2). Relatively good coverage of land seismic data is also available for the Höganäs-Ängelholm area. Corresponding good coverage of seismic data exists for south-western Scania, the southern Baltic Sea area, the waters surrounding Bornholm, and Hanö Bay.

Interpretations of the seismic data have resulted in numerous publications of a descriptive and structural evolutionary nature, e.g. Sorgenfrei & Buch (1964), Baartman & Christensen (1975), Norling & Bergström (1987), EUGENO-S Working Group (1988), Michelsen & Nielsen (1991, 1993), Berthelsen (1992), Erlström et al. (1994, 1997), Mogensen (1994, 1995), Vejbæk et al. (1994), Vejbæk (1997), Berthelsen (1998), and Marek (2000a). These studies have recognised a number of key areas for an understanding of the structural evolution of the south-western margin of Baltica, i.e. the Bornholm-Rønne Graben area, the Scanian part of the Tornquist Zone, and the Skagerrak-Kattegat area.

Previous studies of the Skagerrak-Kattegat area have so far been performed almost exclusively on subsurface information from Danish investigations (e.g. Mogensen 1994, 1995, Mogensen & Jensen 1994, Michelsen & Nielsen 1993, Michelsen 1997, Marek 2000b, in press a, b). Some of the Danish marine reflection seismic surveys shot during the 1960s extend into Swedish waters, but they display poor resolution and have not been involved to any significant extent in earlier modelling work.

In spite of the numerous studies there still remain data and interpretations that have not yet been presented and published. This is the case for the seismic surveys performed in the southernmost Swedish part of the Kattegat, immediately off Kullen and north-west Scania (Fig. 2).

These surveys extend over the Sorgenfrei-Tornquist Zone and adjacent basins to the north. They display a subsurface geology that significantly supplements and refines existing structural models of the southern Kattegat. Data from these surveys have so far only been presented in unpublished reports and maps. This publication thus aims to present an updated subsurface model for the Swedish part of the southern Kattegat to a wider audience. The aim is also to compare and combine data from previous studies in Danish waters and to refine existing models of structural evolution, concentrating on the relationship to the onshore geology of north-western Scania.

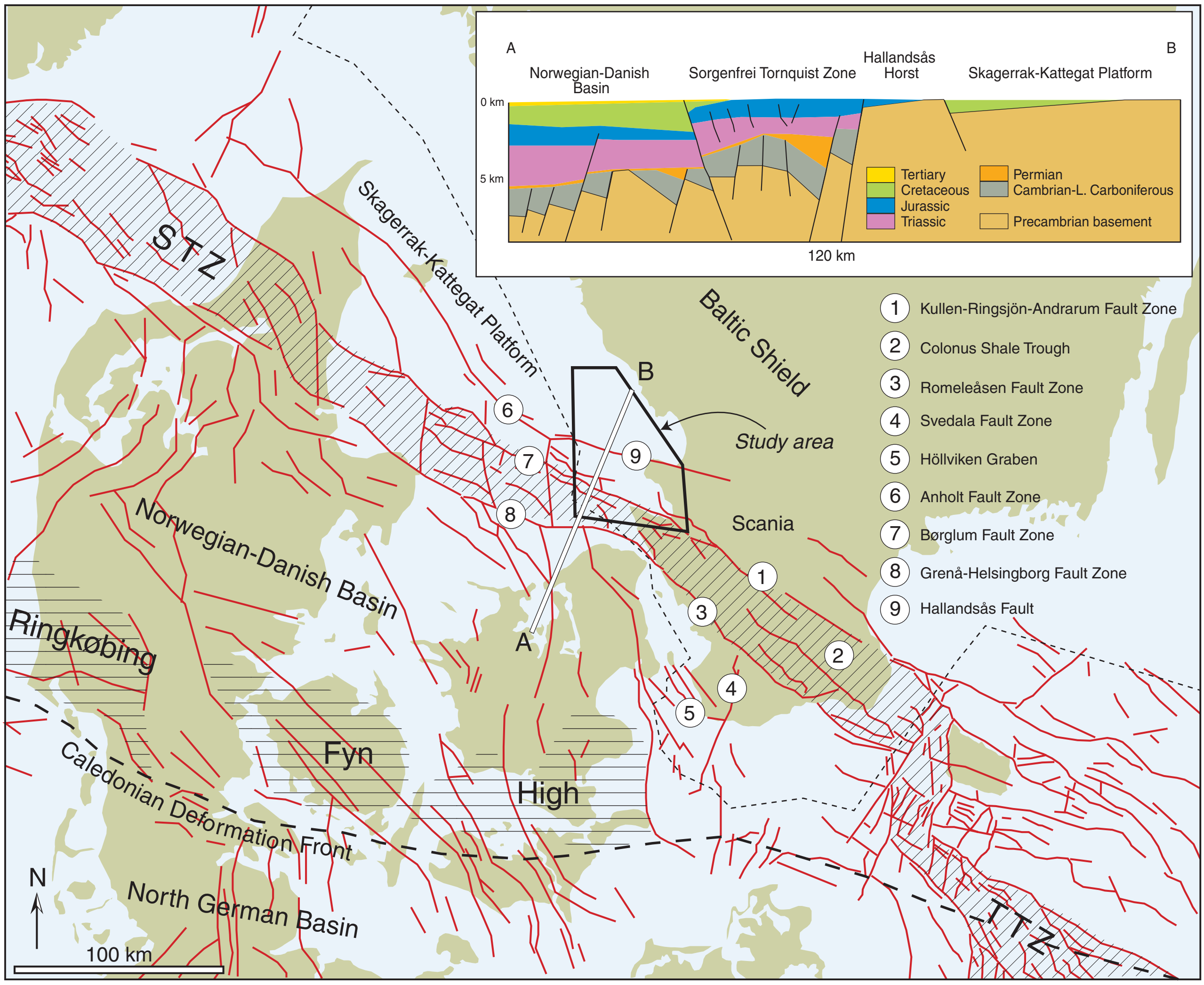


Fig. 1. Map showing the main structural elements at the top pre-Zechstein surface of south-west Scandinavia (partly based on Vejbæk et al. 1994). Inset profile describes a schematic cross-section of the marginal parts of the Norwegian-Danish Basin and the study area (framed). STZ: Sorgenfrei-Tornquist Zone, TTZ: Teissyere-Tornquist Zone.

GEOLOGICAL SETTING

The geological history described in this paper begins when Baltica evolved as an independent plate, as it broke loose from Gondwana in Early Ordovician time. Baltica drifted towards Laurentia and the collision resulted in the Caledonian deformation and junction of the two plates, forming Laurasia. The following tectonic phases include the assembly of continental Europe by microplates joining up with Laurasia at its southern border, and the subsequent formation of Pangaea as the African plate attached to the plate assembly. The oblique junction between the different plates yielded a stress field that resulted in predominantly dextral strike-slip displacements. The central part of Baltica acted as a rigid craton and was more or less unaffected by these movements. Its south-western margin however, was, involved in the processes of rifting, strike-slip faulting, and crustal shortening during the Late Palaeozoic, and in rifting, subsidence, and compression during the Mesozoic. During this period, the Sorgenfrei-Tornquist Zone constituted an important structure around which most of the stresses were released as large-scale displacements in the crust. This resulted in a significant weakening of the south-western part of Baltica.

Between the Trans-European Fault Zone, 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–Mid 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. Late Palaeozoic stress fields in northern Europe are related to the oblique collision between Gondwana and Laurasia resulting in the assemblage of the supercontinent Panagea, 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 (Ziegler 1990). The Late Permian–Early Jurassic is characterised by regional subsidence. Within the Sorgenfrei-Tornquist Zone, the stress field associated with the break-up of Pangaea led to dextral strike-slip fault reactivation, resulting in differentiated subsidence in the Late Jurassic. This was followed by Alpine inversion tectonics in the Cretaceous–Palaeogene. The last dramatic event within the zone, before the Quaternary glaciations, was the more than 1 km Neogene uplift and extensive exhumation (Japsen & Bidstrup 1999).

The Sorgenfrei-Tornquist Zone in the Kattegat is delimited to the north-east by the Børglum Fault and to the south-west by the Grenå-Helsingborg Fault (Fig. 1). The major delineating faults in the zone have repeatedly acted as structures where a large part of the stress release in the area has occurred. The amount of lateral displacement along the Kattegat and Scanian part of the Sorgenfrei-Tornquist Zone has been debated in the last few decades (cf. Bergström 1984, Mogensen 1994, 1995). On the base of recent research, the lateral displacement has been reduced from thousands of kilometres (Pegrum 1984, Liboriussen et al. 1987) to more moderate numbers that give offsets of less than 20 kilometres (Mogensen 1994, Sivhed 1991). The actual observations used to determine lateral offset, however, are few in number, the most important being the observations presented by Mogensen (1994) of Lower Palaeozoic depocentres laterally displaced along the Børglum Fault in the Kattegat.

The study area (Fig. 1) lies in an area where all of these different tectonic phases are displayed. In its northern part, the Hallandsås normal fault forms the west-north-west–east-south-east border between the Skagerrak-Kattegat Platform and the Hallandsås Horst. In this area, the margin of the Skagerrak-Kattegat Platform is slightly affected by the intensive Late Cretaceous–Palaeogene inversion in the adjacent Sorgenfrei-Tornquist Zone. On the Skagerrak-Kattegat Platform margin, in the Båstad Half-Graben, thin Jurassic–Cretaceous strata cover the crystalline basement.

The Hallandsås Horst dips in general terms to the west-south-west, but its onshore north-western part dips towards the north-west (cf. Fig. 16). Jurassic sedimentary rocks cover the crystalline basement in its south-western offshore portion, west of the island of Hallands Väderö. Onshore, the Hallandsås Horst is dominated by Precambrian crystalline rocks, with minor areas with erosion remnants of Lower Cambrian and Upper Triassic strata. The Hallandsås Fault forms an up to 100 m high cliff along the northern shoreline of Bjäre peninsula, on the seaward side of the Hallandsås Horst.

On its south-western side, the Hallandsås Horst is delimited by west-north-west-striking minor normal faults, which form a smooth transition to the Ängelholm-Skälderviken Trough. In the latter structure, rudimentary remnants of Triassic and Jurassic rocks cover the crystalline basement.

In the south-south-west, the reverse Kullen Fault borders the Sorgenfrei-Tornquist Zone. Offshore, the Kullen Fault is connected to the Børglum Fault and to the west, the reverse Anholt Fault forms the boundary between the Ängelholm-Skälderviken Trough and the Anholt Half-Graben (cf. Fig. 16). The Anholt Half-Graben dips to the north-east and close to the Anholt Fault the up to 2.4 seconds TWT (Two Way Time) thick sequence comprises Lower Palaeozoic as well as pre-Cretaceous Mesozoic strata. Carboniferous as well as Permian rocks are probably missing. In the south, the reverse Børglum Fault delimits the Anholt Half-Graben.

The investigated part of the Tornquist Zone comprises different structural elements affected to varying degrees by Late Cretaceous–Palaeogene inversion tectonics. Onshore, the Precambrian crystalline Kullen Horst is a typical landmark, with its highest point about 180 m above sea level. An unnamed normal fault separates the Kullen Horst from the Danhult Ridge (cf. Fig. 16) (Troedsson 1951). In the latter structure, Lower Palaeozoic rocks form the Quaternary subcrop in the northern part of the ridge, while in a southern direction these are successively overlain by Upper Triassic strata and by Jurassic strata in the Höganäs Trough (Troedsson 1951). The onshore faults can also be traced offshore. However, seismic records for this area are of poor quality, making the interpretation more difficult.

The reverse Grenå-Helsingborg Fault Zone forms the south-western delimitation of the Höganäs Trough and also of the Sorgenfrei-Tornquist Zone. The onshore continuation of the Grenå-Helsingborg Fault Zone is the Romeleåsen Fault Zone. On the Barsebäck Platform, onshore south of the Romeleåsen Fault Zone, a sequence of more than 2.0 km of Upper Triassic–Palaeogene sedimentary rocks covers the Precambrian crystalline basement.

In the west, the Kullen Horst, Danhult Ridge, and the Höganäs Trough are cut by the north-north-west-striking reverse Höganäs-Hans Fault. The fault is by Mogensen (1994) considered to be a southward bend of the Børglum Fault. In this study it is, however, referred to as an individual extension fault joining up with the Anholt-Børglum faults to the north and the Grenå-Helsingborg Fault Zone in the south. In the Hans Half-Graben west of this zone, Palaeozoic strata, including Permian and Carboniferous (Devonian strata are not recorded) as well as Mesozoic Triassic and Jurassic strata are identified. The block dips to the north-east, towards the Höganäs-Hans Fault, where the whole sequence has a thickness of more than 4 s (TWT).

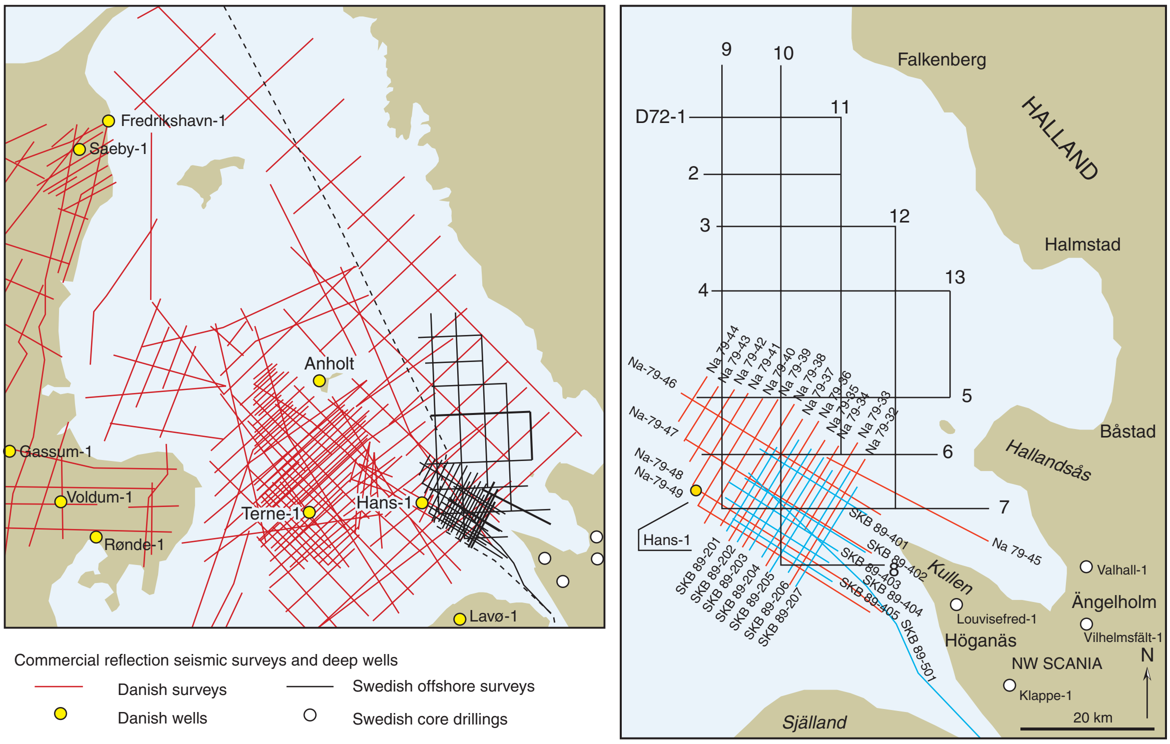


Fig. 2. Seismic surveys and wells in the Skagerrak-Kattegat area. The map to the right illustrates the surveys used in this study.

