# Post mid-Cretaceous inversion tectonics in the Danish Central Graben – regionally synchronous tectonic events?

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Structural analysis of the Upper Cretaceous to Palaeogene succession in the Danish Central Graben suggests continuous inversion heralded in the Late Hauterivian and continuing into Palaeogene times. The following phases of increased intensity are identified: 1) latest Santonian, 2) Mid Campanian, 3) late Maastrichtian, 4) Late Paleocene – Eocene, and 5) Early Oligocene. Phases 1 through 3 are Sub-Hercynian, phase 4 is Laramide, and phase 5 is Pyrenean according to Alpine Orogen nomenclature. A temporal change in structural style is noted from early inversion confined to narrow zones associated with reverse faulting along pre-existing normal faults to late inversion dominated by gentle basinwide flexuring and folding. Inversion phases in the Danish Central Graben seem to be synchronous with inversion phases along the Sorgenfrei-Tornquist Zone. The location of inversion is generally spatially linked to Upper Jurassic – Lower Cretaceous depocentres, whereas older depocentres generally have remained intact.

The origin of the compressional stress field is generally based on suggested compressional stresses transmitted into the foreland from the Alpine Orogen. In the Sub-Hercynian phase, orogenic compression dominated the Eastern Alps and Northern Carpathians to produce a likely NW oriented compression. However, structures in Denmark rather suggest a transpressional environment resulting from NNE–SSW compression. Furthermore, transmission of Alpine orogenic stresses into the foreland commenced in the Turonian, a considerable time after the Late Hauterivian and later inversion precursors. Ridge-push forces transmitted from sea-floor spreading south of the Charlie-Gibbs fracture zone, particularly from the Goban Spur SW of Ireland, acting in conjunction with Alpine orogenic stresses are suggested as the cause for the stress field.

*Keywords:* Inversion, Central Graben, Upper Cretaceous, Chalk Group, Sorgenfrei-Tornquist Zone.

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The purpose of this paper is to summarise the evolution of the Late Cretaceous to Palaeogene inversion movements in the Danish Central Graben, to review the chronology and to make comparisons with other inverted parts in the Danish area. Main emphasis is placed on tectonic effects on the Upper Cretaceous to Danian Chalk Group. For a general introduction to the structural framework of the reader is referred to Michelsen et al. 1992, Korstgård et al. 1993, Vejbæk 1997, Britze et al. 1995b).

Chalk deposition took place on a background of regional subsidence following the former mainly Late Jurassic rifting that strongly abated during the Early Cretaceous. The Chalk Group isopach map of the North Sea region (Fig. 1) suggests local deviations from the background regional subsidence. Anomalously thin or even absent Chalk Group deposits are for instance recorded in the Danish Central Graben, the West Netherlands Basin, the Sole Pit Basin and the Sorgenfrei-Tornquist Zone (see Fig. 2 for location). Zones of anomalously thick Chalk Group deposits flank these thinned areas. This is particularly evident along the Southwest margin of the Sorgenfrei-Tornquist Zone. These anomalies are suggested to be caused mainly by inversion movements during Late Cretaceous – Palaeogene times.

Structural inversion of sedimentary basins is the process by which former areas of subsidence and sedimentation formed in an extensional stress regime are uplifted under the influence of compressive stress. The compressional nature of the inversion is evidenced by dominance of reverse faulting, typically as reactivation of former extensional normal faults, and by flexuring and folding. This leads to uplift of former

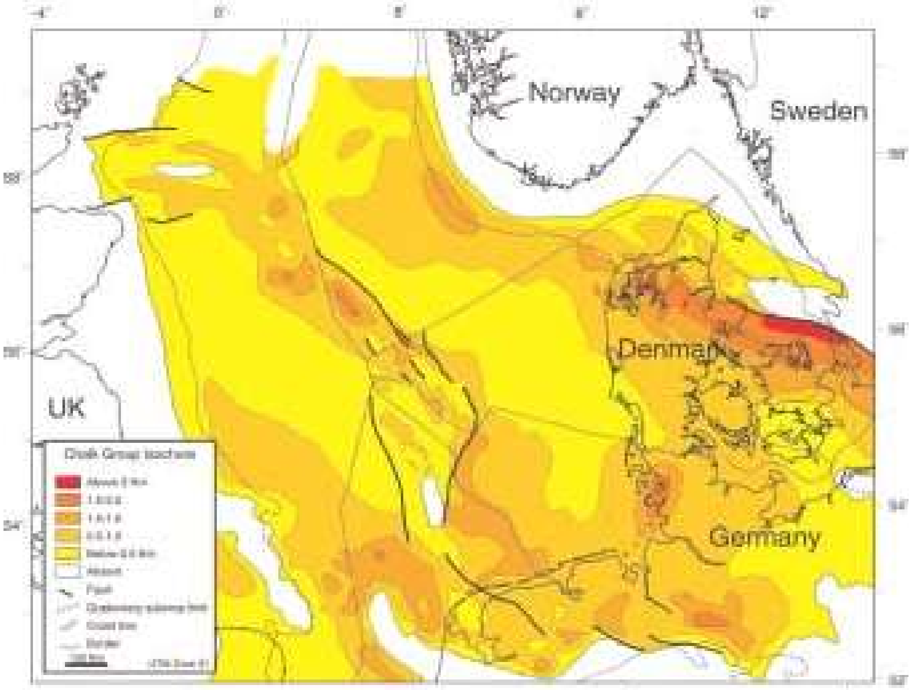


Fig. 1. Chalk Group isopachs of the North Sea region (from Japsen 1998). The limit of the Palaeogene is equivalent to the extent of the erosion of the Chalk Group in Neogene times.

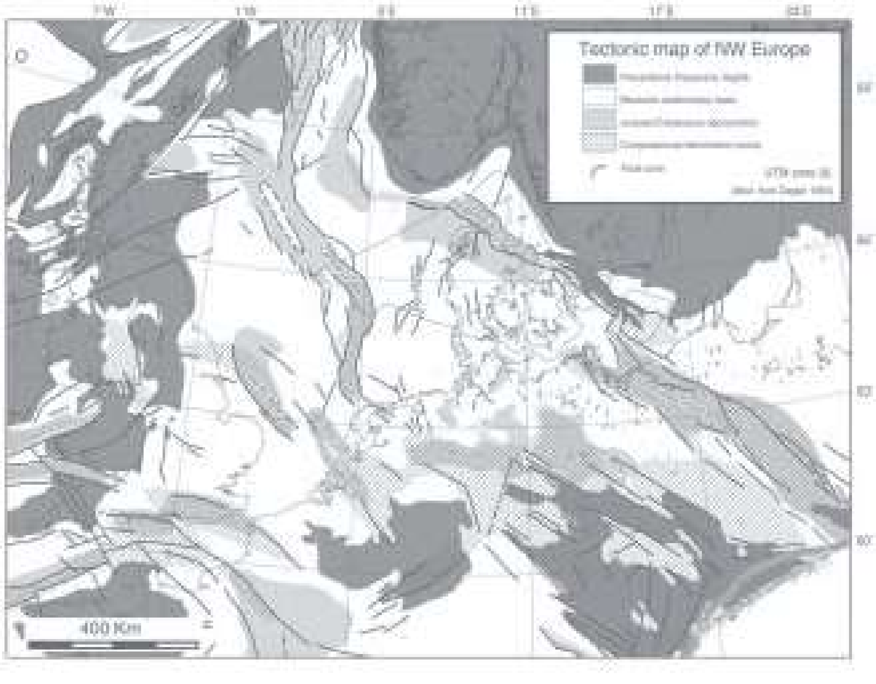


Fig. 2. Northwest European zones of Cretaceous to Palaeogene inversion tectonism (modified from Ziegler 1995).

depocentres associated with a change from uplift and erosion to rapid subsidence on graben flanks. These former rift-shoulder areas may even turn into regional depocentres.

Zones of Late Cretaceous to Palaeogene inversion tectonism in Northwest Europe are shown in Figure 2. The majority and the most intense zones of inversion are found south of the Danish area: the Sole Pit, West Netherlands, and Broad Fourteen Basins (Van Hoorn 1987, Van Wieje 1987). The Central Graben and the Sorgenfrei-Tornquist Zone are the main zones of inversion in the Danish area (Mogensen & Jensen 1994, Mogensen 1995). The Sorgenfrei-Tornquist Zone is part of a continuous inverted zone extending southeastwards into the Polish Trough via an en-echelon dextral side step across the Bornholm area. The general impression of the areal extent of the inversion zones in Northwest Europe suggests a general north-

