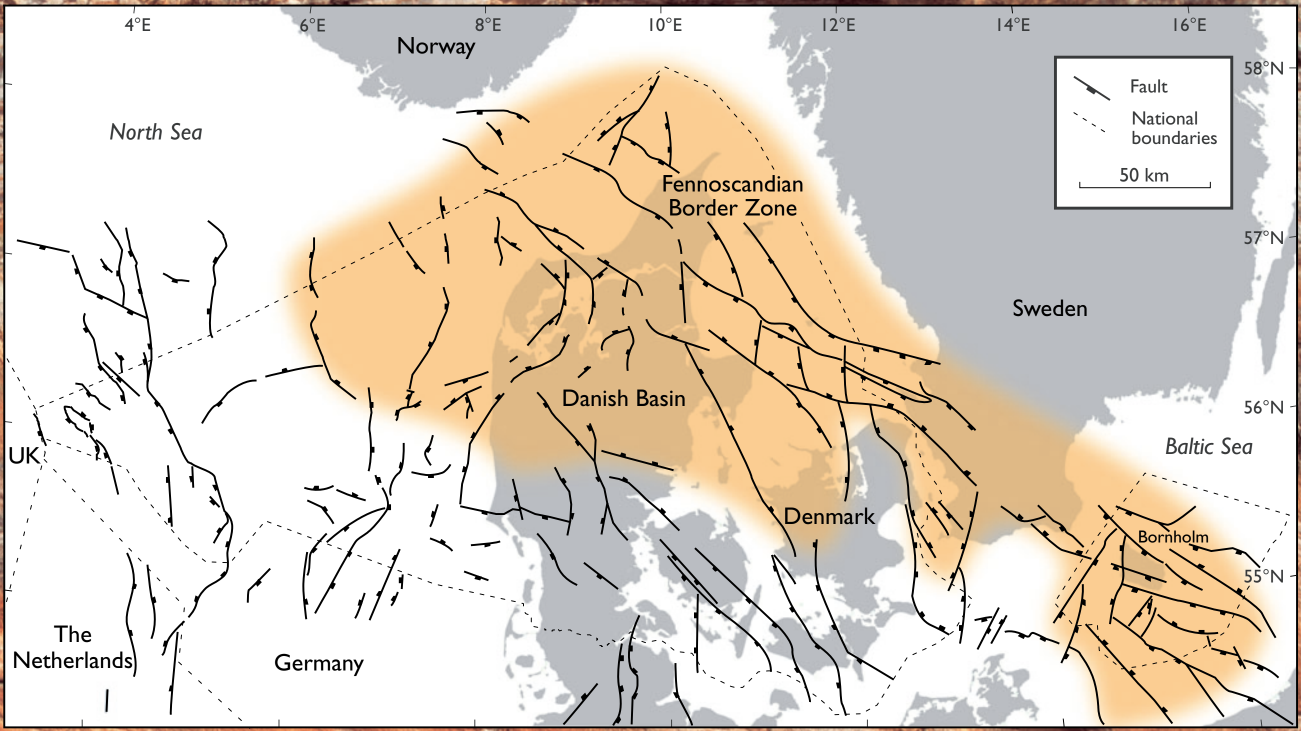
DANISH BASIN AND FENNOSCANDIAN BORDER ZONE



Triassic and Jurassic transtension along part of the Sorgenfrei–Tornquist Zone in the Danish Kattegat

Tommy Egebjerg Mogensen and John A. Korstgård

In the Kattegat area, Denmark, the Sorgenfrei–Tornquist Zone, an old crustal weakness zone, was repeatedly reactivated during Triassic, Jurassic and Early Cretaceous times with dextral transtensional movements along the major boundary faults. These tectonic events were minor compared to the tectonic events of the Late Carboniferous – Early Permian and the Late Cretaceous – Early Tertiary, although a dynamic structural and stratigraphic analysis indicates that the Sorgenfrei–Tornquist Zone was active compared to the surrounding areas.

At the end of the Palaeozoic, the area was a peneplain. Regional Triassic subsidence caused onlap towards the north-east, where the youngest Triassic sediments overlie Precambrian crystalline basement. During the Early Triassic, several of the major Early Permian faults were reactivated, probably with dextral strike-slip along the Børglum Fault. Jurassic – Early Cretaceous subsidence was restricted primarily to the area between the two main faults in the Sorgenfrei–Tornquist Zone, the Grenå–Helsingborg Fault and the Børglum Fault. This restriction of basin development indicates a change in the regional stress field at the Triassic–Jurassic transition. Middle Jurassic and Late Jurassic – Early Cretaceous subsidence followed the Early Jurassic pattern with local subsidence in the Sorgenfrei–Tornquist Zone, but now even more restricted to within the zone. The subsidence showed a decrease in the Middle Jurassic, and increased again during Late Jurassic – Early Cretaceous times. Small faults were generated internally in the Sorgenfrei–Tornquist Zone during the Mesozoic with a pattern that indicates a broad transfer of strike-slip/oblique-slip motion from the Grenå–Helsingborg Fault to the Børglum Fault.

Keywords: Kattegat, Denmark, Sorgenfrei–Tornquist Zone, Triassic–Jurassic, Børglum Fault, Grenå–Helsingborg Fault, transtension, structural evolution

T.E.M., *Norsk Hydro a.s., N-0246 Oslo, Norway.* E-mail: *tommy.mogensen.egebjerg@hydro.com*

J.A.K., *Geological Institute, University of Aarhus, C.F. Møllers Allé 120, DK-8000 Århus C, Denmark.*

The Tornquist Zone is a fundamental tectonic lineament representing the south-western margin of the Baltic Shield (Fig. 1). The lineament runs north-west from the Carpathians across Poland, where it is known as the Teisseyre–Tornquist Zone, and into the Scandinavian area, where it is known as the Sorgenfrei–Tornquist Zone (EUGENO-S Working Group 1988). It crosses northern Denmark in a NW–SE direction and extends as far as the Viking Graben in the North Sea (Pegrum 1984). The lineament had its origin in Precambrian times and faults defining the lineament have been intermittently active until the present day. It is characterised by complex extensional and strike-slip faulting and structural inversion (Liboriussen *et al.* 1987; EUGENO-S Working Group 1988; Mogensen 1992a, b, 1994; Mogensen & Korstgård 1993; Christensen & Korstgård 1994; Mogensen & Jensen 1994).

The Sorgenfrei–Tornquist Zone within and adjacent to the Kattegat area (Fig. 1), has been described in several papers, based on field information (Bergström *et al.* 1982; Norling & Bergström 1987; Sivhed 1991), well data (Michelsen & Nielsen 1991, 1993; Jensen & Michelsen

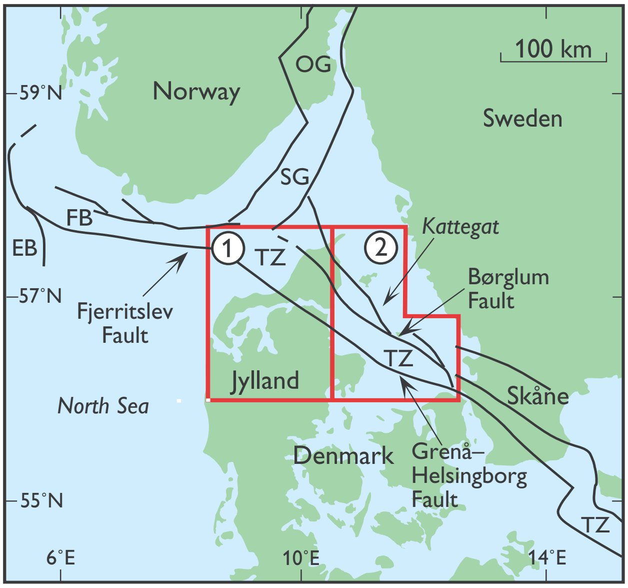


Fig. 1. Southern Scandinavia showing the Sorgenfrei–Tornquist Zone and the area of study (outlined areas **1** and **2** – area 2 was investigated in particular detail). **EB**, Egersund Basin; **FB**, Farsund Basin; **OG**, Oslo Graben; **SG**, Skagerrak Graben; **TZ**, Sorgenfrei–Tornquist Zone.

1992), deep reflection – refraction seismic data (EUGENO-S Working Group 1988; Lie & Husebye 1992), and reflection seismic data (Baartman & Christensen 1975; Bergström 1984; Pegrum 1984; Liboriussen *et al.* 1987; Ziegler 1987, 1990; Aubert 1988; Bergström *et al.* 1990a, b; Ro *et al.* 1990a; Vejbæk 1990). The majority of these studies have proposed lateral movements along the Sorgenfrei–Tornquist Zone with right-lateral movements during the Palaeozoic and generally left-lateral movements during the Mesozoic (Bergström *et al.* 1982; Pegrum 1984; Liboriussen *et al.* 1987; Norling & Bergström 1987; Aubert 1988; Sivhed 1991).

Many of the earlier Kattegat studies based on reflection seismic data suffered from large line spacing (Pegrum 1984; Aubert 1988). The average spacing prior to the seismic surveys from the mid-1980s was around 10 km, which severely hampered detailed structural interpretation such as fault correlation and depocentre configuration along the Sorgenfrei–Tornquist Zone. Interpretation of closely-spaced 2D reflection seismic data (1 km spacing in the middle of Kattegat, Fig. 2), released to Danish research institutions in the early 1990s, and

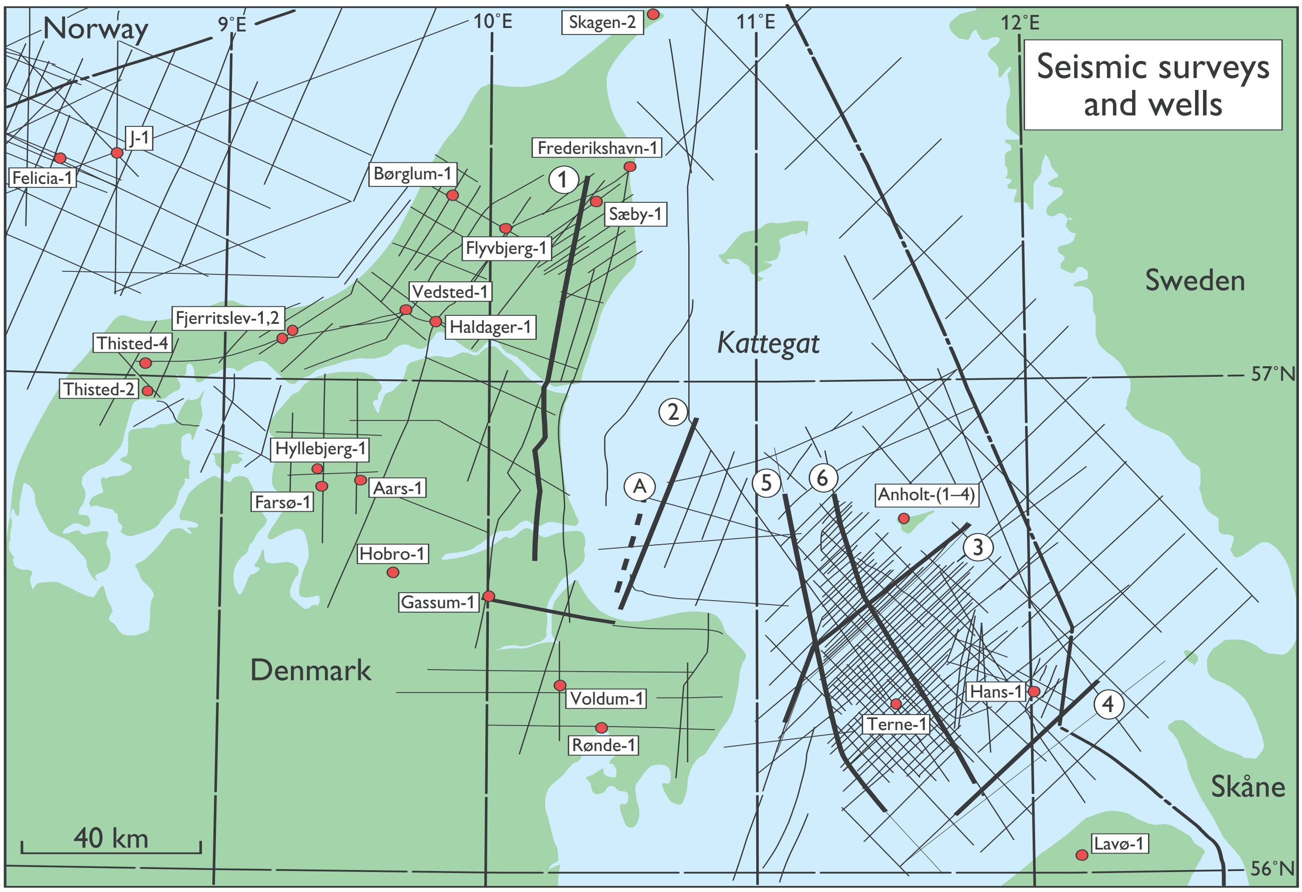


Fig. 2. Seismic surveys and wells used. The geoseismic profiles in Figure 3 are numbered **1**–**6**; the positions of these key profiles are also shown on all subsequent maps (Fig 4–13). The backstripped section in Figure 14 is indicated by the dashed line **A**.

new well data (Michelsen & Nielsen 1991, 1993) has made it possible to undertake a more detailed analysis of the Palaeozoic and Cretaceous structural developments along the Sorgenfrei–Tornquist Zone (Mogensen 1992a, b, 1994; Mogensen & Korstgård 1993; Mogensen & Jensen 1994). The remainder of the Mesozoic, from the Triassic to the Lower Cretaceous, with emphasis on the Jurassic, is the scope of this study.

