DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2014/41

Late Cretaceous stratigraphy and basin development in the Danish Central Graben

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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Summary

A regional study on the Late Cretaceous has been carried out and this paper presents the results of the evaluation on the structural development in the greater Danish Central Graben area during the Late Cretaceous. More than 100 wells have been examined and both 2D and 3D seismic data have been used for the comprehensive evaluation in the area. The structural development is illustrated by regional time-isochore maps, flattened seismic profiles and log correlation panels.

Based on the integration of the biostratigraphy, the petrophysical and the geophysical data a modified Late Cretaceous lithostratigraphy is introduced. The Chalk Group is divided into 10 informal lithostratigraphic units. The distribution of the various units is closely related to the structural development of the inversion ridges associated with the Late Campanian inversion tectonism.

For illustration of the structural development during Upper Cretaceous 10 flattened seismic profiles have been made (Enclosure 1). The study imply that the Chalk Group in the Central Graben can be divided into two successions (**Lower Chalk** and **Upper Chalk**) separated by the distinct and regional Top Hod Unconformity (THU).

The THU is a stratigraphic hiatus and a tectonic feature closely related to the Late Campanian inversion within the Central Graben. The Late Campanian inversion phase was accompanied with a relative sea level fall and in large areas the inverted **Lower Chalk** section was above the storm wave base level which gave rise to severe erosion of the succession. The THU is a major hiatus with variable time gap depending on the degree of truncation into the **Lower Chalk** section. The variation and range in time gap is illustrated in the stratigraphic correlation panels in Enclosure 2.

The deposition of the **Upper Chalk** is highly controlled by the relief created during the Late Campanian inversion. Initially, the eroded material from the ridges was delivered to the basin centers outside the inversion zone. During Maastrichtian time relative thick deposits covers the inversion areas but the succession reveals a high amount of reworked chalk. The reworked chalk is closely related to the flanks of the inversion structures where it is associated with down dip gravity processes. Down-dip sliding and slumping are common along the inversion ridges in addition to turbiditic deposits in the basin centres.

The **Upper Chalk** encounters high porosity chalk due to the prevalence of reworked chalk and represents the most prolific interval in the Chalk Group. Because all structural closures on Top Chalk have been drilled new chalk prospects need to be related to stratigraphic traps. It is therefore necessary to outline areas and intervals with reworked chalk. As a result of this study, it is recommended that upcoming attempts to outline prospective intra-Chalk intervals should be linked to the structural development related to the inversion.

Introduction

The majority of present-day Danish oil and gas production is from fields with chalk reservoirs of late Cretaceous (Maastrichtian) and early Paleocene (Danian) ages located in the southern part of the Danish Central Graben in the North Sea (Figure 1). The Danish Central Graben area is mature with respect to exploration with most chalk fields located in structural traps discovered already in the 1970s. However, the discovery by Mærsk Oil and Gas AS of the large non-structurally and dynamically trapped oil accumulation of the Halfdan Field 1999 northwest of the Dan Field (e.g. Albrechtsen *et al*. 2001) triggered renewed exploration interest – and the need for new exploration models involving non-structural traps in the Chalk.

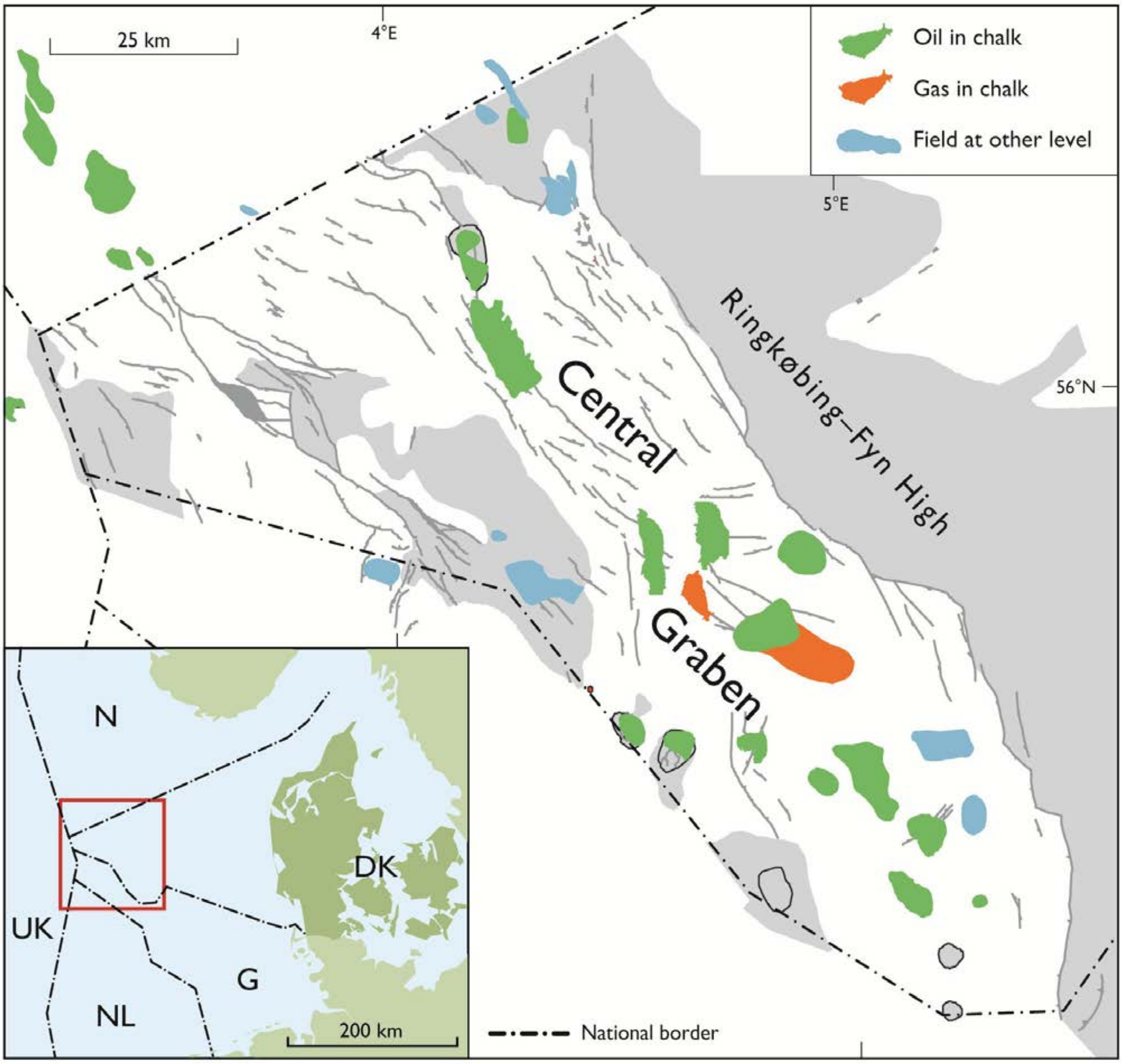


Figure 1. Overview map of the Danish Central Graben showing the distribution of chalk fields in the study area.

Acquisition of new 3D seismic data has enhanced the possibility to subdivide the Chalk Group into several depositional intervals and identify different depositional features within the Chalk succession. The depositional features are closely related to the paleobathymetry; which again is associated with the basin development and structural setting during the Upper Cretaceous (Esmerode *et al.* 2008). For location of non-structural traps in porous chalk GEUS has taken advantage of the new data to unravel basin development by combining 3D seismic interpretation of a large number of seismic markers, well log correlations and 2D seismic inversion. Part of this study is presented in Abramovitz *et al*. (2010) and Jakobsen & Andersen (2010).

Porous chalk is closely related to depositional environment and facies, and is often associated with intervals comprising reworked chalk (Kennedy 1987). This general assumption, however, has to be modified due to the different reservoir properties related to the type of reworking and the structural setting associated with the allochthonous chalk (a.o. Nielsen *et al.* 1990; Bramwell *et al.* 1999 and Anderskouv & Surlyk 2012). The basin development in the Central Graben varies during the Upper Cretaceous and is heavily affected by compressional tectonism triggering significant inversion in the area (Vejbæk & Andersen 2002). The structural development contributes to among others remobilisation and reworking of the chalk along the inversion ridges and consequently deposition of potential reservoir intervals.

This paper presents the results of the evaluation on the structural development in the greater Danish Central Graben area during the Late Cretaceous. The structural development is illustrated by regional time-isochore maps, flattened seismic profiles and log correlation panels.

Based on the seismic data it is possible to divide the Chalk succession into seismic sequences which can be calibrated to the lithostratigraphy conventionally applied to the Central Graben Chalk. Integration of biostratigraphy, petrophysics and geophysical information has resulted in a slightly modified lithostratigraphic framework which is introduced in this study.

For illustration of the structural development the Chalk Group has been divided into two seismically mappable units:

1) **Upper Chalk** covering (Uppermost Late Campanian?)/ Early Maastrichtian - Danian.
2) **Lower Chalk** ranging from Cenomanian - Late Campanian

The units are separated by a distinct basin-wide unconformity, the **Top Hod Unconformity**; which is a stratigraphic hiatus and a tectonic feature closely related to the Late Campanian inversion within the Central Graben. The inversion introduces a seafloor bathymetry with significant relief and is associated with significant erosion of the Chalk section. The development of the relief caused down-flank instability of the chalk deposits and down-dip sliding and slumping are common along the inversion ridges in addition to turbiditic deposits in the basin centres. In addition to the down-slope activity, along-slope current activity is observed in the basin centres (Esmerode *et al.* 2008). An attempt is made to outline areas with prospective chalk intervals based on the structural development. A supplementary seismic attribute analysis awaits a regional interpretation on 3D seismic data of comparable quality.

Study area and database

The study area covers the Central Graben ranging from the German sector to the south to the Norwegian and UK sectors to the north (Figure 2). Within the Danish sector the seismic database involves more than 10 separate 3D data sets (including MC3d-dk, PAM-99 north, PAM-99 south, DUC2005, Kraka extension 2000, ES 2002DK, W. Lulu/Lulu 85/86, Feda Halo 95, Feda Halo 96) and a dense grid of 2D seismic lines of different vintages. The study area covers more than 20.000 km^2.

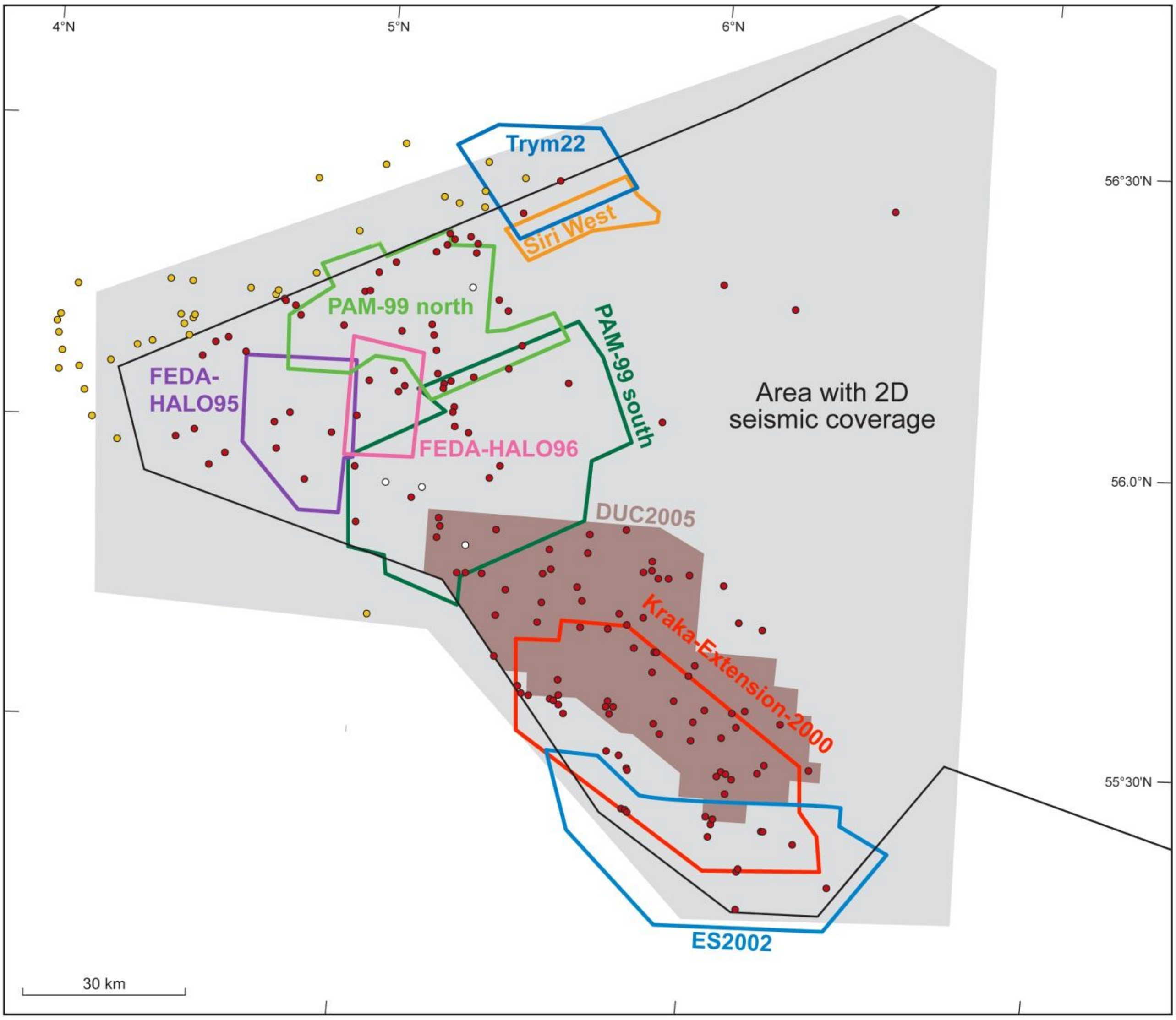


Figure 2. Data base map showing the extension of the 2D and the 3D seismic surveys used in the present study. The seismic data quality varies from survey to survey due to differences in acquisition and processing.

The Chalk section has been examined in more than 100 wells with respect to lithology and stratigraphy (Figure 3). The lithology determination is based on log data with focus on clay content and porosity. The applied chronostratigraphy is primarily based on the Operators Well Completion Reports supplemented by GEUS' in-house work. Unfortunately, the biostratigraphy from the various wells differs in biostratigraphic details according to vintage and type of analysis carried out. Due to the special attention on the hydrocarbon bearing intervals in the Chalk Group a detailed zonation of the Danian and Late Maastrichtian presently makes the dating of this period of time relative precise. Dating of the earlier periods of Late Cretaceous is less detailed. Especially the Maastrichtian/Campanian boundary in the completion reports is generally poorly defined, partly due to severe erosion and reworking in this period of time. In the most recent wells the quality of the stratigraphic work, however, is adequate for identification of hiatii within the chalk succession.

