The Skælskør structure in eastern Denmark – wrench-related anticline or primary Late Cretaceous seafloor topography?

FINN SURLYK, LARS OLE BOLDREEL, HOLGER LYKKE-ANDERSEN & LARS STEMMERIK

Surlyk, F., Boldreel, L.O., Lykke-Andersen, H. & Stemmerik, L. 2010-11-11. The Skælskør structure in eastern Denmark – wrench-related anticline or primary Late Cretaceous seafloor topography? © 2010 by Bulletin of the Geological Society of Denmark, Vol. 58, pp. 99–109. ISSN 0011–6297. (www.2dgf.dk/publikationer/bulletin) https://doi.org/10.37570/bgsd-2010-58-08

Sorgenfrei (1951) identified a number of NW–SE oriented highs in the Upper Cretaceous – Danian Chalk Group in eastern Denmark, including the Skælskør structure and interpreted them as anticlinal folds formed by wrenching along what today is known as the Ringkøbing-Fyn High. Recent reflection seismic studies of the Chalk Group in Øresund and Kattegat have shown that similar highs actually represent topographic highs on the Late Cretaceous – Danian seafloor formed by strong contour-parallel bottom currents. Reflection seismic data collected over the Skælskør structure in order to test the hypothesis of Sorgenfrei show that the Base Chalk reflection is relatively flat with only very minor changes in inclination and cut by only a few minor faults. The structure is situated along the northern margin of a high with roots in a narrow basement block, projecting towards the northwest from the Ringkøbing Fyn High into the Danish Basin. The elevated position is maintained due to reduced subsidence as compared with the Danish Basin north of the high. The hypothesis of wrench tectonics as origin can be refuted. The seismic data show that the upper part of the Chalk Group is characterised by irregular mounded reflections, interpreted as representing contourite drifts, mounds and channels formed by strong, mainly late Maastrichtian bottom currents. The Skælskør structure of Sorgenfrei is thus in reality a Late Cretaceous topographic seafloor high formed by a combination of differential subsidence complemented by topographic features on the seafloor created by bottom currents in the late Maastrichtian.

Keywords: Skælskør structure, Chalk Group, wrenching, seafloor topography, bottom currents.

Finn Surlyk [finns@geo.ku.dk], Lars Ole Boldreel [lob@geo.ku.dk], Lars Stemmerik [ls@geo.ku.dk], Department of Geography and Geology, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark, Holger Lykke-Andersen [hla@geo.au.dk], Geological Institute, University of Aarhus, Høegh-Guldbergs Gade 2, bygning 1670, DK-8000 Aarhus C.

Corresponding author (finns@geo.ku.dk)

In a review of the topography, stratigraphy and tectonics at the base of the Quaternary in central and eastern Denmark Sorgenfrei (1951) noted the presence of NW–SE trending *en echelon* highs on and along the margins of what today is known as the Ringkøbing-Fyn High (Figs 1, 2). These highs were located at the north-eastern part of Stevns Klint, at Feddet south of Præstø, at Egesborg south of Næstved, at Rødby on southern Lolland, at Skælskør on western Sjælland, and at Nyborg and Ringe on western and central Fyn, respectively (Figs 1, 2). Sorgenfrei (1951) interpreted the highs as anticlinal folds formed by regional wrenching along the Ringkøbing-Fyn High which has a WNW–ESE orientation.

Similar highs are known from the Upper Cretaceous – Danian Chalk Group exposed in the 15 km long coastal cliff Stevns Klint where they are expressed by the position of the Cretaceous–Tertiary (K/T) boundary which varies from 5 m below to about 40 m above sea level along the length of the cliff (Rosenkrantz 1938; Lykke-Andersen & Surlyk 2004; Surlyk et al. 2006). An important lowermost Danian hardground situated up to about 1 m above the K/T boundary was interpreted as an originally horizontal marine abrasion surface by Rosenkrantz (1938) who consequently interpreted the topographic relief of the boundary strata as a result of late or post-Danian Laramide folding. Reflection seismic data collected immediately offshore the cliff show, however, that the Base-Chalk reflection is remarkably planar, not folded, and has a gentle northward dip of 0.5° over at least 50 km in a S–N direction (Lykke-Andersen & Surlyk 2004; Esmerode *et al.* 2007a). The seismic profiles also show that a marked seafloor relief with ridges, valleys, drifts and channels was developed throughout deposition of the Chalk Group. The folding hypothesis was thus refuted and the relief of the K/T boundary was instead interpreted as representing a primary Late Cretaceous – Danian seafloor topography caused by long-lived bottom currents (Lykke-Andersen & Surlyk 2004). A similar high in the Danian carbonate succession is known from Øresund, the strait between Denmark and Sweden (Fig. 1) and has been interpreted as formed by post-Danian folding based on regional