Much of the discussion in the following is focussed on the two main faults of the Sorgenfrei–Tornquist Zone in the Kattegat area, the Børglum Fault and the Grenå–Helsingborg Fault. These faults, crossing the area from Skåne, Sweden to north Jylland, Denmark (Fig. 1), are considered as two separate strands of the Sorgenfrei–Tornquist Zone.

Data

This study is primarily based on released 2D reflection seismic data, acquired during a period of hydrocarbon exploration in the area in the early 1980s. Exploration also included drilling of the first two deep wells, Hans-1 and Terne-1 in the central part of Kattegat, and the Sæby-1 well in north Jylland, all penetrating Mesozoic rocks (Fig. 2; Michelsen & Nielsen 1991). The reflection seismic surveys used in this study vary in quality. There is a progressive increase in quality from the onshore single fold seismic, shot in 1967, to the 60 fold seismic data shot in 1985 (Table 1). Resolution of the seismic data is higher in the offshore data, but on a few onshore regional lines continuous reflections down to 4 seconds two-way travel time (TWT) can be seen.

Data from all wells in the area (Table 2), and information from rocks outcropping in Skåne, south-west Sweden, have been used in the study. In the central Kattegat area and onshore Denmark, there is a good tie between well data and the reflection seismic surveys. Elsewhere the interpretation can be more speculative, because of the scarcity of high resolution seismic data (Fig. 2). The location of six key lines, shown in Figure 3, is indicated on all maps.

The study has resulted in a series of maps (Figs 4–13); the structure maps (in TWT) represent top pre-Zechstein (approximately equivalent to the base Triassic over most of the investigated area), base Jurassic and base Cretaceous. Isochore maps (in TWT) have been prepared for the Lower and Upper Triassic successions, the Gassum Formation, the Fjerritslev Formation, the Middle Jurassic, the Upper Jurassic and the Lower Cretaceous successions. Where resolution of the onshore surveys is good, the maps cover both the Kattegat area and the onshore area (Fig. 1, areas 1 and 2); where onshore resolution is poor, the maps only cover the Kattegat area (Fig. 1, area 2).

Table 1. Seismic surveys used in the studies

Survey	Year	Fold	Filtered/ Migrated	Onshore/ Offshore
SSL6267	1964–7	1	Filtered	Onshore
WGC67A	1967	6	Filtered	Offshore
PRKL7374A	1973–4	6–12	Filtered	Onshore
GSI75B	1975	12	Migrated*	Offshore
DNJ8183D	1982–3	12	Migrated	Onshore
RTD81K	1982	48	Migrated	Offshore
DCS81K	1982	48	Migrated	Offshore
GY82K	1983	48	Migrated	Offshore
GECO83AK	1983	48	Migrated	Offshore
DN84D	1984	24	Migrated	Onshore
DK84K	1984	48	Migrated	Offshore
AM84K	1984	60	Migrated	Offshore
TX84K	1984	48	Migrated	Offshore
AO85I	1985	24	Migrated	Onshore
TX85K	1985	48	Migrated	Offshore

* Reprocessed and migrated 1983.

Table 2. Study wells grouped into those penetrating the Mesozoic (**A**) and those terminating in the Mesozoic (**B**)

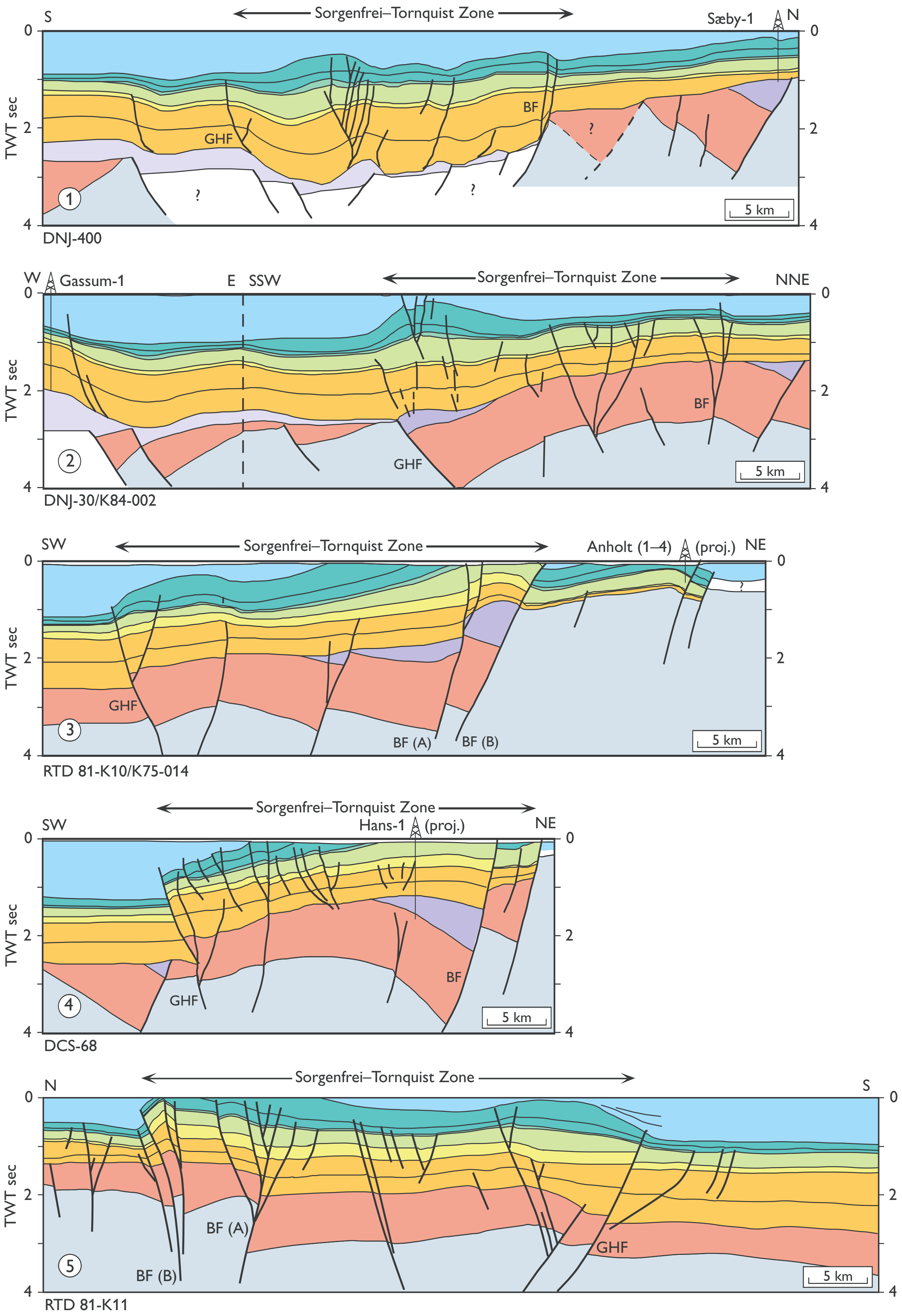
A

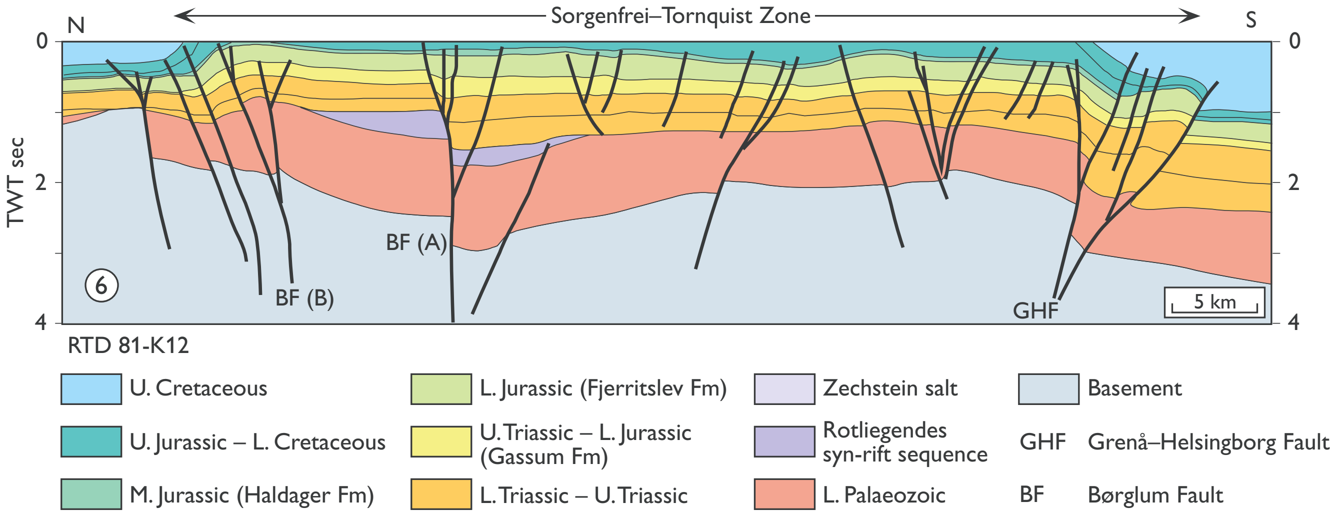
Well	Encounters/Terminates in
Frederikshavn-1	Mesozoic/Precambrian
Gassum-1	Mesozoic/Zechstein
Hans-1	Mesozoic/Upper Carboniferous
Rønde-1	Mesozoic/Upper Silurian
Sæby-1	Mesozoic/Rotliegend
Terne-1	Mesozoic/Cambrian
Thisted-4	Mesozoic/Zechstein

B

Well	Terminates in
Aars-1	Upper Triassic
Børglum-1	Upper Triassic – Lower Jurassic
Farsø-1	Upper Triassic
Fjerritslev-1	Lower Jurassic
Fjerritslev-2	Upper Triassic
Flyvbjerg-1	Upper Triassic
Frederikshavn-2, -3	Triassic
Haldager-1	Lower Jurassic
Hobro-1	Upper Triassic
Hyllebjerg-1	Upper Triassic
Lavø-1	Upper Triassic
Skagen-2	Triassic
Thisted-2	Lower Triassic
Vedsted-1	Upper Triassic
Voldum-1	Upper Triassic

Data from Nielsen & Japsen (1991).


S
Sorgenfrei–Tornquist Zone
Sæby-1
N
TWT sec
0
2
4
BF
GHF
?
1
5 km
DNJ-400
W
Gassum-1
E
SSW
Sorgenfrei–Tornquist Zone
NNE
TWT sec
0
2
4
BF
GHF
2
5 km
DNJ-30/K84-002
SW
Sorgenfrei–Tornquist Zone
Anholt (1–4)
(proj.)
NE
TWT sec
0
2
4
?
GHF
3
BF (A)
BF (B)
5 km
RTD 81-K10/K75-014
Sorgenfrei–Tornquist Zone
SW
Hans-1
(proj.)
NE
TWT sec
0
2
4
BF
GHF
4
5 km
DCS-68
N
Sorgenfrei–Tornquist Zone
S
TWT sec
0
2
4
BF (A)
BF (B)
GHF
5
5 km
RTD 81-K11



Facing page and above:

Fig. 3. Geoseismic profiles (Fig. 2 for locations). Note: (1) the Late Cretaceous anticline with underlying depocentres on profile 2, (2) the extensive Mesozoic small-scale faulting, especially on profiles 4 and 6, (3) the increased Jurassic subsidence in the Sorgenfrei–Tornquist Zone on profiles 3 and 5, and (4) the thinning of the Triassic towards the north-east on profiles 1, 2 and 6. Note also fault strands **A** and **B** of the Børglum Fault (**BF**) on profiles 3, 5 and 6, where the A strand seems to take up the lateral component, whereas the B strand seems to take up any vertical component (see text). Note that profile 2 is constructed from two seismic lines roughly at right angles to each other and that the two lines do not intersect (Fig. 2).

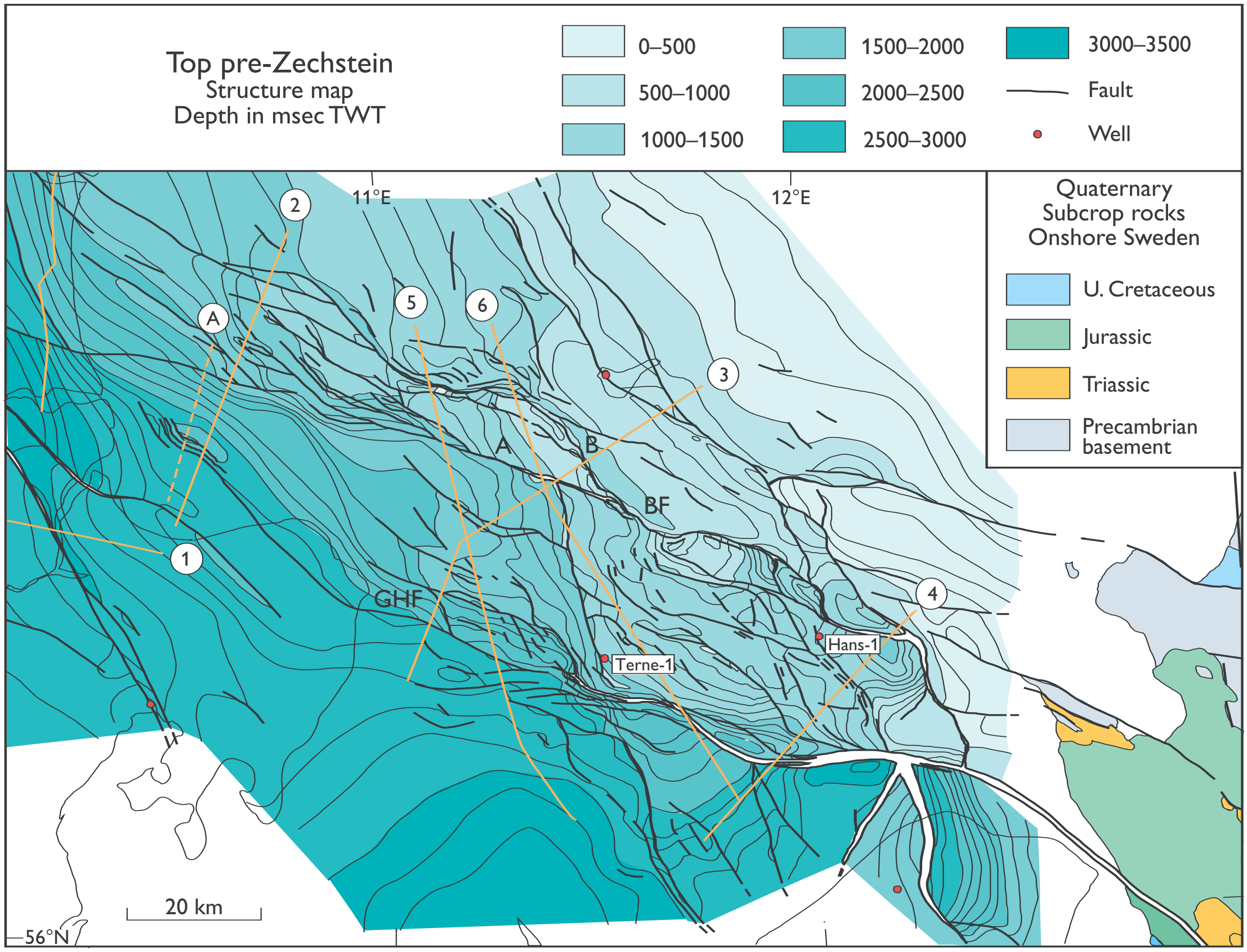


Fig. 4. Top pre-Zechstein TWT structure map. Note that the Jurassic onlaps partly onto the basement, partly onto the Triassic in Skåne, indicating younging of the sediments towards the north-east. Note also the zone of lateral transfer between the Hans-1 and Terne-1 wells. **BF**, Børglum Fault, **A** and **B** are strands of the Børglum Fault; **GHF**, Grenå–Helsingborg Fault.