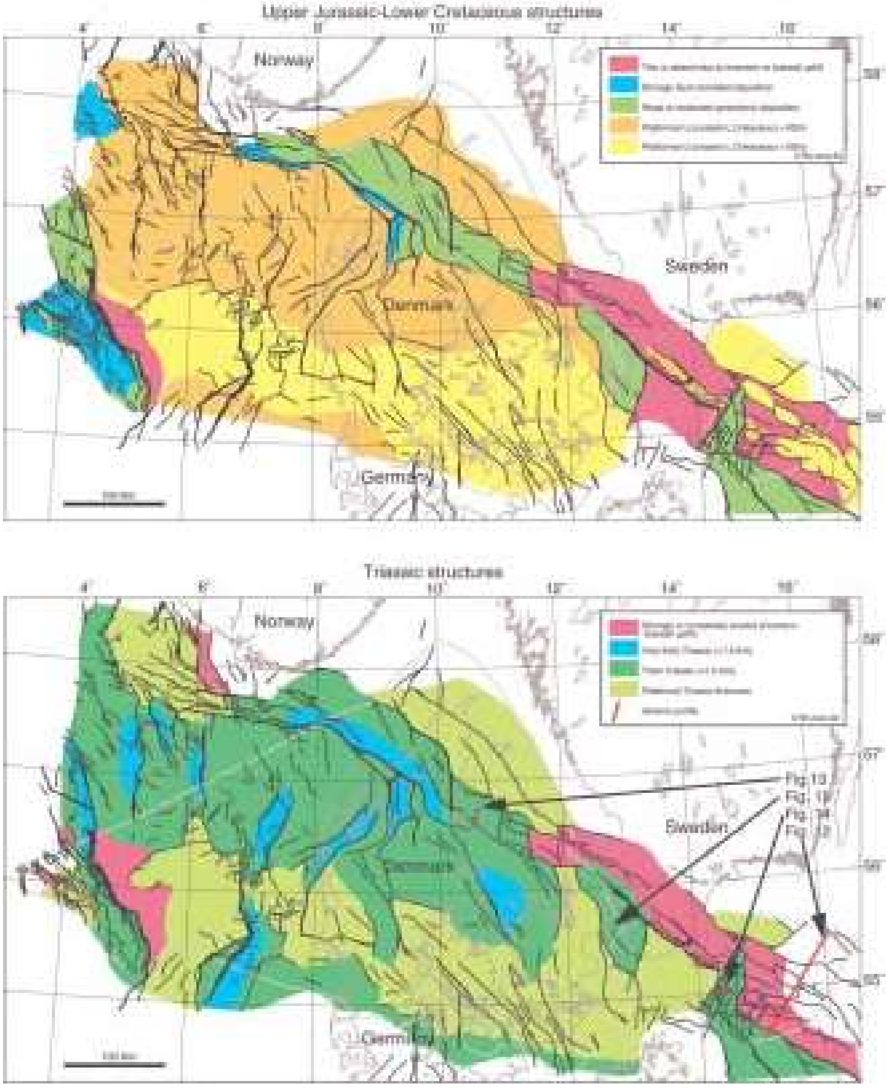


Fig. 3. Simplified maps of the main tectonic features of the Triassic and the Upper Jurassic – Lower Cretaceous. Fault traces are at top pre-Zechstein level and are simplified; from Vejbæk & Britze (1995).

ward decrease in magnitude of the tectonism (Fig. 2). This is the main argument for the interpretation, that a main cause for the inversion is the orogenic plate collision in the Alps (Ziegler 1995).

Positive inversion in Denmark is confined to former depocentres and seems to be laterally controlled by reverse fault movement along the former normal faults defining the pre-existing depocentres. However, Triassic depocentres, which constitute a prominent portion of the sedimentary succession in the subsurface onshore Denmark, have remained virtually unaffected by inversion tectonics (compare Figs 1–3). The Triassic basin consists of an amalgamation of many fault-bounded Triassic depocentres that coalesce into one major basin, the Norwegian Danish Basin (Fig. 3). For instance, the prominent Triassic depocentre of the Horn Graben is virtually unaffected by inversion as resolvable in seismic sections (Vejbæk 1990a, Clausen & Korstgård 1993, Clausen & Huuse 1999). Many of the Triassic faults ceased to be active during Early Jurassic times, but were reactivated during the Middle Jurassic (the so-called Mid Kimmerian tectonic phase). This phase caused regional uplift with renewed rifting especially in the Danish Central Graben and remaining central North Sea rift system (Michelsen et al. 1992, Vejbæk 1992). Modest rates of fault controlled subsidence took place in the Sorgenfrei-Tornquist Zone (Mogensen & Jensen 1994, Fig. 3). Subsidence rates there were only locally above the regional trend, and they barely modified the cooling trend originating from Permian rifting (Vejbæk 1990b, 1997). The tectonism is mainly expressed as more or less continuous Jurassic sedimentation in the Sorgenfrei-Tornquist Zone proper as opposed to flanking areas, where a mid Jurassic hiatus increasing in duration with distance from the Sorgenfrei-Tornquist Zone is recorded (Nielsen in press). Outside these areas of Late Jurassic – Early Cretaceous fault controlled sub-

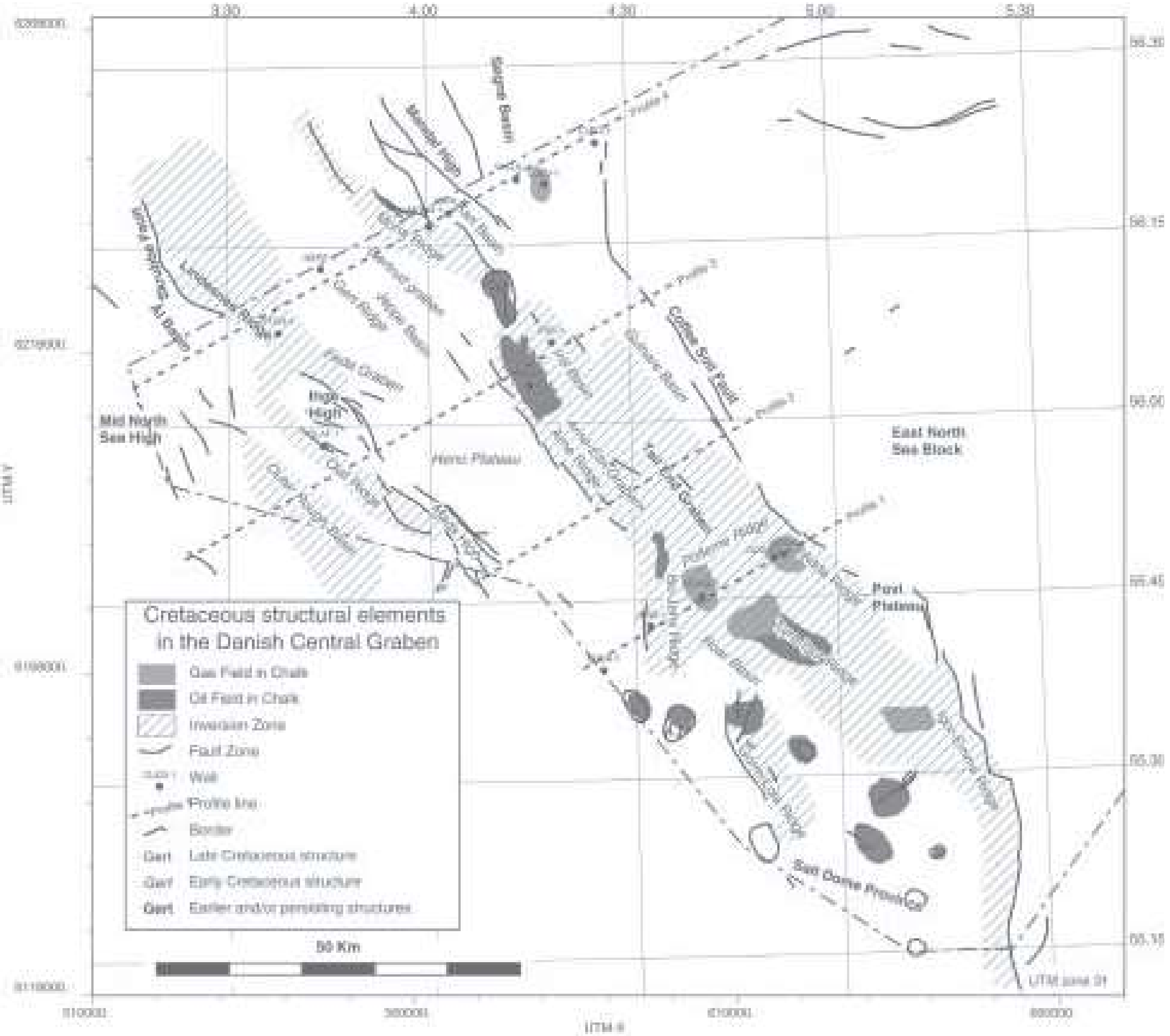


Fig. 4. Danish Central Graben structural elements with faults at Base Chalk level (from Britze et al. 1995b). Hachures indicate areas of positive Late Cretaceous to Palaeogene inversion. Location of cross sections shown in Figure 9 and oil and gas fields with chalk reservoirs are also shown.

sidence only little faulting took place (Fig. 3). The fault-controlled Upper Jurassic – Lower Cretaceous depocentres are also the location of the Late Cretaceous – Palaeogene inversion. It thus seems that there is a remarkable coincidence between areas of Late Jurassic – Early Cretaceous rifting and Late Cretaceous – Palaeogene inversion. Either the rifting immediately preceding inversion created these zones of weakness that localised the release of regional stresses, or the weak zones were already there and thus also responsible for the location of rifting.

The relatively mild inversion in the Danish Central Graben as compared to inverted grabens further south, where the Upper Cretaceous – Palaeogene successions have been totally removed by erosion, makes this area ideal for investigating the chronology of the development of the inversion. In the Danish Central Graben sediments were both deposited between tectonic pulses and were to some extent preserved during and after inversion to allow dating and an estimation of the relative magnitude of the events.