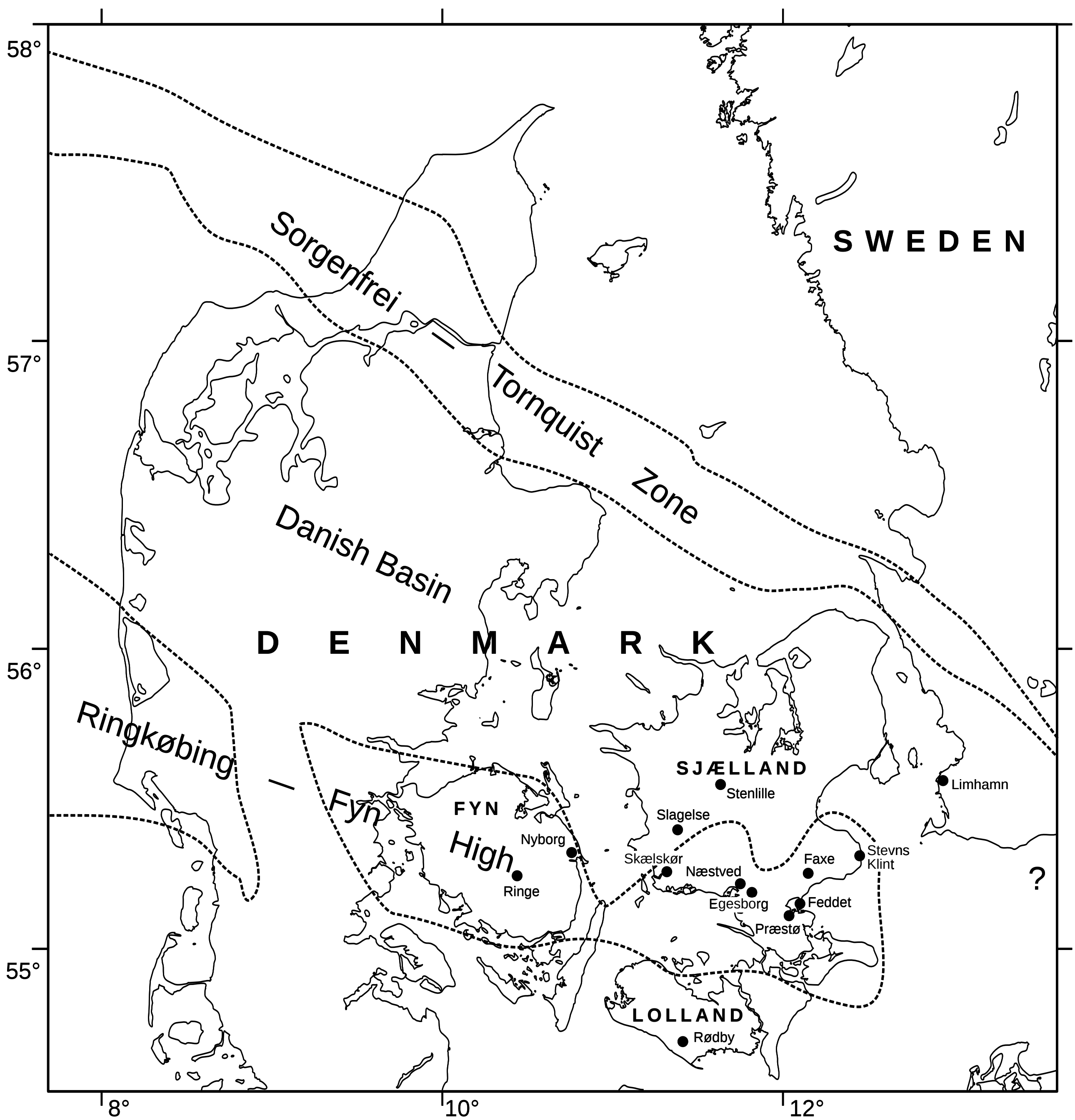


Fig. 1. Map showing the main structural elements of the Danish area and the position of localities mentioned in the text. Some of the localities are also shown in Figure 2.

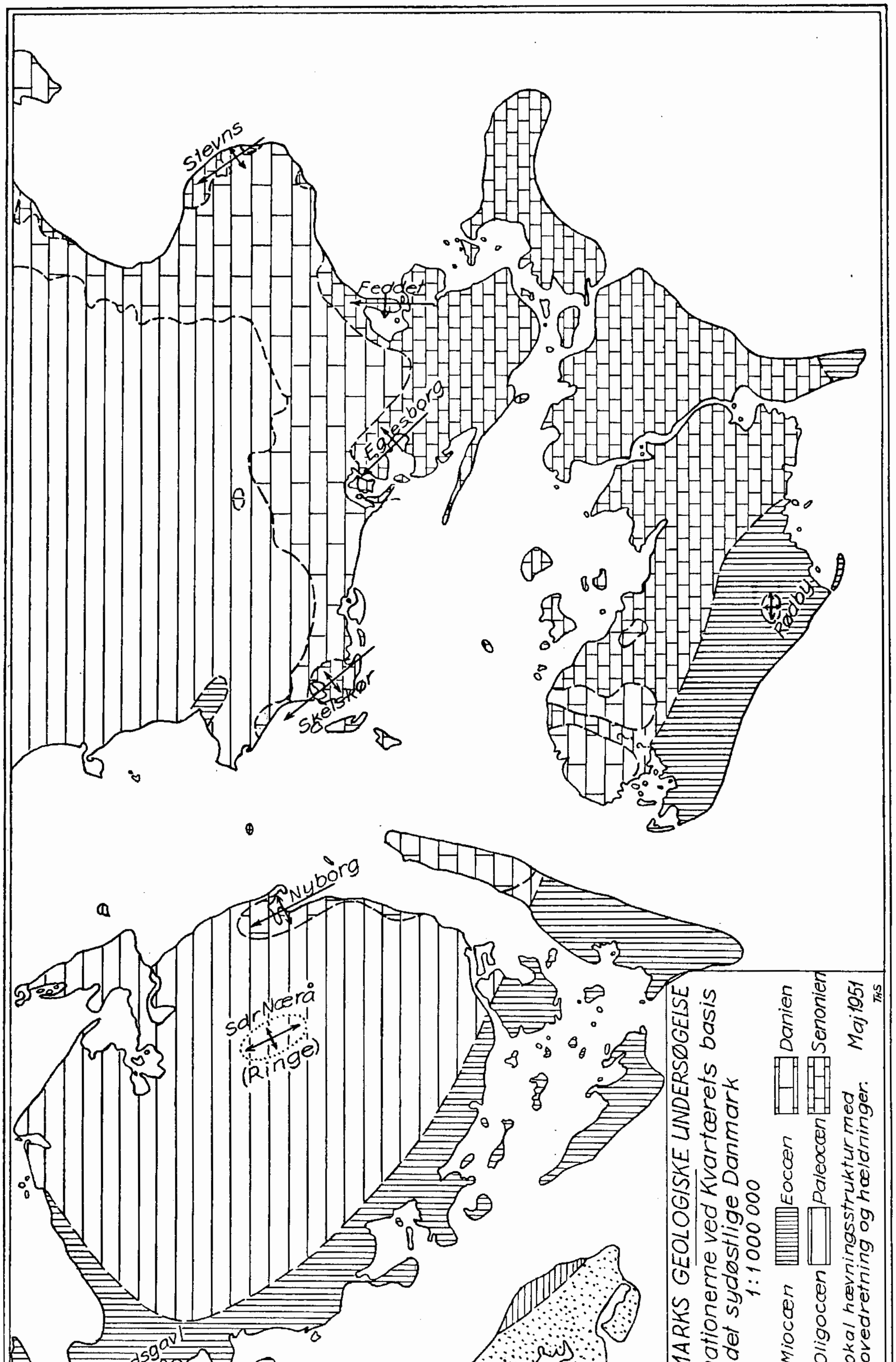


Fig. 2. Map prepared by Sorgenfrei (1951, p. 167), showing the geology of eastern Denmark at the base of the Quaternary. Note the presence of a number of mainly NW–SE oriented anticline-like structures. Sorgenfrei (1951) tentatively suggested that the structures were anticlinal folds formed during the Oligocene by wrenching along the margins of what today is known as the Ringkøbing-Fyn High (Fig. 1). Copied from Sorgenfrei (1951).

considerations (Hennig 1899), shallow boreholes (Brotzen 1959), and shallow seismic profiles (Knudsen *et al.* 1995). However, shallow and conventional deep seismic data supplemented by scuba-diving mapping of large excavations made for bridge piers, clearly show that the high also in this case represents a primary seafloor topography and is not due to folding (Bjerager *et al.* 2010).