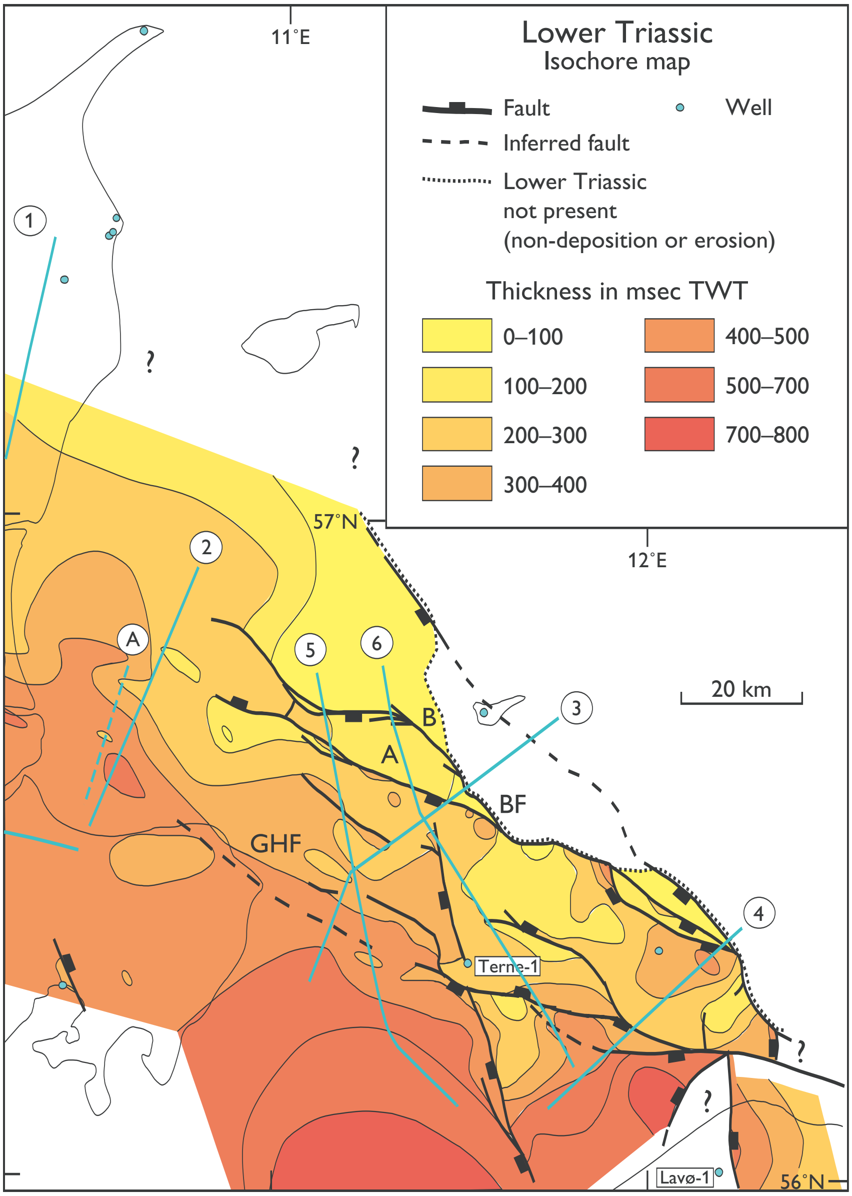


Fig. 5. TWT isochore map of the Lower Triassic. Note the subsidence pattern along the Børglum Fault with maxima and minima, indicating strike-slip motion along this fault with push-up and pull-down. Note also that there is no general differential subsidence within the Sorgenfrei–Tornquist Zone, the zone is merely the eastward limit of the regional Triassic basin to the south-west. **BF**, Børglum Fault, **A** and **B** are strands of the Børglum Fault; **GHF**, Grenå–Helsingborg Fault.

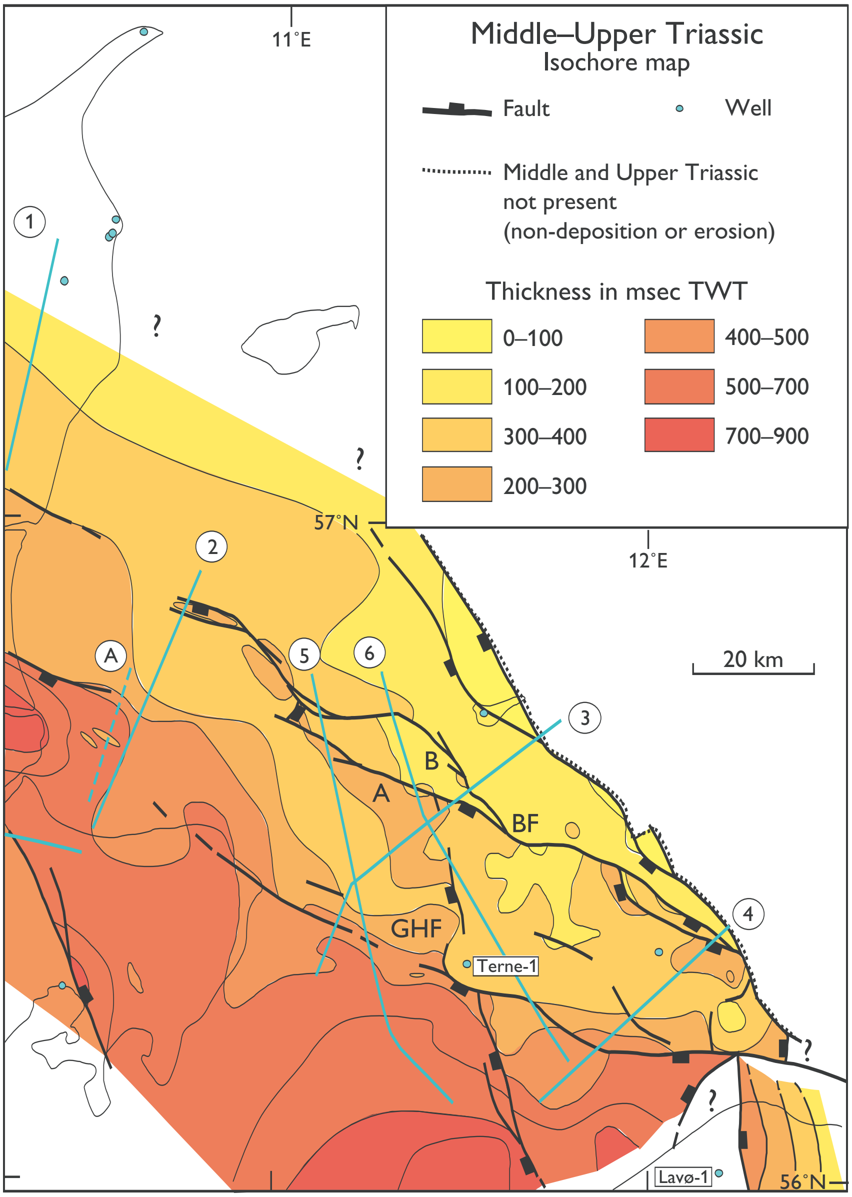
Structural development

Triassic

During the Early Permian, the Kattegat area and the Sorgenfrei–Tornquist Zone were exposed to erosion, and prior to the Late Permian the area had become a peneplain (Figs 3, 4; Michelsen & Nielsen 1991; Mogensen 1994). The top pre-Zechstein TWT structure map (Fig. 4), shows the configuration of this peneplain surface today, formed by the sum of all post-Early Permian tectonic events. The predominant fault orientation is NW–SE, the same as the main trend during the Palaeozoic, but several NNE–SSW- to NNW–SSE-trending faults are also present, both within and outside the Sorgenfrei–Tornquist Zone. After formation of the peneplain, the area started to tilt towards the south-west, with the two main faults in the Kattegat, the Grenå–Helsingborg Fault and the Børglum Fault (Fig. 1), lowering the top pre-Zechstein surface stepwise towards the south-west (Figs 3, 4).

In the south-east, the Grenå–Helsingborg Fault is the dominant fault, whereas the Børglum Fault takes over in an *én echelon* fashion towards the north-west, where it becomes the main Mesozoic fault. In the area between the Hans-1 and Terne-1 wells and the two major faults (Fig. 4), many smaller faults cut the top pre-Zechstein surface. This intense faulting occurs to the north-west of a large bend in the Grenå–Helsingborg Fault, and seems to be linked to this bend. North-west of the Terne-1 well, the Grenå–Helsingborg Fault gradually

Fig. 6. TWT isochore map of the Middle–Upper Triassic. Note the diminishing of maxima and minima along the Børglum Fault, indicating less activity along this fault compared to the Early Triassic. **BF**, Børglum Fault, **A** and **B** are strands of the Børglum Fault; **GHF**, Grenå–Helsingborg Fault.



dies out, and terminates close to profile 2 (Fig. 3). The Børglum Fault also fades out, much further to the north-west, but no clear termination can be seen (Fig. 4). Some branches of the Børglum Fault are relatively straight, and can be followed continuously across the Kattegat for 80–100 km.

The top pre-Zechstein TWT structure map (Fig. 4) also incorporates a Quaternary subcrop map of westernmost Skåne, Sweden. Note that the Jurassic onlaps partly on Precambrian crystalline basement and partly on the Triassic, indicating younging of sediments towards the north-east. This is clearly seen on the interpreted seismic sections which show seismic onlap towards the north-east (Fig. 3), where the youngest Triassic sediments overlie Precambrian basement.

The TWT isochore maps of the Lower Triassic (Fig. 5) and the Middle–Upper Triassic (Fig. 6) illustrate the structural history during the Triassic. Both maps and the geoseismic profiles (Fig. 3) show the general subsidence towards the south-west, where one of the main regional Triassic depocentres of the Northwest European Basin is located (Bertelsen 1980; Vejbæk 1990). The Triassic TWT isochore maps indicate that only minor differential subsidence took place along the Sorgenfrei–Tornquist Zone during the Triassic. The zone was merely the north-eastward limit of the large Triassic basin. During the Early Triassic, some of this minor differential subsidence internally in the Sorgenfrei–Tornquist Zone took place along bends of the Børglum Fault (Fig. 5), whereas other bends only show limited deposition or