## Central Graben inversion

The tectonic regime of the Danish Central Graben changed from strong Jurassic rifting in the Late Jurassic with associated strong footwall uplift of the East North Sea Block to abating extension in the Early Cre-

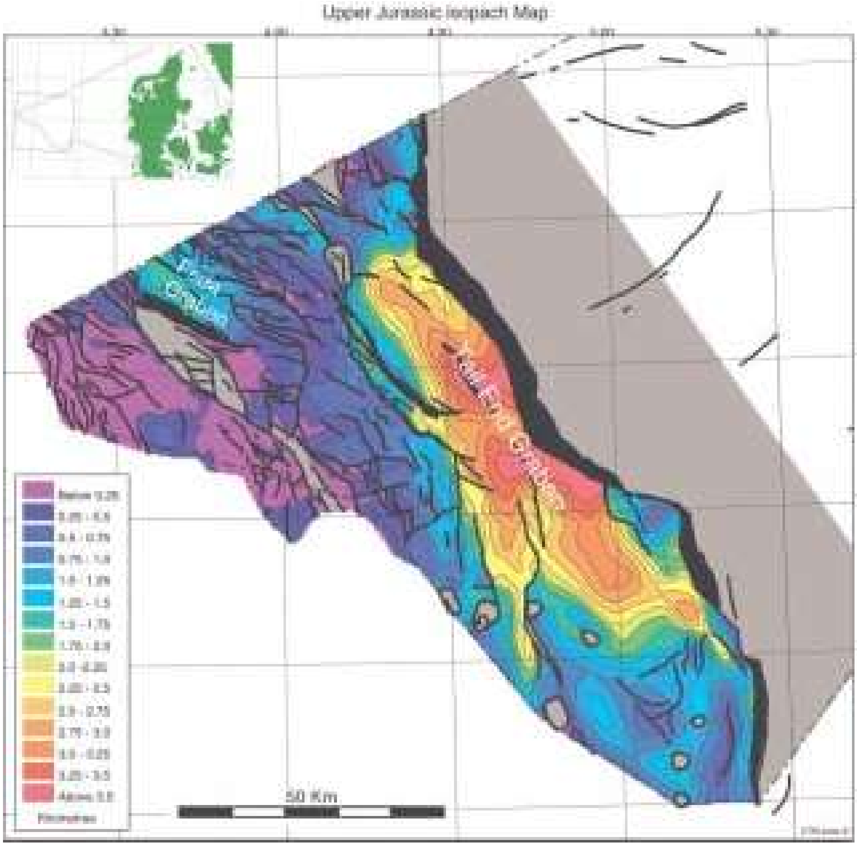


Fig. 5. Upper Jurassic isopach map (Britze et al. 1995d ). Grey areas show thin or absent Jurassic.

taceous and regional subsidence in the Late Cretaceous to Palaeogene (Ziegler 1995). This development was influenced by important inversion phases caused by regional compressional pulses that started already in the Late Hauterivian (Vejbæk & Andersen 1987). At least four phases of inversion can be identified to occur in the Late Hauterivian (1) and culminating in the Turonian–Santonian (2) a strong phase in the Mid Maastrichtian (3) and post Danian Palaeogene (4) (Vejbæk & Andersen 1987).

The general structural configuration of the Danish Central Graben is illustrated in Figure 4. The importance of the inversion for creating structures for hydrocarbon accumulations in the Chalk Group is evident. However, salt tectonics also play a role in many cases (Andersen & Doyle 1990), and a number of Chalk Group hydrocarbon accumulations owe their existence solely to salt movements. The change from depocentre to structural high for many structural elements as a consequence of inversion is for example reflected in the Lower Cretaceous Arne-Elin Graben (Vejbæk 1986, Korstgård et al. 1993, Britze et al. 1995b) turning into the Upper Cretaceous Arne Ridge (Britze et al. 1995a).

The rift-induced depocentres prior to inversion in the Central Graben are illustrated with the Upper Jurassic and Lower Cretaceous isopachs shown in Figures 5 and 6. Even though the Early Cretaceous is dominated by abating tectonic subsidence, the conspicuous Late Jurassic depocentres of the Tail End Graben and the Feda Graben are still clearly visible on the Lower Cretaceous isopach map (Fig. 6, Britze et al. 1995c). The broad eroded area of the East North Sea Block is due to footwall uplift continued from Jurassic times in spite of abating extensional tectonism, and is devoid of pre-Chalk Mesozoic sediments. Other important features of the rift controlled structural pattern are the elevated Heno Plateau and the Søgne Basin, the latter having pre-Chalk successions dominated by Triassic (Korstgård et al. 1993). The general impact of the inversion is illustrated with the Chalk Group isopach map (Fig. 6). Thickness variations of the Chalk Group are mainly related to the two dominating depositional mechanisms: suspension deposition and redeposition caused by tectonically induced slope instability (Nygaard et al. 1983, Bramwell et al. 1999). The main inversion zones from the Igor-Emma Ridge to the Arne Ridge, the Bo-Jens, Mona, and Lindesnes Ridges clearly stand out as inversion ridges with thinly developed Chalk Group coinciding with Upper Jurassic and Lower Cretaceous depocentres. Another important observation is that