The Danian of eastern Denmark comprises bryozoan limestone of the Stevns Klint Formation passing basinwards into chalk (Thomsen 1995; Surlyk 1997; Surlyk *et al.* 2006). At a few locations the bryozoan limestone is interbedded with coralline limestone formed by deep- and cool-water scleractinian corals. The largest occurrence of coralline limestone is in the Faxe quarry and smaller occurrences are known from the Limhamn quarry and from the Saltholm–Malmø High in the Øresund strait (Fig. 1). Coralline limestones are otherwise only known from a few shallow boreholes in southern Sjælland (Figs 1, 2). It is remarkable that these sites are all located over the highs identified by Sorgenfrei (1951). As a working hypothesis it has been proposed that formation of deep-water coral mounds in the Danian of the Danish Basin took place mainly on contemporaneous seafloor highs which were sites of intensified bottom currents, enabling extensive colonisation of azooxanthellate corals by supplying particulate nutrients (Bjerager *et al.* 2010). This is similar to the situation known from modern analogues (e.g. Freiwald *et al.* 1997, 2002).

The present study focuses on the large Skælskør structure of Sorgenfrei (1951). It is poorly known and the aim is to test if the structure is an anticline formed by post-Danian, possibly Oligocene wrenching along the northern margin of the Ringkøbing-Fyn High as suggested by Sorgenfrei (1951), or if it represents a local Late Cretaceous palaeobathymetric seafloor high formed by strong bottom currents.

Methods

The seismic data acquisition was performed on hard paved roads with a pulled geophone array system (72 geophones; separation 2.5 m; near offset 20 m). The seismic source was an IVI MiniVib, producing sweeps in the 10–300 Hz frequency band with four sweeps at each station located at intervals of 7.5 m along the line. The raw data were digitized, pre-processed (i.e. recorded sweeps correlated with sweep signal emitted from the vibrator) and recorded by a Geometrics Strataview recording system. The correlated field data were processed in Promax software to filtered stack sections with sea level as datum. A stack fold of ca. 12 was obtained at CMP-points with 1.25 m spacing. The Two Way Time (TWT) of the stacked sections were converted to depths by adopting a 1-D velocity model for the Chalk Group elaborated from refraction seismic data collected onshore along Stevns Klint (Nielsen *et al.* under revision). The stacked sections were geologically interpreted on PC-workstations with Kingdom Suite Software provided by Seismic Micro Technology.

Eight seismic lines were shot along the main, relatively straight roads around Skælskør but avoiding the main town (Fig. 3). The collected reflection seismic data are generally of excellent quality down to ca. 900–1000 m (600–700 msecs TWT) although parts of some profiles are disturbed by noise of various origins. The upper ca. 150 m (200 msecs TWT) show somewhat poorer reflectivity.

Results

The Quaternary cover is a few tens of metres thick in most of the study area and overlies Danian bryozoan limestone or Maastrichtian chalk. This means that the seismic profiles portray almost all of the Upper Cretaceous – Danian Chalk Group, the Danian part being only about 50 m thick in the area (Thomsen 1995). A strong reflection situated at depths down to about 600 msecs TWT, corresponding to a depth of about 900 m is interpreted as the Base Chalk reflection. It occurs at roughly the same depth as the Base Chalk reflection in seismic data onshore and offshore Stevns Klint where the group has a similar thickness (Lykke-Andersen & Surlyk 2004). The Chalk Group in the borehole Slagelse 1, situated 15–20 km north of the study area is close to 700 m thick (Sorgenfrei & Buch 1964); the position above a low salt pillow explains the somewhat lower thickness. The thickness of the Chalk Group in six boreholes at Stenlille 35–40 km NNE of the study area varies between 932 and 1062 m (Nielsen & Japsen 1991).

Seismic sections and a contour map of the Base Chalk reflection shows the planar, flat and undisturbed nature of the of the Base Chalk reflection (Figs 4, 5). It should be noted, however, that the wide spacing of the seismic lines does not allow detection of smaller topographic or structural features. The Base Chalk level is situated at a depth of about 800 m in the southern part of the study area and dips gently northwards starting with an inclination of about 1.3°. After two kilometres it flattens to about 0.8° until a low at about 900 m is reached north of Skælskør. Further northwards it rises again to a depth of about 850 m.