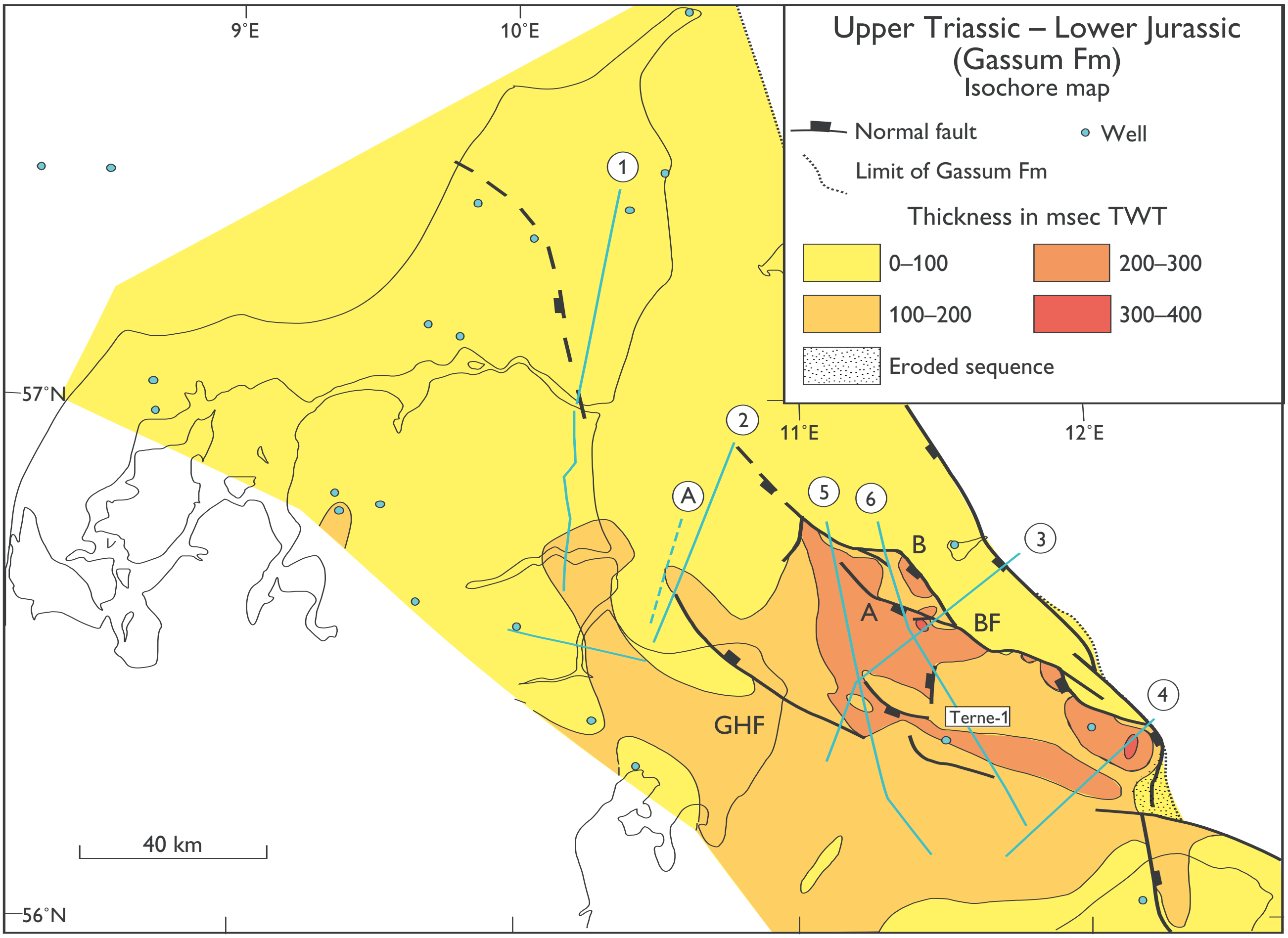


Fig. 7. TWT isochore map of the Gassum Formation. Note the onset of differential subsidence in the Sorgenfrei–Tornquist Zone, with the Børglum Fault being the most active. The Gassum Formation is the youngest unit that is not affected by erosion caused by the Late Cretaceous – Early Tertiary inversion and Neogene uplift. **BF**, Børglum Fault, **A** and **B** are strands of the Børglum Fault; **GHF**, Grenå–Helsingborg Fault.

erosion. This differential subsidence along the Børglum Fault abated during the Middle and Late Triassic (Fig. 6). West of the Terne-1 well, the Grenå–Helsingborg Fault seems to have had only limited effect on deposition (Figs 5, 6), whereas the Børglum Fault had a more pronounced impact on the depositional pattern further to the north-west (Figs 5, 6).

Towards the end of the Triassic, the depositional pattern changed and differential subsidence within the Sorgenfrei–Tornquist Zone started to overshadow regional subsidence with deposition of the Upper Triassic – Lower Jurassic Gassum Formation (Fig. 7). The Børglum Fault was still the most active fault in the Kattegat area, with a variable subsidence pattern along strike (Fig. 7), although the Grenå–Helsingborg Fault seems to have had some influence on the depositional pattern in the western part of the Kattegat, close to profile 2 (Fig. 7). The Gassum Formation has a diachronous upper boundary in the Danish area, younging towards the basin margin (Michelsen & Nielsen 1991) which cannot be seen on the seismic lines due to limited thicknesses outside the central Kattegat area.

Jurassic

The differential subsidence within the Sorgenfrei–Tornquist Zone that started in the Late Triassic was enhanced during the Early Jurassic, as indicated by the TWT isochore map of the Lower Jurassic Fjerritslev Formation (Fig. 8). The thick Lower Jurassic succession has been deeply eroded along the Børglum Fault, primarily along fault strand B (Figs 3 (profile 3), 8), due to subsequent Late Cretaceous – Early Tertiary inversion along this fault

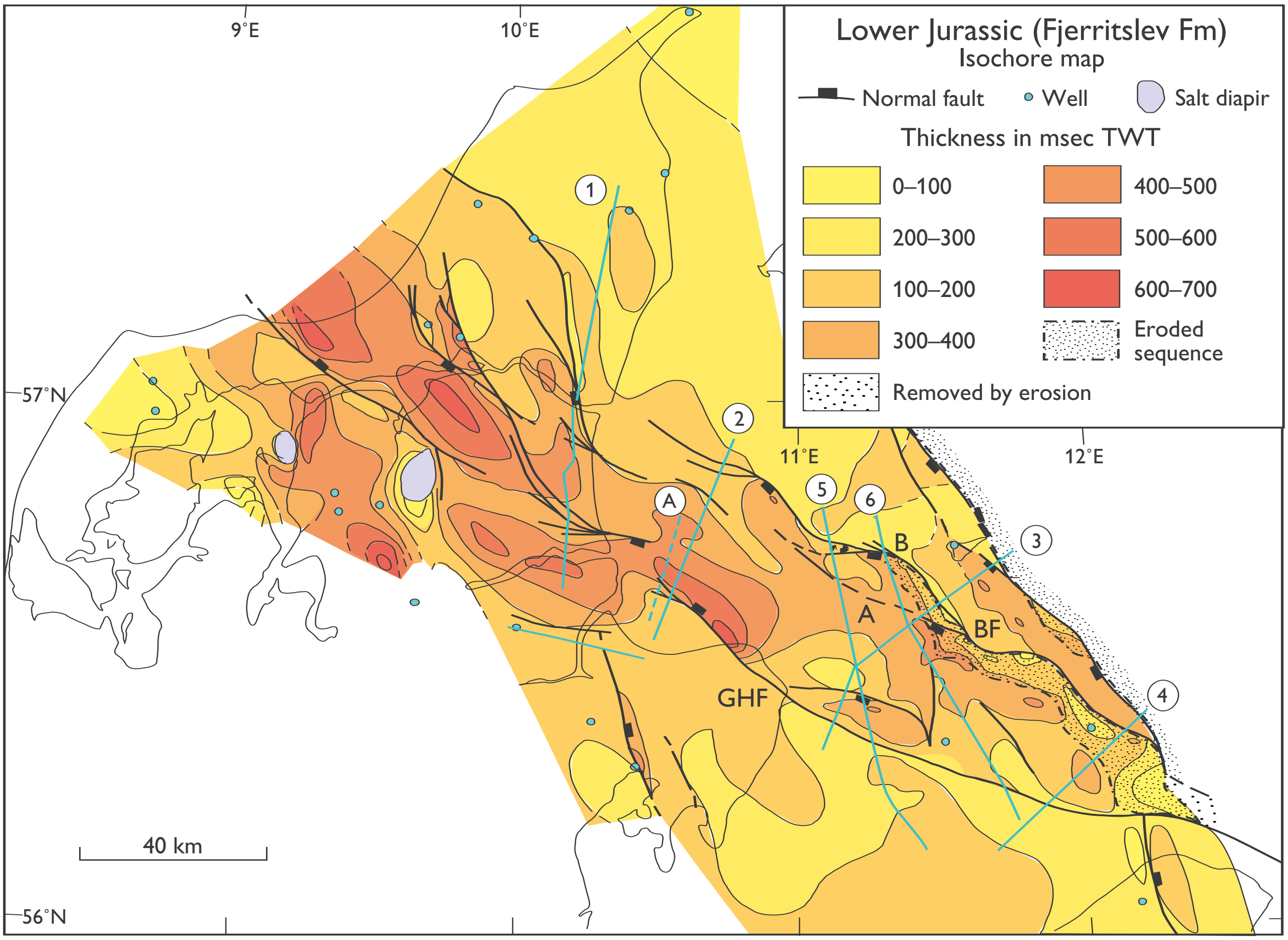


Fig. 8. TWT isochore map of the Fjerritslev Formation. Note differential subsidence all along the Sorgenfrei–Tornquist Zone; the unit is eroded along the Børglum Fault. Note also the depocentre at profile 2 and line A, which might have been caused by dextral transtensional sagging at the termination of the Grenå–Helsingborg Fault (see text). **BF**, Børglum Fault, **A** and **B** are strands of the Børglum Fault; **GHF**, Grenå–Helsingborg Fault.

strand. The Lower Jurassic succession thickens towards the eroded area, making the Børglum Fault the main fault at this time in the central Kattegat area. This contrasts with the Triassic faulting, when fault strand A was the most active (Figs 3 (profile 3), 5, 6). The Grenå–Helsingborg Fault seems to have had the same influence on the Early Jurassic depositional pattern in the western part of Kattegat close to profile 2, as during deposition of the Gassum Formation (Figs 7, 8).

The differential subsidence within the Sorgenfrei–Tornquist Zone continued during deposition of the Middle Jurassic Haldager Sand Formation (Fig. 9), although subsidence seems to have decreased compared to the Early Jurassic. Only minor fault activity took place, and the succession is thin with a rather uniform thickness, although a minor depocentre was formed around the Terne-1 well. The Haldager Sand Formation may also have increased in thickness towards the Børglum Fault, as did the Gassum Formation and presumably the Fjerritslev Formation, but has later been removed by erosion. Increased deposition compared to the Middle Jurassic is seen on the TWT isochore map of the Upper Jurassic Frederikshavn, Børglum and Flyvbjerg Formations (Fig. 10). The differential subsidence within the Sorgenfrei–Tornquist Zone can also be seen on the isochore map, with a thickening of these successions towards the Børglum Fault, although most of these deposits were later removed by erosion following Late Cretaceous – Early Tertiary inversion.

Late Jurassic subsidence patterns continued into the Early Cretaceous (Fig. 11), and small local depocentres developed within the Sorgenfrei–Tornquist Zone, coinciding with the Lower Jurassic depocentres (Fig. 8) and with inversion highs formed during the Late Cretaceous

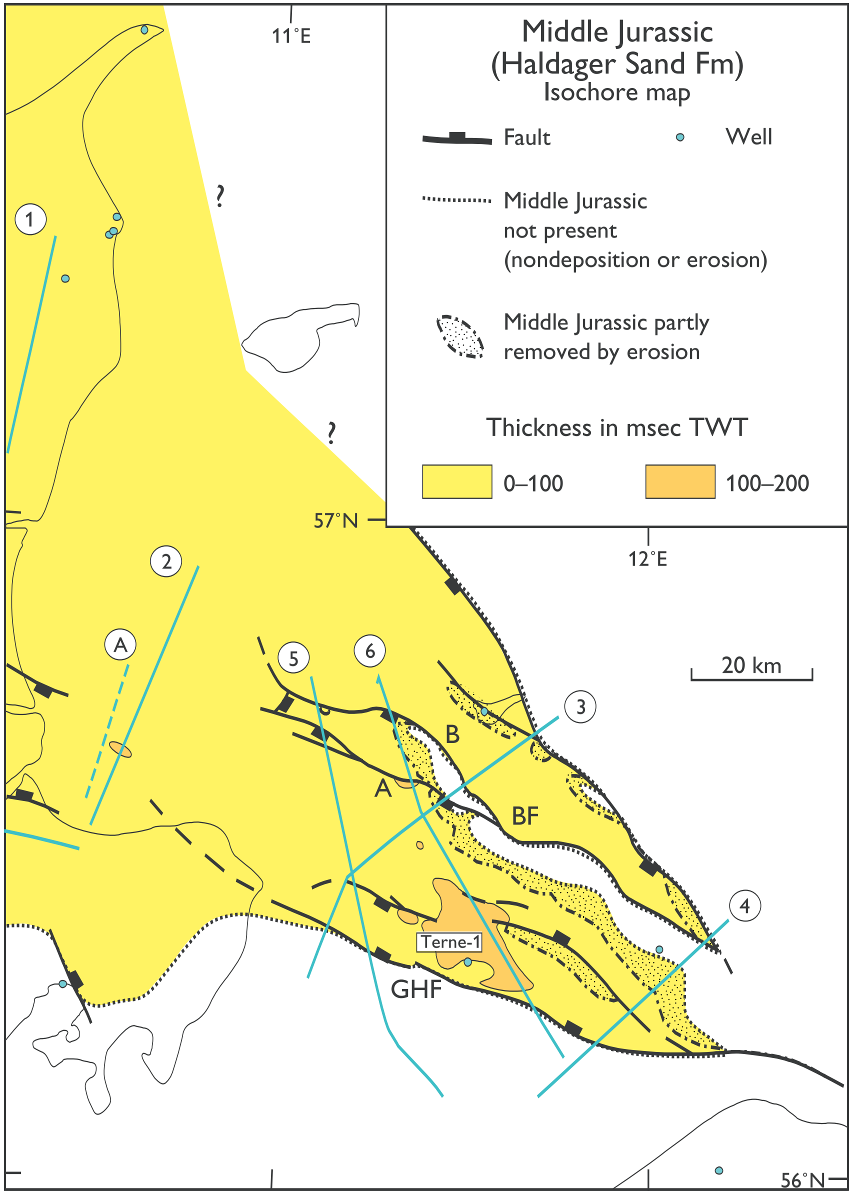


Fig. 9. TWT isochore map of the Haldager Sand Formation. Note the local depocentre around Terne-1 and deposition restricted to within the Sorgenfrei–Tornquist Zone. **BF**, Børglum Fault, **A** and **B** are strands of the Børglum Fault; **GHF**, Grenå–Helsingborg Fault.