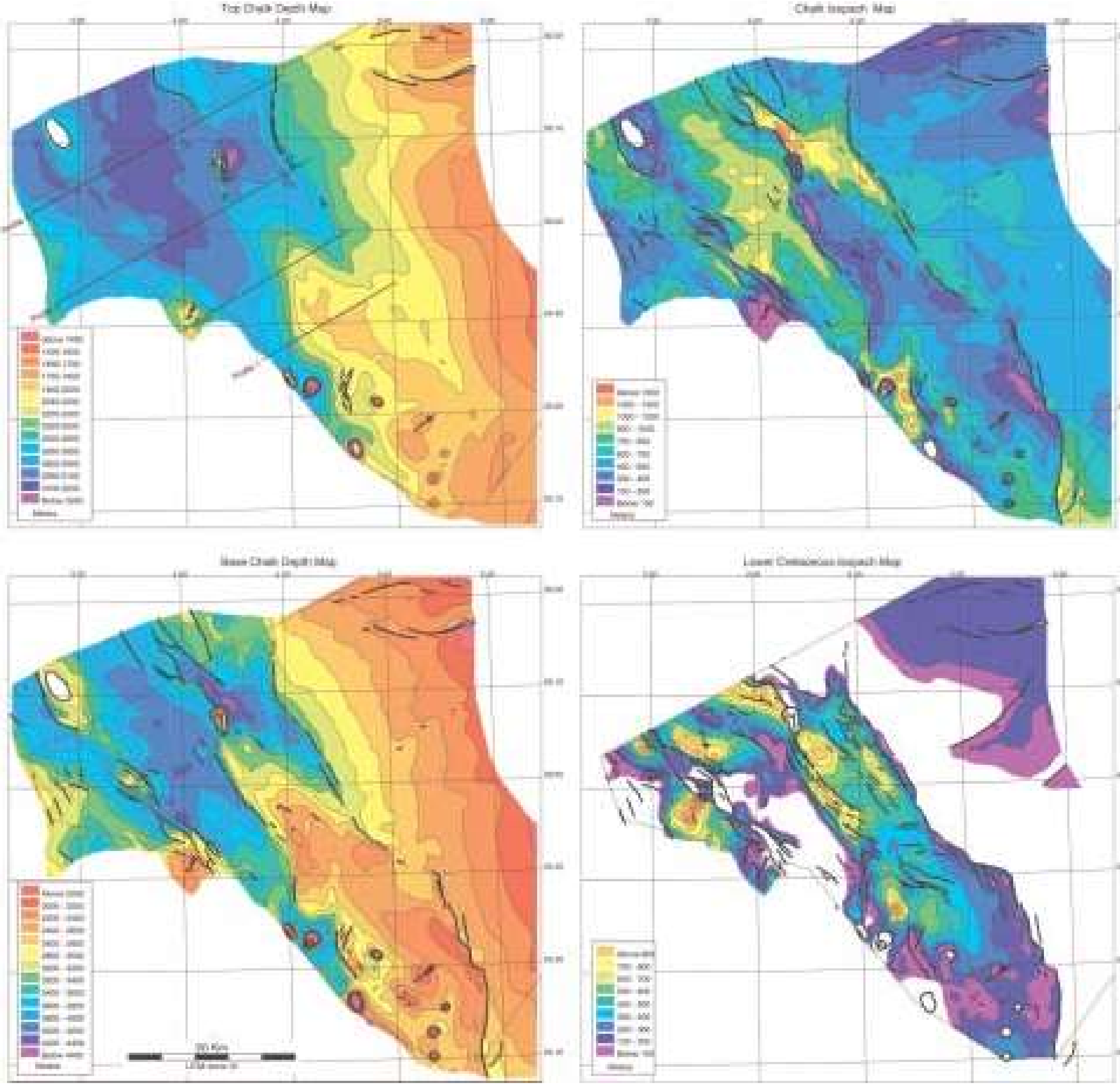


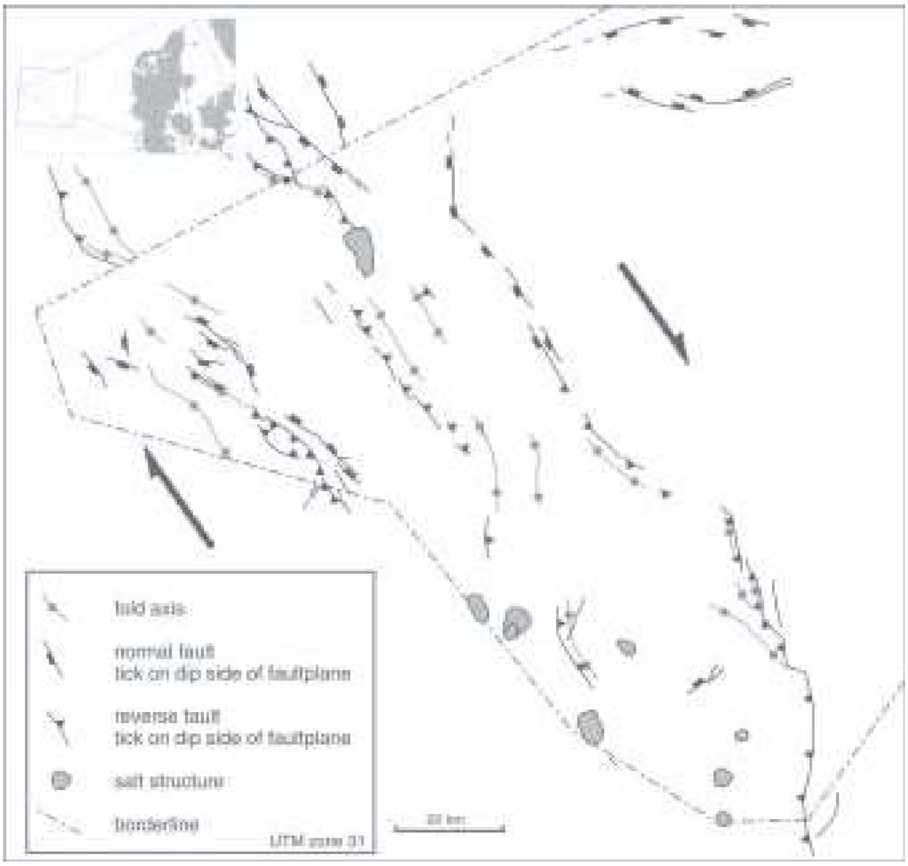
Fig. 6. Lower Cretaceous and Chalk Group isopach maps and Top Chalk and Base Chalk depth structure maps (Britze et al. 1995a, b, c).

the Chalk Group depocentres on the southern East North Sea Block, and the Jeppe and Karl Basins coincide with areas of thinly developed or absent Lower Cretaceous. The inversion thus not only changed areas of subsidence and deposition into areas of uplift and erosion, but also previously uplifted areas into areas of subsidence and deposition. The Late Cretaceous inverted zones are expressed as generally asymmetric anticlines with predominantly NW–SE and N–S trending axes, often arranged in en-echelon like patterns on the Base Chalk depth structure map (Fig. 6). The steeper limbs of the folds are often associated with minor thrust faults that propagate from the tips of former extensional basement attached faults in the substrate. A marked example is the reverse faults along the trace of the southern segment of the Coffee Soil Fault separating the Central Graben from the East North Sea Block.

The post-Danian inversion movements are imaged on the Top Chalk depth structure map (Fig. 6). A marked inversion zone is the Tyra-Igor Ridge in the South. Here the Top Chalk surface is shallower than on the adjacent stable East North Sea Block.

The structures associated with the Late Cretaceous – Palaeogene inversion are highlighted on Figure 7, which also shows faults cutting the Base Chalk level.

Fig.7. Simplified tectonic structures active during the Late Cretaceous – Palaeogene inversion episodes. Northeast – Southwest shortening with a component of dextral strike slip is proposed.



As most reverse faults are reactivations of older normal faults, and fold axes generally are parallel to these faults, orientations rather reflect older fabric than the stress field, which governed the inversions. It is clear though, that the structures indicate shortening perpendicular to the graben axis; i.e. suggesting NE–SW compression (Cartwright 1989). However, left stepping of the active faults at the Mona Ridge and at the Lindesnes Ridge (the Skrubbe Fault, Fig. 4, Farmer & Barkved 1999) is consistent with a dextral movement component in order for these local culminations of inversion to occur. Left stepping of the Igor-Emma Ridge at the southern segment of the Coffee Soil Fault to the Arne Ridge is similarly consistent with a dextral component, since leftstepping in dextral tectonic environment localise compressional deformation along this trend. Components of dextral movement also explain the curious occurrence of extension and subsidence in the Gulnare and Søgne Basins in the Northeast (Clausen et al. 1996, Clausen & Huuse 1999). This area coincides with a change in strike of the Coffee Soil Fault. The compressive structures at the N–S trending Bo-Jens Ridge and to some extent the Gorm-Lola Ridge in the South are, however, not consistent with dextral movements, at least not in a simple way. The western flanks of both inversion zones coincide with former N–S trending extensional basement faults, which controlled subsidence and deposition during the early parts of the Late Jurassic (Britze et al. 1995c, Møller & Rasmussen in press). However, the Gorm-Lola Ridge is also associated with mobile Zechstein salt, which is important for the formation of the Gorm Field structure. A major N–S striking basement fault also visible on the Jurassic isopach map (Fig. 5), controls the salt movement. Whether mobile salt plays a role for the Bo-Jens Ridge is more difficult to ascertain, but it is possible that both this and the Gorm-Lola Ridge owe part of their anomalous structural configuration to salt movements.

Even though the exploitation of pre-existing fabric thus severely complicates structural analysis, the evidence seems to suggest that inversion structures may have been caused by approximately NNE–SSW compression resulting in mild NNW–SSE directed dextral strike slip components. Clausen et al. (1996) have attempted to quantify the Early Cretaceous transtension (sinistral) and Late Cretaceous – Palaeogene transpression along the Arne-Elin Graben/Arne Ridge (Fig. 4). They calculated sinistral movements in the order of one kilometre in the Early Cretaceous, and a similar dextral component in the Late Cretaceous to Palaeogene.

## Inversion subphases

An early phase of inversion in the Late Hauterivian resulted in the development of truncation and onlap at the base of the Late Hauterivian to Barremian Tuxen Formation (Vejbæk 1986, Vejbæk & Andersen 1987). These differential movements caused by inversion tectonics have also been substantiated by detailed log-stratigraphic correlations (Kühnau & Michelsen 1994).

The Chalk Group has been broken down into 8 seismic stratigraphic units (ChG-A – ChG-H) by Nygaard et al. (1990). They integrate the use of wireline logs (density and gamma-ray), biostratigraphy and seismic stratigraphy to subdivide the Chalk Group into sequences bounded by truncation/top-lap, onlap, and down-lap surfaces. The datings based on available industry reports of the top of each of the drilled sequences are summarised in Figure 8. There is a large scatter and overlap in the datings of the uppermost preserved parts of each seismic sequence. These mismatches are partly a consequence of the low resolu-

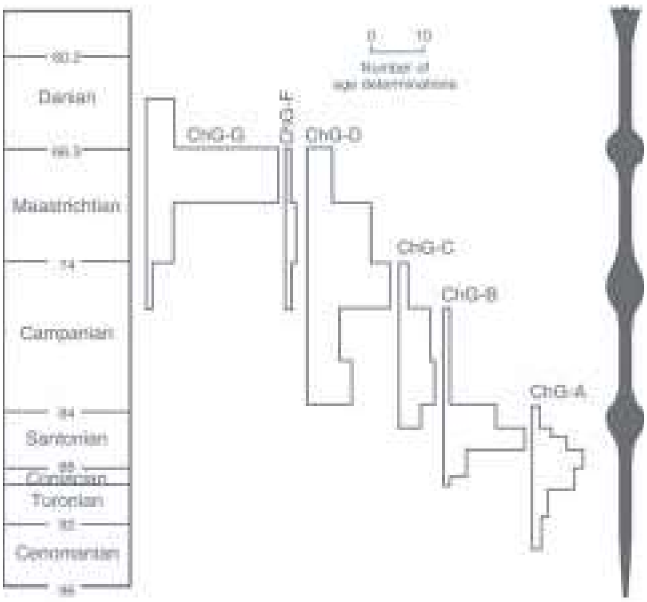


Fig. 8. Dating of top of seismic sequences ChG-A through ChG-G based on industry reports (Andersen et al. 1990). The graph to the right indicates relative magnitude of tectonic activity. The tectonic activity is continuous, but with culminations.