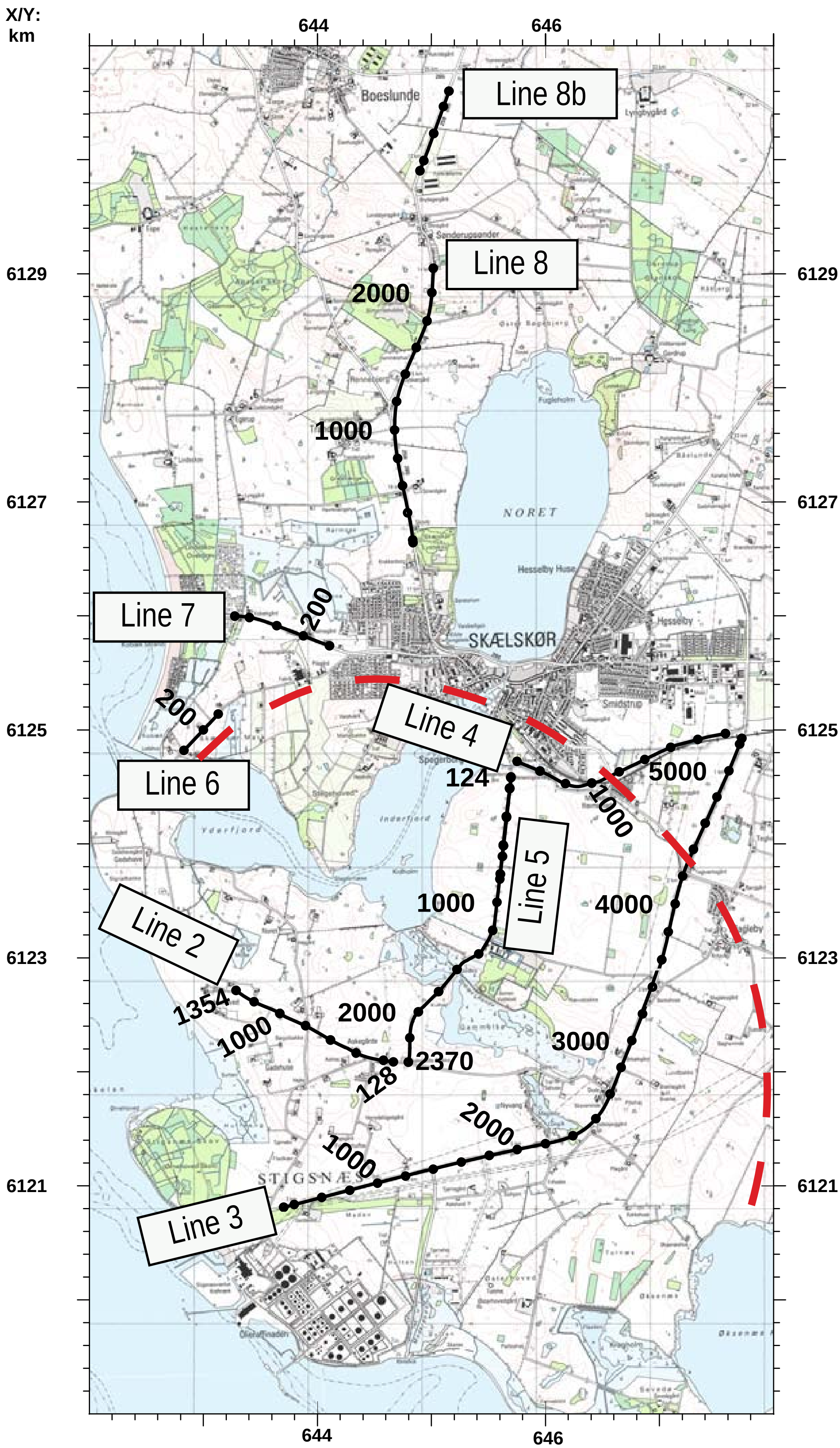


Fig. 3. Map showing the position of the seismic lines around the town of Skælskør. The numbers indicate shotpoints. The dashed red line gives the outline of the Skælskør high adapted from Sorgenfrei (1951), see also Figure 2.

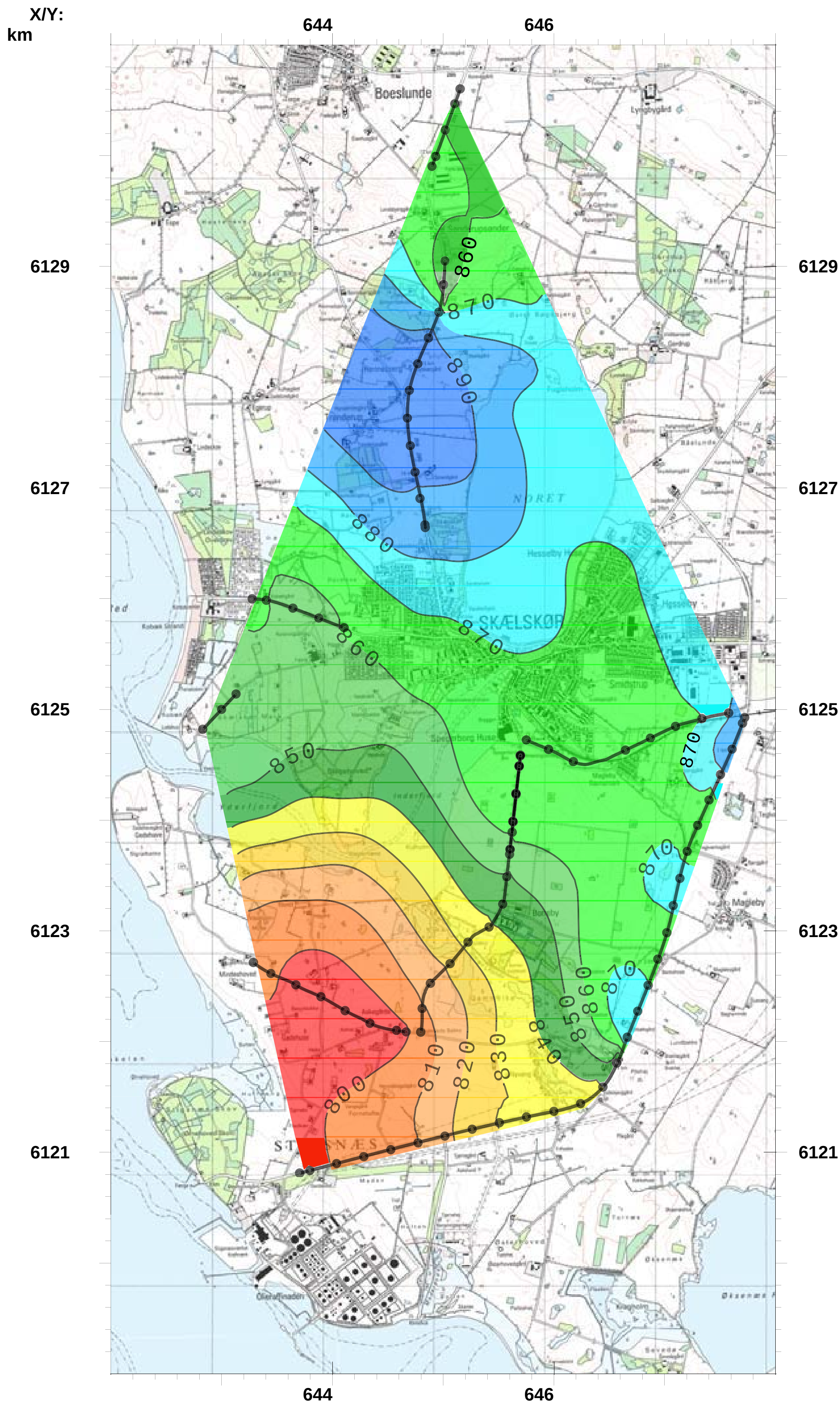
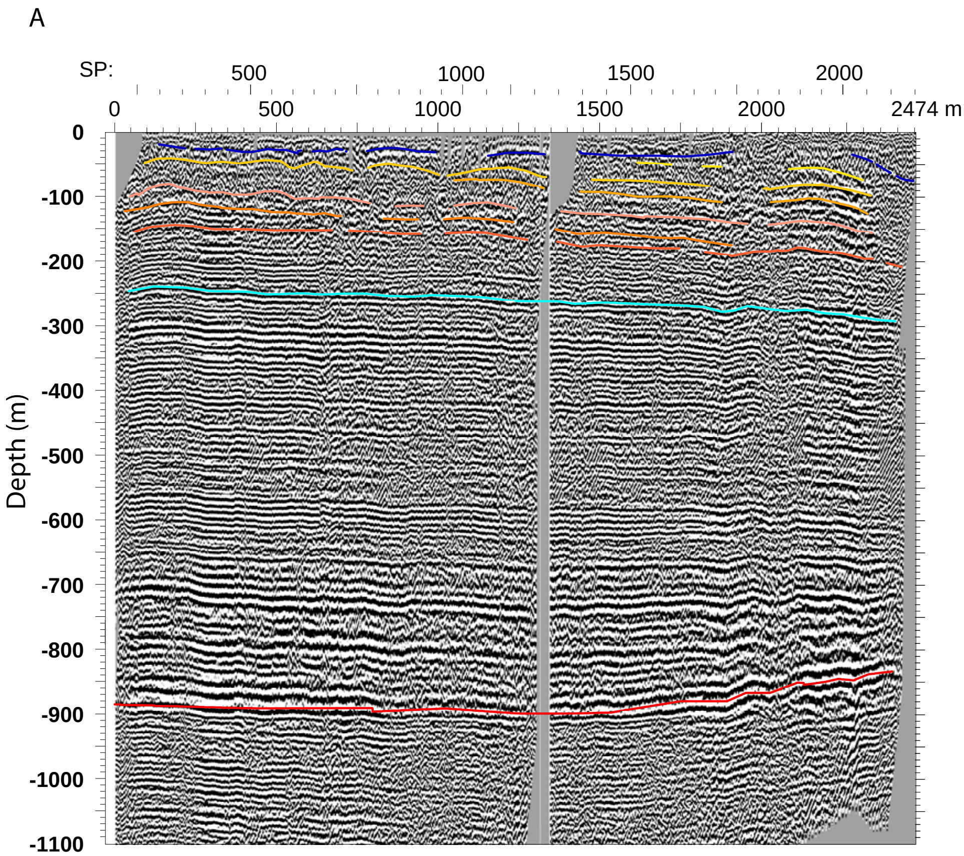