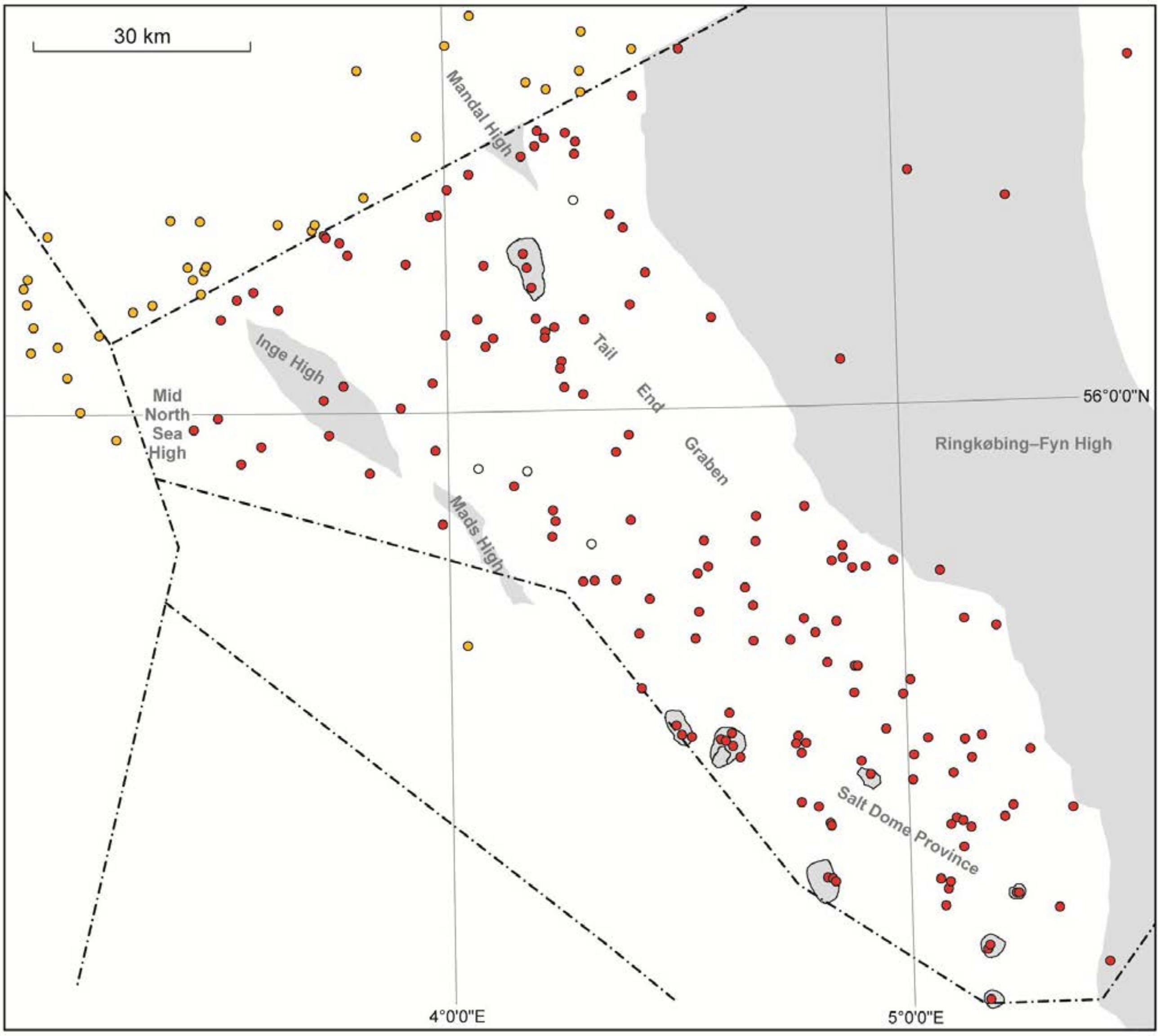


Figure 3. Map of the Central Graben showing the study area and wells examined in this study (red dots).Yellow dots denote Norwegian and UK wells contributing with information to this study. Open circles indicate the location of non-released wells.

Stratigraphy

The lithostratigraphic nomenclature conventionally applied to the Chalk Group in the Central Graben in the North Sea includes the Ekofisk, the Tor, the Hod, the Blodøks and Hidra Formations (Figure 4, Surlyk *et al.* 2003). This lithostratigraphic classification is formally established for the area in the southern part of the Norwegian Central Graben (Deagan & Scull 1977; Isakson & Tonstad 1989) and later extended into most of the Central Graben in UK, Norwegian, Danish, German and Dutch sectors from the expectation of a predominantly pelagic origin of the Chalk (Surlyk *et al.* 2003).

In 1999 a group of operating companies under the Joint Chalk Research (JCR) project introduced a new lithostratigraphic nomenclature valid for the Norwegian and Southern UK Central Graben (Bailey *et al.* 1999) (Figure 4). Although the Chalk formations exhibit lateral and vertical variations it seems possible to establish a lithostratigraphic classification for the Central Graben Chalk Group representing time characteristic deposits, and extension of the JCR-formations into the Danish Central Graben has partly been adopted by Mærsk Oil & Gas A/S in internal reports.

In this study the Chalk log-stratigraphy in more than 100 wells have been re-examined. Utilizing petrophysical characteristics for the various formations combined with biostratigraphy and seismic sequence stratigraphy, the Chalk Group can be divided into eleven informal litho-units: Upper Ekofisk, Lower Ekofisk, Upper Tor, Middle Tor, Lower Tor, Upper Hod, Middle Hod, Santonian-Coniacian Shale, Lower Hod, Herring/Blodøks (including the basal Plenus Marl) and Hidra. The characteristic log pattern for the Chalk units is shown in Figure 4, where a well-developed Chalk Group in the Bertel-1 is used as type section, supplemented and merged in the lower part with a thick developed Hidra unit from the Liva-1 well.

The lithological subdivision of the chalk section in the examined wells is linked to the available biostratigraphy. The biostratigraphy in the chalk section in old wells is often sparse and only based on microfossils. In more recent wells targeting the chalk section, the biostratigraphy includes both analyses of microfossils and nanno-fossils. Lieberkind *et al.* (1982) indicate diachronous formation boundaries in the Danish Central Graben (Figure 4) and seismic sequences established in Andersen *et al.* (1990) and Vejbæk & Andersen (2002) are associated with wide ranges in ages. However, the subdivision of the Chalk in this study assumes isochronous units in the entire Danish Central Graben. In a few (old) wells minor discrepancies between litho-units and age determination are observed, but this is considered as a result of insufficient and uncertain age determination from the biostratigraphy.

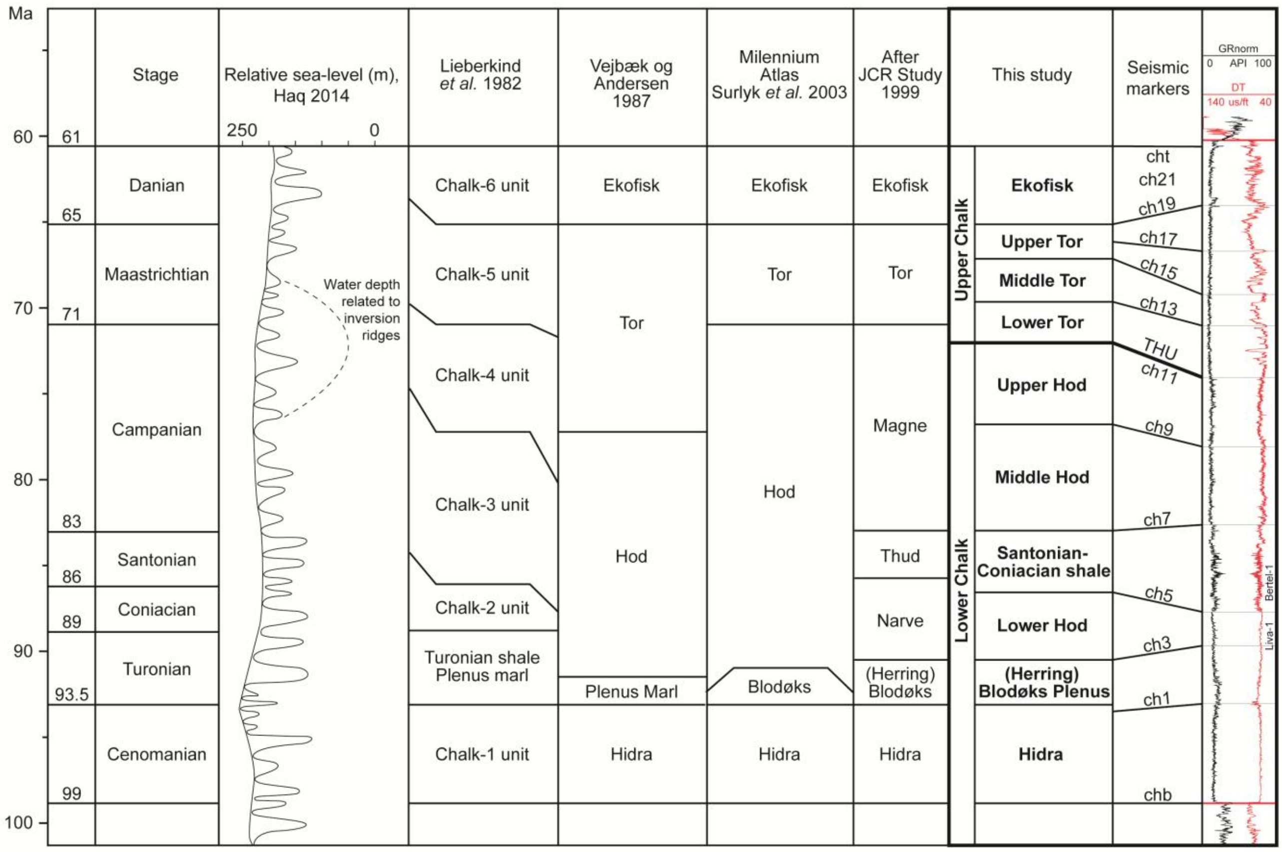


Figure 4. Lithostratigraphic subdivision of the Upper Cretaceous - Danian Chalk Group (Modified from various sources). The characteristic log pattern for the Chalk units is illustrated by the GR and DT logs in the Bertel-1 (and Liva-1) well.

The Central Graben was tectonically active during deposition of the Chalk Group and is characterised by a complex and dynamic interplay between graben subsidence, inversion and salt movements. A number of tectonic phases associated with inversion and sea-level changes are recognized in the Chalk Group (Vejbæk & Andersen 2002; Hampton, Bailey & Jones 2009). The distribution of the various formations/units in the Danish Central Graben area is closely related to the structural development during Late Cretaceous and is often linked to paleo-highs and inversion structures. A number of significant unconformities can be identified in the Chalk Group. One type of unconformity represents a period of non-deposition or condensed sections interpreted to be associated with (global) sea-level change (e.g. during the Santonian). The Upper Campanian unconformity (THU) is closely related to inversion and subsequent truncation which give rise to special depositional conditions with erosion on crestal parts and reworking and transport of sediments into basin centres.

The insertion of reworked material of Campanian age into younger deposits may cause ambiguity in the age determination. This is the situation for the Lower Tor unit where re-deposited Late Campanian sediments and fossils are incorporated in the Early Maastrichtian Lower Tor unit. Due to a slight increase in the clay content and the presence of reworked fossils of Campanian age this chalk section has lithostratigraphically often been considered as part of the Hod Fm. However, the Lower Tor unit is always found above the seismic THU and is in this study considered as part of the Maastrichtian Tor formation. Due to the biostratigraphic uncertainties with respect to the occurrence of Late Campanian fossils (reworked or in situ) in the Lower Tor unit it cannot be ruled out that the part of the formation may be of Upper Campanian age. Therefore, the THU in this study is positioned within the uppermost Late Campanian, and consequently the top Hod Fm is not directly associated with the Campanian/Maastrichtian boundary as indicated by Surlyk *et al*. 2003 (Figure 4).

A limited number of the examined wells are located in a basin setting with a complete chalk succession. The majority of Chalk wells in the Danish Central Graben are drilled on the top of structures where the Chalk section is incomplete and encompasses several hiatii; which can be verified from the biostratigraphy. The time range for the hiatii varies from below biostratigraphic resolution to more than 5 mill. years. An indication of hiatii and range in time gap for the examined wells is shown on the stratigraphic correlation panels in Enclosure 2.

Seismic interpretation

The subdivision of the Chalk Group into lithostratigraphic units can be supported from the seismic data. The formation tops (unit boundaries) are often associated with significant seismic reflectors. A subdivision of the seismic section into Chalk units is shown in Figure 5.

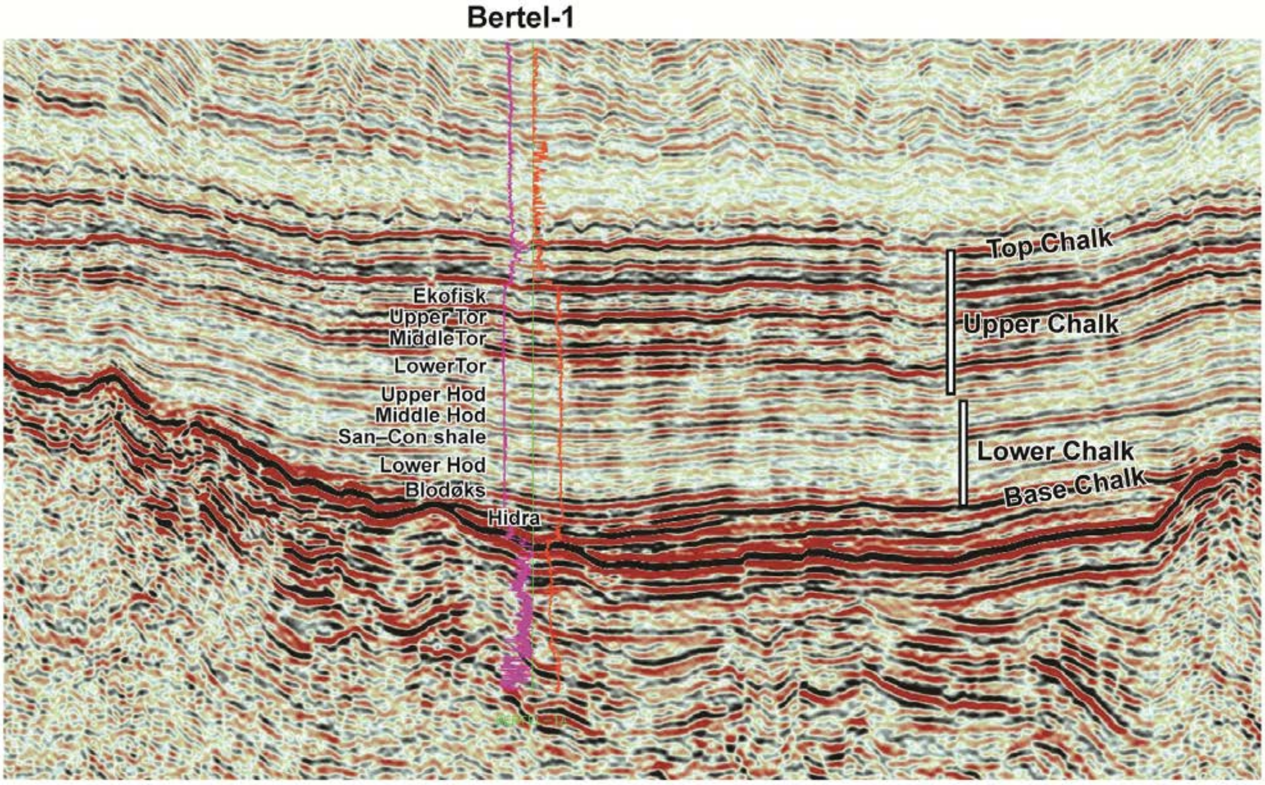


Figure 5. Seismic subdivision of the Chalk Group. The GR and DT logs are displayed in the Bertel-1 well. Angelina2007 line 13642.

The reflectivity of the seismic horizons as well as the seismic character of the various units varies within the Central Graben. Due to the minor difference in lithology in the mono-mineralic chalk succession the seismic signature only to some degree mirror the change in lithology (clay content). Instead the seismic reflectivity is closely related to the variation in porosity. Highly alternating porous and tight beds give rise to parallel high amplitude reflectivity, whereas homogeneous chalk without major porosity variation appears as transparent – low amplitude reflectivity intervals. Reworked chalk intervals may appear with a chaotic seismic signature.