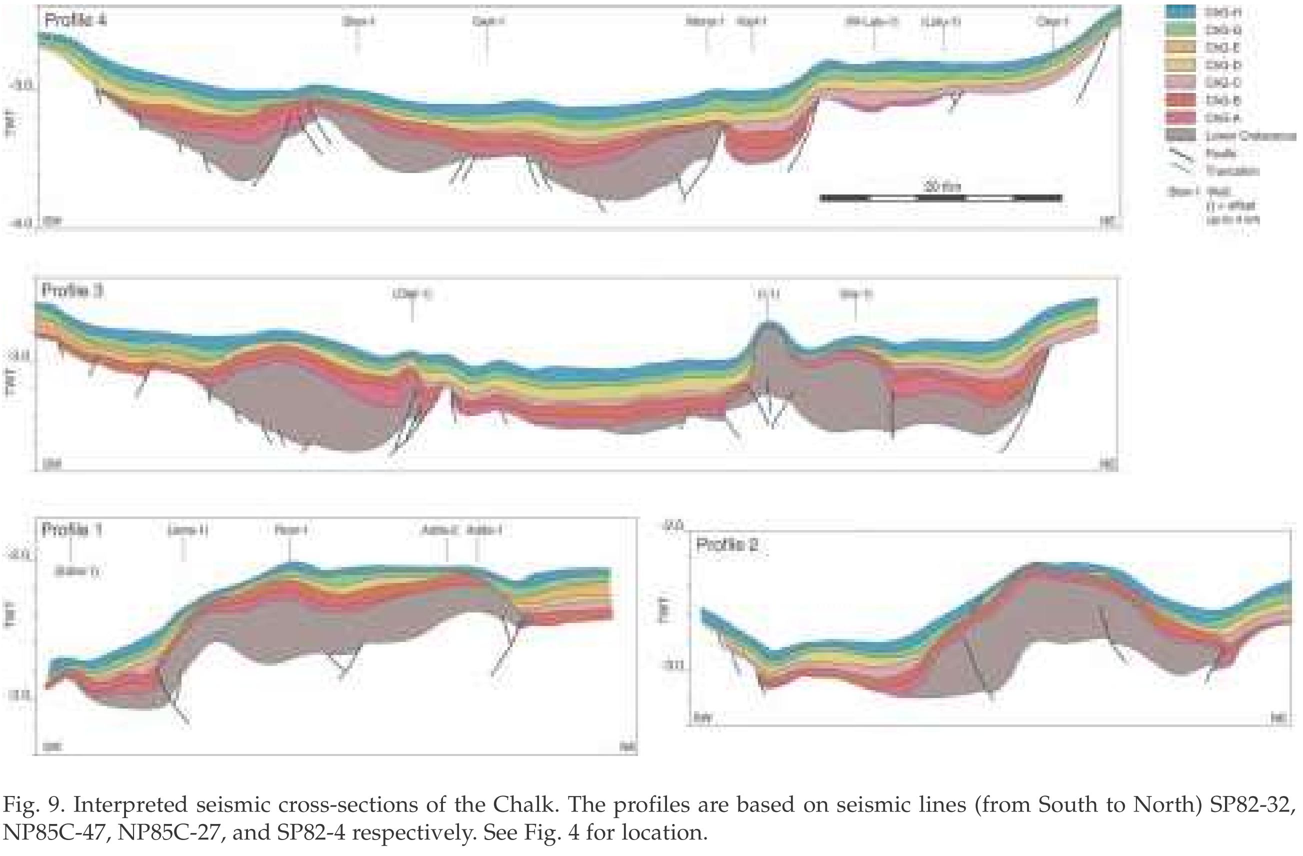
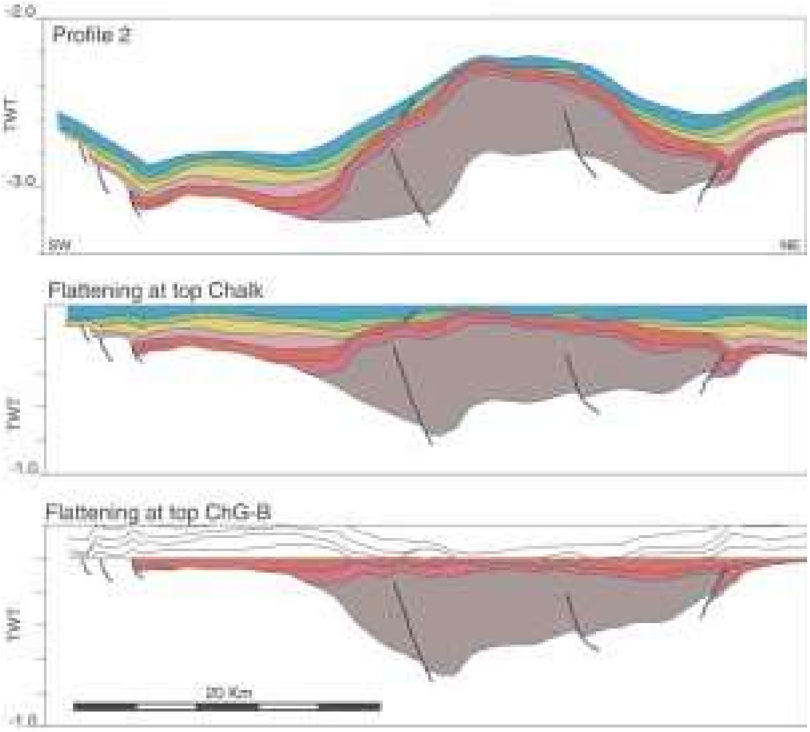


Fig. 9. Interpreted seismic cross-sections of the Chalk. The profiles are based on seismic lines (from South to North) SP82-32, NP85C-47, NP85C-27, and SP82-4 respectively. See Fig. 4 for location.

Fig. 10. Flattening of profile 2 at Top Chalk and at Top ChG-B. The anticline is transitional between the Arne and the Tyra - Igor Ridges. See Figure 9 for legend.



tion of the seismic data (the Chalk Group is seldom represented by more than 10–12 cycles in the seismic signal). They also hint at problems with dating as a consequence of contamination from the drilling process and, more importantly, from reworking penecontemporaneously with deposition (Nygaard et al. 1983, Bramwell et al. 1999).

The profiles in Figure 9 are based on this subdivision and show the thinning and progressive onlapping of the Chalk Group over the flanks of the Ringkøbing Fyn High in the northern part of the Danish Central Graben. This reflects the development from the Early Cretaceous localised subsidence to regional subsidence. However, thinning, onlap, and downlap resulting from syn-sedimentary tectonic movements related to the inversion is also obvious within the Central Graben proper. Internal reflection patterns also display downlap and shingled or hummocky clinoforms indicative of dynamic high-energy deposition from gravity flow (Nygaard et al. 1990). The distribution of these reflection patterns suggests penecontemporaneous redeposition from local uplifted areas. This indicates a tectonic rather than an eustatic origin, since the local topography created by tectonic movements suffice to explain redeposition. These syn-sedimentary tectonic movements explain the dating problems in earlier attempts to provide lithostratigraphic subdivisions of the Chalk Group (Lieberkind et al. 1982, Isaksen & Tonstad 1989). Unit ChG-F cannot be biostratigraphically distinguished from ChG-D. Unit CgG-H comprises the Danian and is approximately equivalent to the Ekofisk Formation (Isaksen & Tonstad 1989). Careful inspection of the cross-sections suggest that major inversion took place following the end of deposition of unit ChG-B, during deposition of unit ChG-D, then again during or at the end of the deposition of unit ChG-G, and finally major inversion in post Danian times (Fig. 8). The Late Cretaceous inversion pulses are evidenced in the seismic reflection pattern as truncational features at the upper boundary of a seismic sequence at the crests of folds, and by associated erosional features that resemble channels and/or slump scars at the flanks. Continued inversion movements are imaged as tilted basal onlaps onto the growth folds. According to the dating of the sequences, the phases are dated approximately to 1: Pre-Campanian – Santonian, 2: Campanian, 3: Maastrichtian and 4: Post Danian. These inversion phases are referred to as sub-phases of the Sub-Hercynian tectonism for the pre-Danian inversion phases, and Laramide inversion for Danian to Palaeogene inversion phases according to Alpine orogenic nomenclature (Ziegler 1995), and compares well with the phases of Vejbæk & Andersen (1987). The flattening of profile 2 shown in Figure 10, makes the tectonic development more visible. The Santonian, the Maastrichtian, and the post Danian inversion phases are clearly depicted, but thinning over the