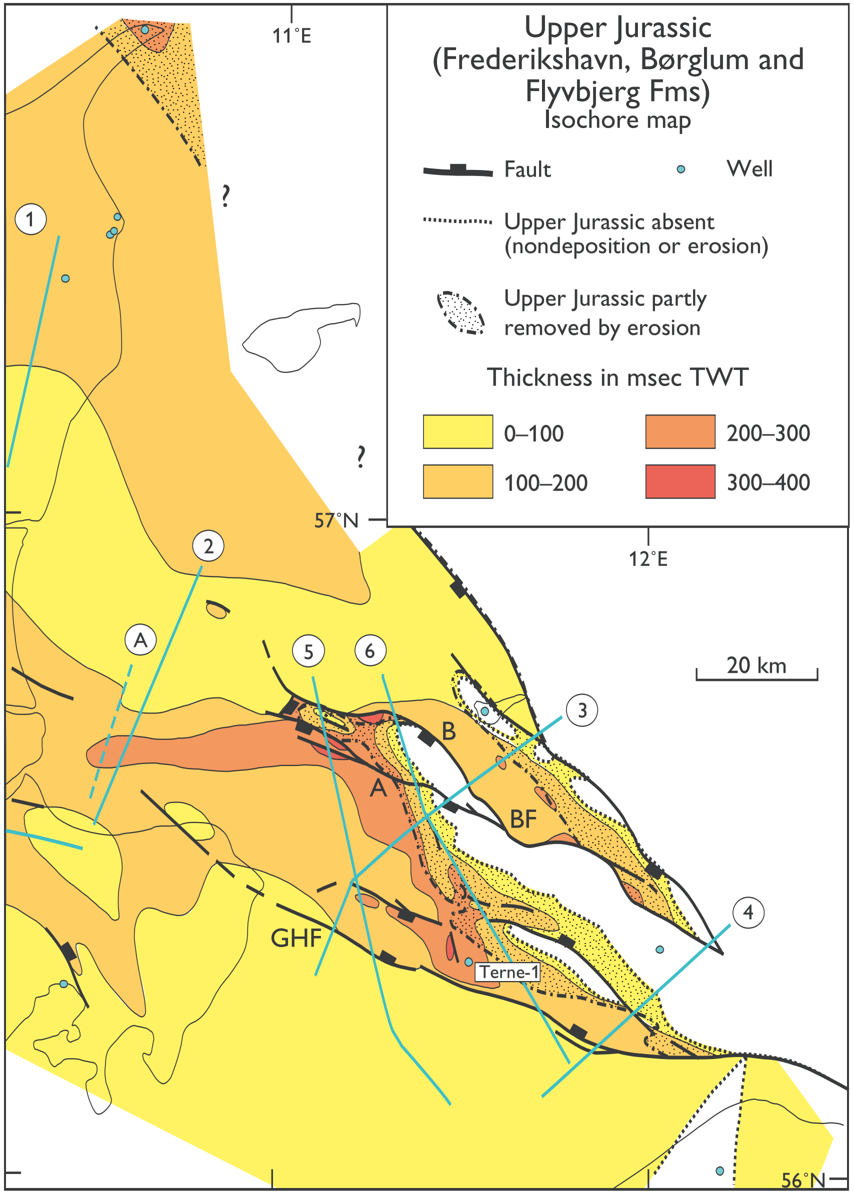


Fig. 10. TWT isochore map of the Upper Jurassic succession. Note the increased subsidence relative to the Middle Jurassic, and the increasing effect of erosion. The depositional pattern indicates a thickening towards the strongly inverted Børglum Fault, where the Upper Jurassic is removed by erosion. **BF**, Børglum Fault, **A** and **B** are strands of the Børglum Fault; **GHF**, Grenå–Helsingborg Fault.

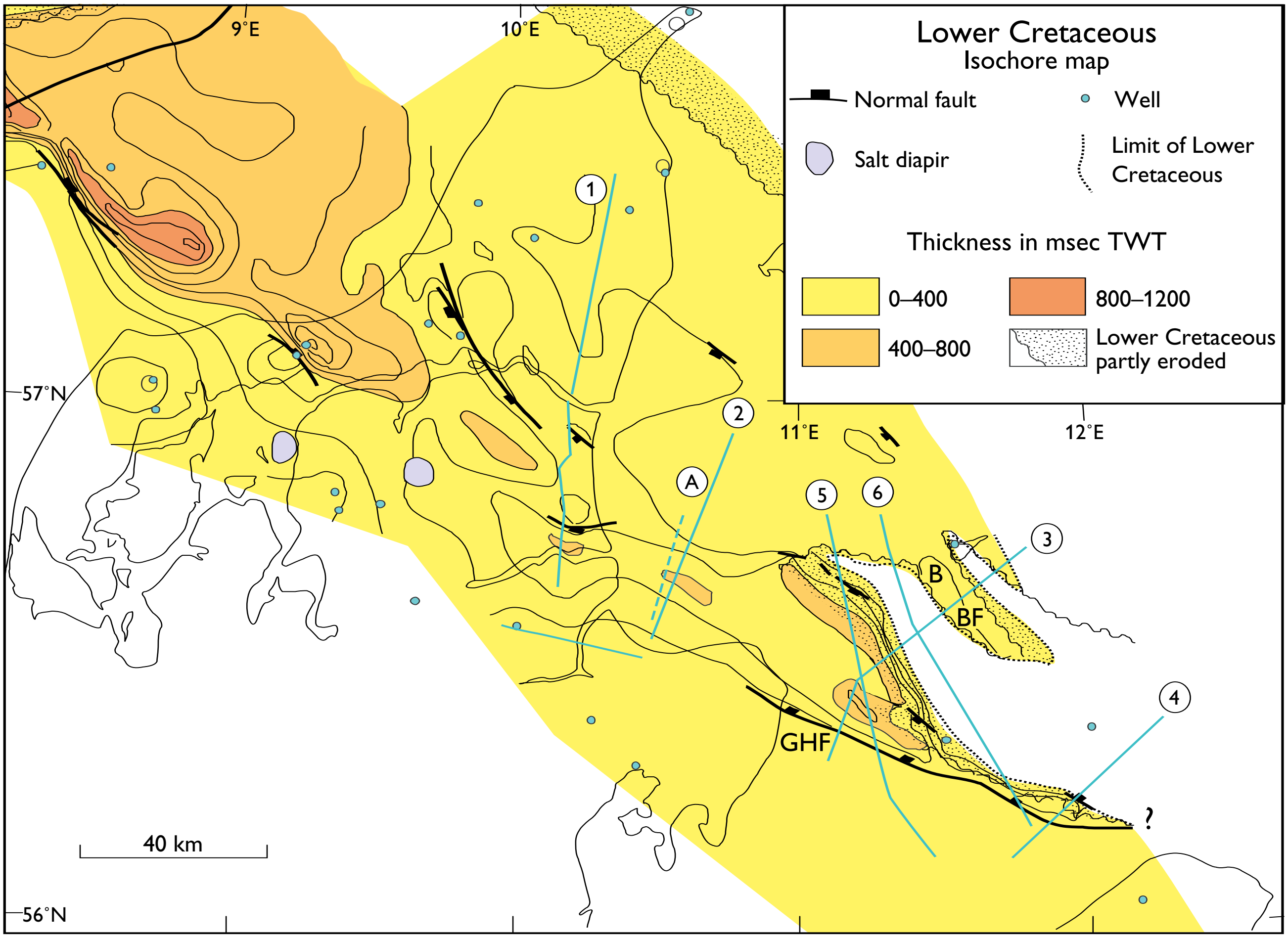


Fig. 11. TWT isochore map of the Lower Cretaceous succession. Note the similarity with the Lower Jurassic depositional pattern (Fig. 8), as well as the increased effect of later erosion. **BF**, Børglum Fault, **B** is a strand of the Børglum Fault; **GHF**, Grenå–Helsingborg Fault.

– Early Tertiary inversion (Mogensen & Jensen 1994). One of these structures can be seen on profile 2 (Fig. 3) and on Line A (see also Fig. 14).

On the top Triassic TWT structure map (Fig. 12), between the Terne-1 and Hans-1 wells, a large number of faults occur, compared to the top pre-Zechstein structure map (Fig. 4). These are small-scale faults that are restricted to the Mesozoic succession (Fig. 3, profile 4). On the base Cretaceous TWT structure map (Fig. 13), this faulting is not indicated, due to the deep erosion of the Mesozoic sequence, but it is clearly seen that the Børglum Fault continues much further to the north than the Grenå–Helsingborg Fault. This reflects a transfer of lateral movement from the Grenå–Helsingborg Fault to the Børglum Fault from south-east to north-west and is probably related mainly to Late Cretaceous – Early Tertiary dextral transpression.

Mesozoic dextral transtensional structural development

Triassic

Rather than being primarily a zone of differential subsidence during the Triassic, as suggested by Michelsen & Nielsen (1991, 1993), we consider the Sorgenfrei–Tornquist Zone in the Kattegat area to represent a staircase stepping down from the north-eastern platform to the deep basin in the south-west, delineating the Triassic Northwest European Basin (Figs 5, 6). Differential subsidence seen internally in the Sorgenfrei–Tornquist Zone to the north-west, along the Fjerritslev Fault (Vejbæk 1990), might be due to salt withdrawal from a Zechstein salt basin along the Fjerritslev Fault (Christensen & Korstgård 1994) triggered by minor Triassic reactivations of this old fault (Norling & Bergström 1987). This would

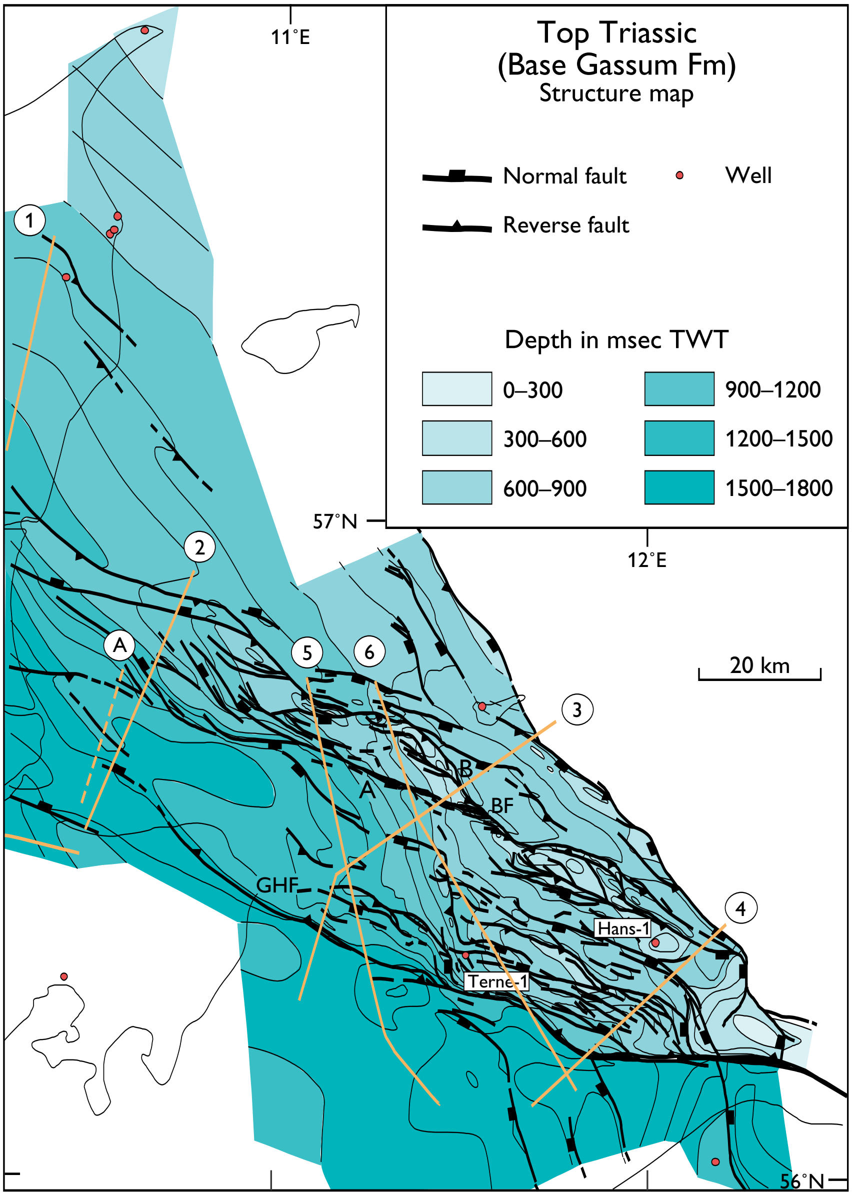


Fig. 12. Top Triassic TWT structure map. Note the large number of faults between Terne-1 and Hans-1, transferring the strike-slip/oblique-slip motion. Note also the horsetail splays at several locations. **BF**, Børglum Fault, **A** and **B** are strands of the Børglum Fault; **GHF**, Grenå–Helsingborg Fault.

imply that no major differential subsidence related to strike-slip faulting took place along the Sorgenfrei–Tornquist Zone during the Triassic, as suggested by Pegrum (1984), Ziegler (1987, 1990) and the EUGENO-S Working Group (1988).

The intense rifting and fault-controlled subsidence of the NNE–SSW-oriented Horn Graben (Vejbæk 1990; Clausen & Korstgård 1993, 1994), indicates a stress field in which the least principal stress axis had a WNW–ESE-orientation. Several normal faults in the Kattegat area, outside the Sorgenfrei–Tornquist Zone, are in accordance with such a stress field e.g. north of the Lavø-1 well, (Figs 5, 6), and the NNE–SSW-trending Svedala Fault in Skåne, Sweden (Norling & Bergström 1987). If such a WNW–ESE-oriented extensional regime existed in the Triassic in the Kattegat area, the NW–SE-trending Grenå–Helsingborg, Børglum and Fjerritslev Faults would experience right-lateral, probably transtensional strike-slip, motion along their fault planes, which is in agreement with Vejbæk (1990). Right-lateral transtensional reactivation of the Fjerritslev Fault, would also favour halokinetic movements and differential subsidence (Koyi & Petersen 1993) resembling rifting along this fault.