High reflectivity is also accompanied unconformities which again is closely related to the structural setting and occasionally associated with truncation of the underlying units. A very prominent reflector is associated with the Top Hod Unconformity; which generally is expressed as a strong negative reflection. The unconformity divides the Chalk Group into a lower part (**Lower Chalk**) including the Hod, Herring-Blodøks and Hidra units and an upper part (**Upper Chalk**) comprising the Ekofisk and Tor units (Figures 4 and 5).

Time structural maps have been generated on Top Chalk (Figure 6), Top Hod Unconformity (Figure 7) and Base Chalk (Figure 8).

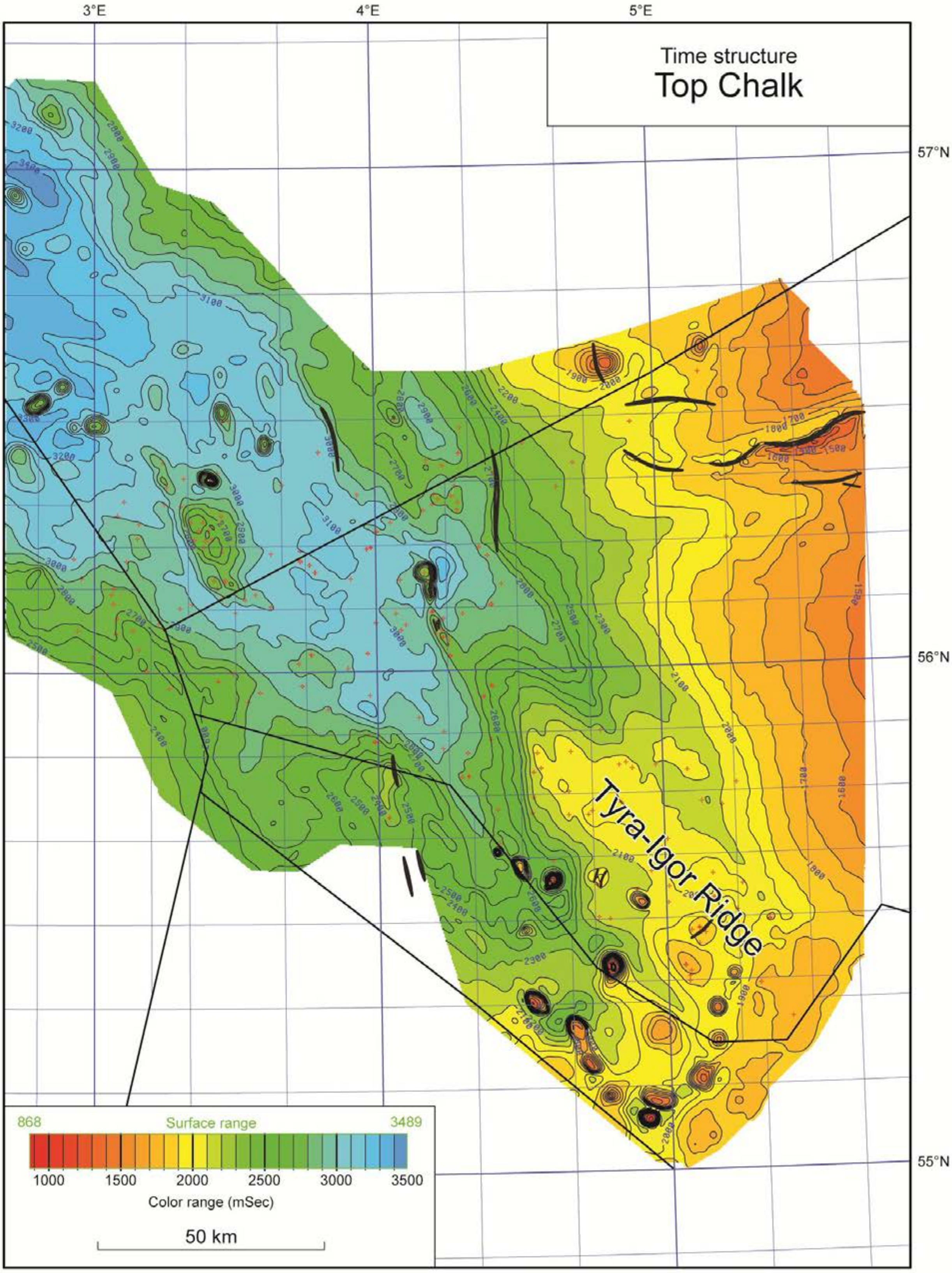


Figure 6. Time structure map on Top Chalk. The map displays the distinct post-Cretaceous inversion structure Tyra-Igor Ridge.

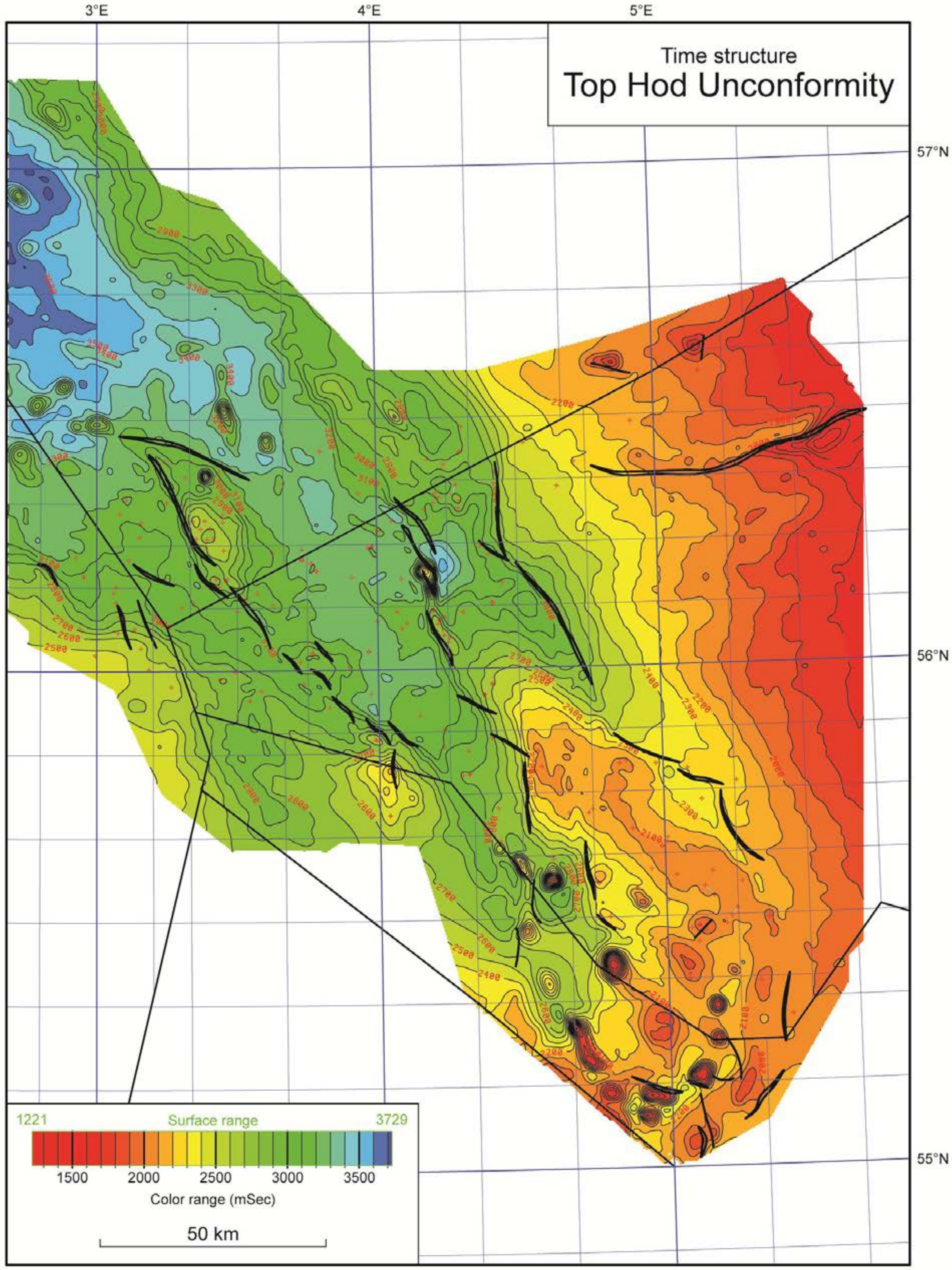


Figure 7. Time structure map on Top Hod Unconformity (THU).

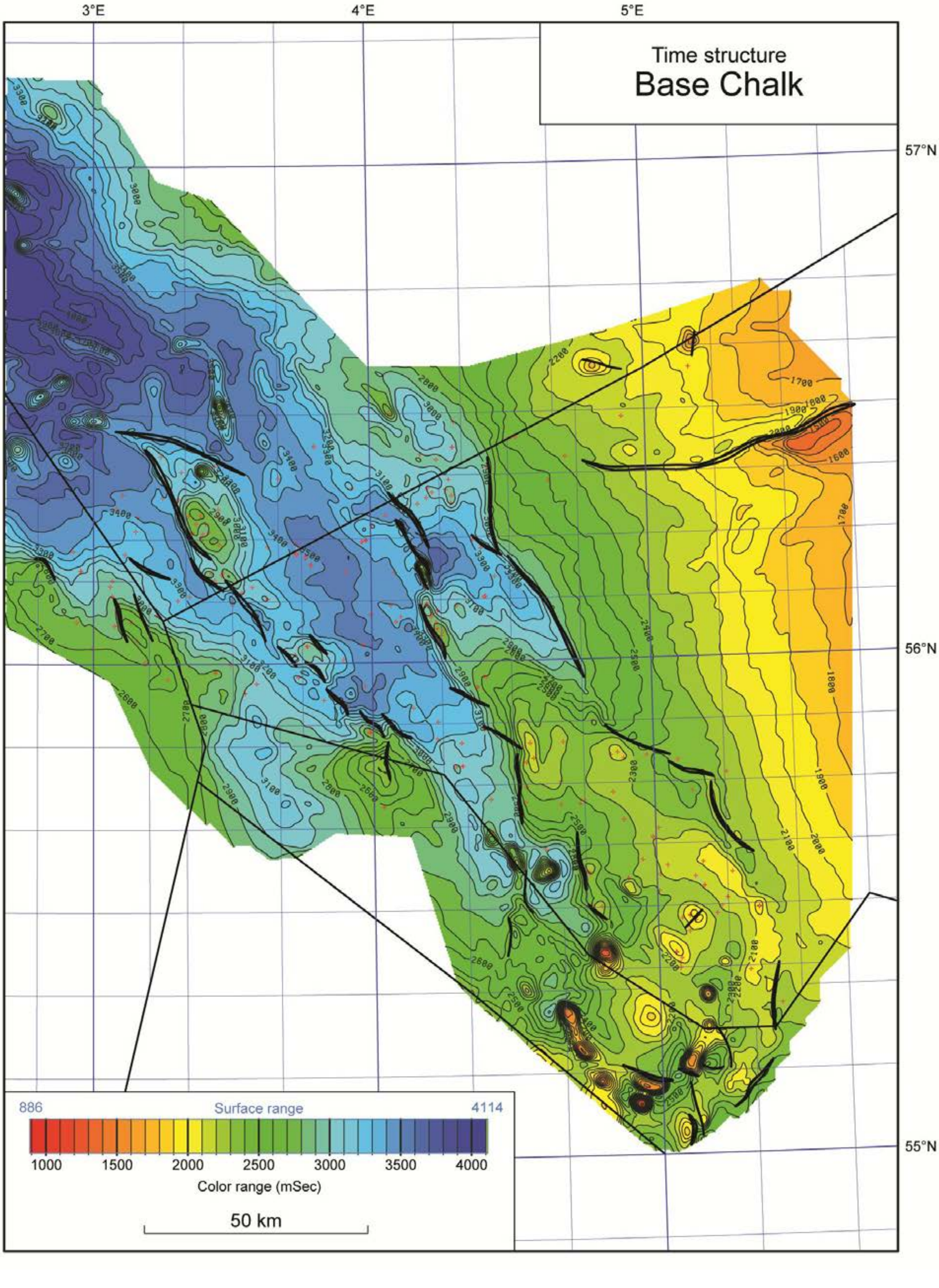


Figure 8. Time structure map on Base Chalk.

Structural framework

During Late Cretaceous the Central Graben was affected by compressional tectonics which induced inversion movements (Vejbæk & Andersen 1987; 2002). The syn-sedimentary inversion has a significant impact on the chalk distribution, which is discussed below. The overall structural development and impact on the distribution and thickness variation is illustrated by the time isopach map on the Chalk Group (Figure 9). The time isopach maps on the **Upper Chalk** (Figure 10) and the **Lower Chalk** (Figure 11) indicate significant differences in the structural development and location of depocentres in the two time periods related to the Upper and Lower Chalk units, respectively.