Fig. 4. Map showing the contours in metres below present sea level of the Base Chalk reflection. The contours are generated in the software package "The Kingdom Suite" provided by Seismic Micro Technology. Some of the features shown on the map are thus artefacts. Note the gentle northward dip of the reflection in most of the study area and a reversal to a S-ward dip in the northernmost part of the area. The latter is interpreted as the expression of low pillow of Zechstein salt (see also Figure 5).



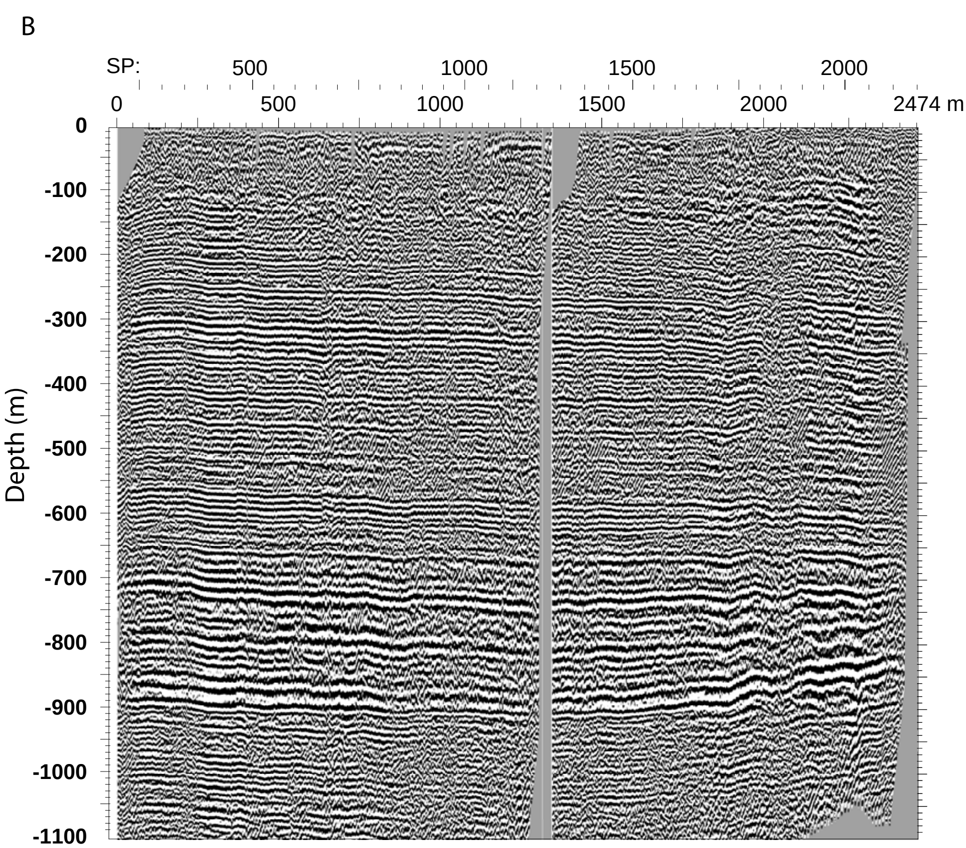


Fig. 5. N–S oriented seismic line 8 (position shown in Figure 3). Vertical scale is in metres below sea level. The unbroken and flat Base Chalk reflection (red, between 800 and 900 m depth) is close to horizontal from SP (shotpoint) 0 to SP 1600 where it starts to rise gently towards the N. This is interpreted as caused by the presence of a low pillow of Zechstein salt with a centre close to the northern end of the line (SP 2150).