The depositional pattern with thin and thick successions related to bends in the Børglum Fault indicates lateral motion along the faults, with push-up at restraining bends and pull-down at releasing bends (Aydin & Nur 1985; Christie-Blick & Biddle 1985; Harding

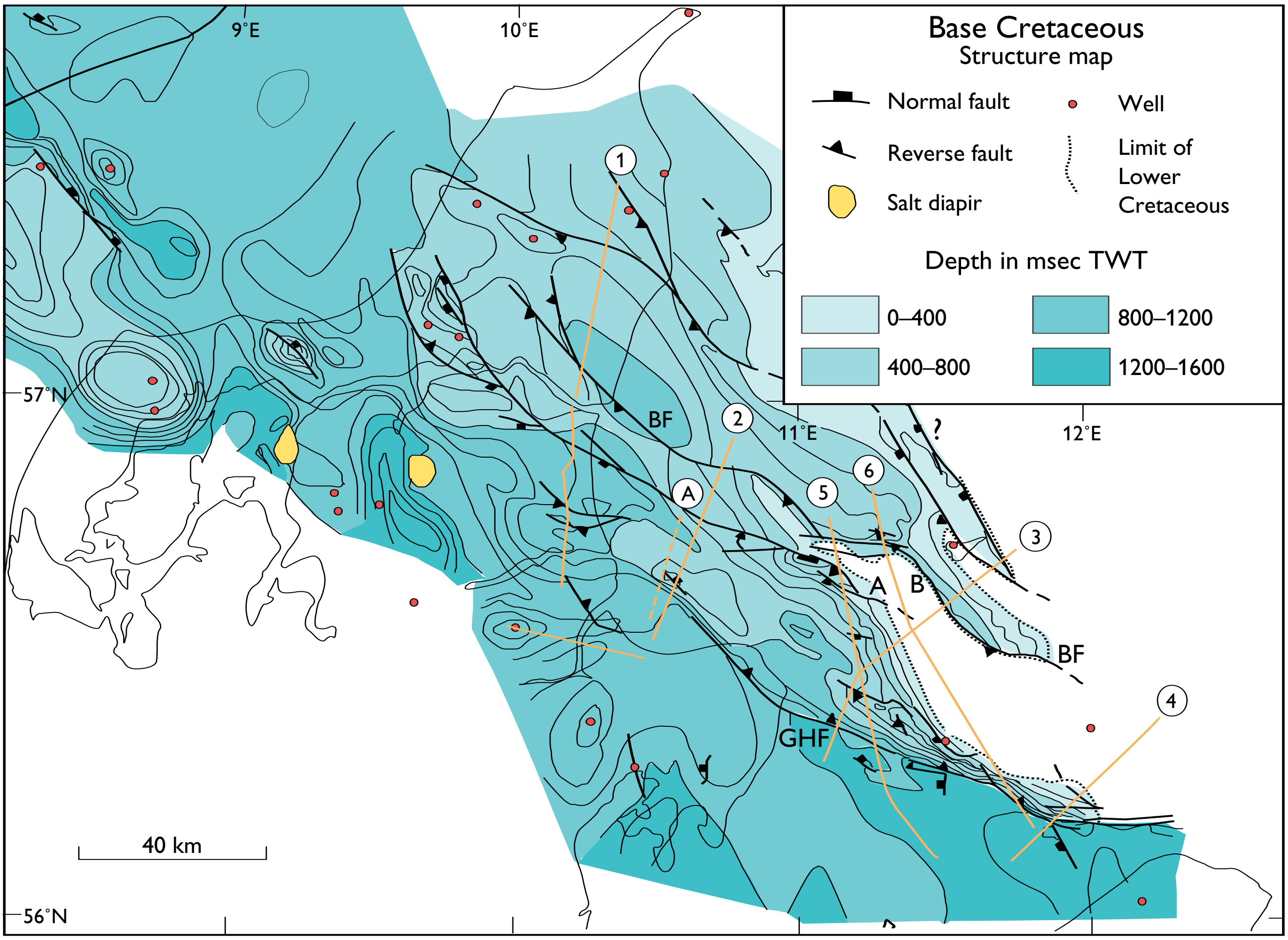


Fig. 13. Base Cretaceous TWT structure map. Note the continuation of the Børglum Fault further to the north than the Grenå–Helsingborg Fault. **BF**, Børglum Fault, **A** and **B** are strands of the Børglum Fault; **GHF**, Grenå–Helsingborg Fault.

et al. 1985). This restraining–releasing bend pattern was especially active during the Early Triassic (Fig. 5, see also Mogensen 1994), and primarily along strand A of the Børglum Fault (profile 3, Fig. 3). Strand A resembles the experiments on reactivation of basement faults under conditions of oblique-slip carried out by Richard (1991). This movement pattern decreased in activity during the rest of the Triassic (Fig. 6), whereas the limited deposition to the north-east of the Terne-1 well persisted throughout the Triassic (Figs 5–7). The area of limited sedimentation coincides with the heavily faulted area between the Terne-1 and Hans-1 wells (Figs 4, 12). This fault pattern indicates a broad transfer of strike-slip or oblique-slip motion from the Grenå–Helsingborg Fault to the Børglum Fault, corresponding to the gradual termination of the Grenå–Helsingborg Fault towards the north-west.

During the Triassic, deposition gradually overstepped the margins of the regional basin, with progressive onlap towards the north-east (Figs 3, 5, 6; Norling & Bergström 1987; EUGENO-S Working Group 1988). While the Triassic was characterised by regional subsidence (Figs 5, 6; Vejbæk 1990), the Jurassic – Early Cretaceous was dominated by differential subsidence in the area between the two main faults in the Sorgenfrei–Tornquist Zone, the Grenå–Helsingborg Fault and the Børglum Fault. The change in this local basin development indicates a shift in the regional stress field (see also Norling & Bergström 1987) probably related to the widespread Late Triassic – Early Jurassic rift phase in Northwest Europe (Ziegler 1990). The change in the stress field occurred during deposition of the Gassum Formation (Fig. 7), and the Lower Jurassic Fjerritslev Formation (Fig. 8), both relatively widespread formations that increase in thickness towards the Sorgenfrei–Tornquist Zone.

The sub-regional subsidence around the Sorgenfrei–Tornquist Zone abated during deposition of the shallow marine to fluvial Gassum Formation (Nielsen *et al.* 1989; Nielsen 2003, this volume). Instead differential subsidence took over in the central part of the Kattegat, within the Sorgenfrei–Tornquist Zone. In this area, no mobile Zechstein salt is present and subsidence was controlled by basement-attached faults only. No differential subsidence seems to have taken place further to the north-west in the Danish part of the northern Zechstein Salt Basin (Fig. 7).

Jurassic

In the Early Jurassic, subsidence controlled by basement-attached faults continued within the Sorgenfrei–Tornquist Zone in the areas where no mobile Zechstein salt was present. In addition, differential subsidence now also started further to the north-west in areas underlain by mobile Zechstein salt (Fig. 8). This change indicates increased fault activity (Norling & Bergström 1987) and in particular salt withdrawal subsidence, possibly triggered by the faulting. Activity along NNW–SSE-trending normal faults outside the Sorgenfrei–Tornquist Zone (Fig. 8) points to a WSW–ENE orientation of the minimum stress axis. This again would indicate right-lateral movements along the NW–SE-oriented major faults of the Sorgenfrei–Tornquist Zone, as in the Triassic. However, since the minimum principal stress axis was at a higher angle to these faults, a reduced amount of strike-slip compared to the Triassic may be suggested.

The local depocentre in the central part of profile 2 (Figs 3, 8), could be regarded as a salt withdrawal basin, similar to those further to the north-west (Koyi & Petersen 1993; Christensen & Korstgård 1994). However, no major accumulation of Zechstein salt is present in the area, and the immobile marginal Zechstein Basin facies starts approximately here (Mogensen 1994). A section across this depocentre (line A in Fig. 8) backstripped (Fig. 14A–E) shows no salt structure evolution matching the size of the Jurassic – Lower Cretaceous depocentre (Figs 14B, E). The Jurassic – Lower Cretaceous depocentre therefore cannot be explained by salt withdrawal. An explanation could be that the Grenå–Helsingborg Fault seems to terminate in this area (Figs 4, 8, 12, 13). Termination of a fault having right-lateral transtensional displacement along strike, causes primarily horsetail splaying and sagging (Christie-Blick & Biddle 1985; Harding *et al.* 1985; Sylvester 1988). This kind of sagging would cause subsidence that might be only slightly influenced by faulting. The configuration of the Jurassic – Lower Cretaceous depocentre (Fig. 14B), is hardly influenced by seismically resolvable faults, and it is therefore proposed that this particular depocentre was caused by dextral transtensional sagging at the north-westernmost termination of the Grenå–Helsingborg Fault. During the Late Cretaceous – Early Tertiary inversion tectonics (dextral transpression as opposed to the former dextral transtension), this depocentre was inverted as a closed anticline (Fig. 13; see also Mogensen & Jensen 1994).

Deposition changed from dominantly marine in the Early Jurassic to more shallow marine to continental dominated in the mid-Jurassic, possibly due to uplift of the crustal block to the north-east of the Sorgenfrei–Tornquist Zone. This change is also reflected in the difference in the depositional pattern between the Lower Jurassic Fjerritslev Formation (Fig. 8) and the Middle Jurassic Haldager Sand Formation (Fig. 9), notably the change in thickness. Fault-related deposition seems to have been limited in the Middle Jurassic, although faulting along the major faults of the Sorgenfrei–Tornquist Zone created space for Middle Jurassic deposits in the central part of the Kattegat (Fig. 9), and caused volcanic activity in Skåne, mainly along NW–SE-trending faults and fracture zones (Erlström *et al.* 1997).

In the central Kattegat area and Skåne, only limited deposition took place outside the Sorgenfrei–Tornquist Zone during the Middle Jurassic (Fig. 9; Norling & Bergström 1987). Due to the limited faulting it is difficult to deduce any stress orientations. Regional indications such as Middle Jurassic normal faulting in the North Sea Central Graben (Mogensen *et al.* 1992) suggest an E–W to ESE–WSW orientation, and if this orientation is extended to the Kattegat area, right-lateral movements would again have been induced along the major faults of the Sorgenfrei–Tornquist Zone. Inside the Sorgenfrei–Tornquist Zone, deposition may have been continuous from the Triassic to the Late Jurassic (Michelsen & Nielsen 1991; Seidenkrantz *et al.* 1993), in contrast to adjacent areas outside the zone (Michelsen 1986, 1989; Nielsen 2003, this volume).

During the Late Jurassic, new marine transgressions invaded the area, filling former irregular topography in Skåne (Norling & Bergström 1987). The Early Cretaceous had the same depositional evolution, except that tectonic activity increased (Ziegler 1987, 1990; EUGENO-S Working Group 1988). Differential subsidence took place along the Sorgenfrei–Tornquist Zone in the central Kattegat area (Fig. 10) and in Skåne (Norling & Bergström 1987) during both the Late Jurassic and the Early Cretaceous. Large parts of the Upper Jurassic – Lower Cretaceous deposits were removed by subsequent erosion, obscuring the depositional pattern in the Kattegat area (Figs 10, 11). However, thickening of the Upper Jurassic and Lower Cretaceous successions towards the eroded area and the Børglum Fault (Fig. 3, profiles 3 and 5), indicates that this was the most active fault in the central Kattegat area during both the Late Jurassic and the Early Cretaceous, as well as during the Late Cretaceous – Early Tertiary inversion phase (Figs 10, 11).

The orientation of a small Upper Jurassic depocentre just west of the Terne-1 well, related to a N–S-trending fault (Fig. 10), might indicate that E–W extension in the Kattegat area also persisted during the Late Jurassic. This is in agreement with a proposed regional Late Jurassic E–W extension, as in the North Sea area (Bartholomew *et al.* 1993; Sears *et al.* 1993). Such an orientation of the tensional stresses would again cause right-lateral transtension in the Kattegat area along the NW–SE-oriented major faults of the Sorgenfrei–Tornquist Zone. Right-lateral transtension might also be indicated by the continuous evolution of the local depocentre at line A (Figs 10, 11) and profile 2 (Fig. 3) in Late Jurassic (Fig. 10) and in Early Cretaceous times (Figs 10, 11). This development could also have been caused by sagging due to dextral transtensional fault termination, as proposed previously.