USED DATA SET

Reflection seismic data

The geoseismic interpretation presented in this study is based on three reflection seismic surveys performed in Swedish waters. The Swedish Oil Prospecting Company (OPAB) performed both the D72 survey, shot by DELTA in 1972, and the Na79 survey, shot by GECO in 1979. The most recent seismic data from the area are from the SKB89 survey, shot by DELFT in 1989 for the Swedish Exploration Consortium (SECAB) (Fig. 2). The three surveys together comprise a total of 1600 line-km of seismic data.

The D72 survey covers the entire Swedish part of the Kattegat. The lines are oriented in a north–south and east–west oriented grid with a line spacing of about 10 km. This survey gives an overview of the geology of the Skagerrak-Kattegat Platform and the Sorgenfrei-Tornquist Zone.

The Na79 and SKB89 campaigns were focused on the extensive sedimentary rock cover in the southern part of the D72 survey, and thus partly cover the Sorgenfrei-Tornquist Zone. Most of the lines are dip oriented (north-east to south-west). Additional lines are strike oriented (north-west to south-east). These surveys were performed with a line spacing of <2 km, making it possible to characterise lateral changes in faults and markers. The majority of the SKB89 lines were shot in between the Na79 survey grid. The seismic network is illustrated in Figure 2.

In general, the Na79 survey exhibits better data quality than the ten years younger SKB89 survey. However, the combination of the two surveys has proved to be important in the interpretation process, even though they cover approximately the same area.

The three surveys were all shot with airguns using a 25 m shot interval. The processing length is to 2 s (TWT) using a 29 fold CDP stack in the D72 survey, and to 4 s (TWT) using a 48 fold CDP stack in the Na79 and SKB89 surveys. The Na79 and SKB89 surveys have been migrated down to 4 s (TWT).

The interpretation has focused on the Na79 survey. The main area of investigation for which most of the modelling work has been performed coincides more or less with the coverage of the Na79 and SKB89 surveys.

For parts of the investigated area, data are also available from Danish surveys. They cover primarily the southern flank of the Sorgenfrei-Tornquist Zone and the marginal parts of the Norwegian-Danish Basin to the south-west. The northern parts of these surveys, however, also extend into Swedish waters. Data from the Danish surveys are presented by e.g. Michelsen & Nielsen (1993), Mogensen (1994, 1995), and Vejbæk (1997).

All interpretations were performed on printouts of original processed data, i.e. migrated stacks. The tapes containing the different stacks were not available or retrievable. Thus, no reprocessing of the original data has been performed. Four distinctive seismic markers have been mapped, i.e. the acoustic basement (Lower Cambrian sandstone and/or Precambrian basement), the base Rotliegendes (base of the syn-rift sequence), the base Zechstein (base of the post-rift sequence), and the near base Lower Jurassic. The mapped markers, beside the acoustic basement, have been correlated to well data from the Hans-1 well.

In some profiles, both the near acoustic basement reflector and the base Rotliegendes are difficult to distinguish. The markers are identified as broad, strong positive amplitude reflectors. The most distinctive marker is the base Zechstein unconformity, which is displayed as two distinct positive reflectors separated by an approximately 0.1 s (TWT) interval of negative amplitude. The near base Lower Jurassic reflector is also fairly easy to distinguish. It is characterised by a narrow, strong positive amplitude reflector. The nature of the seismic markers is exemplified in Figure 4.

Well data

Two offshore wells, Hans-1 and Terne-1, were drilled in the Kattegat in Danish territorial waters and within the Sorgenfrei-Tornquist Zone. The purpose was to evaluate the petroleum potential of the area. However, no hydrocarbons were found in these wells. The hydrocarbon potential (source rock maturity and reservoir rocks) of the area is discussed by Michelsen & Nielsen (1993). They conclude that, despite the existence of several good reservoirs, the source rocks were post-mature in the Palaeozoic succession and immature to marginally mature in the Mesozoic intervals.

The Hans-1 well (Fig. 3) was drilled in 1983 by DUC (Dansk Undergrund Consortium) on the northern margin of the Sorgenfrei-Tornquist Zone. It is located adjacent to the Swedish maritime boundary and the seismic survey presented in this study. The lines Na79-40 and Na-41 are located only a few hundred metres from the well, which is at Lat. 56° 21´56.0” North Long. 12° 0´ 50.0” East. The well was drilled to a total depth of 3005 m b.s.l. and penetrates a succession of Jurassic, Triassic, and Permian strata ending in Carboniferous volcanoclastic strata. Some 40 km west of Hans-1, Amoco drilled the Terne-1 well to a depth of 3324 m b.s.l. in 1985. The well displays a succession of Lower Creta-

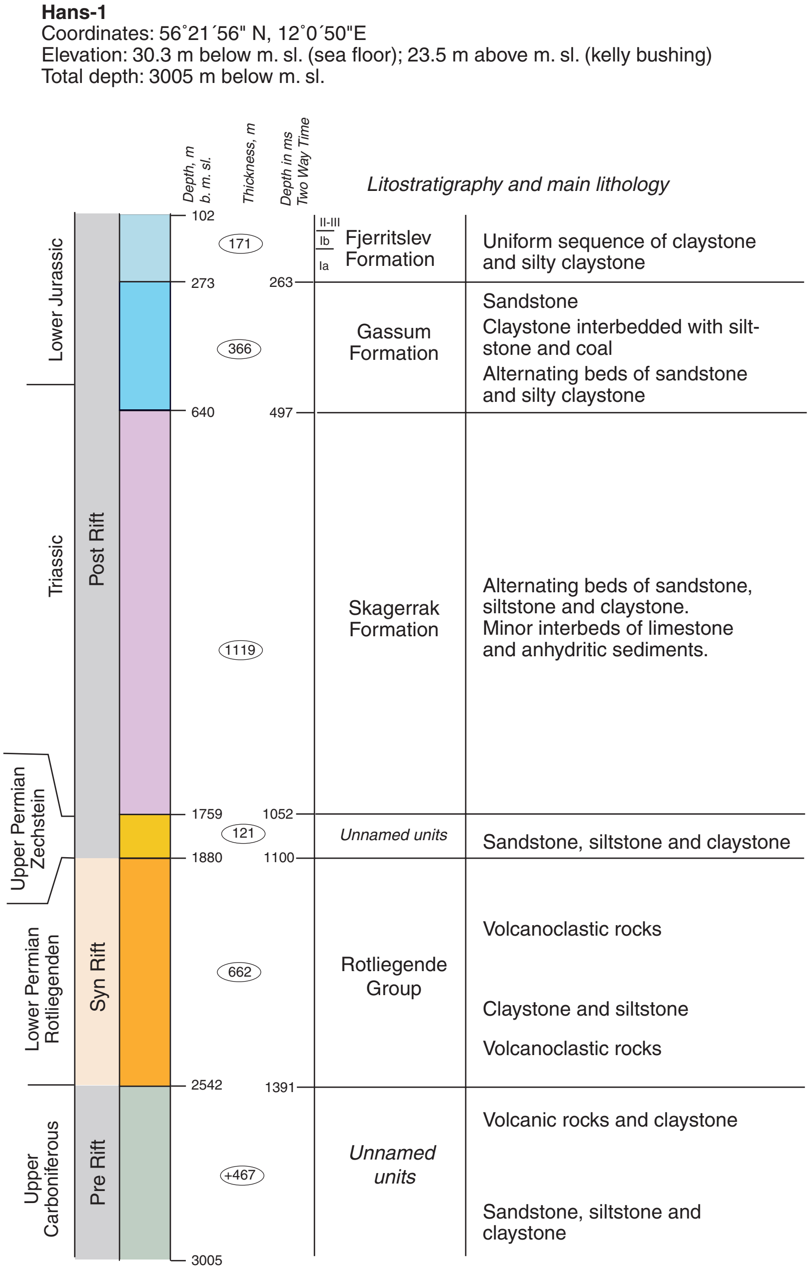


Fig. 3. Stratigraphic subdivision of the Hans-1 well.

ceous, Jurassic, Triassic, Permian, Silurian, Ordovician, and Cambrian strata. Michelsen & Nielsen (1991, 1993) and Nielsen & Japsen (1991) describe both wells in detail.

Bouger gravity and magnetic anomaly data

Aerogeophysical investigations of magnetic anomaly and measurements of Bouguer gravity in the southern Kattegat have been performed by the Geological Survey of Sweden (SGU) in connection with ongoing regional mapping of Scania, and by OPAB during their prospecting campaign in the 1970s.

The SGU aeromagnetic survey was performed at an altitude of 30 m with 200 m line spacing. The OPAB survey has a line spacing of 1.0 km and was recorded at a flight altitude of 600 m. Here, the two data sets have been combined for the first time. The differences in data recordings are partly levelled out by filtering and adjusting to an average recording altitude of 150 m for the SGU data.

The Bouguer gravity map is based on onshore data from Scania and Halland, supplemented by marine profiling along a line parallel to the coast. Especially for the more distal offshore areas, the mathematical gridding of the area is uncertain due to the lack of data.

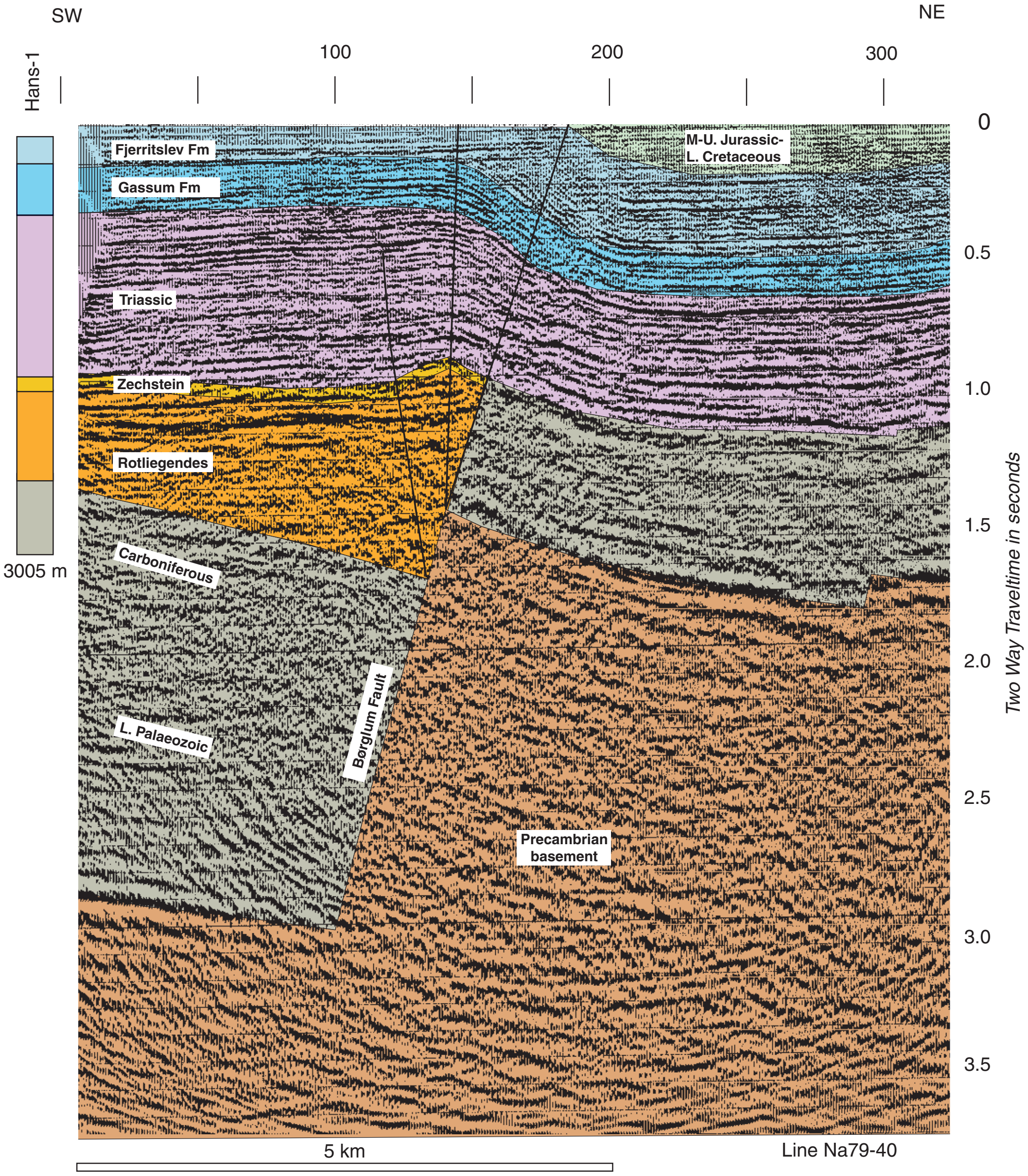


Fig. 4. Example of migrated seismic data (Line Na79-40) and reflector intervals adjacent to the Hans-1 well.

Onshore geology

The well-constrained onshore geology of north-western Scania (Sivhed & Wikman 1986, Wikman & Bergström 1987, Wikman & Sivhed 1992, Norling & Wikman 1990, and Erlström & Guy-Ohlson 1999) has been of essential importance in interpreting the geology of the neighbouring offshore areas. A comprehensive description of the onshore geology is also given by Norling & Bergström (1987) and Erlström et al. (1997). In the Ängelholm Trough and Höganäs Basin there are a number of boreholes through the Jurassic succession, which give valuable information on the subsurface geology (cf. Guy-Ohlson & Norling 1988). The data on fault zones and the representation of strata in different fault blocks have also helped in the process of reconstructing the structural evolution. The existence of a dense set of aerogeophysical and reflection seismic data has also contributed to an understanding of the marine data.

LITHOSTRATIGRAPHICAL REPRESENTATION

The following sequential lithostratigraphic description is based mainly on data from Hans-1 and Terne-1 and the onshore geology of north-west Scania.

Palaeozoic

During the Early Palaeozoic (Cambrian–Early Silurian), large parts of Baltica formed an extensive low-topography shelf area (Jaeger 1984). Shallow marine arenaceous deposits dominate Early Cambrian sedimentation in Scania. The sandstone-dominated Lower Cambrian sequence is here approximately 150 m thick and defined as the Hardeberga Fm, Norretorp Fm, and Rispebjerg Sandstone, followed by the Gislöv Formation (Hamberg 1991, Sivhed et al. 1999). The succession is dominated by the up to 120 m thick Hardeberga Sandstone. In the Kattegat, the Lower Cambrian is known from Terne-1, which reached 11 m into Lower Cambrian Hardeberga Sandstone.