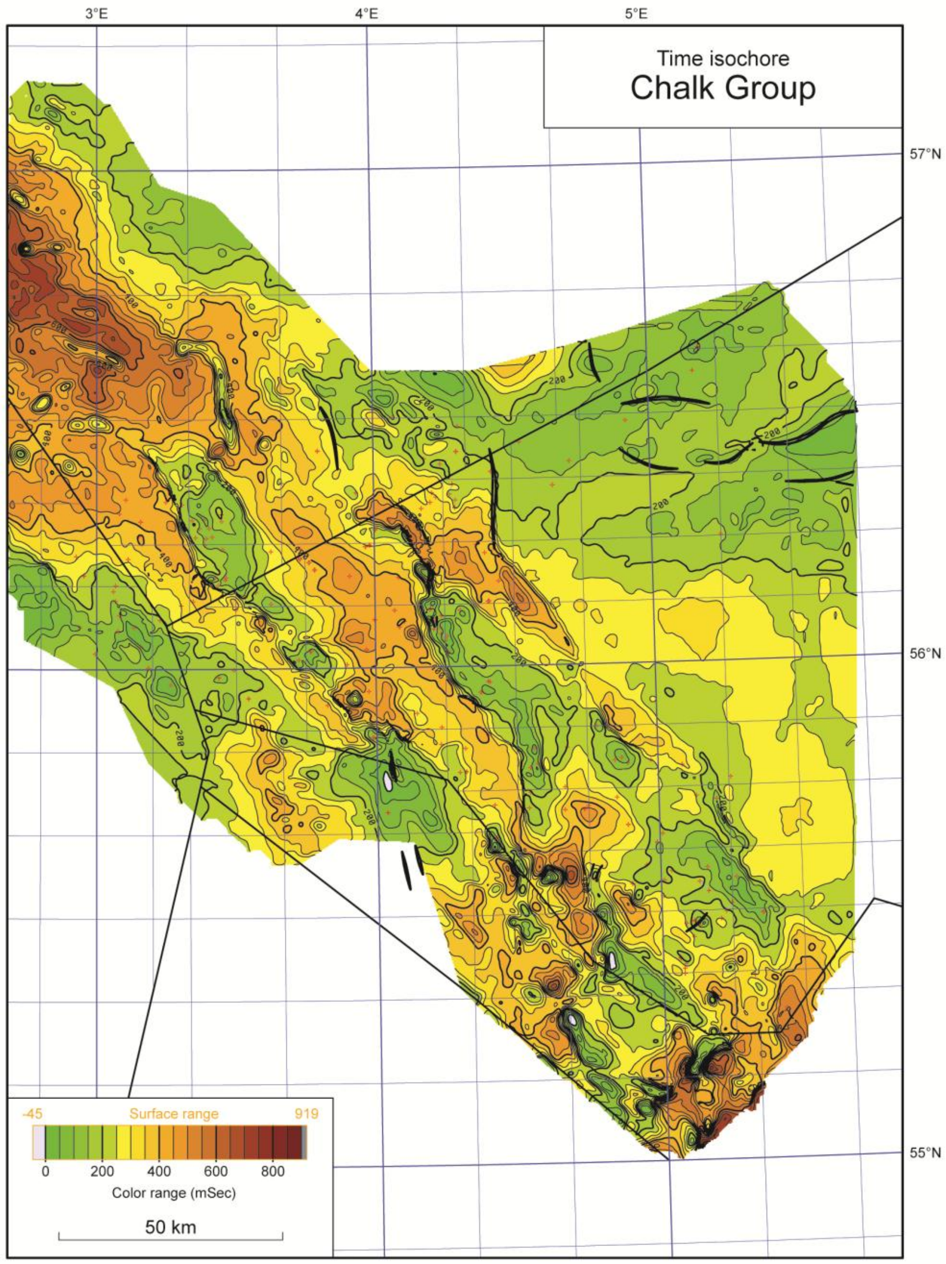
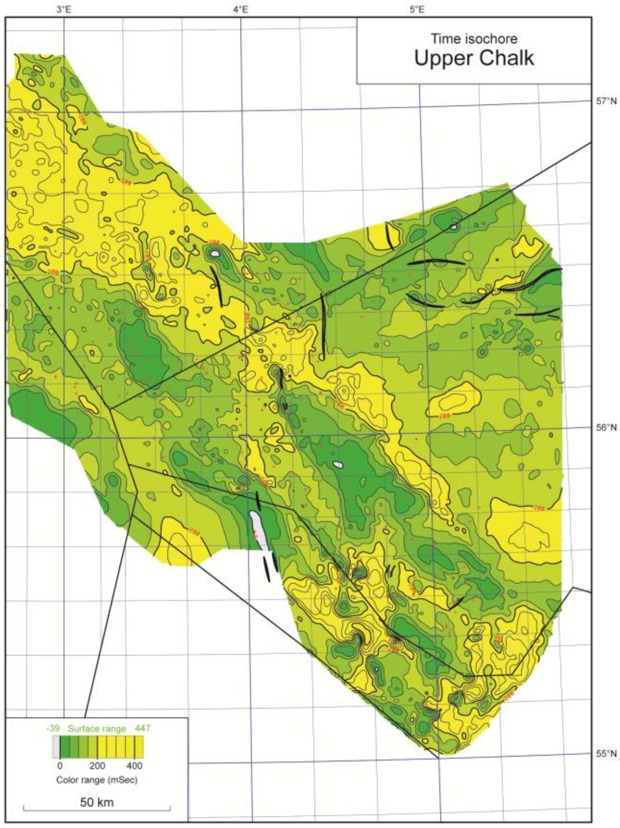


Figure 9. Time isochore map on Chalk Group.



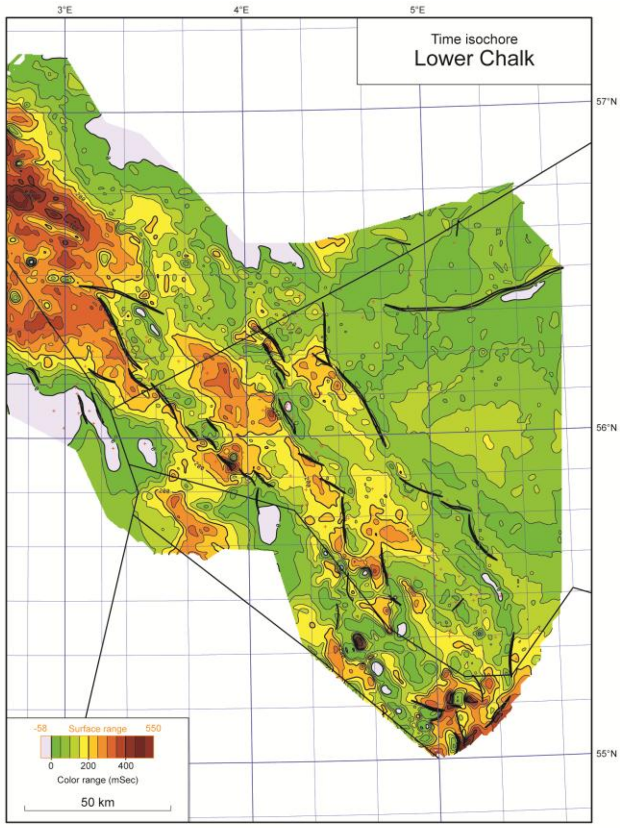


Figure 10. Time isochore map on ***Upper Chalk***

Figure 11. Time isochore map on ***Lower Chalk***

Apart from general post-rift subsidence and halokinesis of Zechstein salt the structural development of the Central Graben during Late Cretaceous is influenced by compressive stress giving rise to uplift of former areas of subsidence formed under a prevailing extensional stress regime (Cartwright 1989; Michelsen *et al.* 1992; Korstgård *et al.* 1993; Vejbæk & Andersen 2002). 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. Vejbæk & Andersen (2002) associate the areas affected by Upper Cretaceous inversion with previous Jurassic and especially Lower Cretaceous depocentres, whereas Upper Cretaceous depocentres are associated with pre-Upper Cretaceous highs. The present study concurs overall with this relationship with the amendment that the deposition of the **Lower Chalk** follows the subsidence history of Lower Cretaceous depocentres. Inversion and erosion of the Hod units took place during the major Late Campanian inversion phase.

The structural framework is dominated by a number of compartments bounded by N-S trending faults (reverse and normal faults) separated by WNW-ESE trending left lateral fault zones closely related to the pre-Cretaceous transverse zones defined by Cartwright (1989).

Figure 12 shows the structural elements related to the Upper Cretaceous Chalk Group. Areas affected by Upper Cretaceous inversion is outlined with grey shading. For clarification the structural elements have been named. The nomenclature for the Upper Cretaceous elements is primarily adopted from stratigraphic older structural elements when comparable in structural and basin development. The nomenclature of the structural elements is adopted from several sources (a.o. Cartwright 1989; Britze *et al.* 1995, Vejbæk & Andersen 2002; Surlyk *et al.* 2003). New names are introduced for structural elements controlled by the Late Cretaceous tectonic activity different from previous structural development.

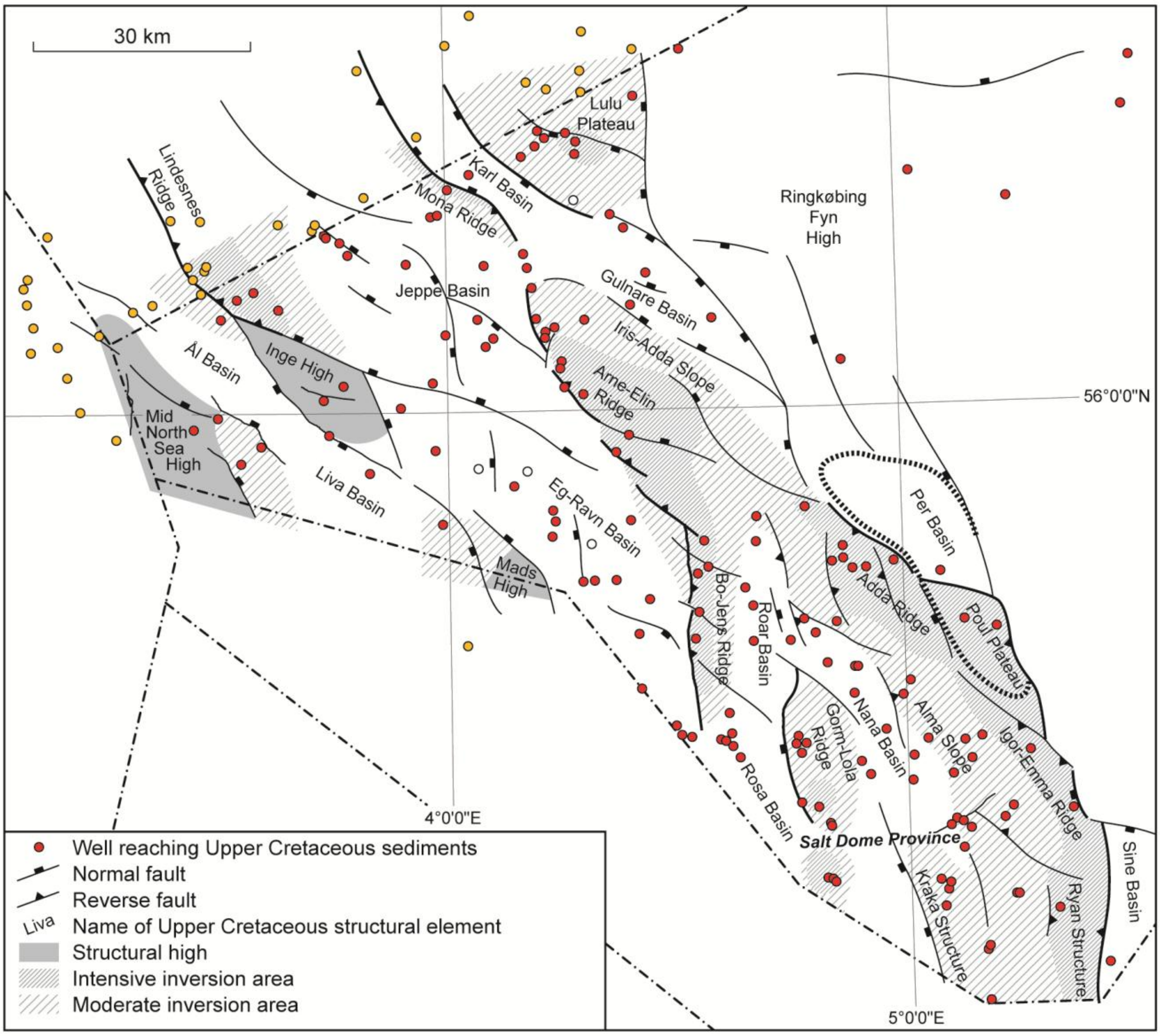


Figure 12: Structural elements related to the Upper Cretaceous in the Danish Central Graben. Hatching indicates areas of positive Late Cretaceous inversion. The structure names are a composite of the established nomenclature for the pre-Cretaceous basins and structural elements and introduction of new names related to the structural elements formed during Late Cretaceous.

Structural development during Late Cretaceous

The tectonic regime of the Central Graben changed from strong Jurassic rifting to abating extension in the Early Cretaceous and regional subsidence in the Late Cretaceous to Palaeogene (Ziegler 1995). The development during Late Cretaceous was affected by inversion phases caused by regional compressional tectonics. Vejbæk & Andersen (2002) refer to four phases of inversion: 1) Late Hauterivian, 2) Turonian-Santonian, 3) Mid Maastrichtian and 4) post-Danian Palaeogene. The present study concurs with the post-Danian Palaeogene inversion; whereas the seismic interpretation combined with the biostratigraphy in the wells indicates one dominating strong inversion phase during Late Campanian rather than during Mid Maastrichtian. The present study does not show evidences for the Turonian-Santonian inversion phase. Examination of the pre-Late Cretaceous succession has not been carried out.

The overall structural style during the Upper Cretaceous is illustrated by the time-structure map of the Top Chalk Group (Figure 6), the Base Chalk Group (Figure 8) and the time-isochore of the total Chalk Group (Figure 9). The time-isochore map displays the result of the tectonic activity during the Upper Cretaceous whereas the time-structure maps also demonstrate the tectonic activity (prior to and) after deposition of the Chalk Group.

The time-structure map on Top Chalk Group (Figure 6) shows the results of the post-Cretaceous tectonics movements. The dominating inversion structure affecting the Top Chalk surface is the gentle NW- SE oriented Tyra - Igor Ridge trapping the Tyra, Tyra SE and Halfdan NE gas accumulations.

The Top Hod Unconformity (THU) is closely linked to the tectonic activity and structural development at the end of Campanian time. Mapping of the THU has been carried out in order to determine the timing of the tectonic activity in more detail. The time-structure map on the Top Hod Unconformity (Figure 7) is structurally comparable to the Base Chalk map whereas the isochore maps on the Upper Chalk Unit (Figure 10**)** and the Lower Chalk Unit (Figure 11) show two periods of different structural and basin development.

The structural and basin development is illustrated by 10 geosections extracted from seismic data across the Central Graben passing through selected wells (Figure 13, Enclosure 1). The geosections demonstrate the distribution and time-thickness variation of the various units and reveal the structural development during Late Cretaceous. The profiles are flattened at Top Chalk in order to eradicate the impact of post-Cretaceous structuring of the Chalk Group. For each profile a log correlation panel (based on GR, DT and density logs) is made in order to illustrate the lithological and stratigraphical variation (Enclosure 1).

The THU is a distinct feature in the Chalk section separating the **Lower Chalk** section from the **Upper Chalk** section. In the profiles the THU is highlighted in order to accentuate the differences in basin development during deposition of the Chalk Units. The distribution and thickness variation of the various units illustrate the basin development. The **Lower Chalk** appears to be associated with gentle subsiding basins followed by a period with uplift and truncation. The **Upper Chalk** comprises on-lapping and thinning units related to paleo-structural highs indicative of a depositional environment controlled by a significant bathymetric relief.