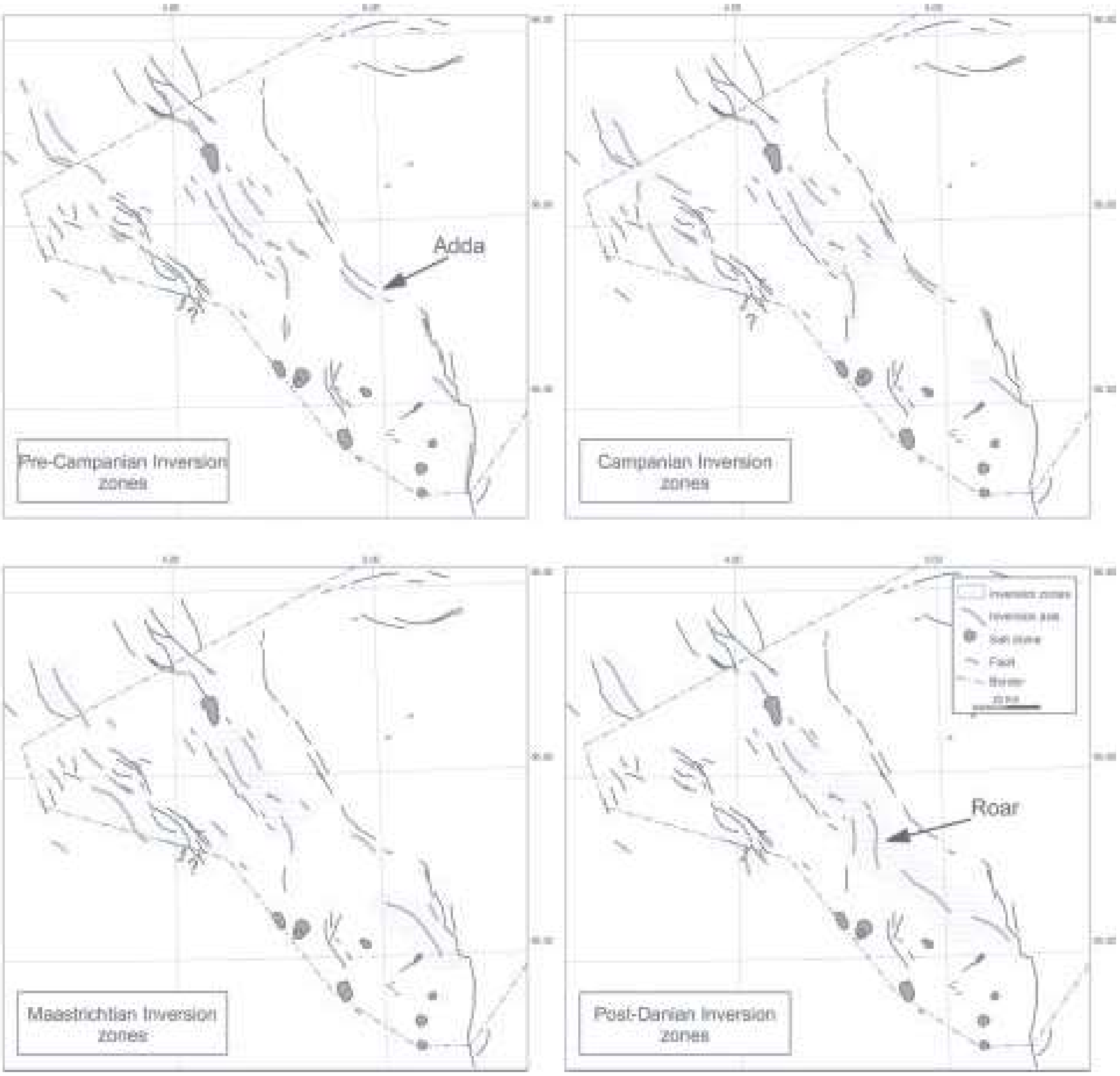


Fig. 11. Location maps of the main activity of the four main inversion phases in the Danish Central Graben. Fault patterns are at the Base Chalk level. Note the narrow inversion zones parallel to the reverse reactivated faults in the early phase and the broad basinwide inversion zone in the late phase.

Lower Cretaceous depocentre and effects of reverse faulting on units ChG-A and B clearly shows that inversion movements were active also in the Late Hauterivian to Santonian time interval. Likewise mild inversion movements can be identified in the Danian (ChG-H) interval. So even though distinct inversion phases can be identified, they have to be considered as culminations on a more or less constant background of compression. In this paper, post Danian inversion has not been subjected to detailed analysis, but the topography of the Top Chalk horizon clearly shows that significant inversion movements continued into the Palaeogene. Clausen & Korstgård (1996) have shown that the post Danian inversion can be subdivided into a Late Paleocene phase, and an Early Oligocene phase based on detailed analysis along the Arne Ridge. Both of these events are associated with dextral transpression along a NNW–SSE direction similar to the earlier events.

The areas affected by the inversion episodes described above are summarised in Figure 11. The compilation is based on the profiles in Figure 9, unpublished seismic facies maps by Andersen et al. (1990), and selected literature (e.g. Farmer & Barkved 1999, Britze et al. 1995a). The early phases show that inversion movements are mainly confined to narrow zones and controlled by pre-existing faults, whereas the late phases are less directly fault controlled and are more expressed as gentle folding and upwarping of the basins. The maps reveal details like the early trap formation of the Adda Field, where hydrocarbons are accumulated in porous Turonian–Coniacian chalks (at the Adda wells Fig. 4) (Andersen & Doyle 1990). No Top Chalk closure exists as inversion abated in this area in post Danian times. Conversely the Roar Field structure (at the Roar-2 well Fig. 4) is seen to be a result mainly of the post Danian inversion.

Inversion zones are to a large extent confined to Upper Jurassic – Lower Cretaceous depocentres. This is consistent with the otherwise curious absence of inversion in the northernmost Tail End Graben and Søgne Basin. The Søgne Basin, which is dominated by thick Triassic has a thinly developed Jurassic – Lower Cretaceous succession (Korstgård et al. 1993) and is thus not a likely location for inversion according to the observed coincidence of Jurassic – Lower Cretaceous depocentres and later inversion tectonics. This may also be the reason for the absence of inversion at the Poul Plateau, where the Jurassic – Lower Cretaceous succession also is thinly developed. The rigid block of the Mandal High – Søgne Basin complex may shelter the Gulnare Basin from inversion, which is both a Lower Cretaceous and an Upper Cretaceous local depocentre. This interpretation implies that the Gulnare Basin is linked with the Mandal High as a rigid block during inversion.

## Inversion in other parts of the Danish area

The other main area of Late Cretaceous – Palaeogene inversion in Denmark is the Sorgenfrei-Tornquist Zone (Liboriussen et al. 1987, EUGENO-S Working Group 1988). This zone is primarily visible on the regional Chalk Group isopach map by virtue of its flanking depocentres (Fig. 1). The Chalk Group has been eroded further subsequent to the inversion movements as a consequence of Neogene uplift (Japsen 1998, Japsen & Bidstrup 1999). The SW limit of this erosion is indicated with a dotted line on Figure 1. The north-eastward increasing thickness of the Chalk until cut by Neogene erosion off the SW coast of Norway suggests that an inversion zone might be located in the SW Norwegian coastal area by comparison to the configuration along the Sorgenfrei-Tornquist Zone in Scania. The Sorgenfrei-Tornquist Zone is also an Upper Jurassic –Lower Cretaceous depocentre along most of its length (Fig. 3, Mogensen 1995). However, the portion of Scania that belongs to the Sorgenfrei Tornquist Zone still has a modest Jurassic – Lower Cretaceous and Triassic succession, even though intense inversion is documented to have occurred (Fig. 3, Erlström et al. 1997) as also witnessed by the flanking depocentres. Major erosion of formerly more widespread Jurassic and Triassic in Scania is documented by outlier occurrences of Triassic (Erlström & Guy-Ohlsson 1999). A formerly more widespread occurrence of Triassic and Jurassic – Lower Cretaceous is indicated in red in Fig. 3. Note, however, that the red areas indicated on the East North Sea Block are due to footwall uplift, mainly during Late Jurassic, and not due to inversion. The erosion in Scania is interpreted to have occurred mainly during the basin inversion which had a mild precursor in the Coniacian–Santonian and its first major pulse in the Campanian coeval with the deposition of the Campanian Lund Sandstone (Erlström 1990, Erlström et al. 1997). To the Southeast, in the Bornholm region, a large area is also affected by relatively intense inversion. Large parts have little or no Triassic, Jurassic and Lower Cretaceous strata. The areas show conspicuous reverse faulting related to inversion, as seen southeast of Bornholm in Figure 12. Here Upper Cretaceous rests directly on Lower Palaeozoic.

The timing of the inversion has been suggested to have a high degree of synchronism in NW Europe (Ziegler 1995) as a consequence of the suggested main causal mechanism: the phases of the Alpine Orogeny

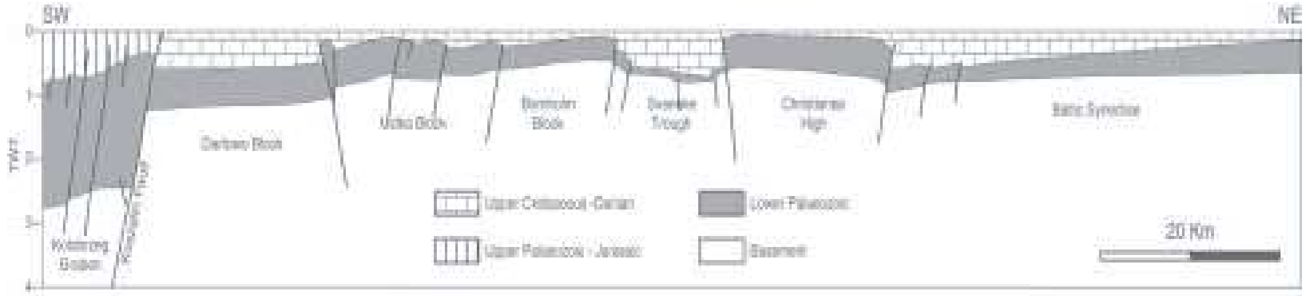


Fig. 12. SW – NE striking geosection Southeast of Bornholm (Vejbæk et al. 1994). See Figure 3 for location.