The Middle and Upper Cambrian and the basal Ordovician (Tremadocian) strata are dominated in Scania by outer shelf black shales with lenses and thin layers of limestone belonging to the Alum Shale Formation. In Scania, the sequence varies in thickness between 40 and 100 m. In the Kattegat (Hans-1), a 66 m thick sequence, the so-called ”high gamma unit” (Michelsen & Nielsen 1991), rests on the Hardeberga Sandstone. This unit is tentatively correlated with the Norretorp and Rispebjerg sandstones and the Alum Shale Formation.

The Ordovician and Silurian strata consist mainly of dark grey to black claystone, mudstone, and dark grey shale. In the Middle and Upper Ordovician, numerous bentonite layers indicate extensive volcanic activity. The Ordovician strata vary in thickness from approximately 80 m in the south-east to 200 m in the north-west of Scania. A 250 m thick sequence in Terne-1 is referred to the Ordovician.

The total Silurian thickness is unknown in Scania. Various estimates have been presented. A general view is that the sequence is in the range of 1.0–1.5 km. The Terne-1 well encountered an incomplete Silurian sequence of 637 m. Seismic data indicate that the complete Silurian sequence is more than 2.0 km thick in the southern part of the Kattegat (cf. Mogensen 1994).

Devonian and Carboniferous deposits are not known from Scania. Redeposited and well-preserved Carboniferous spores are frequently found in Mesozoic strata (Guy-Ohlson 1986, 1990, Guy-Ohlson et al. 1987, Nielsen & Koppelhus 1991, Erlström & Guy-Ohlson 1994), indicating erosion of nearby pre-existing Carboniferous strata. The absence of Upper Palaeozoic strata in Scania is probably due to extensive erosion during Triassic time. In the Kattegat part of the Sorgenfrei-Tornquist Zone, Carboniferous as well as Permian sediments occur in downfaulted half-grabens. In Hans-1, the basal 254.5 m part of the section consists of well-bedded sandstone, siltstone, and claystone. It is tentatively referred to the Late Carboniferous. At its very base, the section consists of a cross-bedded, medium- to fine-grained, well-sorted sandstone interpreted as formed in a semiarid fluvial environment (Michelsen & Nielsen 1991). The overlying Upper Carboniferous volcanic series is subdivided into two parts, a lower 242 m thick volcanic unit and an upper 81 m thick claystone unit. The volcanic series consists of basalt layers and thin siltstone beds.

In Hans-1, a 551 m thick sequence of volcanoclastic rocks, conglomerates, and poorly sorted sandstones (pebbles and grains dominated by volcanic rock fragments) is referred on lithological grounds to the Lower Permian Rotliegendes Group. The Rotliegendes deposits increase in thickness towards the Børglum Fault, reaching a maximum of approximately 1.5 km close to the fault.

In Scania, assumed Permian, probably Rotliegendes, sedimentary rocks consist of an up to 50 m thick conglomeratic silicified sequence (Sivhed et al. 1999). It rests on Silurian rocks in the Höllviken Graben and on the Precambrian crystalline basement on the Skurup Platform. Until recently, these Permian deposits were unknown in Sweden.

In Hans-1, the Zechstein deposit consists of reddish and red-brown interbedded sandstone, siltstone, and claystone representing a marginal marine facies. The sequence is 121 m thick in Hans-1 and 37.5 m in Terne-1.

Mesozoic

The fluviatile Triassic Skagerrak Formation (1119 m thick in Hans-1 and 971.5 m in Terne-1) forms the main part of the Mesozoic sedimentary sequence in this part of the Kattegat. It consists of red and red-brown claystone, siltstone, and a few sandstone interbeds. Anhydrite and carbonate interbeds the sequence. The formation is significantly thinner on the Skagerrak-Kattegat Platform and in Scania than in the Sorgenfrei-Tornquist Zone in the Kattegat. This is probably an effect of Triassic rifting and localised subsidence in this part of the Sorgenfrei-Tornquist Zone. The upper part of the Skagerrak Formation corresponds to the up to 300 m thick Kågeröd Formation in Scania.

The Upper Triassic–Lower Jurassic deltaic Gassum Formation (Larsen 1966, Bertelsen 1978, Nielsen et al. 1989) is divided into three intervals in the area. The lower unit comprises interbedded claystones and sandstones and coal beds (152 m in Hans-1 and 134 m in Terne-1). The middle unit (141 m in Hans-1 and 83 m in Terne-1) consists of a claystone interval with a few sandstone and siltstone beds whereas sandstone beds dominate the upper unit (73 m in Hans-1 and 109 m in Terne-1). On the eastern side of the Børglum fault and north of the Kullen Fault, the Triassic sediments wedge out in a northern and eastern direction, with a maximum thickness of some hundreds of metres close to the faults. The up to 250 m thick Höganäs Formation in Scania is equivalent to the Danish Gassum Formation.

The Lower Jurassic marine Fjerritslev Formation (F1a–FIII) (Michelsen 1989, Michelsen & Nielsen 1991)) forms the uppermost 171 m of the Pre-Quaternary sequence in Hans-1. The Fjerritslev Formation is made up of a grey to dark grey, soft to firm, calcareous claystone, partly silty, with some interbeds of argillaceous, fine-grained calcareous sandstone in its uppermost part. In Scania, the corresponding Rya Formation has a thickness of approximately 300 m.

The composition of the Cretaceous strata in the Swedish part of the Kattegat can only be related to what is known from shallow wells in the Båstad area. Lower Cretaceous deposits similar to the sequence in Terne-1 were probably present over large parts of the Kattegat. The large-scale Late Cretaceous to Palaeogene inversion and Late Palaeogene to Neogene uplift resulted in extensive erosion and the development of a regional unconformity between the Quaternary and the Cenozoic–Mesozoic successions (Michelsen 1997).

SEISMIC INTERPRETATION

Time structure maps

Basement

The basement reflector is in many cases difficult to map, probably due to weathering of the Precambrian crystalline rocks and the corresponding diffuse change in acoustic impedance between overlying sediments and the basement. The near basement acoustic reflector, corresponding to the Lower Cambrian Hardeberga Sandstone, shows a better continuity whenever the Lower Palaeozoic sequence is present. The reflectivity pattern of the Lower Palaeozoic near basement interval is displayed in the same manner in seismic offshore data for the south-western Baltic area (Thomas et al. 1993) and for the Höllviken Graben (Sivhed et al. 1999).

The map in Fig. 5a shows that, in large parts of the area, the basement lies at depths of less than 0.6 s, i.e. there are less than approximately 700 m of cover sediments (at an average velocity of 2500 m/s). It is also clearly seen that the Hallandsås Horst extends far out into the Kattegat and that its westernmost parts have only a thin sedimentary cover. The most conspicuous features at this level are the two down-thrown basement blocks, the Anholt Half-Graben and the Hans Half-Graben (cf. Fig. 16) in the south-western corner of the area. Here the basement dips to the north-east and lies at depths of more than 4 s (TWT) adjacent to the fault. Assuming an average velocity of 3500 m/s this would mean that the basement lies at a depth of approximately 7 km.

Top Carboniferous and Lower Palaeozoic

The map in Fig. 5b shows the correlation between the down-thrown Anholt and Hans half-grabens and the distribution of Palaeozoic rocks. In the south-western part, the reflector represents the interface between an eroded and truncated sequence of north-eastward dipping Palaeozoic strata and the Zechstein sequence. In the deep parts adjacent to the Höganäs-Hans Fault, it represents the top Upper Carboniferous where it is onlapped by Rotliegendes clastic rocks, filling the Hans Half-Graben.

Elsewhere in the area there is a more or less complete absence of Palaeozoic strata, except for some minor occurrences along the coast of Scania, south of Kullen, and on the Bjäre Peninsula. Their marine continuation has not been proven. They probably represent minor local remains of down-thrown blocks that have been protected from erosion. Similar occurrences have not been detected from the seismic data, although they are likely to exist.

Top Permian

Zechstein strata are thin (<0.1 s, TWT) and represent a period of significant denudation of the landscape and a phase of regional subsidence that began in the Norwegian–Danish Basin. The deposits in the Kattegat are of a marginal type and do not include any major evaporitic strata as are found in more distal parts of the basin. The maximum extension of the Zechstein Basin to the north-east probably coincides with the Sorgenfrei-Tornquist Zone. The map in Fig. 6a shows that the Zechstein deposits extended at least as far as the Børglum Fault.

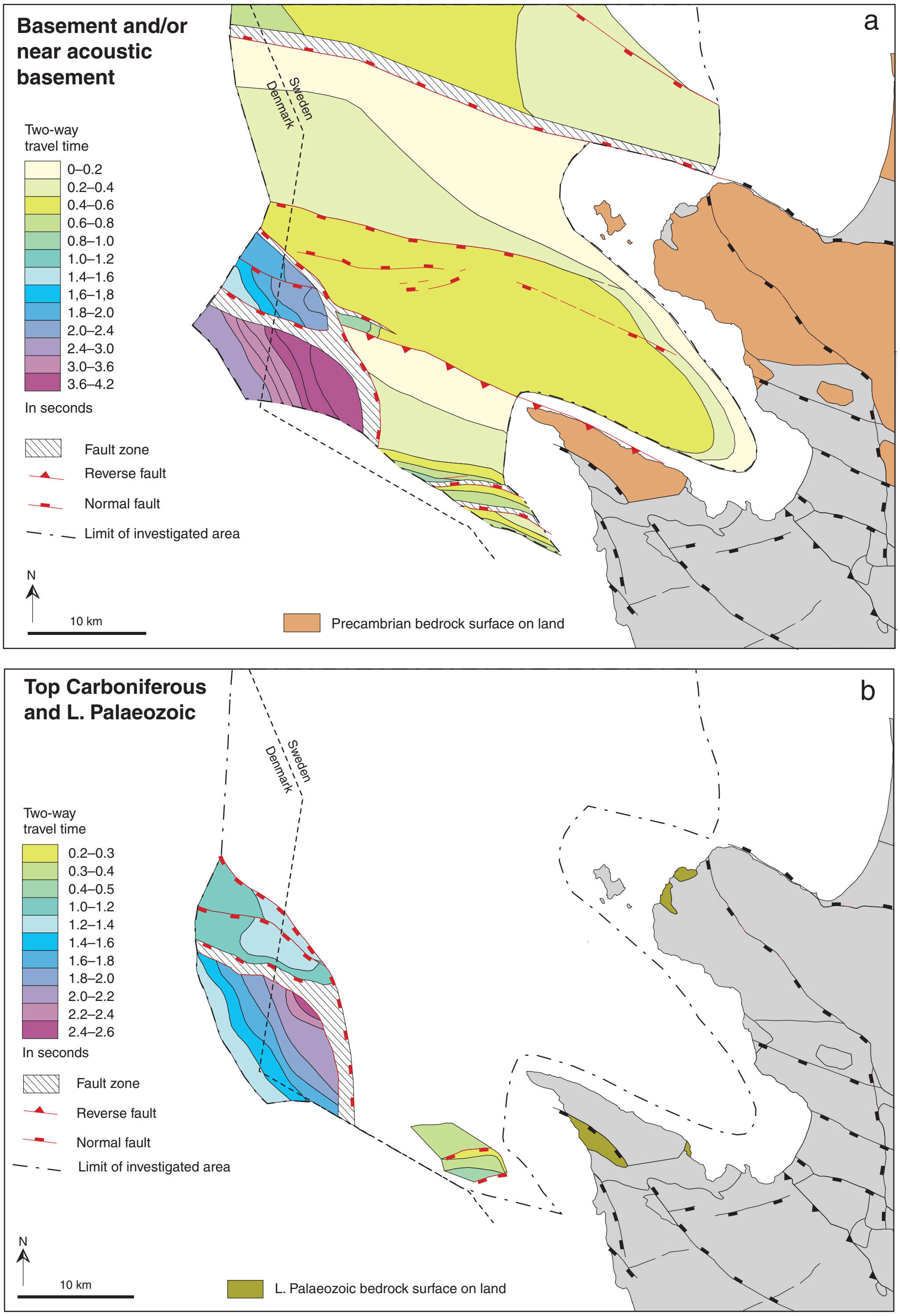


Fig. 5a, b. Time structure maps of basement and/or acoustic basement and top Carboniferous and/or Lower Palaeozoic sequence (i.e. pre-rift sequence). Occurrences of corresponding rock on land are illustrated.

Top Triassic

Triassic strata are widely represented and the base of the Triassic lies deeper in the subsided basins (the Anholt and Hans half-grabens) within the Sorgenfrei-Tornquist Zone than to the north-east of the Anholt–Børglum–Kullen faults (Fig. 6b). The Triassic–Jurassic boundary is positioned just below the near base Jurassic reflector, which is a narrow, strong positive amplitude feature, probably caused by changes in lithofacies related to the Early Jurassic transgression. The presence of Triassic strata in the Ängelholm Trough (cf. Fig. 16) is difficult to detect, as they would overlie a weathered basement with similar acoustic impedance. On the basis of onshore data, there probably exists a thin sequence of Upper Triassic strata in parts of the Ängelholm-Skälderviken Trough. Within the Sorgenfrei-Tornquist Zone, the Triassic sequence is up to 1.5 s (TWT) thick, with marked differential subsidence between different blocks.

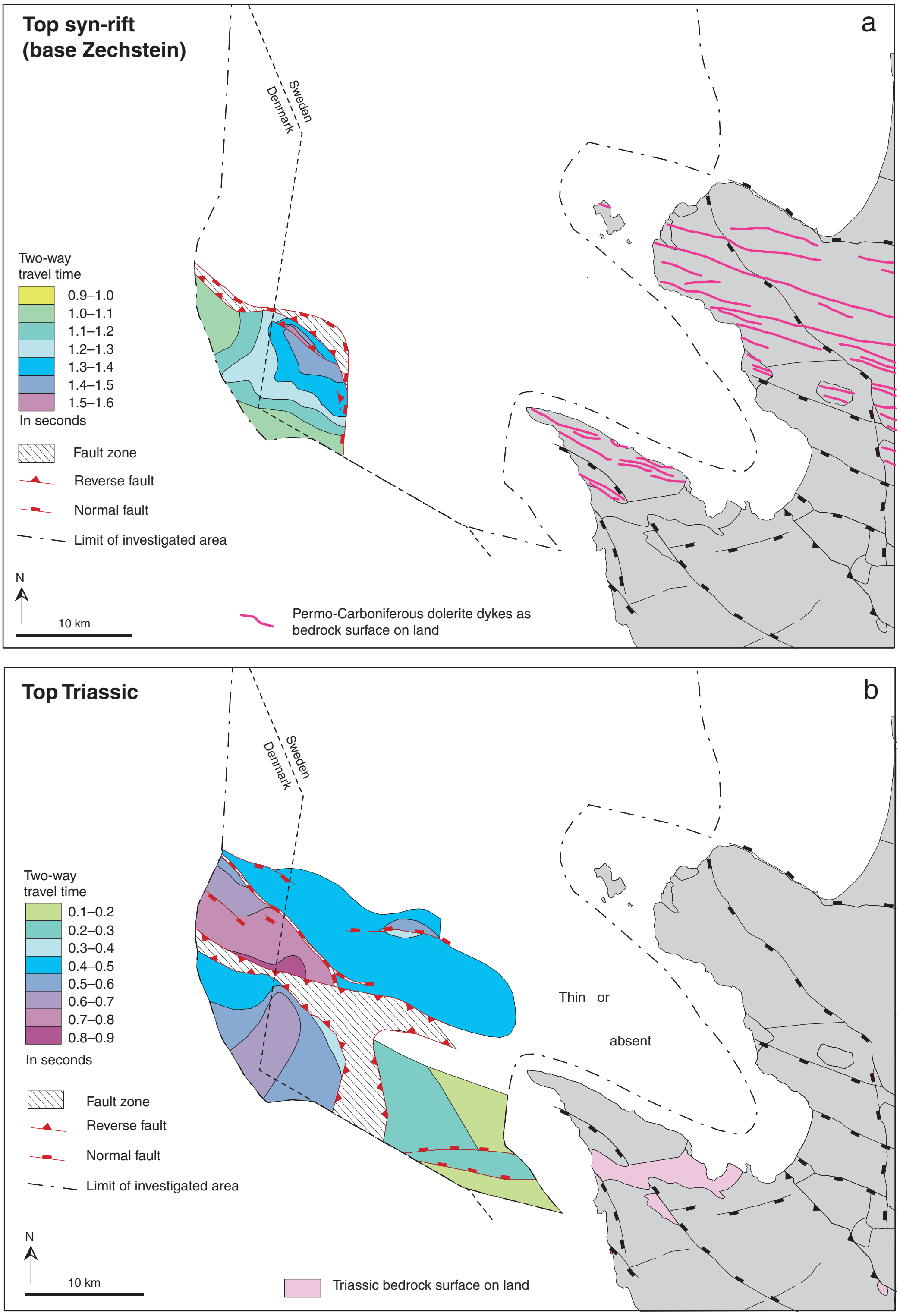


Fig. 6a, b. Time structure maps of base Zechstein (syn-rift sequence) and top Triassic. Occurrences of corresponding rock on land are illustrated.