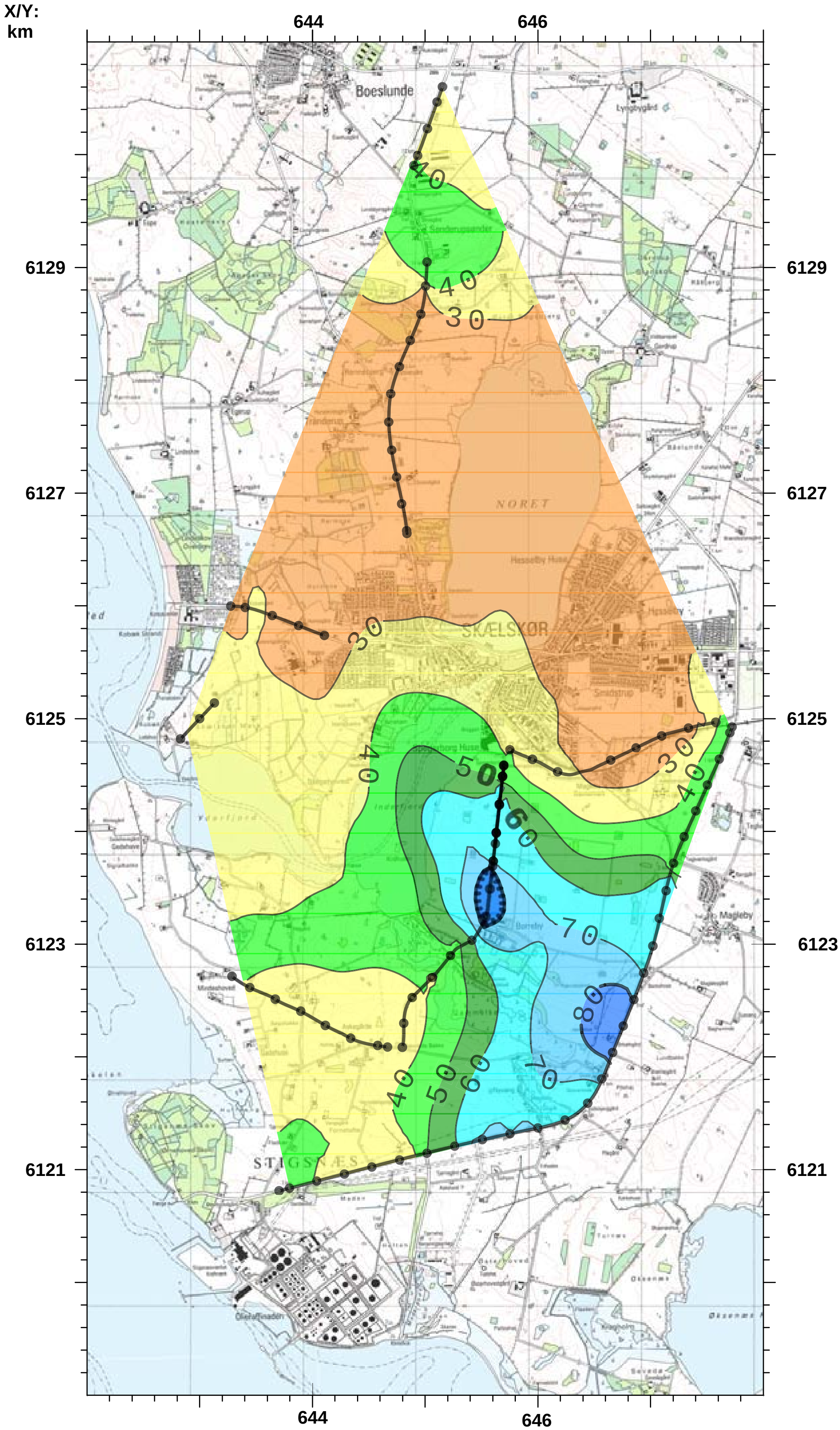


Fig. 6. Map showing contours in metres below present sea level of the top Top Chalk reflection. This surface was to some extent modified by Quaternary erosion and does not provide an exact picture of its original configuration. The contours are generated in the software package "The Kingdom Suite" provided by Seismic Micro Technology.

The southern high has a semicircular appearance in map view (fig. 4). Due to the sparse line coverage in the western part of the area it is believed that the real form is elongate in a direction parallel to the NW–SE trending coastline. The high is located along the NE-flank of a basement sliver protruding NW-wards from the Ringkøbing-Fyn High following the coastline between Skælskør and Stigsnæs as mapped by Vejbæk (1997). The high and the northward dip of the Base Chalk level is interpreted to be caused by increasing rates of subsidence from the basement sliver and out into the Danish Basin. The internal reflections in the Chalk Group diverge slightly basinwards towards the north, indicating that differential subsidence was active through the Late Cretaceous.