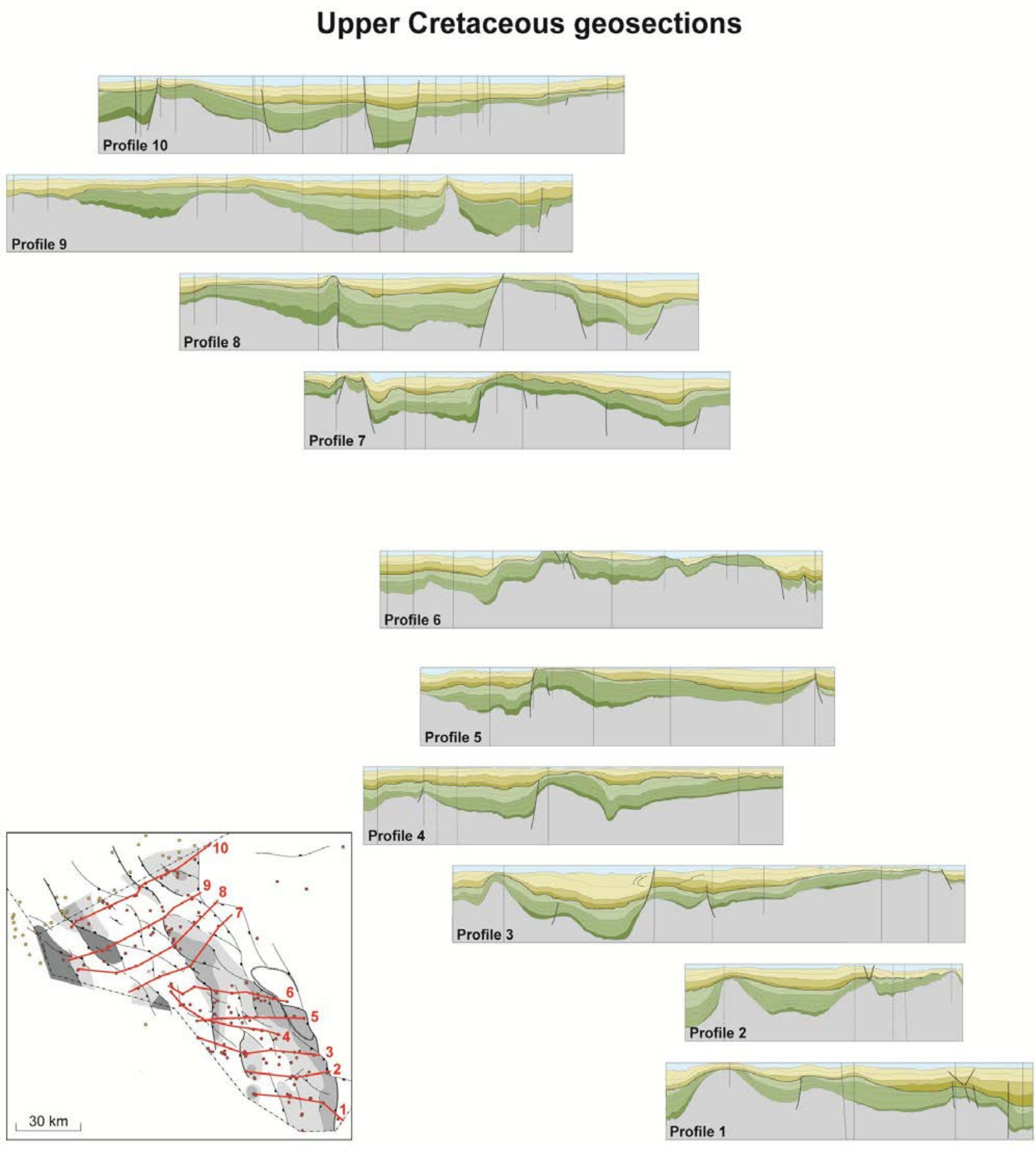
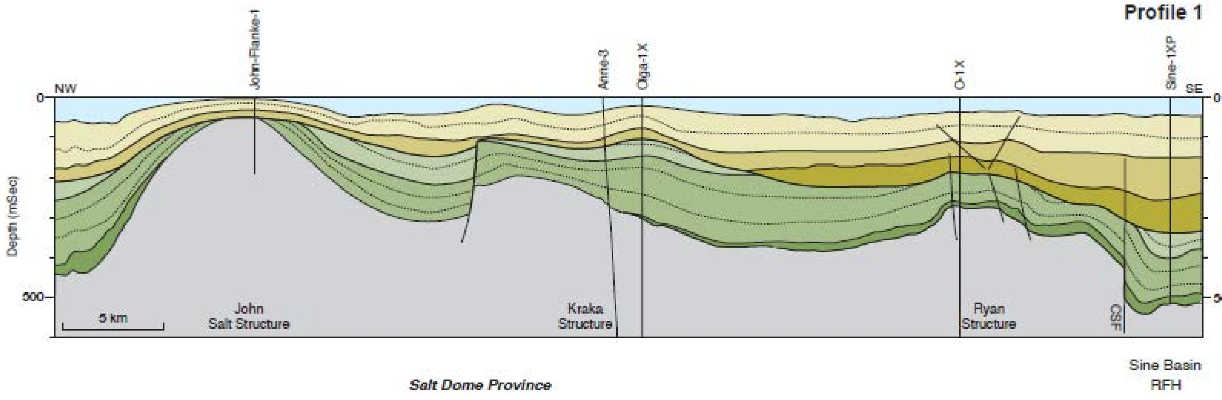


Figure 13. Profile montage. Legend see Encl.1

Profile 1 (Encl. 1. For location see Fig. 13)



The John Flanke-1, Anne-3, Olga-1, O-1 and Sine-1 profile is a W-E transect through the southern Salt Dome Province crossing the Coffee Soil Fault and entering the Ringkøbing-Fyn High. The profile shows regional inversion, partly combined with halokinesis, associated with subsequent erosion, down-flank deposition and on-lapping. The total chalk thickness is larger on the stable Ringkøbing-Fyn High than in the adjacent inverted Central Graben.

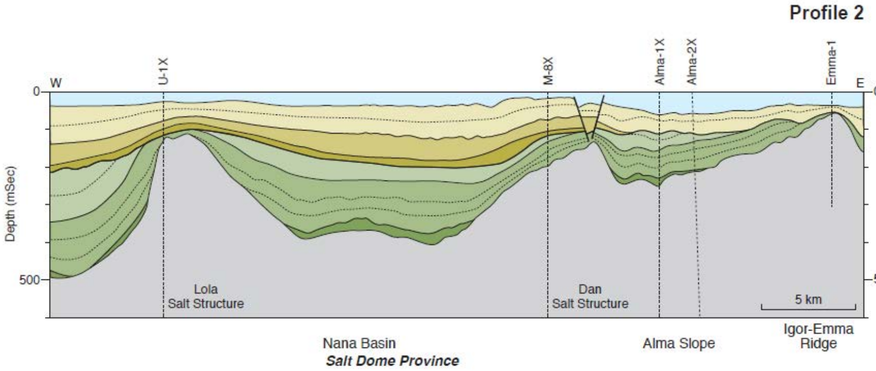
The profile demonstrates a reversal in the location of depocentres below and above THU. Uplift of the Salt Dome province gives rise to an asymmetric basin development during deposition of the **Upper Chalk**. The thickest Upper Chalk section is found along the flanks of the inversion structures. An important part of the succession is the thick Lower Tor unit on the Ringkøbing-Fyn High.

There are indications of an initially uniform and relative thick **Lower Chalk**. Inversion along the Coffee Soil Fault during the Campanian gave rise to uplift and subsequent erosion on top of the Ryan structure (which includes a salt core). The Late Cretaceous Ryan structure does not show evidences of reactivation during Maastrichtian and Danian time, but is later embraced by the post-Cretaceous inversion of the eastern part of the Salt Dome Province developing the Tyra-Igor Ridge.

Salt movements affects the thickness of the chalk section and on top of the John structure the **Lower Chalk** embraces both thin intervals related to condensed sections and thin sections associated with truncation. In the Kraka area there is evidence of a semi regional inversion with subsequent truncation of the **Lower Chalk** instigating the Top Hod Unconformity. The lowermost Tor units wedges out towards the west and are associated with seismic onlap of the THU from the east. This suggests a gradual submerging of the paleo-relief with associated accommodation-space in the deeper part only.

The hiatus between the **Lower Chalk** and **Upper Chalk** ranges from Early Campanian to Early Maastrichtian in age with the longest period of lag-time in the O-1 well (Panel 1, Enclosure 2). The well correlation profile indicates a more or less continuous deposition in the Sine-1 well, but on the seismic data a relative distinct unconformity representing a minor hiatus is found near Mid Campanian. The biostratigraphic resolution in the section above the unconformity in the Sine-1 well is poor and represents a mix of early Maastrichtian and Campanian species.

Profile 2 (Encl. 1. For location see Fig. 13)



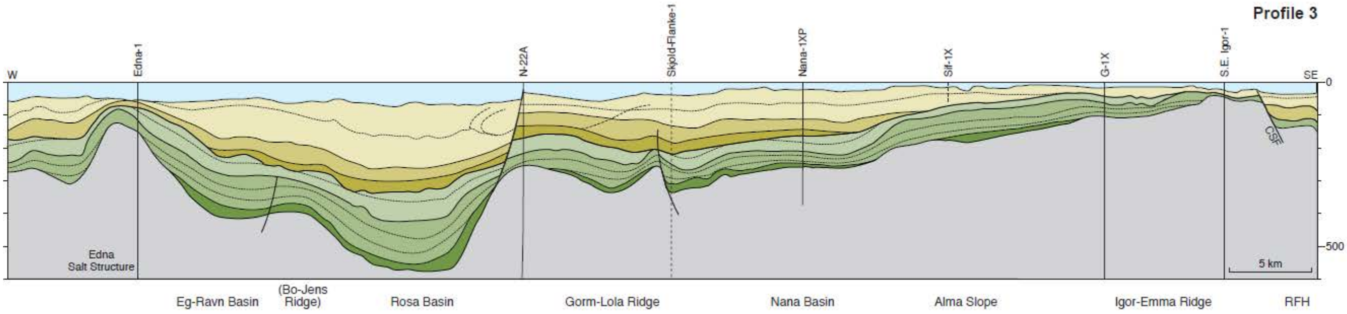
The profile is a W-E line from the Gorm-Lola Ridge (U-1) crossing the Dan Field (M-8), the Alma-1 and -2 wells terminating east of the Emma-1 well next to the Coffee Soil Fault. A thick Chalk succession is found in the basin between the Gorm-Lola Ridge and the Dan Field salt structures. There is evidence of Lower Tor deposits (lowermost Maastrichtian) in the basin.

The chalk section is affected by salt movements. The salt movements are active during deposition of the **Lower Chalk**, whereas a quiet period in the salt movements characterises the deposition of the **Upper Chalk**. The thinning of the **Lower Chalk** above the Dan Field and Lola salt structures suggests syn-depositional salt movements resulting in condensed chalk units on a paleo-high. In addition, the Lola structure triggered a push-up/penetration of the **Lower Chalk** during the Campanian associated with severe truncation.

The wedge-shaped **Lower Chalk** with thinning towards the east reveals an asymmetric inversion associated with differential erosion with the deepest truncation of the section near the Emma-1 well. The thickness variation of the **Upper Chalk** mirrors the impact of the pre-Maastrichtian paleo-relief in the Emma area. The inversion structure does not show evidence of reactivation during Maastrichtian and Danian times, but is later embraced by the post-Cretaceous inversion of the eastern part of the Salt Dome Province developing the Tyra-Igor Ridge.

The hiatus between the **Lower Chalk** and **Upper Chalk** sections ranges from Early Campanian to Early Maastrichtian (Panel 2, Enclosure 2). In the Emma-1 well the Lower Chalk is missing. The absence of the Cenomanian to Turonian (Hidra and Lower Hod units) in the U-1 and M-8 wells suggests the presence of a paleo-relief in the Chalk Sea at the beginning of Late Cretaceous, where the missing Hod units are a result of erosion on the crest of the paleo-highs. The biostratigraphy in the Emma-1, Alma-1 and -2 and M-8 wells indicate a minor hiatus at the K/T boundary (Panel 2, Enclosure 2). The K/T boundary is often associated with a hardground.

Profile 3 (Encl. 1. For location see Fig. 13)



The profile is a W-E line from the Edna salt structure to the Igor-Emma Ridge to the east, crossing the Rosa Basin, the Gorm-Lola Ridge and the Nana Basin. The profile exhibits the presence of relative thick Hidra, Blodøks and Lower Hod units revealing an early basin subsidence. In the Rosa Basin the chalk section is relative complete with "unbroken" deposition across the THU. Rapid basin subsidence also took place in the Rosa Basin during Late Maastrichtian time. Down-flank the Gorm structure, the Tor units form part of a mega slide relocated several hundreds of metres into the basin centre (see Figure 24).

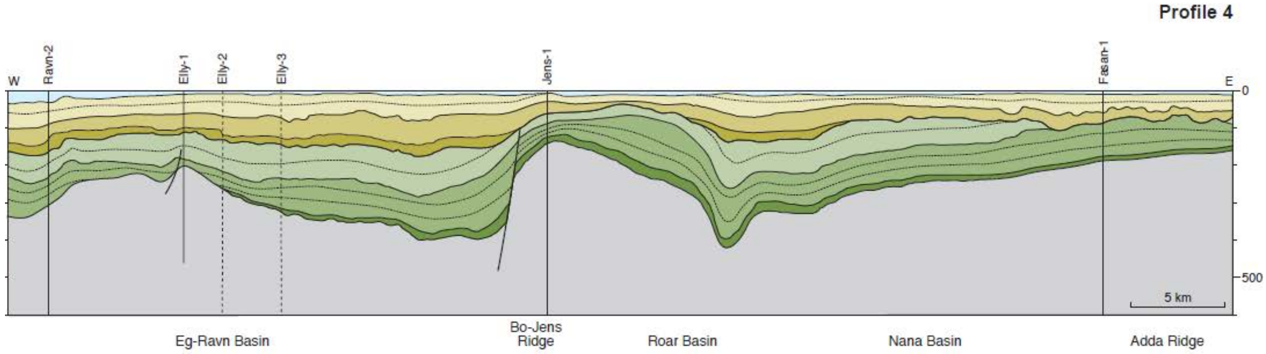
The Edna salt structure was active throughout Late Cretaceous generating varying relief at the seafloor affecting the distribution and thickness of the chalk. In the Gorm-Lola Ridge and Nana Basin area and on the Igor-Emma Ridge the **Lower Chalk** is thinner than in the Rosa Basin. The thickness variation may be due to a structural situation with less accommodation space in the Nana Basin than in the Rosa Basin. Comparing the **Lower Chalk** units in the Nana Basin and on the Alma Slope an inverse unit thicknesses are seen. This indicates local and separate development of the two basins (the Nana Basin and the Alma Slope) during deposition of the **Lower Chalk**.

Significant inversion and associated truncation during Late Campanian can be observed in the Igor-Emma Ridge area. To the east the THU represents a hiatus ranging from Santonian to Late Maastrichtian (Panel 3, Enclosure 2). In the S.E.Igor-1 well only very thin Latest Maastrichtian and Danian chalk are drilled. The lowermost Tor units wedges out towards the east and are associated with seismic onlap of the THU from the west. This suggests a gradual submerging of the paleo-relief with associated accommodation-space in the deeper part only.

A chaotic seismic signal in the Maastrichtian units down-dip the western flank of the Igor-Emma Ridge (the Alma Slope) suggests reworking, slumping and sliding downslope a paleo-relief. The slump indicates downslope reworking of soft sediment. The instability on a gentle dipping slope may be the result of tectonic pulses connected with renewed inversion of the ridges.

The biostratigraphy in all wells in the profile indicate a minor hiatus at the K/T boundary (Panel 3, Enclosure 2). The K/T boundary is often associated with a hardground.

Profile 4 (Encl. 1**.** For location see Fig. 13)



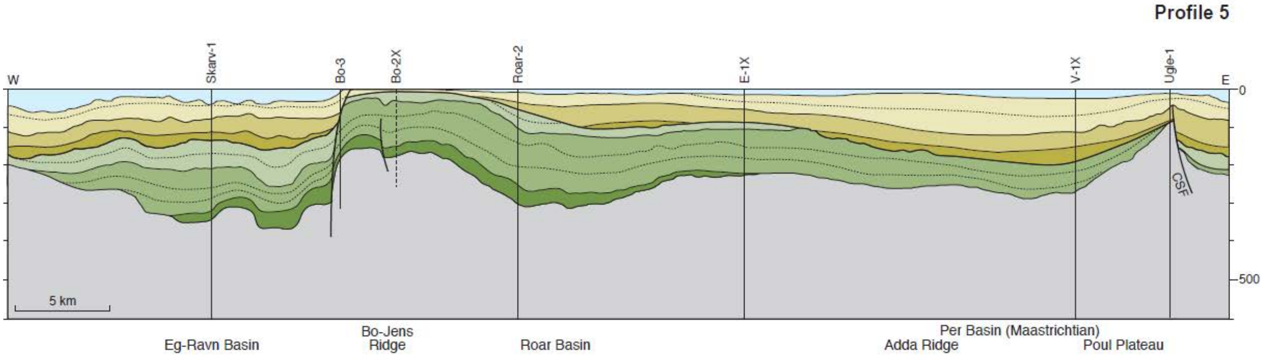
The profile crosses the Eg-Ravn Basin, the southern part of the N-S trending Bo-Jens Ridge, the Roar Basin and Nana Basin terminating on the Adda Ridge. The line reveals a wide **Lower Chalk** basin with a basin centre located in the area which later was associated with the Bo-Jens inversion Ridge. An initial thick and complete **Lower Chalk** section appears to have been deposited in the original basin; which is verified by Ravn-2 and Elly-1,-2 and -3 wells. The present day thickness variation and distribution of the **Lower Chalk** is a result of the changes in the basin development after deposition of the **Lower Chalk**. Inversion of the Bo-Jens Ridge and the Adda Ridge during Late Campanian gave rise to erosion of the Upper Hod unit. In the Eg-Ravn Basin the Chalk Group is stratigraphically complete with “unbroken” deposition across the THU. A thin **Upper Chalk** section above the Bo-Jens Ridge is indicative of the presence of a structural high during Maastrichtian and Danian times.