Isopach maps

Three isopach maps (Figs. 7a, b, 8), based on the four mapped seismic reflectors, have been compiled. They correspond to the thickness of the pre-, syn-, and post-rift sequences.

The preserved pre-rift sequence represents the remains of a much wider distribution of Cambrian to Carboniferous strata on the south-western margin of Baltica. The isopach map in Fig. 7a shows a more than 1.5 s (TWT) thick sequence in the north-eastern part of the Hans Half-Graben. Correction for dip gives a true thickness of

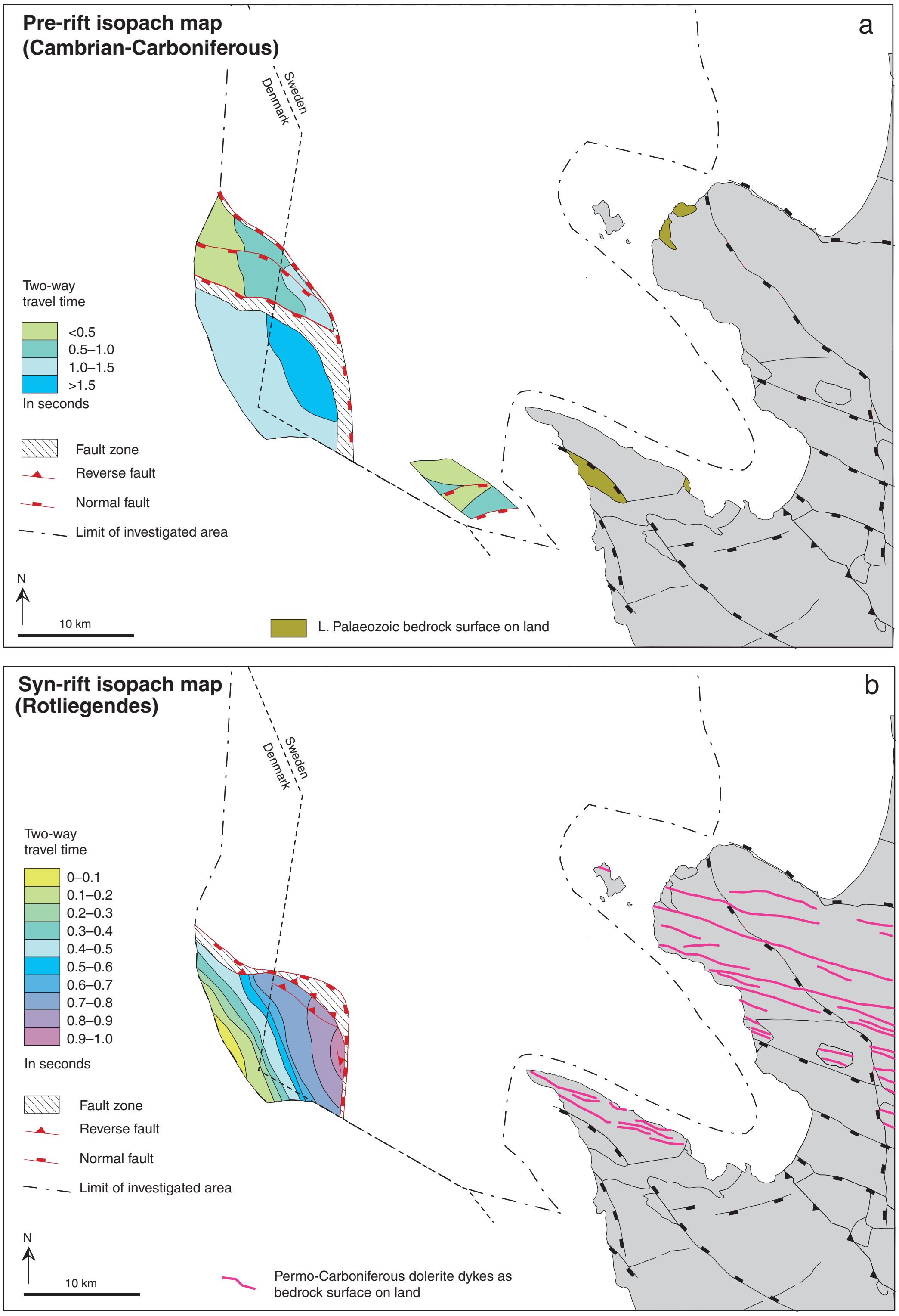


Fig. 7a, b. Isopach maps of pre-rift and syn-rift sequences.

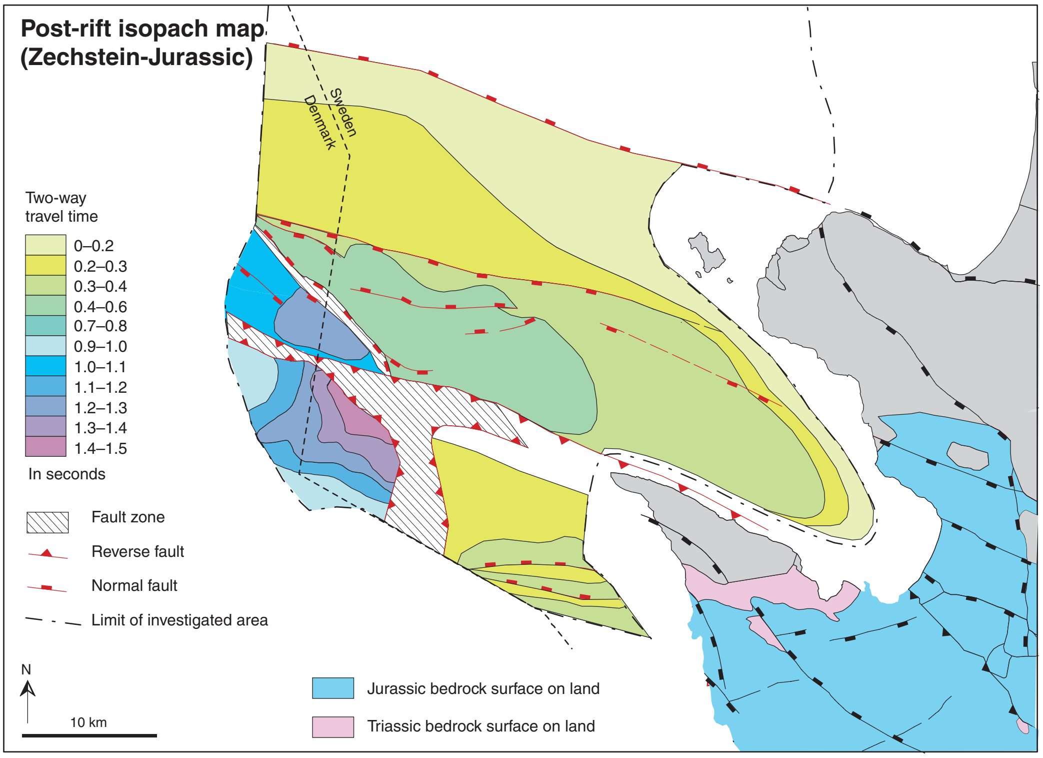


Fig. 8. Isopach map of the post-rift sequence corresponding to the Zechstein-Jurassic sequence.

1–1.2 s (TWT) for the pre-rift sequence, corresponding to approximately 2.2–2.5 km for the complete sequence. In the Anholt Half-Graben, the eroded incomplete pre-rift sequence has an estimated metric thickness of 1.0–2.0 km.

The syn-rift isopach (Fig. 7b) refers to the Rotliegendes strata formed in depocentres on the western side of the extension fault. The deposits probably represent alluvial fans building off the fault scarp and filling the evolving half-graben. The sequence rapidly increases in thickness towards the fault scarp, where it is up to 1 s (TWT) thick, which equals approximately 1.5–2.0 km.

The post-rift map (Fig. 8) indicates differential subsidence in the Sorgenfrei-Tornquist Zone during the Triassic and Jurassic. Depocentres formed during the Triassic overlap more or less with the basins formed during the Permian extension. The metric thickness for the post-rift sequence is up to 2.0 km, but this sequence is strongly truncated, owing to the Late Cretaceous–Palaeogene inversion and erosion that removed large parts of the Middle–Upper Jurassic and Cretaceous strata.

Geoseismic profiles

The subsurface two-dimensional geology is displayed in the interpreted profiles presented in Figs. 9–12. The dipping blocks of pre-rift Palaeozoic strata, the syn-rift depocentre, the Triassic differential subsidence and the Late Cretaceous–Palaeogene inversion are evident in the display, especially in line Na79-36 (Fig. 9). Joining the dip-oriented lines (Fig. 13) in a 3D model shows how the thicknesses and geometry of the individual units are strongly related to the activity of the Børglum Fault.

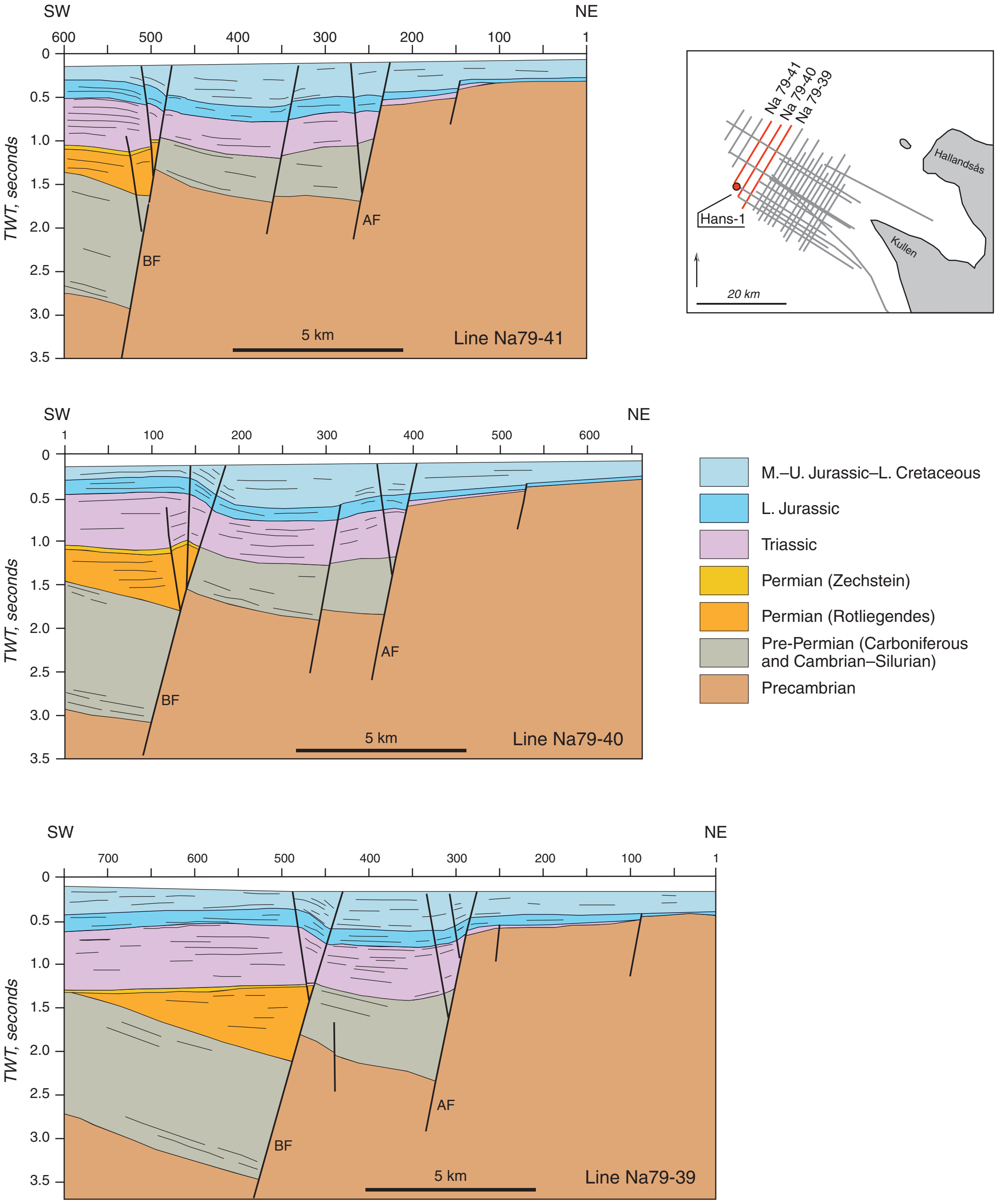


Fig. 9. Geoseismic profiles. Dip-oriented profiles, Na79 survey. AF = Anholt Fault, BF = Børglum Fault.