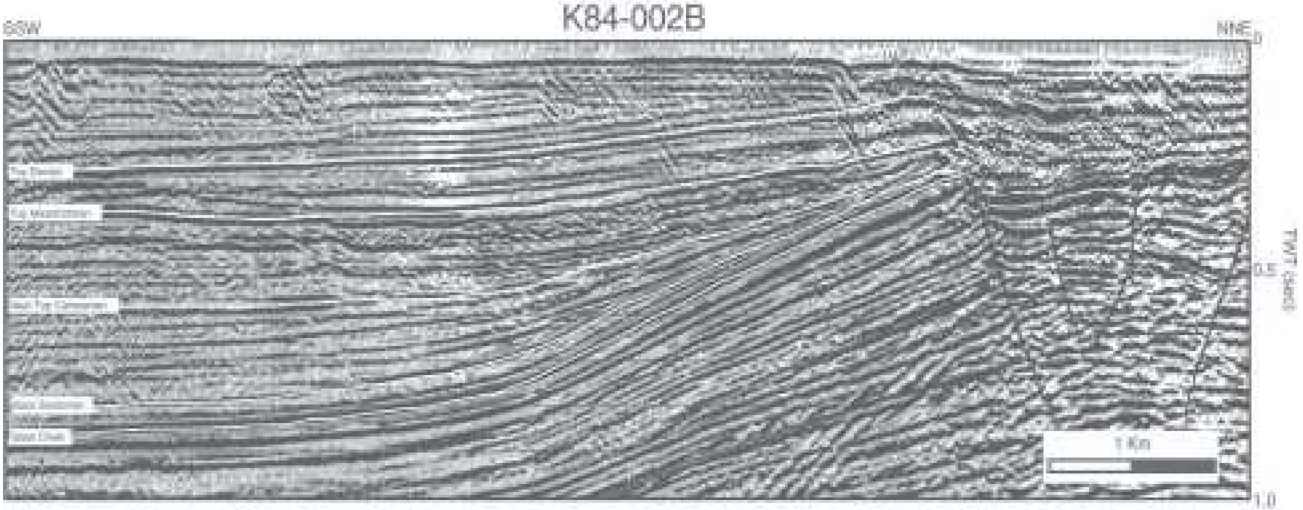


Fig. 13. Example of inversion in the Sorgenfrei Tornquist Zone. The seismic line is located in Kattegat North of Djursland. The approximate ages assigned to the reflections are from Liboriussen et al. (1987). See Figure 3 for location.

to the South. As inversion of the Sorgenfrei Tornquist Zone seems to be laterally continuous, it may be expected that movements within the zone are internally synchronous, irrespective of the cause for the inversion. However, if synchronism of inversion subphases between the Central Graben and the Sorgenfrei Tornquist Zone can be proved, it may support the hypothesis of a common external cause for the inversion. This is discussed below.

The example from the western Kattegat area North of Djursland (Fig. 13) shows an inversion structure expressed as an anticline across the east-dipping Grenå–Helsingborg Fault that is located below the centre in the figure (cf. Vejbæk 1997). The domal structure to the right is located on the hanging wall side of this fault in the Sorgenfrei-Tornquist Zone proper. The anticline includes a local Lower Cretaceous depocentre and thus conforms to the observed coincidence of location of Lower Cretaceous depocentres and inversion structures. An adjacent line on this structure has been interpreted by Liboriussen et al. (1987) from whom a simplified Chalk Group subdivision has been

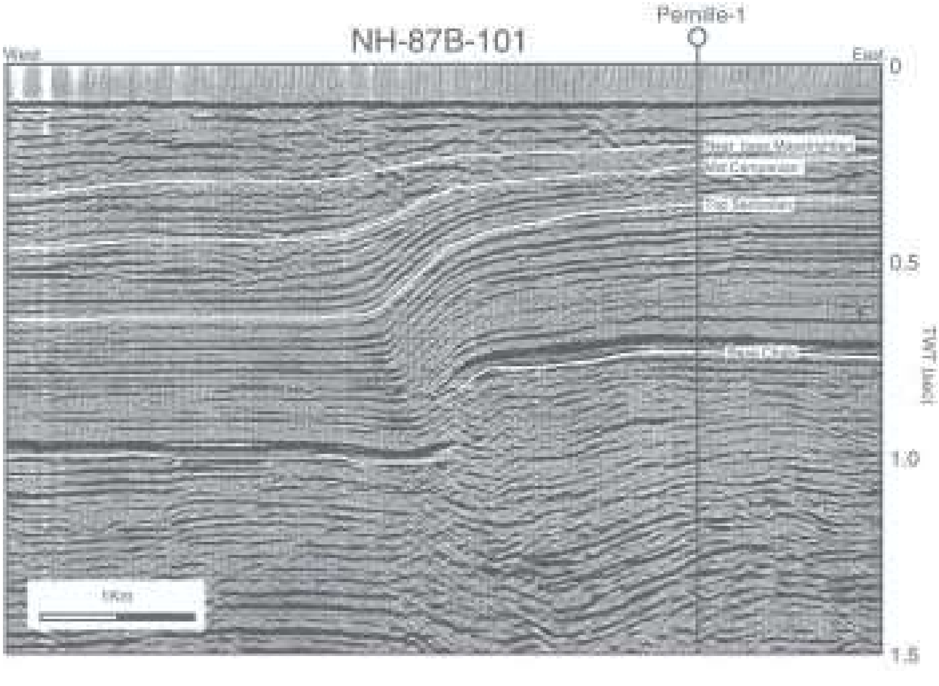
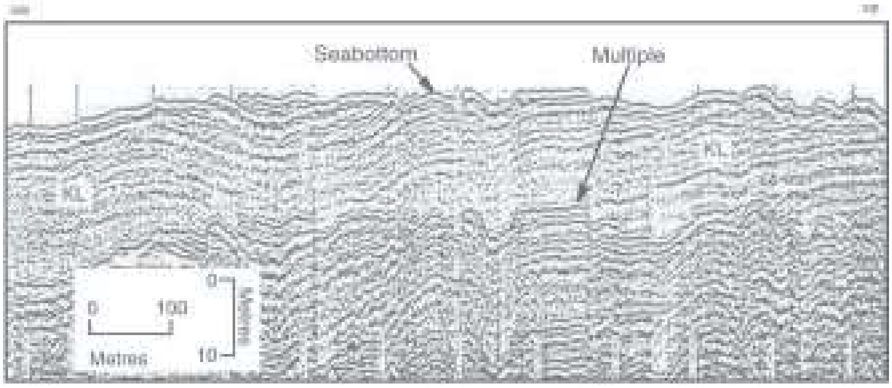


Fig. 14. East – West seismic line through the Pernille-1 well located in the Rønne Graben 30 Km Southwest of Bornholm. The lowermost marked reflector is the base Upper Cretaceous. Only a few meters of Quaternary is between the sea floor and the Maastrichtian limestone. See Figure 3 for location.

Fig. 15. Boomer profile perpendicular to fold axes from the Øresund area showing small scale folding with a few meters amplitude. The folds occur in the Danian København Limestone (KL) and are expressions of mild post Danian inversion. The line is located in the Drogden navigational channel outside the Amager Coastline (from Rasmussen & Andersen 1994). See Figure 3 for location.



adopted. Inversion phases are simply identified by thinning of sequences across the anticline. It is thus seen that no pre-chalk inversion can be identified, as pre-chalk reflectors are diverging to the right into the former depocentre. Weak inversion is, however, seen as thinning in the pre-Santonian chalk succession, and quite clearly in the Santonian to Campanian succession. The Maastrichtian succession is also thinning, and reflection patterns may even suggest penecontemporaneous reworking of the sediments during the Maastrichtian as also pointed out by Liboriussen et al. (1987). The Danian succession has no clear indication of inversion, but the Top Danian clearly shows conspicuous continued inversion, – but over a wider area. However, this profile should be interpreted with some caution due to modest occurrences of salt (e.g. Mogensen 1995). The structure is nevertheless likely to have been affected by both pre-Campanian, Campanian, Maastrichtian and post-Danian inversion. No evidence of Late Hauterivian inversion is seen, but otherwise the observations may suggest synchronism with Central Graben inversion phases.

The example from the Bornholm area shows an inversion structure at the Pernille-1 well location (Fig. 14). A reverse fault is centrally cutting the Base Upper Cretaceous (the lowermost interpreted reflector), which rests on Jurassic sediments. This fault was a normal fault in Jurassic times. Less than 25 m of Quaternary resting on Maastrichtian limestone constitutes the uppermost unit. Approximate ages are assigned according to datings cited in the operator's completion report. The Cretaceous succession below the Top Santonian has negligible thickness changes across the fault, which suggests that inversion was insignificant in pre-Campanian times. However thickness changes for both the unit below and above the mid-Campanian reflector across the fault show that inversion took place in Campanian times. In the shallowest portion to the west, slightly diverging reflectors suggest that also Maastrichtian inversion took place. It is impossible to ascertain whether or not Palaeogene inversion movements have affected this fault due to lack of Palaeogene sediments. It thus seems that evidence exist to suggest synchronous inversion in the Bornholm area and the Central Graben for the Campanian and the Maastrichtian phases. However, pre-Campanian inversion seems to be negligible in the Bornholm area, and the Palaeogene inversion phases are not proven. The youngest Cretaceous deposit onshore Bornholm is the Santonian Bavnodde Greensand. Thus it is older than the main inversion phases and possible effects of these phases cannot be ascertained (Christensen 1984).

An example from the Øresund area, slightly outside the Sorgenfrei-Tornquist Zone, demonstrates that Palaeogene compression also affected this area (Fig. 15). The boomer section from the Drogden navigational channel East of the Amager coastline shows small scale folding of the Danian København Limestone. Similar small scale inversion features outside the Danish main inversion zones, the Danish Central Graben and the Sorgenfrei-Tornquist Zone, have also been reported by Clausen & Huuse (1999) from southern Denmark.

## Discussion

Structural inversion in the Central Graben seems to have commenced in the late Early Cretaceous and persisted into the Palaeogene punctuated by several maxima. Even though the exploitation of pre-existing fabric severely complicates structural analysis, the evidence seems to suggest that inversion structures may be caused by approximately NNE–SSW compression resulting in mild NNW–SSE directed dextral strike slip components.