The seismic data display a hummocky appearance in the section above the THU on the western flank of the Adda Ridge (in the Fasan-1 area). The seismic features are interpreted as evidence of reworking, slumping and sliding downslope a paleo-relief.

The hiatus between the **Lower Chalk** and **Upper Chalk** signified by the THU represents a minor time gap within the Late Campanian in the Eg-Ravn Basin. A time gap ranging from Early Campanian to Early Maastrichtian is seen in the Jens-1 and Fasan-1 wells (Panel 4, Enclosure 2).

The biostratigraphy in the wells in the profile indicates a minor hiatus at the K/T boundary. The K/T boundary is often associated with a hardground.

Profile 5 (Encl. 1. For location see Fig. 13)



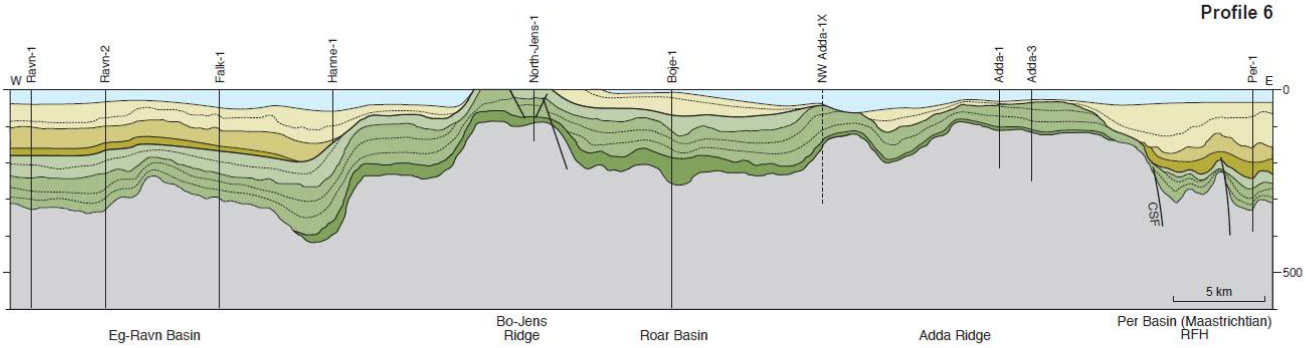
The profile is a W-E section crossing the Eg-Ravn Basin, the Bo-Jens Ridge, the Roar Basin, the Adda Ridge and the Poul Plateau terminating on the Ringkøbing-Fyn High. The profile reveals a wide **Lower Chalk** basin with a basin centre located in the area which later was involved in the inversion of the Bo-Jens Ridge. A comprehensive and thick Chalk Group succession appears to have been deposited in the original basin (verified by the Skarv-1 well). In the V-1 and Ugle-1 area the profile shows the development of the distinctive Maastrichtian Per Basin situated within the formerly inverted Adda Ridge and Poul Plateau area.

Uplift of the **Lower Chalk** basin took place during the Late Campanian. The inversion of the Bo-Jens Ridge was associated with erosion of the Upper Hod unit. Contemporaneous deposition took place in the Eg-Ravn Basin down-flank the inversion high. The Bo-Jens Ridge has acted as a structural high throughout the Maastrichtian. There is no clear evidence of continuous inversion during the Maastrichtian, but periods with renewed re-activation of the inversion process cannot be excluded.

In the area between the E-1 and Ugle-1 wells the truncated **Lower Chalk** is overlain by early Maastrichtian chalk. The truncation is interpreted to be associated with a Late Campanian (prior to Early Maastrichtian) uplift of the area. During the Maastrichtian the area forms part of the rapid subsiding Per Basin. Deposition of the Early Maastrichtian Lower Tor unit indicates a rapid and early change from uplifted area to subsiding basin. The Per Basin is bounded by the Adda Ridge to the west and to some degree by the Coffee Soil fault to the east. Slumping and reworking within the **Upper Chalk** down-flank the eastern slope of the Adda Ridge are identified from the seismic (Figure 21).

The hiatus related to the THU represents, except for the Bo-Jens Ridge, a relative minor time gap within the Late Campanian (Panel 5, Enclosure 2). On the crest of the Bo-Jens Ridge Maastrichtian is missing. The biostratigraphy in all wells in the profile indicate a minor hiatus at the K/T boundary. The K/T boundary is often associated with a hardground.

Profile 6 (Encl. 1. For location see Fig. 13)



This profile is a W-E section from the Ravn-1 well in the Eg-Ravn Basin to Per-1 on the Ringkøbing-Fyn High crossing the Bo-Jens Ridge, the Roar Basin and the Adda Ridge. The profile is located along a NW-SE transverse fault zones (the Adda transverse zone of Cartwright 1987); separating the southern Salt Dome Province from the northern Tail End Graben. The profile comprises a number of minor separate structural elements.

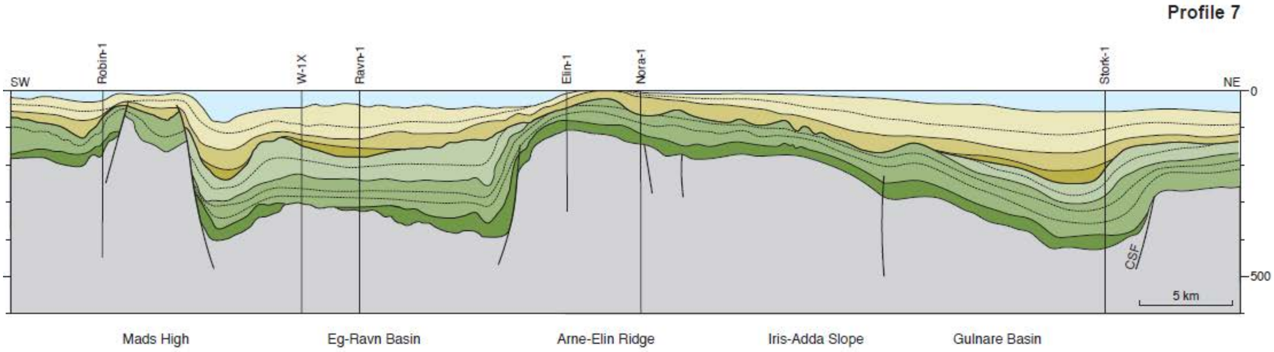
The profile reveals a wide **Lower Chalk** basin with a basin centre located in the area which later was involved in the inversion of the Bo-Jens Ridge. A complete and thick Chalk Group succession appears to have been deposited in the original basin, which is preserved in the Eg-Ravn Basin (Ravn-1, Ravn-2 and Falk-1 wells).

An inversion of the basin affecting the area from the Hanne-1 well to the Ringkøbing-Fyn High during Late Campanian gave rise to erosion of the Upper Hod and Middle Hod units. Erosional material was deposited down-flank the inverted area. Outside the inversion zone (in the Eg-Ravn Basin to the west and the Ringkøbing-Fyn High to the east) the **Upper Chalk** section is stratigraphic complete with "unbroken" deposition across the THU. The Danian section in this profile is slightly thicker than in the profiles to the south.

A thin **Upper Chalk** section above the inversion zone indicates the presence of a structural high during Maastrichtian. The profile advocates for the possibility of renewed tectonic activity during Late Maastrichtian in a narrow zone along the Bo-Jens Ridge and the Adda Ridge.

The hiatus related to the THU represents in the Eg-Ravn Basin a relative minor time gap within the Late Campanian (Panel 6, Enclosure 2). On the Adda Ridge the time gap ranges from Santonian to Late Maastrichtian. On the crest of the Bo-Jens Ridge Maastrichtian and Danian is missing. The biostratigraphy in the easternmost wells in the profile indicate a minor hiatus at the K/T boundary. The K/T boundary is locally associated with a hardground.

Profile 7 (Encl. 1. For location see Fig. 13)



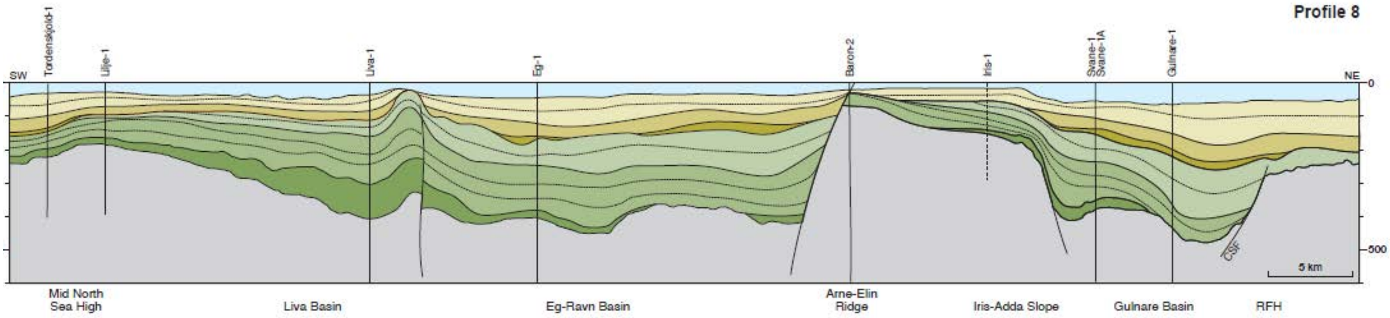
This profile is a SW-NE trending transect from the Mads High to the west crossing the Eg-Ravn Basin, the Arne-Elin Ridge and the Gulnare Basin terminating on the Ringkøbing-Fyn High. The profile reveals a wide-spread **Lower Chalk** basin. A thick Hidra unit at the base of the **Lower Chalk** succession indicates an early developed and rapid subsiding Upper Cretaceous basin in the centre of the Central Graben. Parts of the Ringkøbing-Fyn High form part of this basin.

Significant inversion associated with erosion of the crestal part along the NNW-SSE trending Arne-Elin Ridge (associated with the Lower Cretaceous Arne-Elin Graben system) took place during Late Campanian. A hummocky appearance of the THU on the Iris-Adda Slope is related to channel like features and interpreted to be associated with bottom currents. Continuous deposition during Early Maastrichtian took place down-flank the inversion zone (both the Eg-Ravn Basin to the west and the Gulnare Basin to the east comprises Lower Tor).

During Maastrichtian time a renewed period of basin subsidence took place with deposition of thick uniform Middle and Upper Tor deposits. Within the inversion zones renewed inversion activity took place at the end of the Maastrichtian time. The inversion involved the Mads High to the west and a narrow zone of the Arne-Elin Ridge along the Baron-Elin Fault. Continuous subsidence took place in the Gulnare Basin and on the Ringkøbing-Fyn High where thick Danian Ekofisk was deposited.

The hiatus related to the THU represents in the area outside the Arne-Elin Ridge and Mads High a minor time gap within the Late Campanian (Panel 7, Enclosure 2). In the inversion zones the time gap ranges from Santonian to Early Maastrichtian. Danian deposits are missing in areas affected by the renewed inversion during Maastrichtian.

Profile 8 (Encl. 1. For location see Fig. 13)



This cross-section runs from the Liva Basin in the west through the Eg-Ravn Basin, the southern part of the Jeppe Basin, the Arne-Elin Ridge and the Gulnare Basin terminating on the Ringkøbing-Fyn High to the east. The profile reveals a wide-spread Chalk basin comprising thick and relative constant deposition in the basin centre throughout the Upper Cretaceous. The Ringkøbing-Fyn High form part of the Chalk basin from Early Maastrichtian onwards.

A thick Hidra unit at the base of the Lower Chalk succession indicates an early developed and rapid subsiding Upper Cretaceous basin in the central part of the Central Graben. Syn-sedimentary normal faulting along the Inge-Mads Fault during the Cenomanian created a depocenter in the Liva Basin giving rise to deposition of an atypical thick Hidra (e.g. in Liva-1). The absence of Hidra and the thin and condensed Lower Chalk section in the Baron-2 and Iris-1 wells is interpreted to be a result of a contemporaneous relief associated with the inversion of the Lower Cretaceous Arne- Elin Graben feature culminating in the Arne-Elin Ridge.

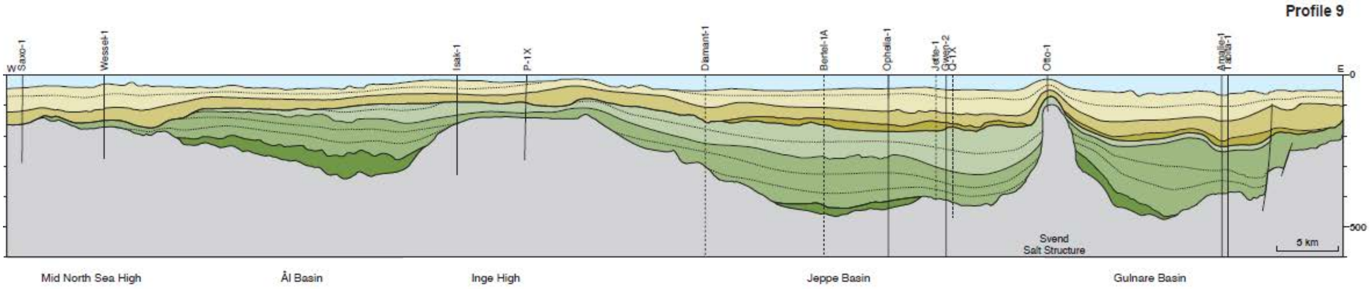
The gradual thinning of the **Lower Chalk** onto the Mid North Sea High mirrors the paleo-slope associated with the Mid North Sea High. Further westward the **Lower Chalk** section is absent.

The profile only shows evidences of Late Campanian inversion and associated erosion in restricted areas. On the Mid North Sea High truncation of the Upper Hod has taken place. The THU is here overlain by the early Maastrichtian Lower Tor and Middle Tor units indicative of a hasty return to basin conditions. Severe truncation of the **Lower Chalk** on the crest of the Arne-Elin Ridge is interpreted to be related to inversion of the structure. The oldest deposits above THU are associated with the Upper Tor unit; which suggests the presence of a topographic high with low or non-deposition in the time period for deposition of the **Upper Chalk**.

Continuous deposition took place outside the inversion zones (in the Eg-Ravn Basin and the Jeppe Basin to the west and the Gulnare Basin to the east)..

The hiatus related to the THU is in the Eg-Ravn Basin, the Jeppe Basin and the Gulnare Basin characterised by a minor time gap within the Late Campanian (Panel 8, Enclosure 2). In the Outer Rough Basin the time gap ranges from Santonian to Early Maastrichtian. On the Arne-Elin Ridge the time gap ranges from Coniacian to Late Maastrichtian. There is no stratigraphic evidence of a hiatus at the K/T boundary in the wells on the profile.

Profile 9 (Encl. 1. For location see Fig.13)



This profile runs from the Saxo-1 well on the Mid North Sea High to the west crossing the Ål Basin, the Inge High, the Jeppe Basin, the Svend salt structure and the Gulnare Basin terminating on the Lulu Plateau to the east. The profile reveals a wide-spread Chalk basin comprising thick and relative constant deposition throughout the Upper Cretaceous, especially in the Jeppe Basin and the Gulnare Basin. The wedging out of the **Lower Chalk** towards the Inge High suggests the presence of a structural high at the time of deposition. The highly irregular distribution of the **Lower Chalk** around the Svend salt structure mirrors the complex syn-sedimentary salt movements with development of rim synclines etc. as well as piercing of the **Lower Chalk** section.