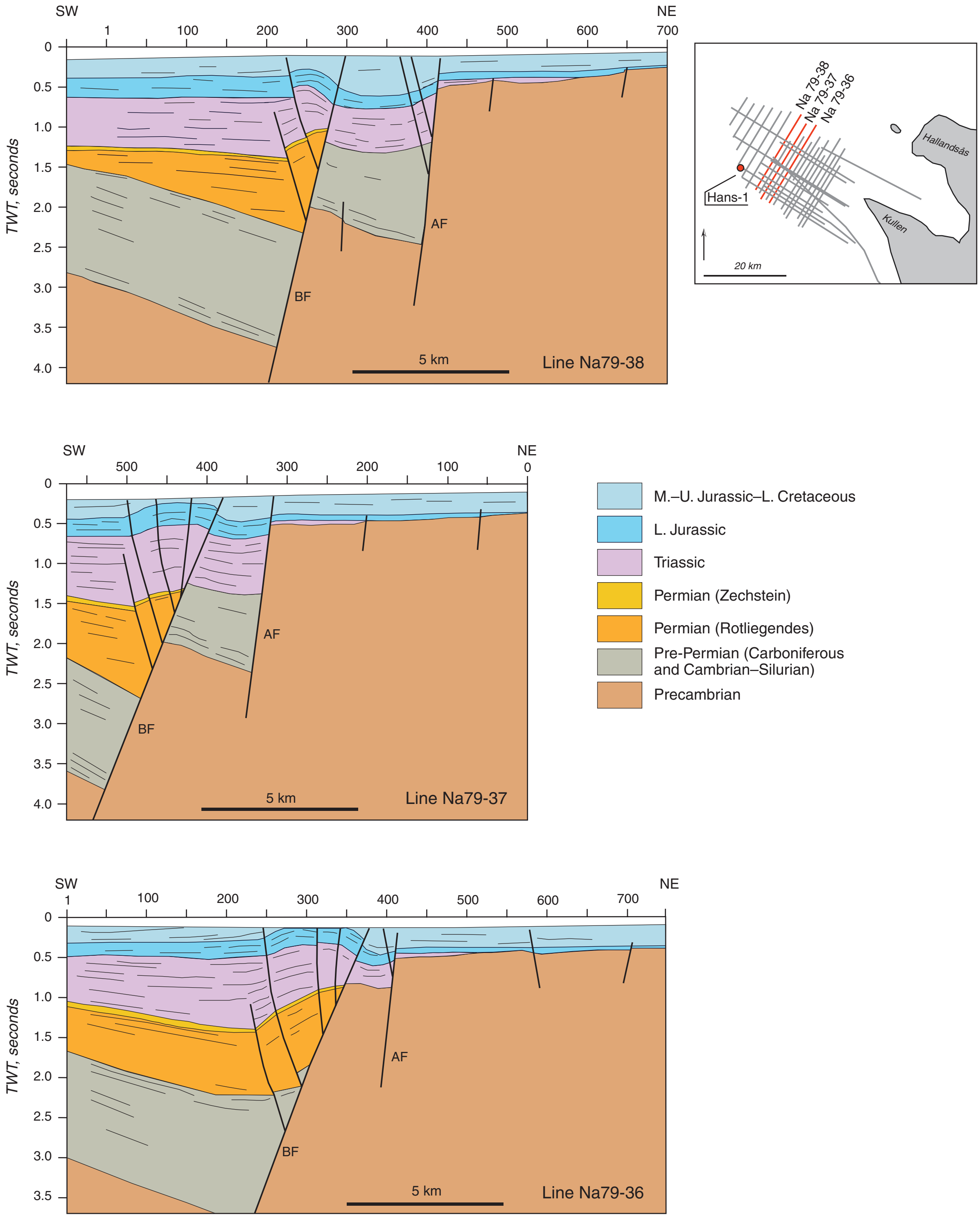


Fig. 10. Geoseismic profiles. Dip-oriented profiles, Na79 survey. AF = Anholt Fault, BF = Børglum Fault.

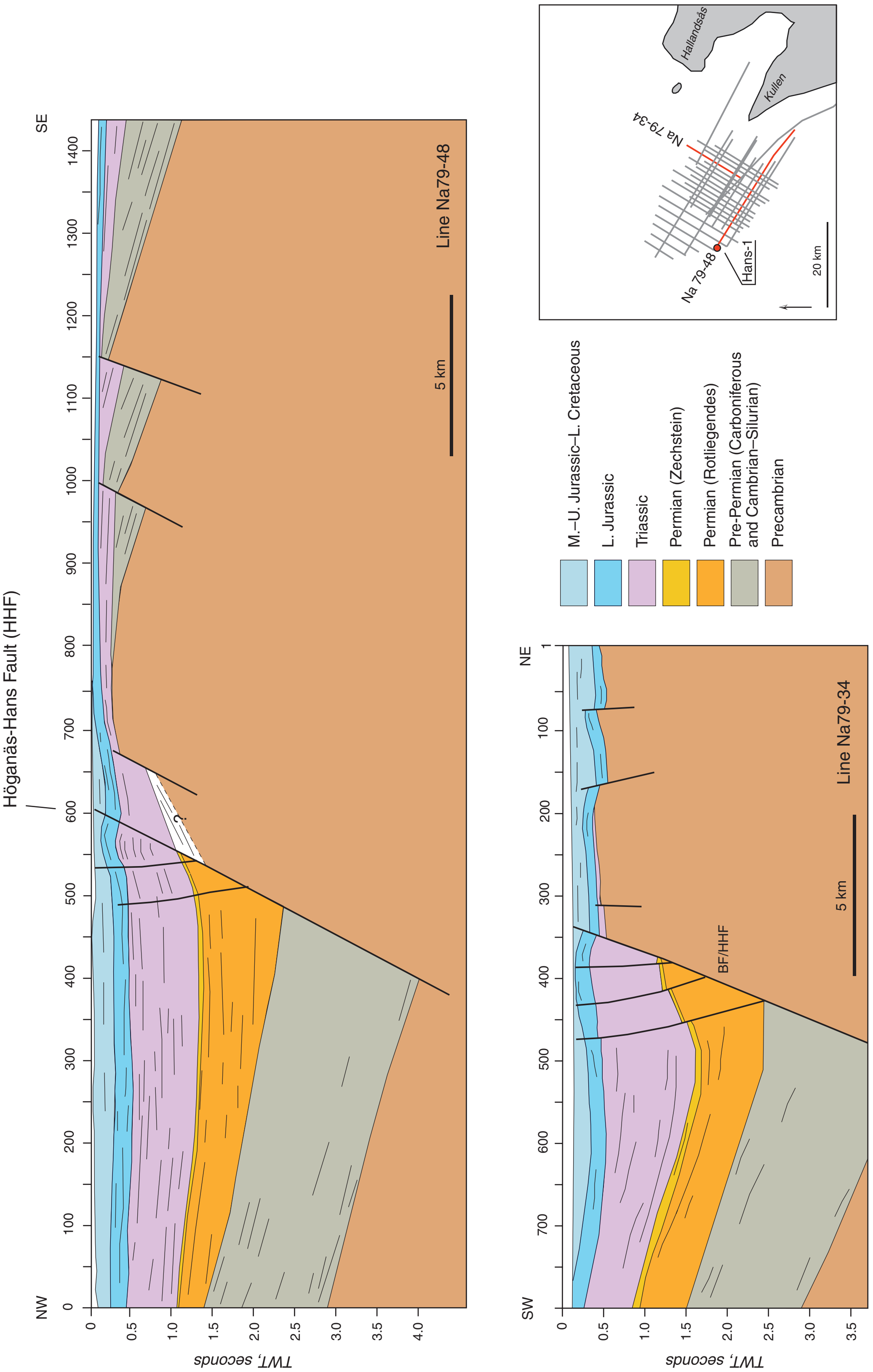


Fig. 11. Geoseismic profiles. Na79 survey.

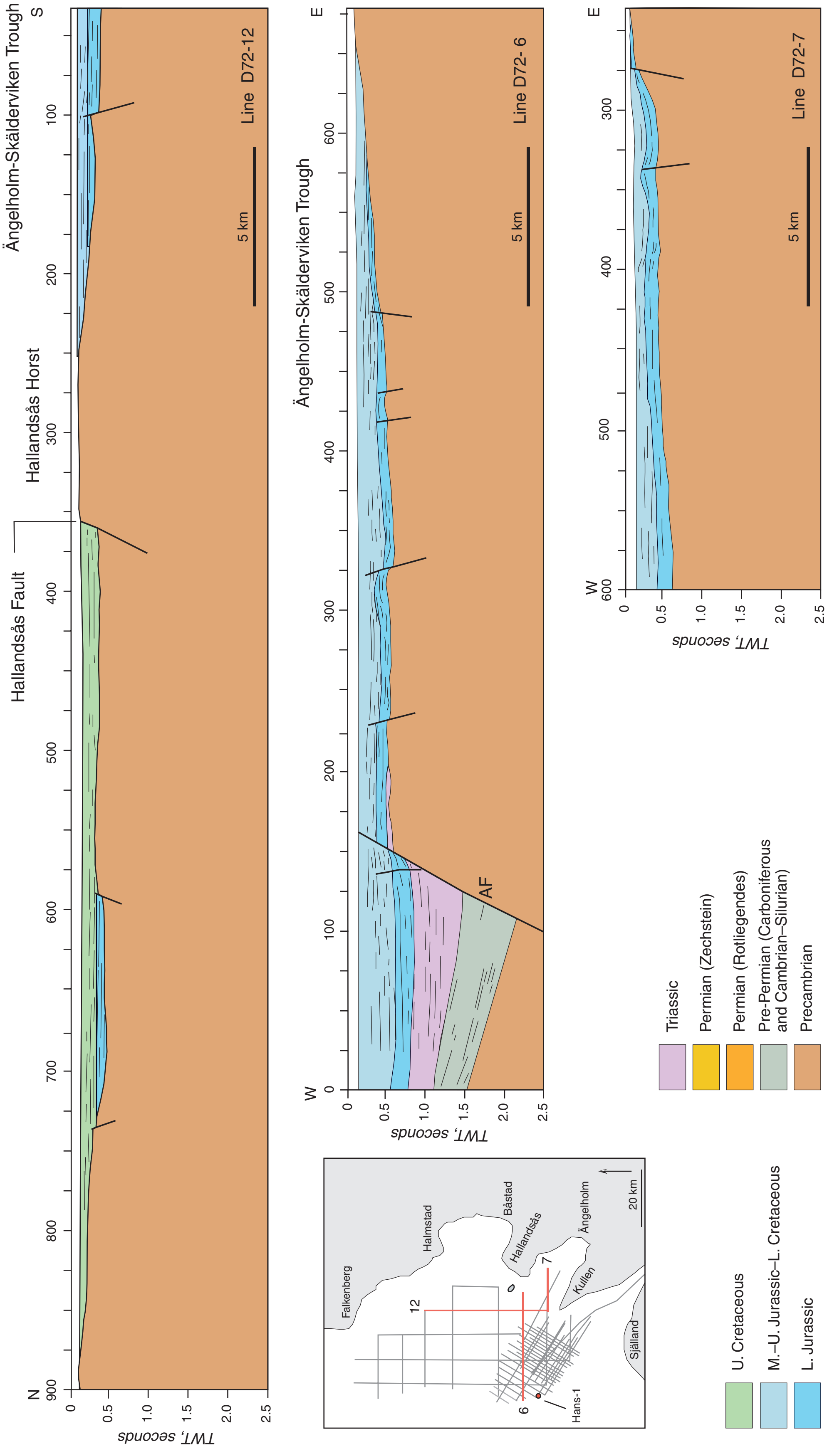


Fig. 12. Geoseismic profiles, D72 survey. AF = Anholt Fault.

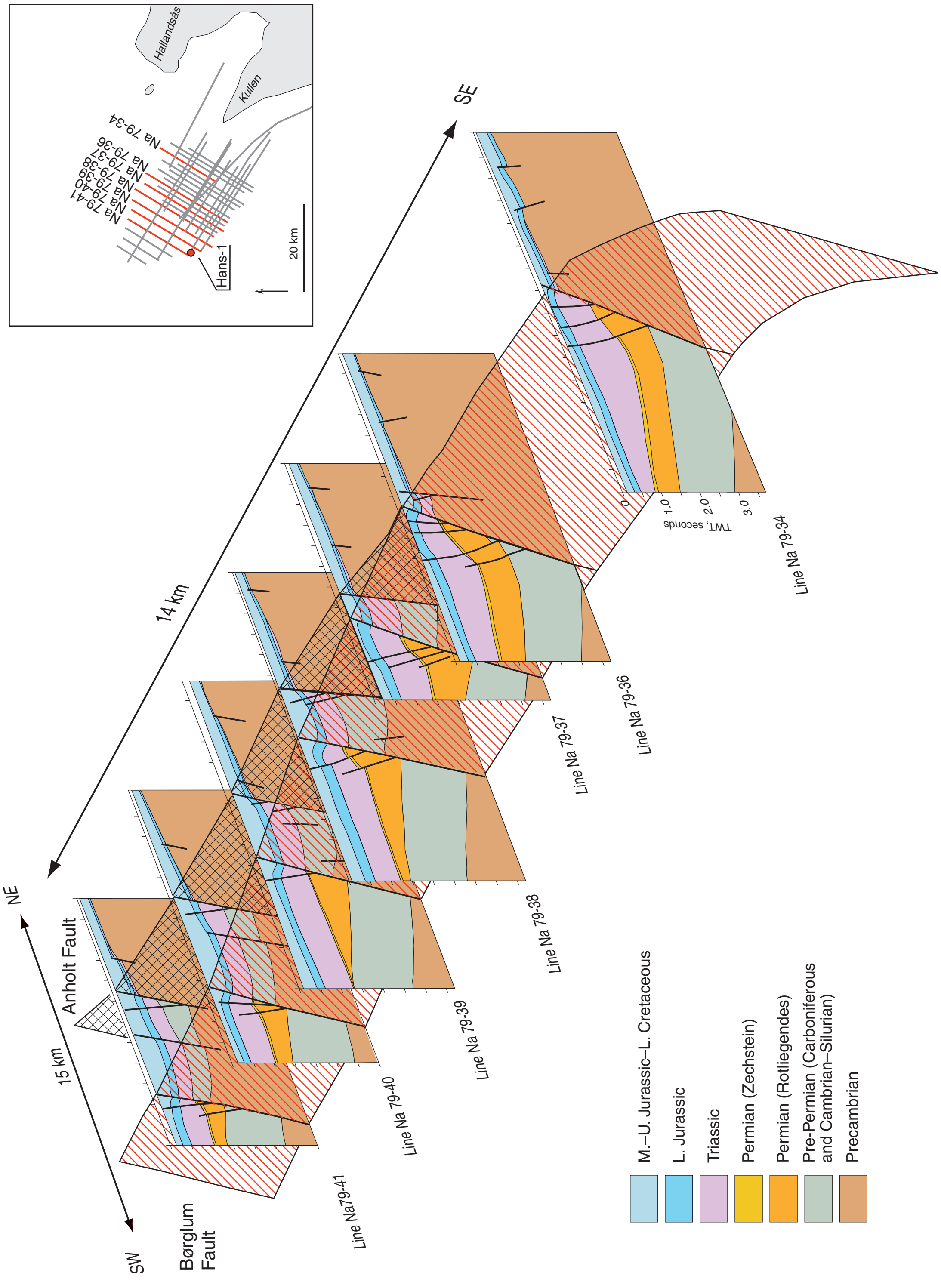


Fig. 13. Sequential linking of interpreted dip-oriented profiles.