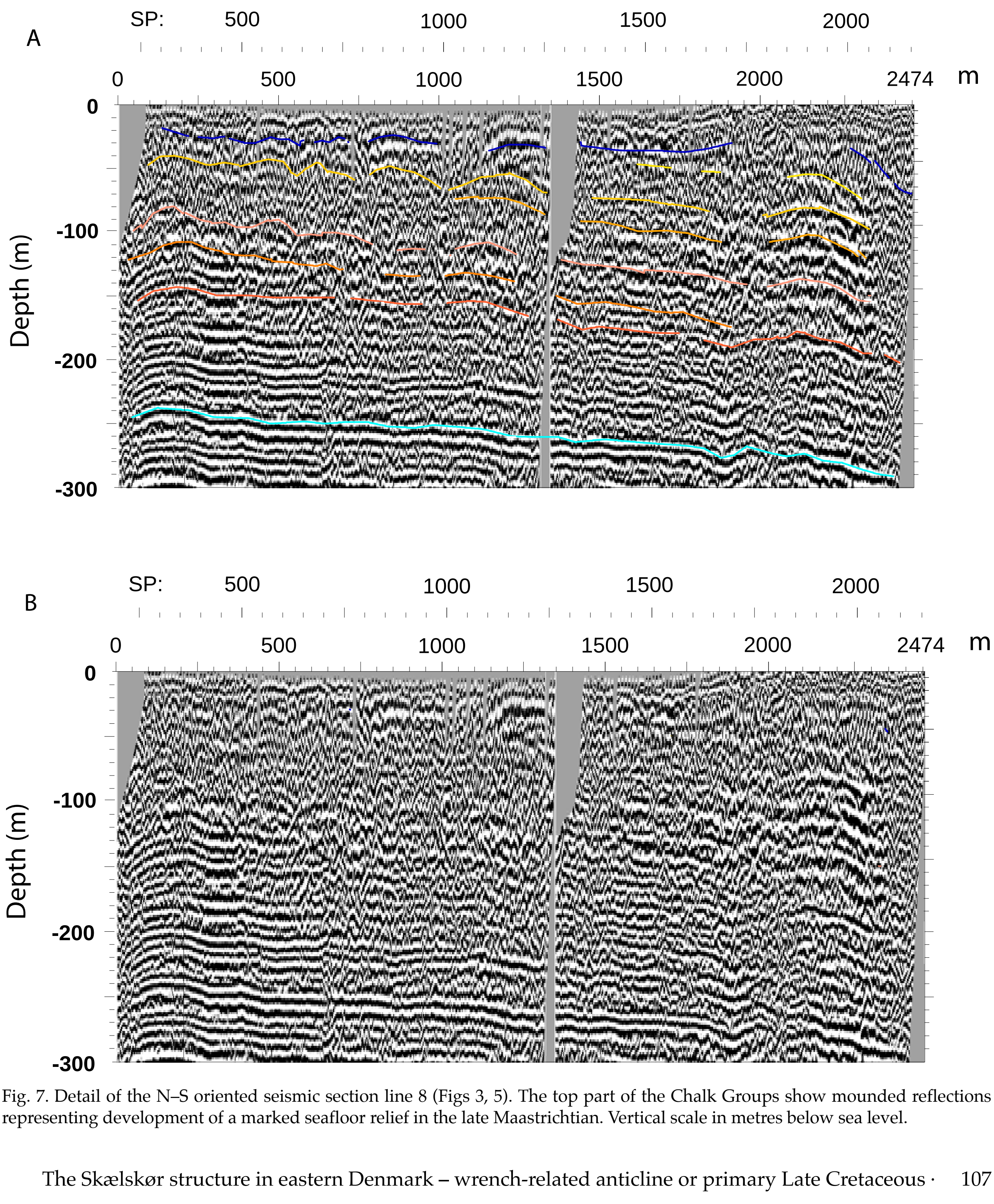


Fig. 7. Detail of the N–S oriented seismic section line 8 (Figs 3, 5). The top part of the Chalk Groups show mounded reflections representing development of a marked seafloor relief in the late Maastrichtian. Vertical scale in metres below sea level.

The Skælskør structure described by Sorgenfrei (1951) is located approximately above and to the north of the southern high (Figs 3, 4). The extent of the high mapped by Sorgenfrei (1951) was based on water wells penetrating into chalk, and the elliptic form depicted by Sorgenfrei shows the estimated outer limit of Upper Cretaceous chalk surrounded by Danian bryozoan limestone at the base of the Quaternary deposits. The Base Quarternary is an erosional surface and the observed distribution in map view of Maastrichtian chalk surrounded by Danian limestone proves the existence of a seafloor high at the the time of the K / T-boundary.

The location of the Skælskør structure indicates that differential subsidence took place at the southern edge of the Danish Basin. The hypothesis of wrenching as the cause of the Skælskør-high can therefore be rejected.

The change in dip in the northernmost part of the study area is clearly seen on line 8, where the reflection shows a very low dip towards the N in the southern part of the profile, changing to a S-ward dip at the northern end (Figs 4, 5). This rise in the position of the reflection is interpreted as caused by a deeper situated low pillow of Zechstein salt. Low salt pillows are common in the region, for example at the Stenlille boreholes (Japsen 1992).

The Top Chalk surface is to some extent modified by Quaternary erosion. The contour map shows a pronounced low in the SE part of the study area and an overall rise towards the NW and N. The highest part is found in the northernmost part of the study area and along seismic line 8 (Figs 5, 6).

The lower part of the Chalk Group is evenly bedded with parallel reflections (Fig. 5). Other seismic sections show slightly northwards diverging patterns. This pattern changes at depths of 150–200 m and the reflections above this level show a pronounced topographic relief with several scales of mound and channel-like features (Fig. 7). These features characterise the group all the way to the erosional top where it is overlain by Selandian siliciclastic sediments or Quaternary tills and outwash sands. Major palaeotopographic seafloor highs occur in the upper part of the Chalk Group in the southern, western and northernmost parts of the study area but the Base Chalk is flat and undisturbed beneath these highs and the intervening lows.

A similar development is seen elsewhere in NW Europe where a major palaeoceanographic change took place at the early–late Maastrichtian transition and the late Maastrichtian was characterised by strong bottom currents which sculpted the seafloor into drifts, channels and moats in several orders of magnitude, but commonly reaching amplitudes of more than 100 m and widths of several kilometres. These topographic features are parallel to the bathymetric contours of the seafloor in all areas where these can be estimated and they have thus been interpreted as formed by contour currents (Lykke-Andersen & Surlyk 2004; Surlyk & Lykke-Andersen 2007; Esmerode *et al.* 2007a, b; Surlyk *et al.* 2008; Esmerode & Surlyk 2009). The mounded reflections in the top part of the Chalk Group at Skælskør are likewise interpreted as representing a highly irregular seafloor relief formed mainly in the late Maastrichtian by bottom currents, possibly enhanced by bryoozoan growth as has been demonstrated for mounded chalk of the lower Sigerslev Member and the Højerup Member at Stevns Klint (Surlyk *et al.* 2006; Anderskouv *et al.* 2007).