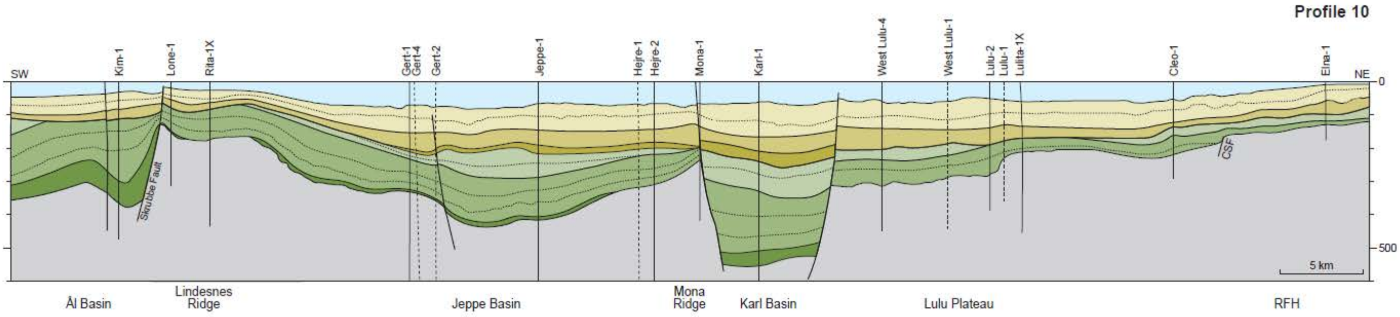
The profile shows only evidence of limited Late Campanian inversion and associated erosion. The gradual thinning of the **Lower Chalk** onto the Mid North Sea High mirrors the paleo-slope associated with the Mid North Sea High. To the west the **Lower Chalk** is absent. During the Maastrichtian the Mid North Sea High displays higher subsidence rates than the Ål Basin.

Minor evidences of erosion of the **Lower Chalk** section are observed above the Inge High. There are, however, no unambiguous evidences for an inversion of the Inge High. Therefore, the truncation alternatively may be interpreted to be related to high energy conditions associated with fall in sea level.

The missing Upper Hod unit in the Amalie-1 and Tabita-1 wells suggest truncation of the **Lower Chalk** in the Gulnare Basin. The THU is here overlain by the early Maastrichtian Lower Tor revealing of a hasty return to basin conditions. Continuous deposition took place in the Jeppe Basin throughout the Upper Cretaceous. Thick Danian dominates the geosection.

The hiatus related to the THU in the Jeppe Basin is associated with a minor time gap within the Late Campanian (Panel 9, Enclosure 2). In the Gulnare Basin, on the Inge High and in the Outer Rough Basin the time gap ranges from Early Campanian to Middle Maastrichtian. There is no stratigraphic evidence of a hiatus at the K/T boundary in the wells on the profile.

Profile 10 (Encl. 1. For location see Fig. 13)



This transect follows the Danish-Norwegian boundary. Seven structural elements dominate the profile: the Ål Basin, the Lindesnes Ridge, the Jeppe Basin, the Mona Ridge, the Karl Graben, the Lulu Plateau and the Ringkøbing-Fyn High.

The profile reveals a wide-spread but diversified Chalk basin comprising a relative thick Chalk Group. The Ringkøbing-Fyn High form part of the Chalk basin from Campanian onwards.

Hidra is found west of the Lulu Plateau. Syn-sedimentary normal faulting bounding the Karl Graben and faulting at the western edge of the Lindesnes Ridge created local depocentres giving rise to deposition of atypical thick Hidra and Hod sections (e.g. in Kim-1 and Karl-1). The absence of Hidra and the thin and condensed **Lower Chalk** section on the Lulu Plateau suggest that the area formed part of a structural high during Cenomanian to Campanian time. The gradual thinning of the **Lower Chalk** from the west onto the Mona Ridge is indicative of a paleo-high in the area. A paleo-relief may also have occurred associated with the Lindesnes Ridge during Cenomanian.

Truncation of the **Lower Chalk** is observed in the Lindesnes Ridge area and on the Lulu Plateau. The truncation of the **Lower Chalk** is interpreted to be associated with Late Campanian inversion and uplift. "Contemporaneous" deposition of the Lower Tor took place in the Jeppe Basin and in the Karl Graben. During the Middle Maastrichtian the various structural elements joins in a uniform subsiding basin continuing into the Danian where thick Ekofisk was deposited.

The hiatus related to the THU represents in the Jeppe Basin and the Karl Graben a minor time gap within the Late Campanian (Panel 10, Enclosure 2). In the Lone-Rita area (on the southern extension of the Lindesnes Ridge) and on the Lulu Plateau the time gap ranges from Santonian to Middle Maastrichtian. The hiatus in the Mona-1 well is biased by a crosscutting fault zone.

Profile summary

The structural development identified from the maps and profiles display a dynamic basin development with large thickness variations in the units, changes in the location of depocentre throughout time and tectonic uplift resulting in reworking and truncation in the Chalk Group. Because there is a close relationship between depositional origin and reservoir properties it is important to have a comprehensive knowledge to the basin development throughout the Late Cretaceous. An overall summary is given below. More details on the basin development during Upper Cretaceous need a more comprehensive and multidisciplinary approach.

Depositional conditions

The depositional environment for the Chalk Group is characterised by pelagic deposits drapping the sea floor. Bottom currents sculptured the chalk sea-floor relief creating important features such as channels, drifts, valleys and ridges. Along steep dipping slopes, instability of the previously deposited chalk gave rise to gravity-driven re-sedimentation downslope. The type of reworked chalk is controlled by the complexity in processes and controlling parameters for the re-sedimentation e.g. type of relief, dip of the slope, consolidation of the reactivated sediment and distance of movement.

The distribution of the chalk proves the existence of structural highs and the presence of a bathymetric relief during deposition of the Chalk Group. Pre-existing relief is draped with chalk units slightly thinner on the crest. Thinning/condensing is anticipated to be a result of sweeping off the chalk on structural high lying areas and transport into the basin centre.

Post-depositional uplifted features are linked with erosional truncation on the crest of the structural highs and partly erosion of the chalk down-flank resulting in units wedging out towards the highs (Figure 14). The erosion on top of the structural highs is anticipated to take place in a high energy environment related to a relative sea-level fall induced by a combination of inversion and eustatic fall. There is no evidence for sub-aerial exposure of the chalk succession but it is expected that the structural highs may be located in a high energy zone above the storm wave base (Farmer & Barkved 1999, Sikora *et al.* 1999). Bottom currents may cause erosion and redeposition of the chalk but the contourites-like currents are concentrated along the basin slopes and not on the crestal part of the bathymetric highs. Channel like features down dip the structural highs perpendicular to the basin axis is interpreted to be a result of gravity-driven reworking of the chalk.

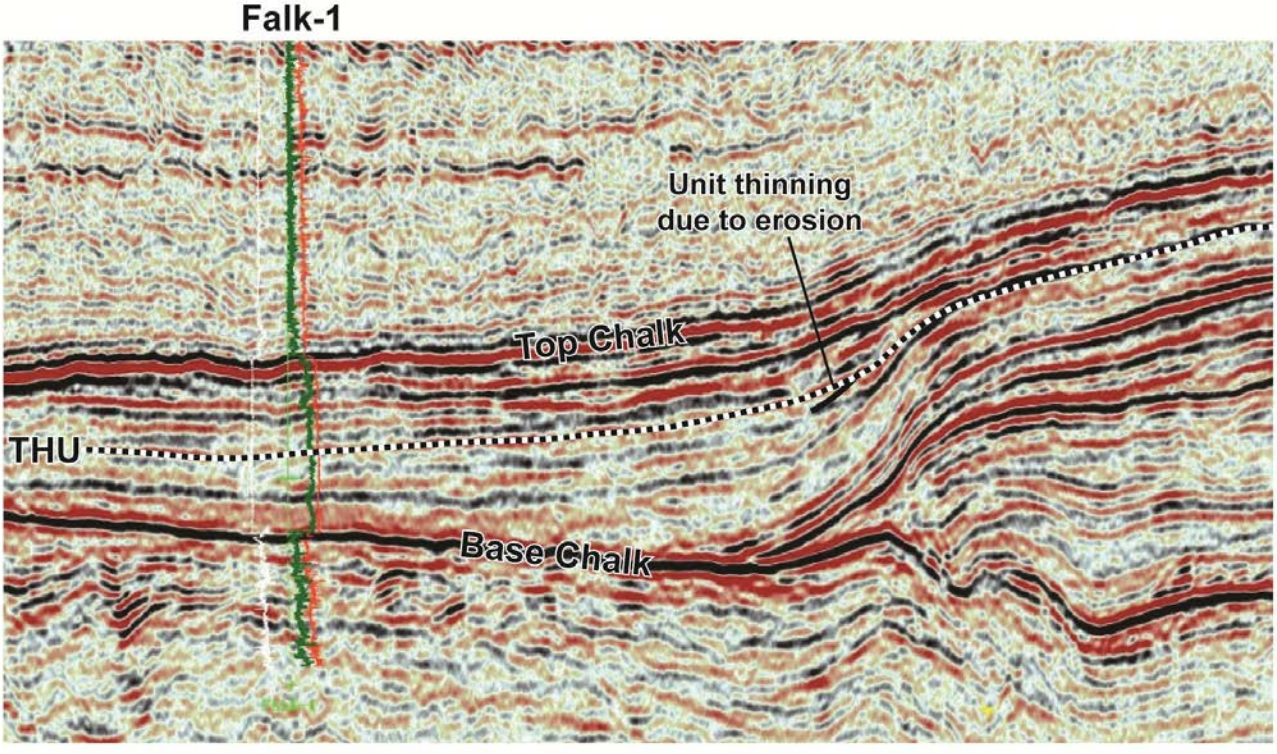


Figure 14. Seismic line showing truncation on inversion structure, unit thinning up-slope due to erosional truncation.

The exact bathymetry of the chalk seafloor is unknown due the lack of reliable depth indicators and the fact that the chalk was deposited over a wide range of water depths. Guesstimates for the water depth in the chalk sea ranges from <50 m to more than 1000 m. A general lack of remains of light dependent organisms indicates minimum depths below the euphotic zone which has been estimated to extend down to 150 – 200 m (Håkansson *et al.* 1974, Scholle 1974). Results from examination of the biofacies components carried out in the Eldfisk and Ekofisk area in the Norwegian Central Graben indicate a predominant bathyal biofacies representing depths from 200 to1000m (Hampton *et al.* 2010).

Channel-like features, moats and other erosional features can be seen in the chalk in the Danish Basin and are associated with contourites active at depths of more than 500-600 m (Surlyk & Lykke-Andersen 2007).

The absence of pelagic chalk on highs is indicative of removal of the sediment and both syn-sedimentary (sweeping) and post-depositional erosion may have taken place within the structural high areas. Winnowing and erosion takes place in high energy zone above the storm wave base (Farmer & Barkved 1999, Sikora *et al.* 1999) and it is suggested that the crest of inversion highs was situated in a shallow water and high energy environment.

The origin of the clay in the chalk has been discussed for several decades. The general low content of clay in the chalk is explained by high eustatic sea-level associated with a low relief hinterland and a coastline, outlining the source area for the detritital material, far from the basin centre. It is unknown if the variation in clay content is caused by sea-level fluctuations and erosion from nearby bathymetric highs, related to volcanic activity or controlled by orbital cyclicity. The thick marly Santonian-Coniacian unit suggests a depositional environment involving a change in basin configuration, sea-level fall and supply from nearby/local highs.

Basin development during Upper Cretaceous

Deposition of the Upper Cretaceous – Danian Chalk Group in the study area took place during a phase of regional post-rift subsidence following Late Jurassic rifting associated with a generally transgressive period. This period was marked by generally high-sea-level, high-surface temperature and a peak in production of organic matter. The **Lower Chalk** section comprises prevailing pelagic chalk. A moderate relief inherited from the Lower Cretaceous is thought to be partly wiped out or modified in importance in connection with the Cenomanian-Early Campanian sea level rise.

Although the chalk deposition primarily is related to pelagic sedimentation on a regional scale the thickness variation of the various Chalk units is controlled by the bathymetry and deposition space and reveals a dynamic basin development. The time-isochore map on the total Chalk Group shows very large thickness variations from less than 100 mSec on top of salt diapirs and paleohighs and more than 800 mSec in the rim-synclines and basin centres (Figure 9). Reduced thicknesses are associated with inversion structures. Whereas the thickness reduction related to the inversion structures seen in the **Lower Chalk** (Figure 11) primarily is caused by truncation, the thin **Upper Chalk** above inversion structures (Figure 10) is controlled by the syn-depositional relief created by the inversion. The truncation of the inverted **Lower Chalk** section involves removal of the originally deposited uppermost Campanian units – an aspect to deal with during a reconstruction of the basin development and determination of the original thickness of the units.

Based on the chalk thickness and distribution from the time-isopach maps (Figures 9-11) and the seismic cross sections (Enclosure 1), the basin development and structural development during deposition of the Chalk Group in the Central Graben are reconstructed and summarized below.

Cenomanian-Late Campanian

The transition from Early to Late Cretaceous is characterized by a sea level rise and change from terrestrial clay dominated sediments to pelagic dominated marly chalk deposits. The fine-grained siliciclastic and clay content in the Hidra and Blodøks units imply a nearby source area. The absence of the lowermost Chalk section on the Ringkøbing-Fyn High and Mid North Sea High suggests that these areas acted as source area for the detrital supply. The gradual decrease in clay content in the Blodøks unit indicates a general sea-level rise; submerge of the surrounding high areas and an increased distance to the source area for the clay. The uppermost part of the Blodøks unit is dominated by a homogeneous clean pelagic dominated chalk (the Herring Fm, Deegan & Scull 1977) suggesting a full marine (and protected) basin with nearly no clay influx.

The Hidra unit is present in most of the Central Graben area. The distribution of the Hidra is controlled by the paleo-relief at the end of Early Cretaceous time. The initial basin setting at the onset of the chalk deposition is confined to an area as indicated in Figure 15. Syn-sedimentary faulting along the Inge-Mads fault introduces a thick Hidra in the Outer Rough Basin (Profile 8).