BOUGUER GRAVITY AND MAGNETIC ANOMALY MAPS

The strong positive Bouguer gravity anomaly over the area (Fig. 14) correlates with a regional high-density zone that coincides with the Sorgenfrei-Tornquist Zone in central and north-western Scania and through the southern Kattegat. Shallow high-density rocks related to the anomaly do not exist. The gravity high in Scania is, therefore, presumed to relate to intrusive bodies of high-density rock deep in the crust (cf. Balling 1990). A similar model is presented by Thybo et al. (1990) for the Silkeborg gravity high in central Jutland.

In central Scania, the high-density zone partly correlates to the Colonus Shale Trough, with up to 1.5 km of Lower Palaeozoic strata on top of the basement (Larsson 1984, Erlström et al. 1999, 2001). Unless there are several hundred metres thick basaltic bodies in this sequence, there is no other explanation than that the anomaly relates to deeper phenomena in the crust, and possibly to Carboniferous volcanism (cf. Berthelsen 1992). Bodies of intrusive rocks deep in the crust were, however, also probably formed during intense Mid-Jurassic volcanism in central Scania (Norling et al. 1993). Basalt of Lower Jurassic age is inferred by Wikman & Bergström (1987) to occur on Hallands Väderö, suggesting that corresponding Jurassic volcanism occurred in the southern Kattegat.

Narrow west-north-west oriented magnetic anomalies in Scania are almost exclusively related to the occurrence of vertical to sub-vertical, up to 50 m wide dolerite dykes. They were formed towards the close of the Carboniferous, when Baltica's south-western crust, around Scania and neighbouring areas, became fissured and intruded by a dense swarm of basalt dykes. These are probably remnants of feeder dykes for a cap of subaerially extruded Late Carboniferous basalt flows. A basaltic cover probably capped at least parts of Scania (Bergström et al. 1982, Sørensen 1986). In the Kattegat and in Jutland, borehole data verify Carboniferous volcanism in the vicinity of the Sorgenfrei-Tornquist Zone (Michelsen & Nielsen 1993). The narrow positive anomalies are also seen in Skälderviken Basin, indicating thin Triassic–Jurassic cover strata, which permits the dykes to be resolved by the magnetic data (Fig. 15).

More or less north–south and north-east to south-west oriented anomalies are also seen in the magnetic data (Fig. 15). These are more evident in south-eastern Scania

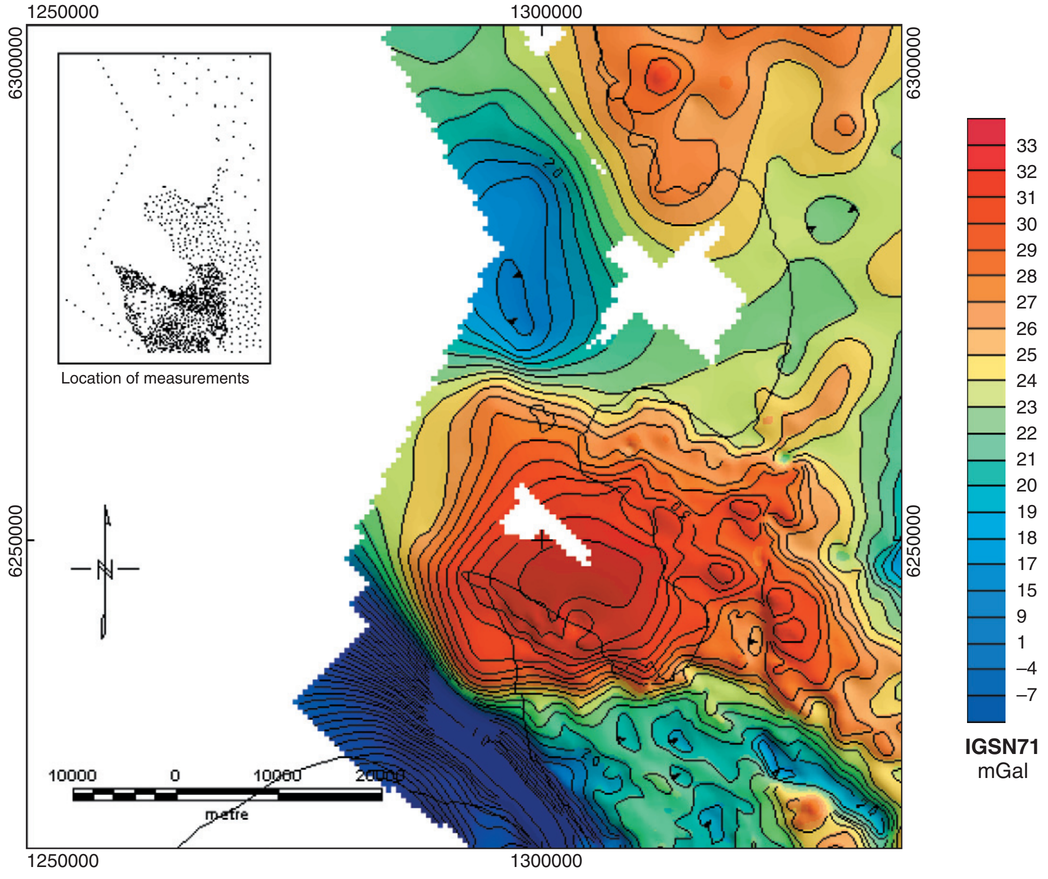


Fig. 14. Bouguer gravity map of north-west Scania and immediately adjacent offshore areas.

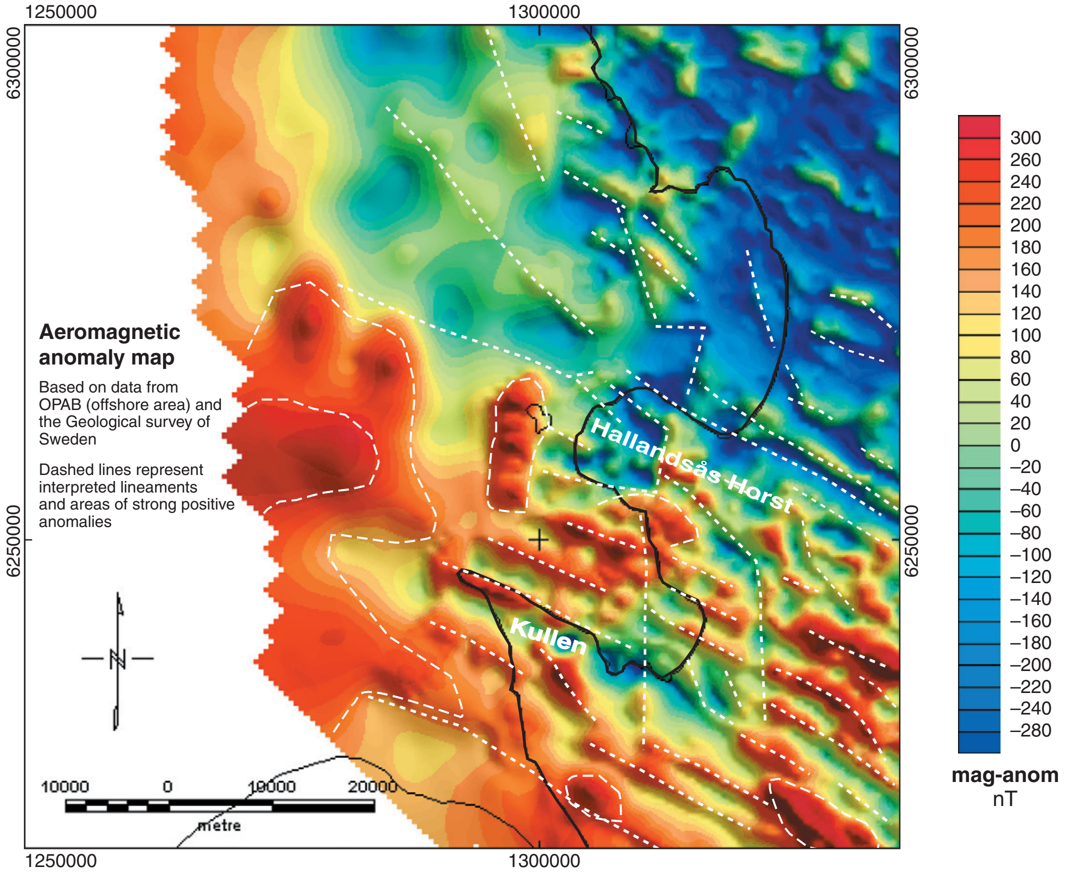


Fig. 15. Aeromagnetic anomaly map of north-west Scania and the southern Kattegat.

(Erlström et al. 2001) and are interpreted as partly related to extension faults of Late Palaeozoic age.

The quality of the magnetic data for the southern Kattegat does not permit an equally detailed interpretation. Positive magnetic anomalies in the offshore area off Kullen, however, seem to correlate with the bodies of Carboniferous basalt in the Hans Half-Graben, as documented by the Hans-1 well. Conspicuous strong positive anomalies in the offshore continuation of the Hallandsås Horst are not attributed to the same source. The two westerly semicircular anomalies seem to correlate to the junction between the Hallandsås and Anholt fault zones.

MODEL OF BEDROCK GEOLOGY

For the first time, a composite map (Fig. 16) of both onshore and offshore bedrock geology can be presented for north-western Scania and the southern Kattegat. The map displays a dominant Jurassic bedrock surface in the offshore areas. However, a detail subdivision the Jurassic strata is difficult. The Quaternary subcrop north-east of the Børglum Fault probably consists of Middle and Upper Jurassic strata, while the Jurassic in the area south-west of the fault is older. This is the result of inversion, uplift and erosion during the Late Cretaceous–Palaeogene.

The Precambrian onshore terrain of the Hallandsås Horst extends approximately 20 km offshore to the north-west. The horst block dips gently to the south-west and is, in the same direction, progressively covered by Triassic–Jurassic strata. The Hallandsås Fault separates the horst from the Late Cretaceous bag-shaped basin in the north (Fig. 13). The southern flank of the horst is less well defined. It consists of a series of parallel stepwise faults towards the Ängelholm-Skälderviken Trough.

Pre-existing cover strata have been more or less completely removed within the Precambrian horst terrain. At relatively high altitudes on the horst there exist erosional remains of Lower Jurassic cover strata. A Norian–Rhaetian outlier at 155 m a.s.l. occurs at Killeröd (Erlström & Guy-Ohlson 1999). Corresponding stratigraphic Lower Jurassic levels at Killeröd occur at 200–400 m b.s.l.

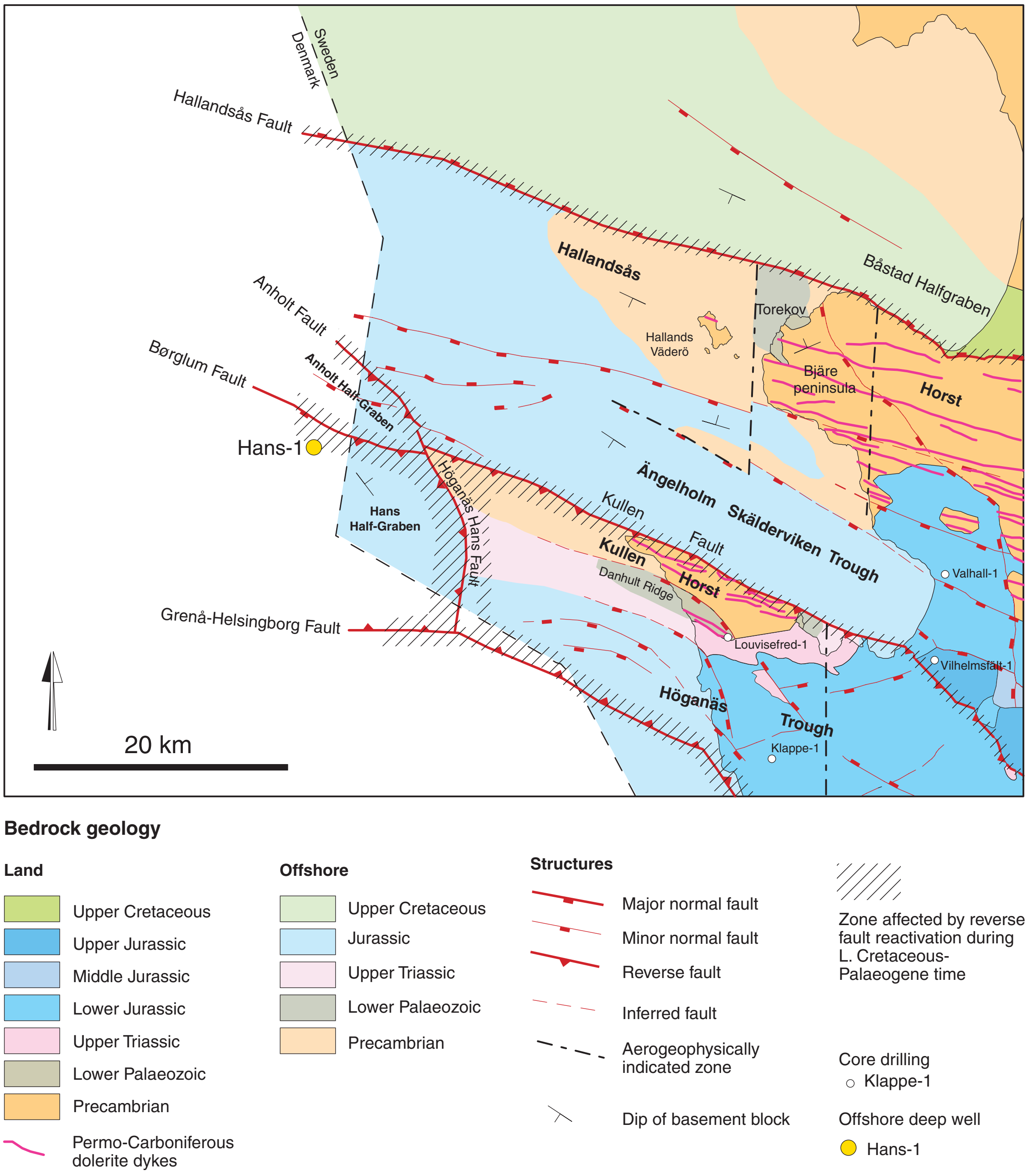


Fig. 16. Model of bedrock geology of the southern Kattegat and north-west Scania.

in the Ängelholm-Skälderviken Trough. Occurrences of Lower Palaeozoic strata at Torekov (Wikman & Bergström 1987) may be the outskirts of an offshore continuing north-westward dipping block, between Hallands Väderö and the mainland.

Cretaceous strata only occur to the north of the Hallandsås Fault. Upper Cretaceous (Santonian–Maastrichtian) marine sediments dominate the deposits. The strata are truncated to the north-east by a mainly Palaeogene erosion surface. Scattered outliers have been verified along the coast of Halland, e.g. at Särdal (Bergström et al. 1973). Cretaceous deposits overlie the Precambrian crystalline basement in the easternmost parts of the area. In some parts of the investigated area, the Cretaceous overlies a thin Jurassic, probably Lower Jurassic, succession (Fig. 12). In the Båstad area, the Cretaceous sequence consists of Albian–Cenomanian glauconitic sand and Santonian–Campanian glauconitic sand and biocalcarenite with a total thickness of more than 100 m.