Conclusions

- Reflection seismic data over the Skælskør structure clearly show that the Chalk Group has not been subjected to major syn- or post-depositional folding or faulting although a few minor faults have been detected.
- The Chalk Group shows differential subsidence across the northern flank of a basement high located in the southern part of the study area and forming a projection towards the northwest from the northern margin of the Ringkøbing-Fyn High. Subsidence thus increased from the high towards the north into the Danish Basin
- The Base Chalk reflection is essentially flat and undisturbed with only minor changes in inclination probably due to growth of a flat salt pillow in the northern part of the area.
- The upper part of the Chalk Group shows the development of a marked seafloor relief at the end of the Cretaceous, particularly in the late Maastrichtian.
- The hypothesis of Sorgenfrei (1951) that the high represents an anticline caused by wrenching along the Ringkøbing-Fyn High can thus be refuted.
- The high instead represents mounded drifts on the late Maastrichtian seafloor which were inherited into the Danian, and was superimposed on the northern flank of a small basement high south of the main study area.

Acknowledgements

This project was supported by Geocenter Denmark and the Danish Natural Science Research Council. We thank the seismic crew from the University of Aarhus for excellent work during data collection and Kresten Anderskouv and Erik Thomsen for useful comments on the manuscript.

References

Anderskouv, K., Damholt, T. & Surlyk, F. 2007: Late Maastrichtian chalk mounds, Stevns Klint, Denmark – combined physical and biogenic structures. Sedimentary Geology 200, 57–72.

Bjerager, M., Surlyk, F., Lykke-Andersen, H., Thibault, N. & Stemmerik, L. 2010: Danian cool-water coral reefs in southern Scandinavia localised over seafloor highs. Marine and Petroleum Geology 27, 455–466.

Brotzen, F. 1959: On *Tylocidaris* species (Echinoidea) and the stratigraphy of the Danian of Sweden. Sveriges Geologiska Undersökning ser. C 571, Årsbok 54, 1–81.

Esmerode E.V., Lykke-Andersen, H. & Surlyk, F. 2007a: Ridge and valley systems in the Upper Cretaceous chalk of the Danish Basin: contourites in an epeiric sea. In: Viana, A.R. & Rebesco, M. (eds): Economic and Palaeoceanographic Significance of Contourite deposits. The Geological Society, London, Special Publication 276, 265–282.

Esmerode, E.V., Lykke-Andersen, H. & Surlyk, F. 2007b: Interaction between bottom currents and slope failure in the Late Cretaceous of the southern Central Graben, North Sea. Journal of the Geological Society. London 165, 55–72.

Esmerode, E.V. & Surlyk, F. 2009: Origin of channel systems in the Upper Cretaceous Chalk Group of the Paris Basin. Marine and Petroleum Geology 26, 1338–1349.

Freiwald, A., Henrich, R. & Paetzold, J. 1997: Anatomy of a deep-water coral reef mound from Stjernsund, West Finnmark, Northern Norway. In: James, N.P. & Clarke, J.A.D. (eds.): Cool-water Carbonates. Special Publication – SEPM (Society for Sedimentary Geology) 56, 141–162.

Freiwald, E., Hohnerbach, V., Lindberg, B., Wilson, J.B. & Campbell, J. 2002: The Sula Reef Complex. Facies 47, 179–200.

Hennig, A. 1899: Studier öfver den baltiske Yngre kritans bildningshistoria. Kap. 5. Tertiäre dislokationer inom sydvestra Skånes Kritområde. Geologiska Föreningens i Stockholm Förhandlingar 21, 178–182.

Japsen, P. 1992: Landhævningerne i Sen Kridt og Tertiær i det nordlige Danmark. Dansk geologisk Forening, Årsskrift for 1990–91, 169–182.

Knudsen, C., Andersen, C., Foged, N., Jakobsen, P.R. & Larsen, B. 1995: Stratigraphy and engineering geology of København Limestone. Dansk Geoteknisk Forening Bulletin 11, 117–126.

Lykke-Andersen, H. & F. Surlyk 2004: The Cretaceous–Palaeogene boundary at Stevns Klint, Denmark: Inversion tectonics or sea-floor topography?: Journal of the Geological Society, London 161, 343–352.

Nielsen, L., Boldreel, L.O., Hansen, T.M., Lykke-Andersen, H., Stemmerik, L., Surlyk, F., Thybo, H. under revision. Integrated seismic analysis of the Chalk Group in eastern Denmark – implications for estimates of post-depositional uplift in southwest Scandinavia. Tectonophysics.

Nielsen, L.H. & Japsen, P. 1991: Deep Wells in Denmark 1935–1990. Lithostratigraphic subdivision. Geological Survey of Denmark, DGU Series A, 31, 1-179.

Rosenkrantz, A. 1938: Bemærkninger om det østsjællandske Daniens stratigrafi og tektonik. Meddelelser fra Dansk Geologisk Forening 9, 199–212.

Sorgenfrei, T. 1951: Oversigt over prækvartærets topografi, stratigrafi og tektonik i området Fyn-Sydsjælland-Lolland-Falster-Møn. Meddelelser fra Dansk Geologisk Forening 12, 166–171.

Sorgenfrei, T. & Buch, A. 1964: Deep Tests in Denmark 1935–1959. Danmarks Geologiske Undersøgelse 3. Rk., Nr. 36, 1–146.

Surlyk, F. 1997: A cool-water carbonate ramp with bryozoan mounds: Late Cretaceous – Danian of the Danish Basin. In: James, N.P. & Clarke, J.A.D. (eds.): Cool-water Carbonates. Special Publication – SEPM (Society for Sedimentary Geology) 56, 293–307.

Surlyk, F., Damholt, T. & Bjerager, M. 2006: Stevns Klint, Denmark: Uppermost Maastrichtian chalk, Cretaceous–Tertiary boundary, and lower Danian bryozoan mound complex. Bulletin of the Geological Society of Denmark 54, 1–48.

Surlyk, F., Jensen, S.K. & Engkilde, M. 2008: Deep channels in the Cenomanian–Danian Chalk Group of the German North Sea sector: Evidence of strong constructional and erosional bottom currents and effect on reservoir quality distribution. AAPG Bulletin 92, 1565–1586.

Surlyk, F. & Lykke-Andersen, H. 2007. Contourite drifts, moats and channels in the Upper Cretaceous chalk of the Danish Basin. Sedimentology 54, 405–422.

Thomsen, E. 1995: Kalk og kridt i den danske undergrund. In: Nielsen, O.B. (ed.): Danmarks geologi fra Kridt til idag. Aarhus Geokompendier 1, 31–67.

Vejbæk, O.V. 1997: Dybe strukturer i danske sedimentære bassiner. Geologisk Tidsskrift, 4, 1–31