It has been suggested that inversion is the result of collisional coupling between the Alpine thrust front with the foreland. This is based primarily on the apparently increasing degree of deformation towards the Alpine deformation front (Ziegler 1995). The inversion is therefore suggested to have started after impingement of the Alpine thrust front onto the former southern passive margin of Europe following the closure of oceanic basins in the Mediterranean region. These compressional forces were concentrated in the Eastern Alps and Northern Carpathians where the earliest compressional reactivation in the Bohemian Massif is identified in the Turonian and continuing into the Senonian (Ziegler 1995). This is consistent with the earliest evidence for compression in the Polish Trough as being Late Turonian (Dadlez et al. 1995). However, with little compressional contribution from the western Alps, the direction of compressional forces exerted by the eastern Alps and northern Carpathians must be approximately SE–NW and thus incompatible with the observed deformations in the Danish area. The compression exerted by the Northern Carpathians – East Alpine thrust front continued and culminated in the Late Paleocene coeval with the main inversion phase in the Polish Trough (Dadlez et al. 1995). This compression is even suggested to have impeded onset of seafloor spreading in the northern North Atlantic and Norwegian – Greenland Sea north of the Charlie Gibbs Fracture Zone (e.g. Roberts et al. 1999). Increased collisional coupling between the main orogen and the foreland in the Western Alps took place during the Eocene – Oligocene resulting in transmittal of significant compressional forces into the foreland (Ziegler 1995). Only minor compression is noted in the Eastern Alps and Northern Carpathians at that time. It is therefore only the latest Eocene – Oligocene inversion phase in the Central Graben (Clausen & Korstgård 1996) that may be linked to events in the Western Alps.

A possible explanation for the discrepancy in directions of maximum horizontal compression between structures in the Danish Central Graben and the NW–SE compression from the Carpathians, may be an interplay between the forces originating from Alpine Orogeny and ridge push forces exerted by seafloor spreading south of the Charlie Gibbs Fracture Zone during opening of the North Atlantic (Cartwright 1989, Clausen & Huuse 1999).

Another problem with the explanation of inversion as caused by Alpine compression is the evidence, that the inversion started as early as Late Hauterivian and continued with albeit weak compression until the first main phase in end Santonian times. According to Roberts et al. (1999) NW–SE trending extensional faulting in the Goban Spur area off the Southwest coast of Ireland was followed by sea-floor spreading in Albian times. The onset of sea floor spreading in that area giving rise to NE–SW directed ridge-push compression could, combined with NW–SE directed compression from the North Carpathians, result in N to NNE directed compression compatible with inversion structures in the Danish Central Graben. The Albian is, however still too late for the Late Hauterivian mild precursor inversion in the Danish Central Graben.

Zones of relative weakness of the lithosphere seem to be a necessary condition for inversion to occur (Hansen et al. 2000). This means that basins and grabens that have had sufficient time to regain strength, whether they originally were caused by strain softening (deep unhealed fractures) or thermal anomalies, are unlikely to be the locations of inversion. They may even be more resistant to inversion than the surroundings because of shallower and thus stronger lithospheric mantle. In this context it may be considered enigmatic that old cratons like the Fennoscandian shield seems virtually unaffected by the compressional tectonics because it has a very thick crust, and thus lack the strong upper mantle that makes consolidated grabens relatively more resistant to tectonic deformation. It is possible that also lateral differences in viscoelastic properties of the mantle and/or lower crust (as for instance caused by differences in content of volatiles) have to be considered.

## Dansk sammendrag

Strukturel undersøgelse af den øvre kretassiske til palæogene lagfølge i Dansk Central Grav viser kontinuerlig inversion, initieret i sen Hauterivien og fortsættende ind i Palæogen tid med flere faser af forøget intensitet i: 1) Santonien, 2) midt Campanien, 3) sen Maastrichtien, 4) sen Paleocæn – Eocæn og 5) tidlig Oligocæn. Faserne 1 til 3 benævnes sub-hercyniske, fase 4 benævnes laramisk og fase 5 benævnes pyrenæisk i henhold til nomenklaturen for alpine orogene faser. Der ses et skift i strukturel stilart over tid fra tidlig inversion i snævre zoner associeret med reverse bevægelser langs tidligere normal forkastninger, til sen inversion domineret af mild foldning og fleksurdannelse over større dele af bassinet.

Inversionsfaserne i den danske Central Grav er formodentlig omtrent samtidige med inversionsfaser langs Sorgenfrei-Tornquist Zonen. Dog synes præ-Campanien inversion at være ubetydelig i Bornholms området. Placeringen af inversionszonerne er i høj grad sammenfaldende med øvre Jura – nedre Kridt depocentre, medens ældre depocentre synes at være uberørte. Et uløst problem består med hensyn til den ofte foreslåede primære årsag til inversionsbevægelserne: kompression fra det Alpine orogen overført til forlandet: under den sub-hercyne fase dominerer orogen kompression i de østlige Alper og de nordlige Karpather, hvilket burde give nordvest rettet kompression, medens strukturer i Danmark antyder NNØ rettet kompression. Ydermere antages overførsel af kompression fra Alperne først at have startet i Turon, – altså lang tid efter de tidlige bevægelser i sen Hauterivien, som ses i Dansk Central Grav. Det foreslås at ryg-afglidningskræfter overført fra havbundsspredning syd for Charlie-Gibbs fraktur-zonen, i særdeleshed ved Goban Spur sydvest for Irland, kan have virket sammen med alpin orogen kompression og bevirket det sandsynlige NNØ–SSV rettede spændingsfelt for inversionen i Danmark.

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# Erratum

## ”Post Mid-Cretaceous Inversion Tectonics in the Danish Central Graben — regionally synchronous tectonic events?”

Bulletin of the Geological Society of Denmark, 49(2) (2002), 93-204. Vejbæk, O. V. & Andersen, C.
In this paper Fig. 11 was printed indistinctly such that information was lost.

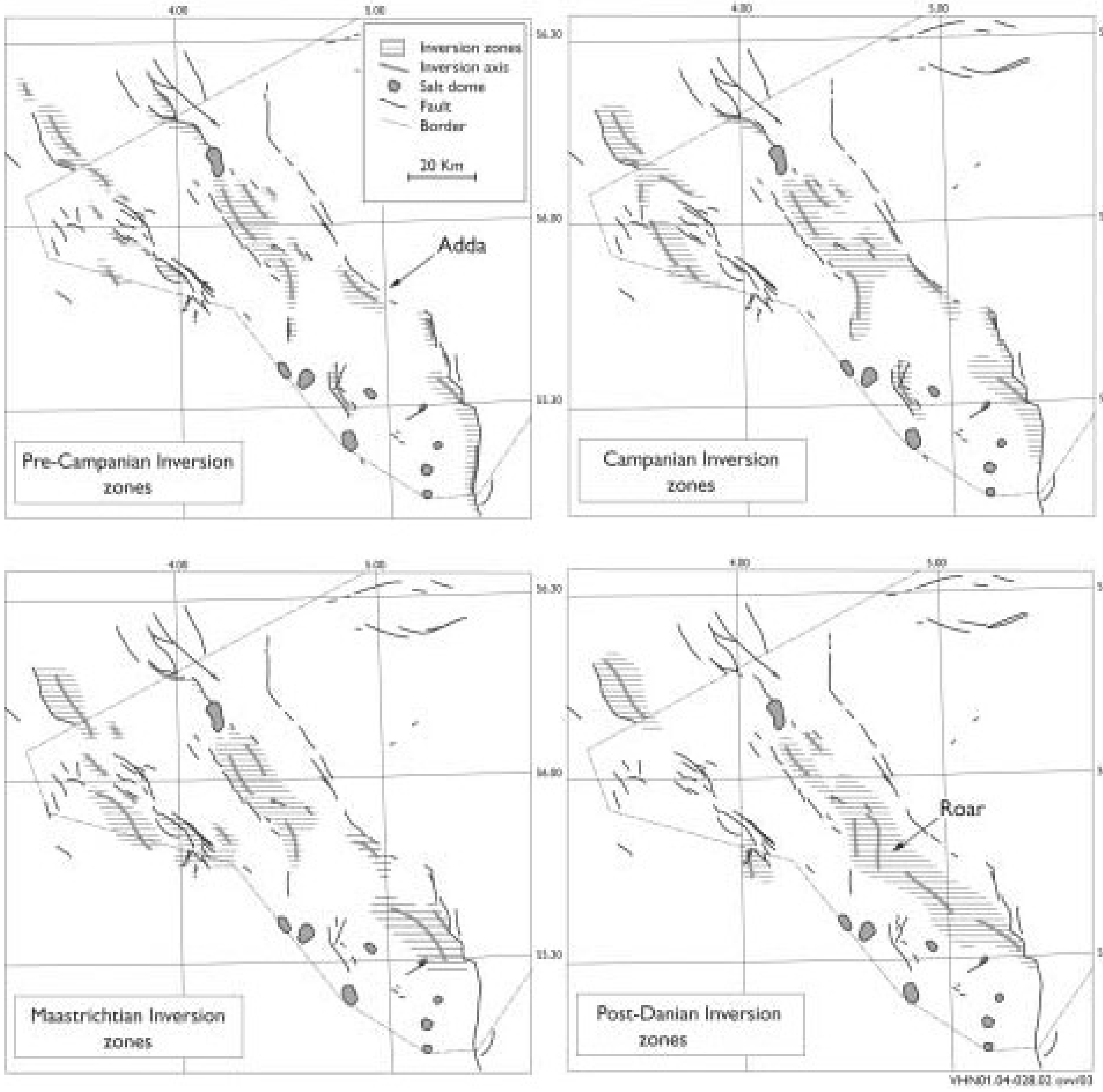

Fig. 11. Location maps of the main activity of the four main inversion phases in the Danish Central Graben. Fault patterns are at the Base Chalk level. Note the narrow inversion zones parallel to the reverse reactivated faults in the early phase and the broad basin-wide inversion zone in the late phase.