The bedrock geology in the area sandwiched between the Kullen and Grenå-Helsingborg fault zones is complex and difficult to define. Several sub-parallel north-west-oriented faults that transect the area contribute to the complexity of the bedrock geology. The presented geology of this area is therefore speculative, especially in the transition zone between land and offshore data. The bedrock geometry is characterised by a Precambrian basement high, distinctively bordered to the north by the Kullen Fault and to the south by a number of stepwise normal faults. The sedimentary cover strata are truncated by erosion, yielding successively younger strata to the south. In general, Triassic strata overlie the Precambrian basement, except for areas with Lower Palaeozoic erosional remains.

The offshore continuations of the main faults are easy to map. These faults are all associated with significant throws, which in the case of the Børglum Fault reach more than 7 km. They are commonly associated with an inverse component, which is especially significant in the Grenå–Helsingborg and Børglum faults. The inversion and reverse reactivation of these faults is here displayed as a relative uplift of the deposits on the uplifted side, caused by movements along antithetic fault splays that link with the main fault at depth. The anticlinal dome-like uplifted block is then severely truncated by erosion (cf. cross-sections in Figs. 10–11).

STRUCTURAL DEVELOPMENT

Reconstructions of the tectonic events are illustrated in Figs. 17a–c and 18 and relate to a dip-oriented profile across the study area. The different phases and events are partly based on information from Mogensen (1994, 1995) and Erlström et al. (1997, 2001).

Pre-rift

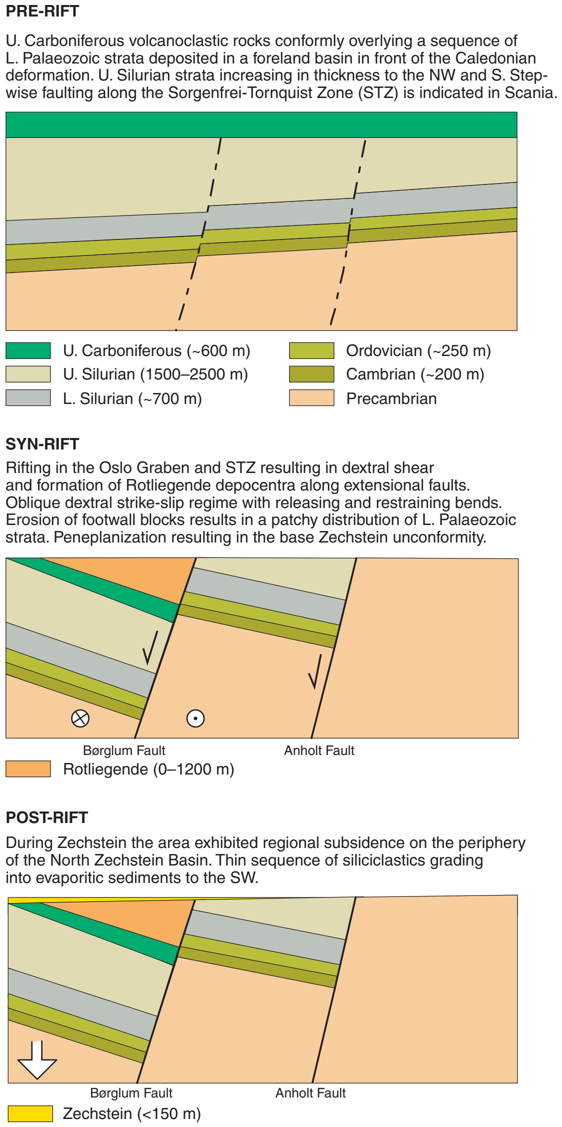
The pre-rift Cambrian–Carboniferous succession includes Upper Carboniferous volcanoclastic rocks conformably overlying a thick sequence of Lower Palaeozoic fine-grained strata. Deposition of these units took place in a subsiding foreland basin in front of the Caledonian orogenic belt. All the pre-rift strata are, as seen in Figures 9–12, parallel and conformable, indicating a uniform regional subsidence.

However, the pre-rift sequence experienced deep erosion during later tectonic events, especially in connection with peneplanation and formation of the base Zechstein unconformity. This has resulted in a patchy and generally incomplete representation of pre-rift strata on the south-western part of Baltica. Only at a few scattered locations along the Sorgenfrei-Tornquist Zone, where syn-rift deposits have protected the pre-rift sequence in down-faulted half grabens, is there evidence of the complete thickness.

One of these locations is in the Hans Half-Graben on the down-thrown side of the Børglum Fault (Fig. 17a). Here the whole succession is preserved and the thickness can be accurately estimated from the seismic data. In the Swedish sector of the Kattegat, this is in excess of 3.5 km. These thicknesses are dip-corrected and use relations based on acoustic surveys in Terne-1 (Nielsen & Japsen 1991). Mogensen (1994) gives a thickness of up to 4.0 km for adjacent Danish parts of the Kattegat.

In central Scania, the thickness of the preserved pre-rift sequence is estimated to be in the region of 1.5 km, i.e. significantly less than in the Kattegat area. However, in Scania, parts of the Silurian and all of the postulated Carboniferous strata have been removed by erosion. Seismic data from the Bornholm Gat, off south-eastern Scania, indicate pre-rift sequences in the range of 1.8–2.0 km thick. On the basis of information on the pre-existence of Carboniferous strata (cf. previous sections), borehole data from Hans-1 and Terne-1 and seismic data, it is postulated that the complete sequence of Scanian pre-rift deposits is unlikely to have exceeded 3.5 km.

The Cambrian–Lower Silurian interval is fairly constant in thickness over the whole south-western part of Baltica (Bergström et al. 1982, Michelsen & Nielsen 1991). The subsidence culminated in the Late Silurian (Michelsen & Nielsen 1991, 1993), as is verified by Upper Silurian strata increasing in thickness to the north-west and south. This corresponds to a foreland deep in front of the Scandinavian Caledonides (Mogensen 1994). The thickness of the Upper Silurian is estimated to be in the range of 2.5 km in the Swedish part of the Kattegat and 700–1000 m in central Scania. Early Palaeozoic stepwise faulting towards the south is indicated in Scania along the main faults which were to be involved in the subsequent formation of the Sorgenfrei-Tornquist Zone (Erlström et al. 1999, 2001). Early Palaeozoic movements occurred especially along the Kullen-Ringsjön-Andrarum Fault Zone. The Upper Carboniferous volcanoclastics are approximately time-equivalent to the volcanic activity in the Oslo Graben (Michelsen & Nielsen 1993) and to the extensive occurrence of north-west–south-east striking dolerite dykes in Scania. These deposits were formed as precursors to the Early Permian rifting and the development of the Sorgenfrei-Tornquist Zone.



PRE-RIFT

U. Carboniferous volcanoclastic rocks conformly overlying a sequence of L. Palaeozoic strata deposited in a foreland basin in front of the Caledonian deformation. U. Silurian strata increasing in thickness to the NW and S. Stepwise faulting along the Sorgenfrei-Tornquist Zone (STZ) is indicated in Scania.

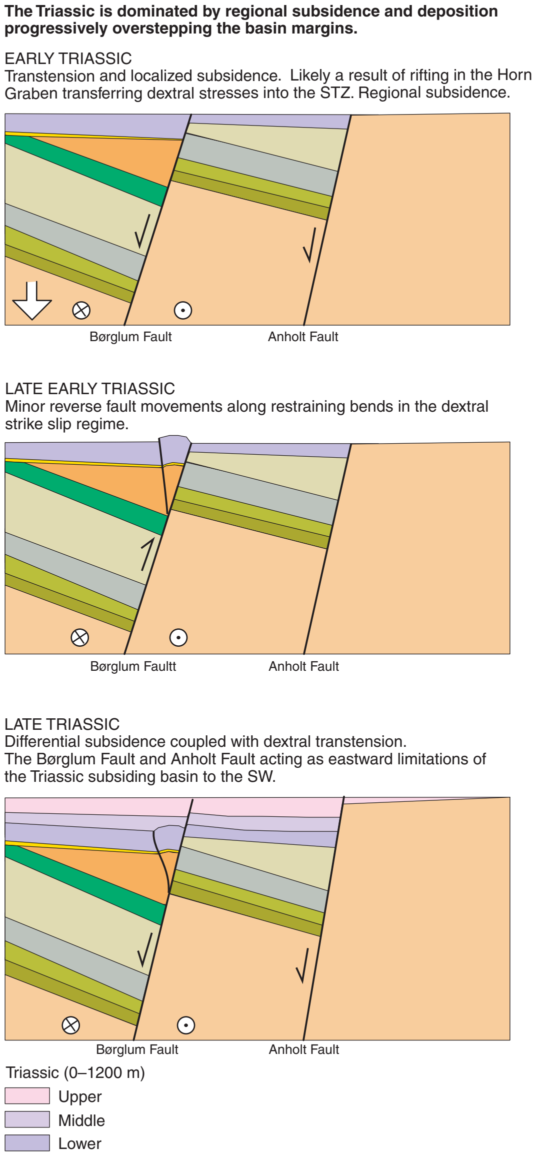
SYN-RIFT

Rifting in the Oslo Graben and STZ resulting in dextral shear and formation of Rotliegende depocentra along extensional faults. Oblique dextral strike-slip regime with releasing and restraining bends. Erosion of footwall blocks results in a patchy distribution of L. Palaeozoic strata. Peneplanization resulting in the base Zechstein unconformity.

POST-RIFT

During Zechstein the area exhibited regional subsidence on the periphery of the North Zechstein Basin. Thin sequence of siliciclastics grading into evaporitic sediments to the SW.

Fig. 17a. Summary of main tectonic events and structural evolution of the investigated area.



The Triassic is dominated by regional subsidence and deposition progressively overstepping the basin margins.

EARLY TRIASSIC

Transtension and localized subsidence. Likely a result of rifting in the Horn Graben transferring dextral stresses into the STZ. Regional subsidence.

LATE EARLY TRIASSIC

Minor reverse fault movements along restraining bends in the dextral strike slip regime.

LATE TRIASSIC

Differential subsidence coupled with dextral transtension. The Børglum Fault and Anholt Fault acting as eastward limitations of the Triassic subsiding basin to the SW.

Fig. 17b. Summary of main tectonic events and structural evolution of the investigated area.

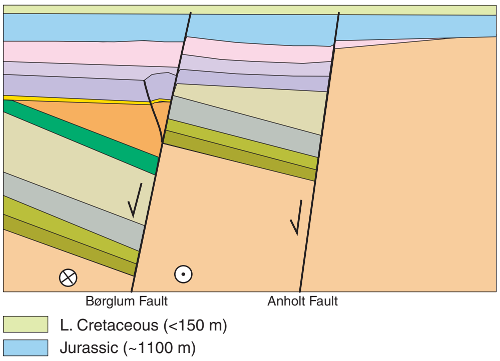
Syn-rift

During the Early Mesozoic (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 saw extension in the Oslo Graben and an oblique dextral shear on the Sorgenfrei-Tornquist Zone. This led to zones of uplift and subsidence accompanied by restraining and releasing bends along the Sorgenfrei-Tornquist Zone in the Kattegat (Fig. 18).

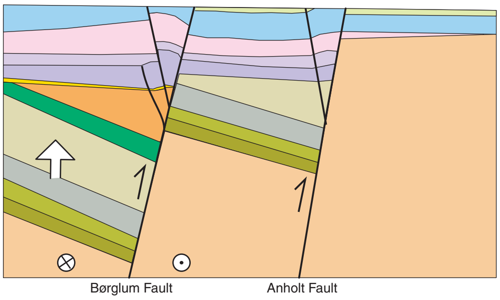
The Lower Palaeozoic sequence was downfaulted and more or less protected against denudation in half-grabens (Fig. 17a). This pattern can be followed eastward into Scania. Here the Colonus Shale Trough displays the same pattern (Mogensen 1994, Erlström et al. 2001). Local depocentres formed along releasing 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 basin when the subsidence ended in the Mid Permian.

Similar release caused by transtension in south-western Scania, along the Öresund and Svedala faults, resulted in the down-throw of Lower Palaeozoic strata in the Höllviken Graben. Sivhed et al. (1999) postulate on the basis of lithological data from cores and seismic surveys the occurrence of thin remains of a syn-rift coarse clastic Rotliegendes sequence in the Höllviken Graben.

JURASSIC – EARLY CRETACEOUS
Extension and differential subsidence during M. Jurassic associated with minor lateral movements. Regional subsidence during E. Cretaceous.



LATE CRETACEOUS – PALAEOGENE
Dextral transpression/inversion. Reactivation of major fault zones.



NEOGENE
General uplift. Extensive erosion of U. Cretaceous strata.

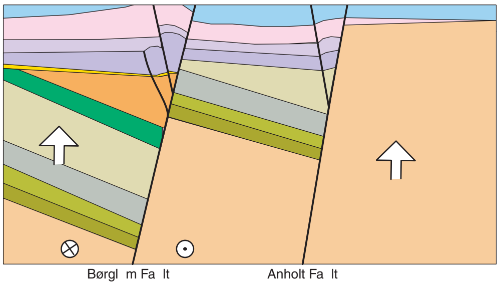


Fig. 17c. Summary of main tectonic events and structural evolution of the investigated area.

In the study area, two extensional subsiding half-grabens developed along the Anholt and Børglum faults. This is clearly illustrated in the cross-sections in Figure 17a and in the pre-rift isopach map (Fig. 7). Syn-rift 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, i.e. Höganäs-Hans Fault (cf. Fig. 16). The lateral displacement along the fault is estimated at 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 (Fig. 18).

Post-rift

Upper Permian

At the end of the rifting phase, probably in the Middle Permian (Michelsen & Nielsen 1991, Mogensen 1994, 1995), the investigated area was eroded and a major regional discordant erosion surface was formed, resulting in the pre-Zechstein unconformity. The top pre-Zechstein structure map (Fig. 6, Vejbæk et al. 1994) shows the present-day configuration of the peneplane and also sums up all the post-Middle Permian tectonic events.

During the Zechstein, the area underwent regional subsidence on the periphery of the Northern European Basin and the Sorgenfrei-Tornquist Zone acted as an arbitrary north-eastern margin of the North Zechstein Basin. This sequence of siliciclastic sediments in the border area grades into evaporitic sediments in a south-west direction. The Zechstein deposits have an approximate maximum thickness of less than 150 m in the investigated part of the Kattegat. These deposits probably did not extend far beyond their present distribution. The Sorgenfrei-Tornquist Zone and the Skagerrak-Kattegat Platform began during the Mid–Late Permian to act as a marginal zone to the subsiding Norwegian-Danish Basin that was evolving to the south-west. In contrast to the distal parts of the basin, the mobility of the Zechstein in the area was insignificant, since the deposits are of a marginal clastic character without major salt layers.

Triassic

Regional subsidence continued into the Early and Middle Triassic. Sedimentation was strongly influenced by rifting and block faulting in a west-north-west to north-west trending zone from Scania to northern Jutland. The Triassic sequence rests conformably on the Zechstein evaporites and oversteps onto Lower Palaeozoic sediments to the north-east. Uplift and erosion of the adjacent Baltic Shield to the north-east provided material for a thick coarse clastic succession.