Indications of the sense of lateral transtensional displacement along the Sorgenfrei–Tornquist Zone boundary faults become more obscure in mid-Jurassic – Early Cretaceous times, due to the effect and overprint of later inversion tectonics. The few clear indications of the sense of lateral displacement in this period as well as in all former Mesozoic periods, seem to favour right-lateral displacement. We therefore suggest a general dextral transtensional displacement along the NW–SE-trending Grenå–Helsingborg Fault, and in particular the Børglum Fault, during the whole of the Mesozoic (for

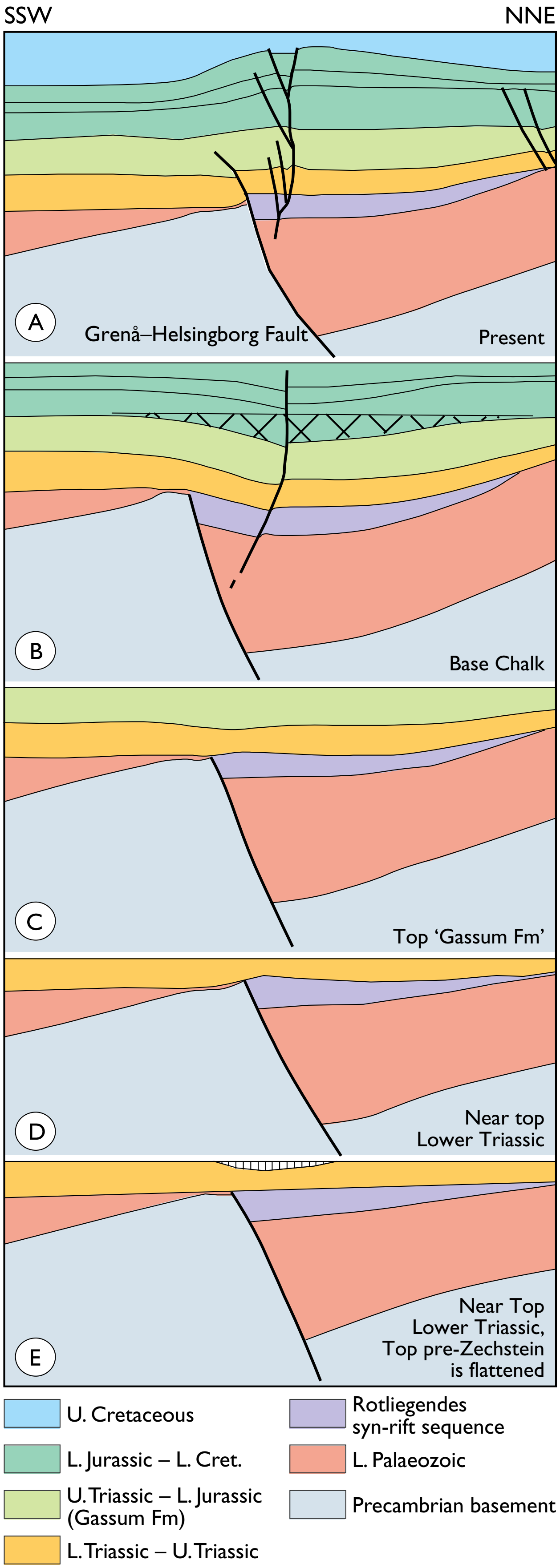


Fig. 14. Backstripping sequence across the Grenå–Helsingborg Fault (Fig. 2, line A; seismic line K84-001). The anticlinal structure in the Lower Cretaceous succession was created by inversion of a Late Triassic to Early Cretaceous syncline. The configuration of this depocentre (crosses on profile **B**) could indicate salt withdrawal subsidence over an escaping salt pillow, but backstripping down to the surface of 'no differential subsidence over fault', close to top Lower Triassic (profile **D**), gives no indication of salt structure development (hatched area on **E**) that could match the depocentre on **B**. Another explanation could therefore be right-lateral transtensional sagging at the tip of the Grenå–Helsingborg Fault which terminates in this area.

displacement during the Late Cretaceous, see Mogensen & Jensen 1994). This contrasts with the view of Pegrum (1984) who proposed left-lateral displacement, especially during the latter part of the Mesozoic. An interpretation of the fault configuration in the south-eastern part of Kattegat by Aubert (1988, fig. 56) also favoured left-lateral displacement. Our interpretation of a more closely-spaced seismic grid has changed this fault configuration into a major bend in the Grenå–Helsingborg Fault (Fig. 4). Right-lateral movements along the Grenå–Helsingborg Fault start to be transferred to the Børglum Fault, in order to accommodate this major bend.

Sivhed (1991) suggested 4 km of left-lateral displacement along the Fyledal Fault, Skåne, based on the displacement of a possible post-Early Permian channel. However, age relationships between channels on both sides of the Fyledal Fault appear to be uncertain because of different lithologies in the channel fill (Sivhed 1991). Left-lateral movement would be possible on a fault in

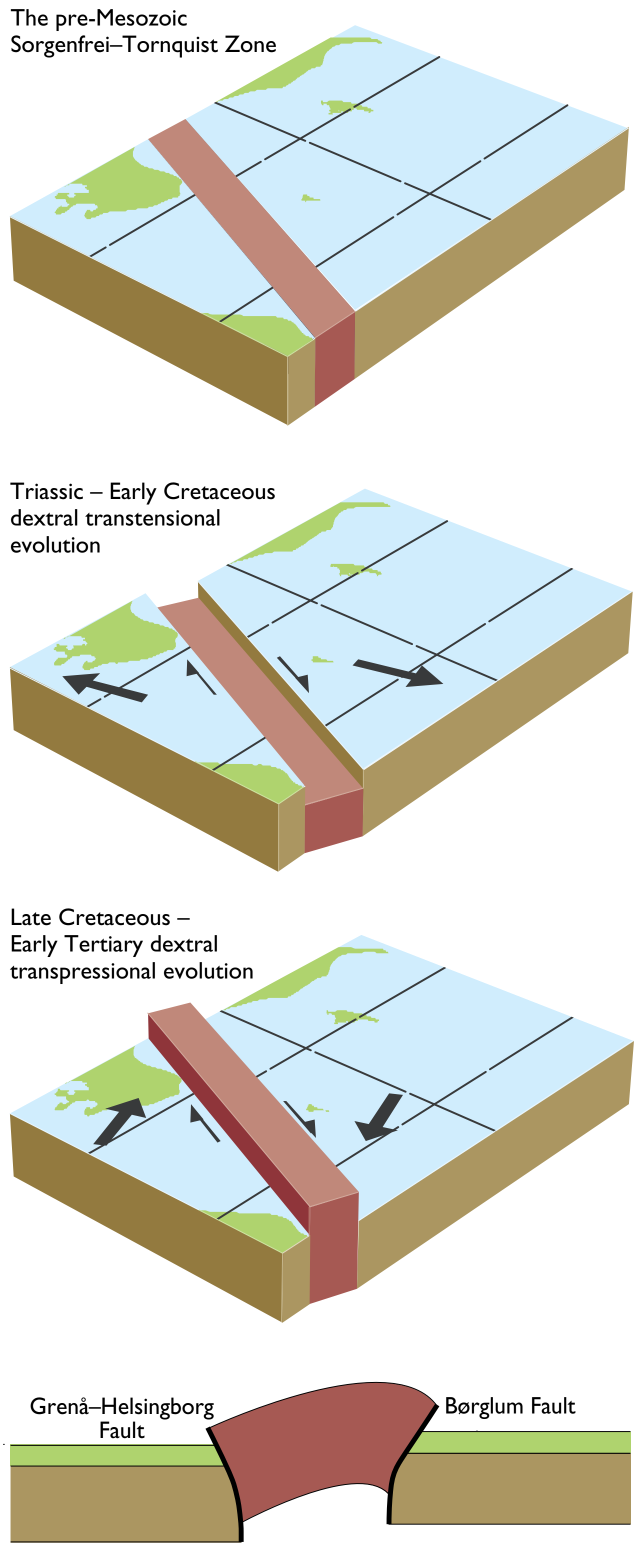


Fig. 15. Schematic diagram showing the response of the Sorgenfrei–Tornquist Zone to a changing stress field and illustrating how the zone acted as a buffer zone between more coherent crustal blocks, whenever changes in the regional stress field were induced.

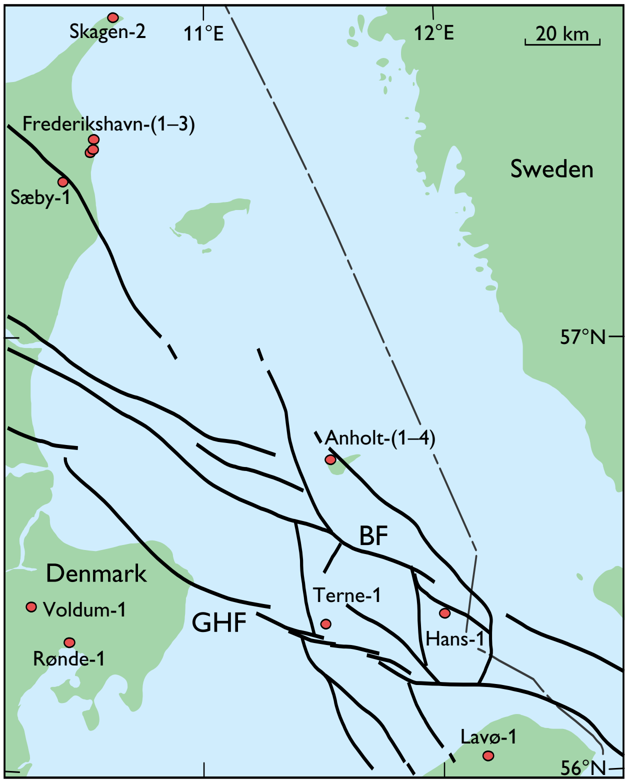


Fig. 16. Major Palaeozoic faults of the Kattegat area, which, when compared with the different Mesozoic maps (Figs 4–13), show that almost all Mesozoic faults are reactivated Palaeozoic faults. **BF**, Børglum Fault; **GHF**, Grenå–Helsingborg Fault.

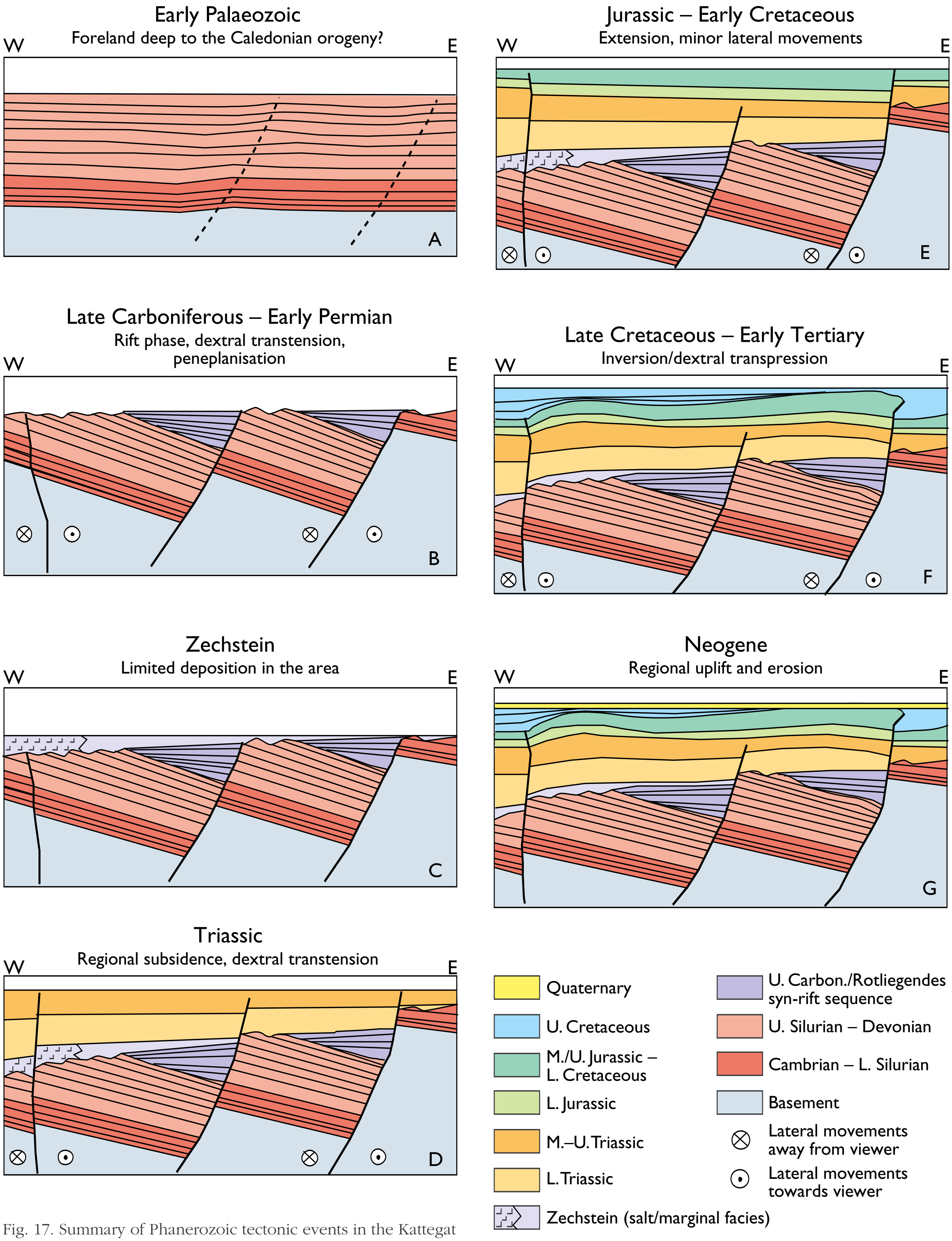


Fig. 17. Summary of Phanerozoic tectonic events in the Kattegat area and along the Sorgenfrei–Tornquist Zone.

a right-lateral fault zone, depending on the orientation of the fault. However, 4 km of sinistral movement along a fault with a NW–SE orientation such as the Fyledal Fault seems unlikely.

The Sorgenfrei–Tornquist Zone as a buffer zone

We consider the Scandinavian part of the Tornquist Zone to be a very old and weak intercratonic boundary (Pegrum 1994), between crustal blocks with thicknesses along the zone in the order of 25–30 km (Ro *et al*. 1990b), and with total lateral displacements of only 20–30 km (Mogensen 1994). As a boundary between crustal blocks, the Sorgenfrei–Tornquist Zone is also a deep-seated fault zone where changes in the stress field are more easily accommodated than in the more coherent adjacent crustal blocks (Fig. 15).

Mesozoic reactivation of old, weak basement lineaments in an extensional regime with an oblique angle to the principal stress directions has been described from the North Sea (Bartholomew *et al*. 1993; Sears *et al*. 1993). Comparison of the faults from the different Mesozoic maps (Figs 4–13) with the Palaeozoic fault pattern (Fig. 16) shows that almost all the Mesozoic faults are reactivated Palaeozoic faults. The weak crustal Sorgenfrei–Tornquist Zone is bounded by the Grenå–Helsingborg Fault and the Børglum Fault. Depending on the orientation of the stress field, these boundary faults may exhibit transpressional or transtensional strike-slip motion. Only very special orientations of the stress field will give pure strike-slip motions or pure extension during reactivation.