Differential subsidence inside the Sorgenfrei-Tornquist Zone started to overshadow the regional subsidence during the deposition of the Late Triassic–Early Jurassic Gassum Formation.

Minor Middle Triassic tectonic activity is demonstrated by minor thrust faults terminating in the Triassic.

In the Late Triassic, the area was dominated by a lateral strike-slip regime (dextral transtension) initiated by the intensive rifting in the Horn Graben (Clausen & Korstgård 1993) with a west-north-west–east-south-east oriented stress field.

Late Triassic deposition took place in releasing bends (pull-apart basins) and push-ups in the Sorgenfrei-Torn-

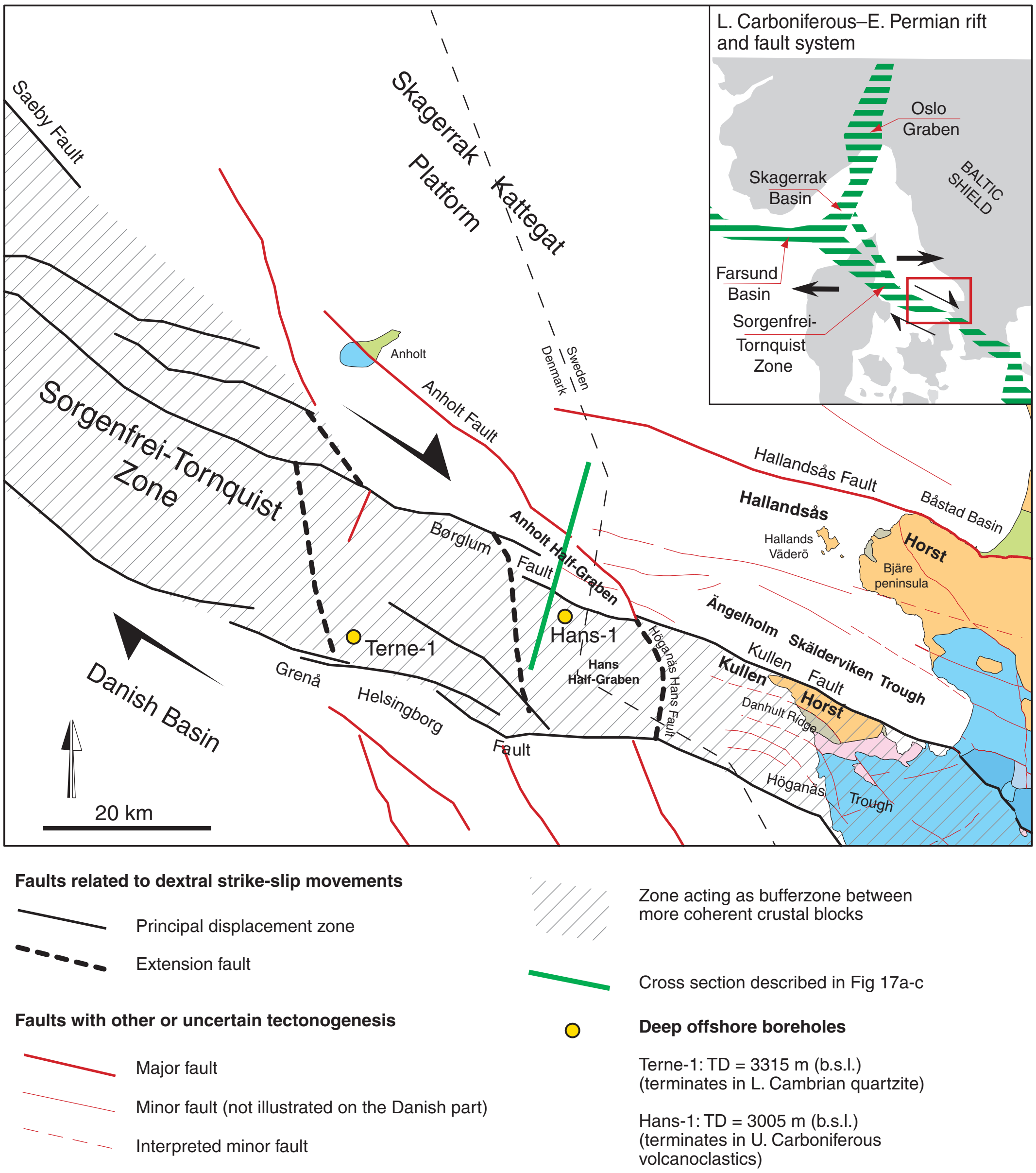


Fig. 18. Regional structures in the southern Kattegat (partly based on Mogensen 1994, 1995). Legend for bedrock geology, see Fig. 16.

quist Zone. The Svedala Fault and the Höllviken Graben (Erlström et al. 1997, Sivhed et al. 1999) in south-western Scania are other examples of fault systems active at the same time.

Differential subsidence during this time is indicated south-west of the Børglum Fault and in the area between the Børglum and Anholt faults (Fig. 17b). Here, the Triassic strata dip to the north-east, increasing in thickness in the same direction. Their maximum thickness is 1 s (TWT), corresponding to about 2 km. The subsidence decreases stepwise in a north-eastern direction, and Triassic sediments are thin or absent on the investigated part of the Skagerrak-Kattegat Platform. A 15 m thick sequence of Upper Triassic sediment resting on Precambrian crystalline rocks in a fault-bounded trough is, however, found on the Hallandsås Horst in Scania (Erlström & Guy-Ohlson 1999).

Jurassic–Early Cretaceous

The Late Triassic differential subsidence continued in the Middle and Late Jurassic and the Early Cretaceous, with restricted fault activity (Mogensen 1995). On the Skagerrak-Kattegat Platform, north of the Hallandsås Fault, sedimentary rocks interpreted as Middle Jurassic–Early Cretaceous are preserved in a downfaulted area beneath a Cretaceous succession (Fig. 12).

The Lower Jurassic sequence pinches out north of the Børglum Fault. North of the Anholt Fault and north of the eastern part of the Børglum Fault, the Lower Jurassic sequences overlap the Precambrian crystalline basement of the Skagerrak-Kattegat Platform. Thin, rudimentary Triassic strata might, however, cover parts of the Precambrian crystalline basement.

There is a stepwise decrease in the thickness of the Lower Jurassic sequence north-east of the Anholt and Kullen faults. This is an indication of Early–Mid Jurassic tectonic activity (mid-Kimmerian tectonics), coupled with tectonic uplift and erosion of the area north of the fault (Norling & Bergström 1987, Ziegler 1987, 1990, Mogensen 1995).

Owing to repeated transgression, regression, and tectonic activity, the Jurassic deposits exhibit a complex stratigraphy in Scania (Norling et al. 1993).

The Early Cretaceous was a period of relative quiescence, with the deposition of uniform, fairly thin mixed clastic deposits in the marginal parts of the Norwegian-Danish Basin. These are represented by thin sequences of Cenomanian (Albian?) glauconitic sandstone in the Båstad Half-Graben (Wikman & Bergström 1987).

Late Cretaceous–Palaeogene

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 Palaeogene. 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 reached its maximum 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 (Erlström 1990, Sivhed et al. 1999).

The inversion regained its force again in northern Europe during the Palaeocene, especially in the south-eastern part of the Tornquist Zone, i.e. the Polish Trough. This inversion is referred to as the Laramide phase (Norling & Bergström 1987, Ziegler 1990).

Compression and crustal shortening was accommodated by reactivation of the main faults incorporated in the Sorgenfrei-Tornquist Zone. The inversion was caused by right lateral transpression along this feature. 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 (Fig. 17c). The absence of major inversion features along the Anholt Fault implies that compression was accommodated along this fault by dextral strike-slip displacement (Kape 1997). This is illustrated in the profiles crossing the Børglum Fault (Figs. 9–12), which clearly show inversion in the southern part of the fault. The same diagrams show minor inversion on the southern side of the Anholt Fault.

The inverted uplifted area was bordered to the north and south by subsiding basins where sedimentation continued through the Late Cretaceous–Early Palaeogene. 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).

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 pre-existing 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).

As a result of the inversion, a coherent Upper Cretaceous cover in the North Sea Basin, including the Kattegat-Skagerrak Platform, is missing in the investigated area south of the Hallandsås Fault. North of the Hallandsås Fault and north of the area with intense inversion tectonics, Cretaceous strata are identified in seismic sections (Fig. 13). The Cretaceous sequence is protected against weathering in a downfaulted area dipping slightly to the south-east. It can be followed eastward into the Båstad Half-Graben on the Swedish mainland and westward into the North Sea Basin.

Neogene uplift

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 which has affected the continental margins around the North Atlantic. On the basis of basin modelling and well data, Japsen & Bidstrup (1999) calculated the missing sequence to be 1.0–1.2 km thick along the Skagerrak-Kattegat Platform (within the investigated area).

DISCUSSION

The subsurface geology and structural evolution of this part of the Kattegat is partly well known from seismic data tied into well data, including the Hans-1 and Terne-1 wells. Uncertainties still remain, however, concerning the exact configuration of the linkage between the Børglum, Kullen, and Anholt fault systems. This is mainly due to difficulties in correlation. The seismic lines obtained close to the coast and across the wide zone of minor antithetic faults developed in connection with the inversion are of relatively poor quality.

Mogensen (1994, 1995) considers the Børglum Fault to join up with the Anholt Fault and bend southwards, joining up with the Grenå-Helsingborg Fault. Others (Vejbæk et al. 1994, Kape 1997) consider the southward bend to be a separate extension fault branching off the Børglum Fault in the same manner as two other faults to the west (Mogensen 1994). In this study we consider the joining fault as a separate extension fault, i.e. the Höganäs-Hans Fault. Our study cannot verify that there is a clear continuous communication between the Børglum and Kullen faults. However, it is most likely that the two faults are related, since there are indications of dextral transtension along the Kullen-Ringsjön-Andrarum Fault Zone in Scania similar to that found along the Børglum Fault in the Kattegat. The exact mode of connection between the two may be of an overstep character, with an interfingering relay ramp. In our study we consider this to be the most likely model.

The exact manner of the Jurassic–Lower Cretaceous differential subsidence is another area of uncertainty in our modelling work, since the sequence is strongly affected by deep erosion during the inversion and uplift phases. There are also problems in the stratigraphic determination of the Jurassic levels on the north-east side of the Børglum Fault. Our interpretation is based only on seismic reflector characterisation and data from onshore geology in the Ängelholm-Skälderviken Trough.

In spite of this the subsurface data from the southern Kattegat provide valuable information, complementing data on the onshore geology of north-western Scania.

The detailed subsurface structure of the intra-plate Sorgenfrei-Tornquist Zone in Scania is relatively unknown. Since only minor hydrocarbon exploration has been performed within and north of the Sorgenfrei-Tornquist Zone in Scania, onshore information in this area is almost entirely restricted to shallow wells and a few onshore seismic lines. For this reason, the exact three-dimensional architecture of the different fault systems is poorly known.

A good example of how offshore and onshore data complement each other is the Palaeozoic history of the area. Early Palaeozoic sedimentary rocks are mainly known from south-east Scania. For north-west Scania, on the other hand, only limited information is available. For this reason there has been much speculation as to the total thickness of the same sequence. The Kattegat study presents part of the solution, as we here can see the entire thickness of the Lower Palaeozoic sequence.

There are only minor indications of Early Palaeozoic tectonic movements along the Børglum and Grenå-Helsingborg faults. The onshore continuation of these fault systems in Scania consists of the Kullen-Ringsjön-Andrarum and Romeleåsen faults. These faults form the north-east and also the north-western part of the south-west delimitation of the Colonus Shale Trough. This means that the Colonus Shale Trough was not an active depocentre during the Late Silurian. It is instead a downfaulted area caused by Variscan wrench faulting in which the Lower Palaeozoic sequence was more or less protected from denudation. The structure has been overprinted by Alpine inversion.

Another interesting question is the origin of the numerous Late Carboniferous–Early Permian dolerite dykes in Scania. These dykes are only known from Scania and the question has been raised whether any extrusive deposits, such as lava flows and volcanic ashes were connected with them. The same situation is reported from Hans-1. In Hans-1, however, only Rotliegendes volcanoclastic rocks have been recognised.

The origins of tectonic structures such as the north-south orientated Svedala Fault and the Höllviken Graben in south-western Scania are probably connected to periods of wrench faulting and deposition of thick clastics in downfaulted areas in the Mid–Late Triassic. In the offshore part of the Sorgenfrei-Tornquist Zone, however, this event started in the Late Permian.

Late Cretaceous–Early Palaeogene Alpine inversion tectonics are, in Scania, mainly documented by the interplay between uplift, erosion and deposition. Synchronously with the uplift of areas within the Sorgenfrei-Tornquist Zone, large amounts of clastics were eroded from the uplifted highs and deposited adjacent to the fault scarps, e.g. the up to 900 m thick Lund Sandstone (Erlström 1990).

CONCLUSIONS

The results represent a further contribution to the complex and important geology of the southern Kattegat and north-western Scania. On the basis of constrained onshore geology and commercial marine seismic surveys, maps and profiles have been generated which outline the subsurface geometry and bedrock geology of the Swedish part of the southern Kattegat. Using these, the structural evolution of the area has been reconstructed.

The study area underwent a complex geological evolution, with dextral strike-slip movements along the main faults bordering the Sorgenfrei-Tornquist Zone. The transtension was accommodated by a number of north–south directed extension faults branching off the Børglum Fault. Localised depocentres were formed and thick Rotliegendes syn-rift deposits were laid down. The underlying protected Lower Palaeozoic sequence provides valuable information about the thickness of the pre-rift deposits on the south-western margin of Baltica in the Caledonian foreland basin. Up to 3.5 km thick pre-rift deposits are indicated by the seismic data.

The study has also demonstrated the existence of Carboniferous and Permian strata in Sweden which, prior to this study, had not been presented to a wider audience.

Aeromagnetic and Bouguer gravity data have been presented for the first time, showing anomalies that are interpreted as mainly Carboniferous intrusion of magmatic rocks in the crust.

Extensive erosion is verified by a pre-Zechstein unconformity prior to the rapid subsidence and formation of the Norwegian-Danish Basin. The Swedish part of the Kattegat began from the Zechstein to act as a marginal zone to the basin evolving to the south-west. Especially during the Triassic–Jurassic, significant differential subsidence occurred in the area of the Sorgenfrei-Tornquist Zone. Thick Triassic deposits adjacent to the downthrown side of the Børglum and Anholt faults indicate that these were active. To the north of the zone, Triassic strata are thin or absent.

The Jurassic strata are strongly affected by deep erosion in the Sorgenfrei-Tornquist Zone, as are the Cretaceous strata, which have been completely removed as a result of Late Cretaceous–Palaeogene inversion and Neogene uplift in the range of 1–3 km in the Scania–Kattegat area. The inversion was mainly released by reverse reactivation of the main faults bordering the Sorgenfrei-Tornquist Zone in a dextral transpressional regime. The Neogene uplift resulted in a sub-Quaternary unconformity truncating the Mesozoic sequence.

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