Along the Børglum Fault, a total estimate of 7 km of right-lateral displacement, from the Late Palaeozoic to the present, was proposed by Mogensen (1994). Quantification of the amount of lateral displacement during different tectonic episodes is difficult, and can only be done relative to each episode. The period with the largest dextral movements was probably the Triassic, as estimated from the configuration of small fault-bend related depocentres and the regional stress orientation (see above). As much as half of the dextral displacement (3–4 km) could be attributed to the Triassic movements. This leaves 3–4 km to the rest of the Mesozoic transtensional and transpressional movements, of which the Late Cretaceous – Early Tertiary transpressional movements were probably the most important. Dextral displacement during the Jurassic – Early Cretaceous therefore must have been only a few kilometres.

Conclusions

A better understanding of the Triassic–Jurassic (–Early Cretaceous) tectonic processes along the Sorgenfrei–Tornquist strike-slip fault zone has been provided through the interpretation of closely-spaced 2D reflection seismic data in the Kattegat area, Denmark. Based on this interpretation, several maps have been generated, which in combination with key regional seismic sections outline in detail the structural development of the Kattegat area and the Sorgenfrei–Tornquist Zone during this period (Fig. 17).

During the Permian, the area was exposed to erosion and was peneplaned. Regional Triassic subsidence and tilting resulted in onlap towards the north-east, where the youngest Triassic sediments are found overlying Precambrian crystalline basement. During the Early Triassic, in particular, several of the major Late Carboniferous – Early Permian faults were reactivated, with dextral strike-slip along the Børglum Fault.

Differential subsidence within the Sorgenfrei–Tornquist Zone started at the transition between the Late Triassic and the Early Jurassic, primarily with deposition of the Fjerritslev Formation. This differential subsidence was restricted mainly to the area between the two main faults in the Sorgenfrei–Tornquist Zone, the Grenå–Helsingborg Fault and the Børglum Fault. The restricted basin development indicates a change in the regional stress field. Subsidence during the Middle Jurassic and the Late Jurassic – Early Cretaceous followed the Early Jurassic pattern with differential deposition within the Sorgenfrei–Tornquist Zone, but now even more restricted to the zone. The Early Cretaceous subsidence pattern was a direct continuation of the Late Jurassic subsidence with no hiatus in between. The only difference was the increased rate of subsidence during Early Cretaceous times.

Many small faults were generated during the Mesozoic in the area between the Terne-1 and Hans-1 wells and the Grenå–Helsingborg and Børglum Faults. This fault pattern indicates a general transfer of strike-slip/oblique-slip motion from the Grenå–Helsingborg Fault to the Børglum Fault. Reactivation of old basement faults caused dextral movements along the major boundary faults of the NW–SE-oriented Sorgenfrei–Tornquist Zone during the entire Mesozoic due to the orientation of the regional stress field.

Acknowledgements

We thank S. Olausson and O. Simonsen for comments on the manuscript. O.R. Clausen and J.E. Christensen contributed to our discussions during preparation. We also thank the reviewers, R.M. Pegrum and O.V. Vejbæk for constructive comments and F. Surlyk for numerous suggestions for improvements. T.E. Mogensen was supported by a grant from the Danish Natural Science Research Council.

References

Aubert, K. 1988: Strukturell og stratigrafisk utvikling i Kattegat, 126 pp. Unpublished cand. scient. thesis, Oslo Universitet, Norge.

Aydin, A. & Nur, A. 1985: The types and role of stepovers in strike-slip tectonics. In: Christie-Blick, N. & Biddle K.T. (eds): Strike-slip deformation, basin formation, and sedimentation. Society of Economic Paleontologists and Mineralogists Special Publication **37**, 35–44.

Baartman, J.C. & Christensen, O.B. 1975: Contributions to the interpretation of the Fennoscandian Border Zone. Danmarks Geologiske Undersøgelse II. Række **102**, 47 pp.

Bartholomew, I.D., Peters, J.M. & Powell, C.M. 1993: Regional structural evolution of the North Sea: oblique slip and the reactivation of basement lineaments. In: Parker, J.R. (ed.): Petroleum geology of Northwest Europe: proceedings of the 4th conference, 1109–1123. London: Geological Society.

Bergström, J. 1984: Lateral movements in the Tornquist Zone. Geologiska Föreningens i Stockholm Förhandlingar **106**, 379–380.

Bergström, J., Holland, B., Larsson, K., Norling, E. & Sivhed, U. 1982: Guide to excursions in Skåne. Sveriges Geologiska Undersökning Serie Ca **54**, 94 pp.

Bergström, J., Kumpas, M.G., Pegrum, R.M. & Vejbæk, O.V. 1990a: Evolution of the northwestern part of the Tornquist zone – part 1. Zeitschrift für Angewandte Geologie **36**, 41–45.

Bergström, J., Kumpas, M.G., Pegrum, R.M. & Vejbæk, O.V. 1990b: Evolution of the northwestern part of the Tornquist zone – part 2. Zeitschrift für Angewandte Geologie **36**, 107–114.

Bertelsen, F. 1980: Lithostratigraphy and depositional history of the Danish Triassic. Danmarks Geologiske Undersøgelse Serie B **4**, 59 pp.

Christensen, J.E. & Korstgård J.A. 1994: The Fjerritslev Fault offshore Denmark – salt and fault interactions. First Break **12**, 31–42.

Christie-Blick, N. & Biddle, K.T. 1985: Deformation and basin formation along strike-slip faults. In: Christie-Blick, N. & Biddle, K.T. (eds): Strike-slip deformation, basin formation, and sedimentation. Society of Economic Paleontologists and Mineralogists Special Publication **37**, 1–34.

Clausen, O.R. & Korstgård, J.A. 1993: Faults and faulting in the Horn Graben area, Danish North Sea. First Break **11**, 127–143.

Clausen, O.R. & Korstgård, J.A. 1994: Displacement geometries along graben bounding faults in the Horn Graben, offshore Denmark. First Break **12**, 305–315.

Erlström, M., Thomas, S.A., Deeks, N. & Sivhed, U. 1997: Structure and tectonic evolution of the Tornquist Zone and adjacent sedimentary basins in Scania and the southern Baltic Sea area. Tectonophysics **271**, 191–215.

EUGENO-S Working Group 1988: Crustal structure and tectonic evolution of the transition between the Baltic Shield and the North German Caledonides (the EUGENO-S Project). Tectonophysics **150**, 253–348.

Harding, T.P., Vierbuchen, R.C. & Christie-Blick, N. 1985: Structural styles, plate-tectonic settings, and hydrocarbon traps of divergent (transtensional) wrench faults. In: Christie-Blick, N. & Biddle, K.T. (eds): Strike-slip deformation, basin formation, and sedimentation. Society of Economic Paleontologists and Mineralogists Special Publication **37**, 51–77.

Jensen, L.N. & Michelsen, O. 1992: Tertiær hævning og erosion i Skagerrak, Nordjylland og Kattegat. Dansk Geologisk Forening Årsskrift **1990–91**, 159–168.

Koyi, H. & Petersen, K. 1993: Influence of basement faults on the development of salt structures in the Danish Basin. Marine and Petroleum Geology **10**, 82–94.

Liboriussen, J., Ashton, P. & Tygesen, T. 1987: The tectonic evolution of the Fennoscandian Border Zone in Denmark. In: Ziegler, P.A. (ed.): Compressional intra-plate deformations in the Alpine Foreland. Tectonophysics **137**, 21–29.

Lie, J.E. & Husebye, E.S. 1992: Deep crust and mantle structures related to rifting and basin formation in Skagerrak; new results from reprocessing of deep seismic profiles. Geologiska Föreningens i Stockholm Förhandlingar **114**, 245–247.

Michelsen, O. 1986: The Danish pre-Tertiary lithostratigraphy – status of the lithostratigraphic nomenclature, onshore and offshore Denmark. DGU Internal report **12**, 9 pp. Copenhagen: Geological Survey of Denmark.

Michelsen, O. 1989: Revision of the Jurassic lithostratigraphy of the Danish Subbasin. Danmarks Geologiske Undersøgelse Serie A **24**, 21 pp.

Michelsen, O. & Nielsen, L.H. 1991: Well records on the Phanerozoic stratigraphy in the Fennoscandian Border Zone, Denmark. Hans-1, Sæby-1, and Terne-1 wells. Danmarks Geologiske Undersøgelse Serie A **29**, 37 pp.

Michelsen, O. & Nielsen, L.H. 1993: Structural development of the Fennoscandian Border Zone, offshore Denmark. Marine and Petroleum Geology **10**, 124–134.

Mogensen, T.E. 1992a: Strukturel analyse af Kattegat områdets præ-Kænozoiske aflejringer. Dansk Geologisk Forening Årsskrift **1990–91**, 129–134.

Mogensen, T.E. 1992b: Late Cretaceous seismic sequence stratigraphy of the Tornquist Zone, Kattegat area, offshore Denmark. Mesozoic and Cenozoic sequence stratigraphy of European basins, Dijon, France, 18–20 May 1992. Centre National de la Recherche Scientifique – Institut Français du Petróle. Abstracts, 148–149.

Mogensen, T.E. 1994: Palaeozoic structural development along the Tornquist Zone, Kattegat area, Denmark. In: Cloetingh, S. *et al.* (eds): Dynamics of extensional basin formation and inversion. Tectonophysics **240**, 191–214.

Mogensen, T.E. & Jensen, L.N. 1994: Cretaceous subsidence and inversion along the Tornquist Zone from Kattegat to the

Egersund Basin. First Break **12**, 211–222.

Mogensen, T.E. & Korstgård, J.A. 1993: Structural development and trap formation along the Børglum Fault, Tornquist Zone, Denmark compared with the Painted Canyon Fault, San Andreas Zone, USA. In: Spencer, A.M. (ed.): Generation, accumulation and production of Europe's hydrocarbons III. European Association of Petroleum Geoscientists Special Publication **3**, 89–97.

Mogensen, T.E., Korstgård, J.A. & Geil, K. 1992: Salt tectonics and faulting in the NE Danish Central Graben. In: Spencer, A.M. (ed.): Generation, accumulation and production of Europe's hydrocarbons II. European Association of Petroleum Geoscientists Special Publication **2**, 163–173.

Nielsen, L.H. 2003: Late Triassic – Jurassic development of the Danish Basin and the Fennoscandian Border Zone, southern Scandinavia. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin **1**, 459–526 (this volume).

Nielsen, L.H. & Japsen, P. 1991: Deep wells in Denmark 1935–1990. Danmarks Geologiske Undersøgelse Serie A **31**, 177 pp.

Nielsen, L.H., Larsen, F. & Frandsen, N. 1989: Upper Triassic – Lower Jurassic tidal deposits of the Gassum Formation on Sjælland, Denmark. Danmarks Geologiske Undersøgelse Serie A **23**, 30 pp.

Norling, E. & Bergström, J. 1987: Mesozoic and Cenozoic tectonic evolution of Scania, southern Sweden. In: Ziegler, P.A. (ed.): Compressional intra-plate deformations in the Alpine Foreland. Tectonophysics **137**, 7–19.

Pegrum, R.M. 1984: The extension of the Tornquist Zone in the Norwegian North Sea. Norsk Geologisk Tidsskrift **64**, 39–68.

Richard, P. 1991: Experiments on faulting in a two-layer cover sequence overlying a basement fault reactivated in oblique slip. Journal of Structural Geology **13**, 459–469.

Ro, H.E., Stuevold, L.M., Faleide, J.I. & Myhre, A.M. 1990a: Skagerrak Graben – the offshore continuation of the Oslo Graben. In: Neumann, E.-R. (ed.): Rift zones in the continental crust of Europe – geophysical, geological and geochemical evidence: Oslo–Horn Graben. Tectonophysics **178**, 1–10.

Ro, H.E., Larsson, F.R., Kinck, J.J. & Husebye, E.S. 1990b: The Oslo Rift – its evolution on the basis of geological and geophysical observations. In: Neumann, E.-R. (ed.): Rift zones in the continental crust of Europe – geophysical, geological and geochemical evidence: Oslo–Horn Graben. Tectonophysics **178**, 11–28.

Sears, R.A., Harbury, A.R., Protoy, A.J.G. & Stewart, D.J. 1993: Structural styles from the Central Graben in the UK and Norway. In: Parker, J.R. (ed.): Petroleum geology of Northwest Europe: proceedings of the 4th conference, 1231–1243. London: Geological Society.

Seidenkrantz, M.-S., Koppelhus, E.B. & Ravn-Sørensen, H. 1993: Biostratigraphy and palaeoenvironmental analysis of a Lower to Middle Jurassic succession on Anholt, Denmark. Journal of Micropalaeontology **12**, 201–218.

Sivhed, U. 1991: A pre-Quaternary, post-Palaeozoic erosional channel deformed by strike-slip faulting, Skåne, southern Sweden. Geologiska Föreningens i Stockholm Förhandlingar **113**, 139–143.

Sylvester, A.G. 1988: Strike-slip faults. Geological Society of America Bulletin **100**, 1666–1703.

Vejbæk, O.V. 1990: The Horn Graben, and its relationship to the Oslo Graben and the Danish Basin. In: Neumann, E.-R. (ed.): Rift zones in the continental crust of Europe – geophysical, geological and geochemical evidence: Oslo–Horn Graben. Tectonophysics **178**, 29–49.

Ziegler, P.A. 1987: Late Cretaceous and Cenozoic intra-plate compressional deformations in the Alpine Foreland – a geodynamic model. In: Ziegler, P.A. (ed.): Compressional intra-plate deformations in the Alpine Foreland. Tectonophysics **137**, 389–420.

Ziegler, P.A. 1990: Geological atlas of western and central Europe, 2nd edition, 239 pp. Amsterdam: Elsevier for Shell Internationale Petroleum Maatschappij.

Manuscript received 1 November 1995; revision accepted 2 September 1997.