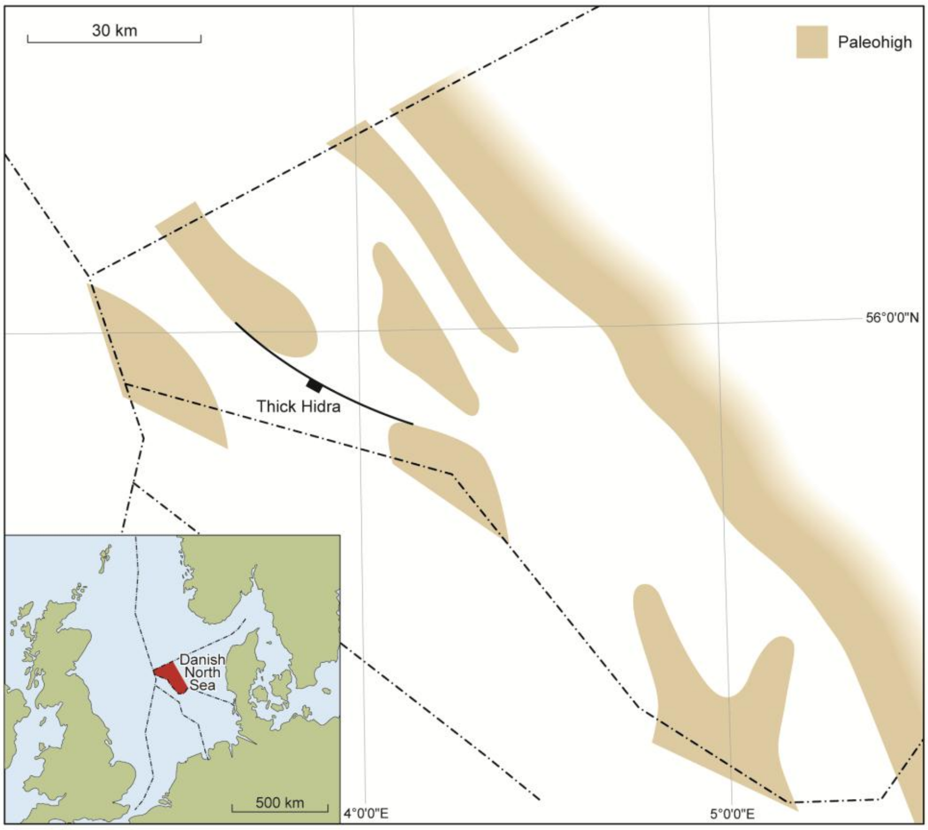


Figure 15. Structure map showing the distribution of paleo-highs during deposition of the Cenomanian Hidra unit. The map displays the initial basin setting at the onset of the chalk deposition.

A wide-ranging basin expansion in the Central Graben area with prevailing pelagic chalk deposition dominates in the Turonian to Late Campanian. The distribution of Turonian to Santonian Blodøks, Lower Hod and Santonian-Coniacian Shale units indicate a uniform section blanketing the basin centre including the structural features active during deposition of the Hidra unit. Depocentres during this period is found in the Jeppe Basin, the Eg-Ravn Basin, the Rosa Basin and the Nana Basin. The thickness distribution of the **Lower Chalk** indicates basin subsidence in areas with thick Lower Cretaceous.

Thinning and wedging out of the **Lower Chalk** units are found associated with salt structures and syn-depositional relief. Active salt movements during Turonian - Santonian times are common in the Salt Dome Province e.g. the John structure (Profile 1), the Lola structure (U-1, Profile 2) and Edna structure (Profile 3). Syn-depositional structural highs are identified in the Elly-1 area (the structural high with Elly-1), along the Arne- Elin Ridge and associated with the Inge High. Platform associated deposits are seen on the Lulu plateau. Evidences of a syn-depositional relief associated with early inversion are seen along the Bo-Jens Ridge (Profile 4), the Arne-Elin Ridge (Profile 8) and the Mona Ridge (Profile 10).

The Santonian - Coniacian shale is a characteristic clay-rich interval found in the entire basin and represent a period with relative high supply of clastic material. The variation in clay content/clean chalk in the interval is anticipated to be related to eustatic sea-level variations (Haq *et al.* 1987; Haq 2014).

Sedimentation of relative clean pelagic chalk in deep water conditions prevailed during deposition of the Middle and Upper Hod units. The thickness distribution of the Middle and Upper Hod units shows evidence of contemporaneous paleo-highs e.g. the Inge High (Profile 8). The actual thickness of the upper part of the **Lower Chalk** is due to erosion not fully indicative for the basin development. It is, however, anticipated that the original thickness of the eroded Lower Chalk units in the inversion zones are comparable with the thicknesses recorded in the adjacent basins not involved in the inversion.

An initial inversion during deposition of the Middle and Upper Hod units may have taken place (Vejbæk & Andersen 2002) but has not been identified from the present examination of the distribution and thickness of the established units.

Late Campanian tectonism

Tectonic activity during Mid-Late Campanian was dominated by compressional tectonism (Vejbæk & Andersen 2002; Surlyk *et al.* 2003). The regional subsidence was interrupted by widespread inversion in the form of compression along old extensional fault trends. The inversion and contemporaneous salt movements resulted in the development of bathymetric highs and formation of local depocentres in the intervening lows. The structural movements (together with possible sea-level fall) resulted in the THU, easily recognized as truncation and seismic top-lap. The THU represents a stratigraphic hiatus of varying timespan depending on the structural setting relative to the inversion axis.

The Late Campanian inversion affects large parts of the Central Graben but varies in intensity depending on the structural setting. The inversion and uplift of large parts of the Central Graben is associated with truncation of the **Lower Chalk** succession. The intensity of inversion is illustrated in Figure 16 where the degree of erosion is a proxy for the inversion. Inverted areas are marked by hatching and the most eroded parts are indicated with the dense shading. The inversion varies in the Central Graben and is primarily restricted to reactivated older structural elements. The inversion is associated with reverse faulting along old N-S trending faults and the most intensive inversion took place along the southern part of the Coffee Soil Fault and the Arne-Elin Ridge and Lindesnes Ridge.

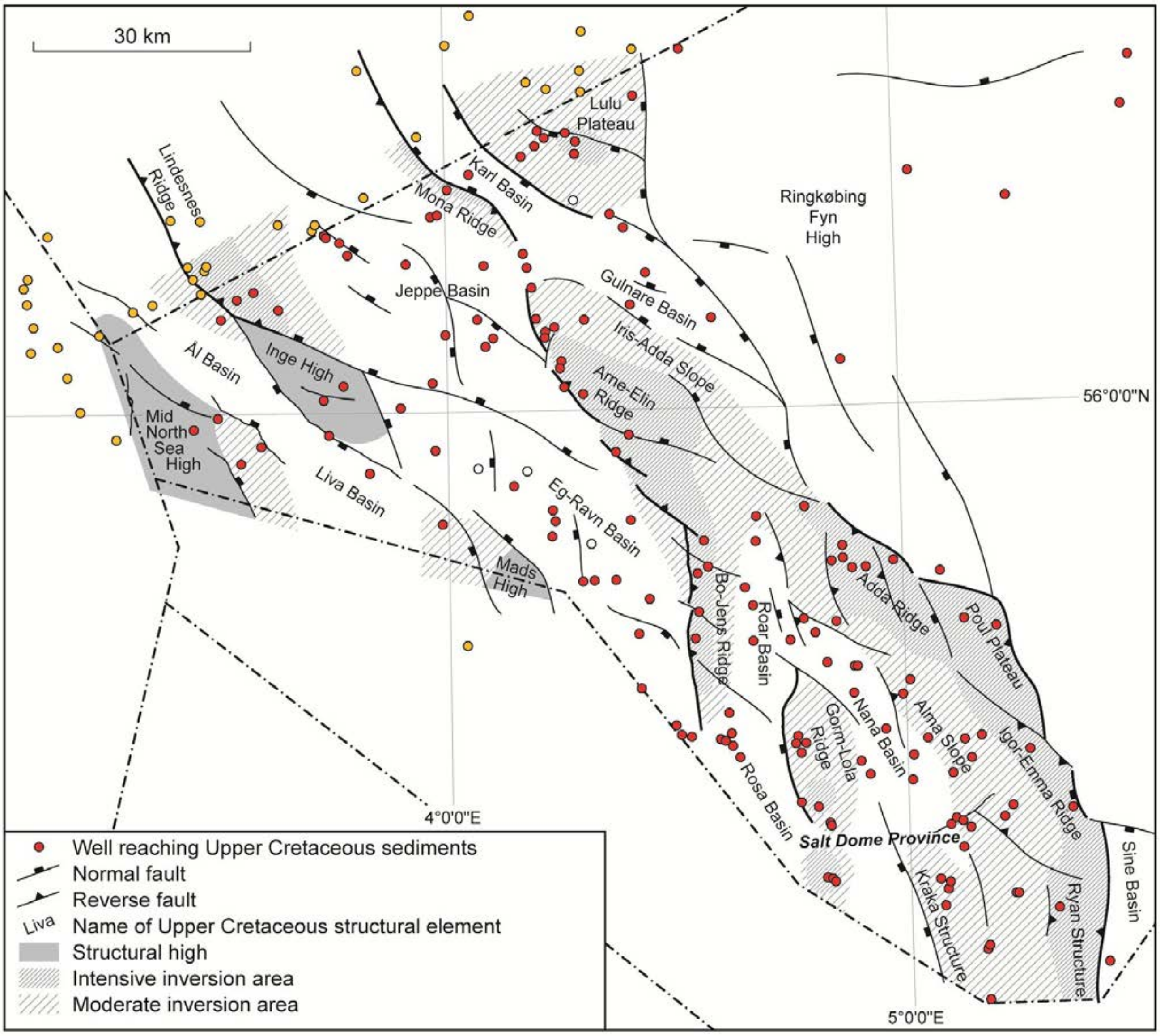


Figure 16. Map showing the inversion structures and intervening basins related to the Late Campanian inversion.

The erosive THU can easily be identified from the seismic data and can be mapped in the entire Central Graben (Figure 7 and Profiles 1-10 (Enclosure1)). The THU represents a major hiatus where the range of the missing section primarily is associated to the degree of truncation of the **Lower Chalk** and secondary associated with non-deposition of the **Upper Chalk** on the crestal parts of the inversion ridges. The time gap related to the truncation of the **Lower Chalk** and non-deposition of the **Upper Chalk** is shown in the stratigraphic panels in Enclosure 2.

The truncation of the **Lower Chalk** is associated with contemporaneous re-deposition related to the Lower Tor unit in the intervening basins. A tentative age for the Lower Tor is, as mentioned above, of questionable Upper Campanian - Early Maastrichtian age.

The erosion on top of the inversion highs indicates conditions with high energy. Biofacies from the Valhall Field on the Lindesnes Ridge in Norway show evidence of shallow water conditions and indicate that the sea bottom was located above the storm wave-base (Farmer & Barkved 1999; Sikora *et al.* 1999). There are no indications of subaerial exposure in the Danish Central Graben, but the high energy indicates a water depth on the crestal part of the inversion ridges within the range for the wave-base.

The inversion is bounded to the east by the Coffee Soil Fault. The Ringkøbing-Fyn High continued to subside and acted as receiver area for the down-flank deposits related to the erosion on the crest of the inverted area. A mixed Early Maastrichtian – Late Campanian palyno/nanno plankton suite is identified above THU in the Sine-1 well on the RFH indicative of pelagic deposits supplemented with reworked material. It is anticipated that a biostratigraphic reversal in the succession above the THU caused by the subsequent deeper truncation of the Hod Formation on the inversion ridge can be found in the Sine-1 well, but this has to be verified by detailed biostratigraphic studies.

The change in water depth and increase in energy level is expected to be a combination of the tectonic influenced inversion accompanied with eustatic sea-level fall. The development of channel features and evidences of bottom current concentrated in the basin centres associated with the THU mark an increased intensity in sea-floor activity which may be related to an eustatic sea-level fall (Surlyk & Lykke-Andersen 2007). The sea-level fall also gave rise to erosion of the chalk on top of salt structures during this period. A few areas in the Central Graben are characterised by structural stable blocks which have not been inverted but nevertheless show evidence of erosion of the Lower Chalk - a situation evident of an eustatic sea-level fall.

Maastrichtian – Danian

The tectonic activity during Late Campanian introduced a dramatic change in the basin development. The inversion ceased during Late Campanian and/or earliest Early Maastrichtian and at the same time a possible sea level rise took place. The subsidence/depositional space during Maastrichtian time were highest in the areas outside the inversion area. The bathymetric relief formed during the Late Campanian inversion sustained to be active, possibly as a result of reactivation of the inversion. Vejbæk and Andersen (2002) identified the presence of a Mid Maastrichtian phases of inversion affecting the Chalk Group. This inversion phase, however, has not been clearly recognized in this study. It can be questioned if the inversion was a long lasting process initiated during Late Campanian continuing to Mid Maastrichtian or the inversion was related to a single short-term phase during Late Campanian leaving a stable longstanding paleo-relief affecting the deposition during Maastrichtian.

The Late Campanian inversion is bounded to the east by the Coffee Soil Fault. To the east the Ringkøbing-Fyn High continues the subsidence and act as receiver area for the down-flank deposits related to the erosion on the crest of the inverted area. A narrow zone with relative high subsidence during the Maastrichtain took place along a NW-SE trending basin running from the Per Basin to the east crossing the Mona-Karl area into the Norwegian Feda Basin and north of the Valhall structure (Figure 9).

A special basin development took place in the Poul Plateau area, where the **Lower Chalk** succession initially was involved in the Late Campanian uplift and subsequent erosion but rapidly changed into a subsiding basin (the Per Basin) where thick Maastrichtian chalk was deposited (Profile 5). The early Maastrichtian deposits above a heavily truncated **Lower Chalk** section in the Per Basin describe a local and atypical hasty change in basin development from inversion to subsidence. In the area west of the main inversion zone thick continuous deposition took place in the Jeppe Basin and the Eg-Ravn Basin.

The inversion ridges acted as bathymetric highs and in the beginning of the Early Maastrichtian the pelagic deposits were swept away from the crests. The sea-level rise and lowering in energy level at sea bottom lead to a steady deposition of the pelagic chalk draping the sea floor. The thickness variation indicates that the pelagic chalk did not simply drape the seafloor but was redistributed in connection with different reworking processes down-flank the inversion ridges. In the course of the relative sea level rise during Maastrichtian, the water depth became sufficient for accumulation of chalk deposits on the Mid North Sea High, the Mads High and the Ringkøbing-Fyn High.

The Middle Tor represents pelagic dominated chalk with seismic onlap onto inversion highs suggesting continuously high energy conditions and non-deposition on the crests of the paleo-highs. Alternatively, but less obvious, the Middle Tor deposits may initially have draped the seafloor but was later eroded on the crests in connection with renewed inversion activity.

Reworked chalk as slump, slides and turbidites are observed in the Middle Tor down-flank the inversion ridges. The reworked chalk suggests the presence of a syn-depositional relief with re-activation of unstable deposits on the dipping slopes. Re-activation of the unstable slope deposits may have been triggered by tectonic activity related to recurrence of the inversion.

Upper Tor is found in the entire study area and dominated by chalk of pelagic origin. The section exhibits in the southern Central Graben a regionally correlatable cyclical pattern in the 1-3 m scale of high and low porosity intervals. The seismic data in this succession is characterized by sub-parallel high amplitude reflectivity.

Salt movements and faulting during Maastrichtian gave rise to mega sliding down dip the slope of the Gorm Field and Skjold Flanke-1 (Figure 24)

Tectonic activity took place at the K/T boundary and gave rise to new changes in the basin development. A thickness map of the Danian has not been made but the Danian seems to be thin in the central part of the Central Graben, moderate thick to the south and with the thickest section in the northern part of the Central Graben (Profile 10). In several wells in the southern part of the Central Graben the K/T boundary is associated with a hardground and hiatus. The time gap is often negligible (see Stratigraphic panels in Enclosure 2).

Post-Danian

During Eocene time a new phase of inversion of the southern Central Graben took place and developed the Tyra-Igor Ridge (Vejbæk & Andersen 2002); which can be seen as a structural feature on the Top Chalk structure map (Figure 6). The Top Chalk surface on the eastern flank is cut by low angle listric faults indicating early post-Danian slumping of poorly consolidated chalk caused by renewed inversion along the ridge.

The Tyra-Igor Ridge inversion involves the area including the inversion ridges related to the Late Campanian inversion but does not mirror the previous inversion structures (Figure 17). The crest of the broad Eocene inversion ridge is displaced to the west compared to the former inversions ridges. This suggests that the Tyra-Igor Ridge represents a separate tectonic event and not a continuation of former inversion events.

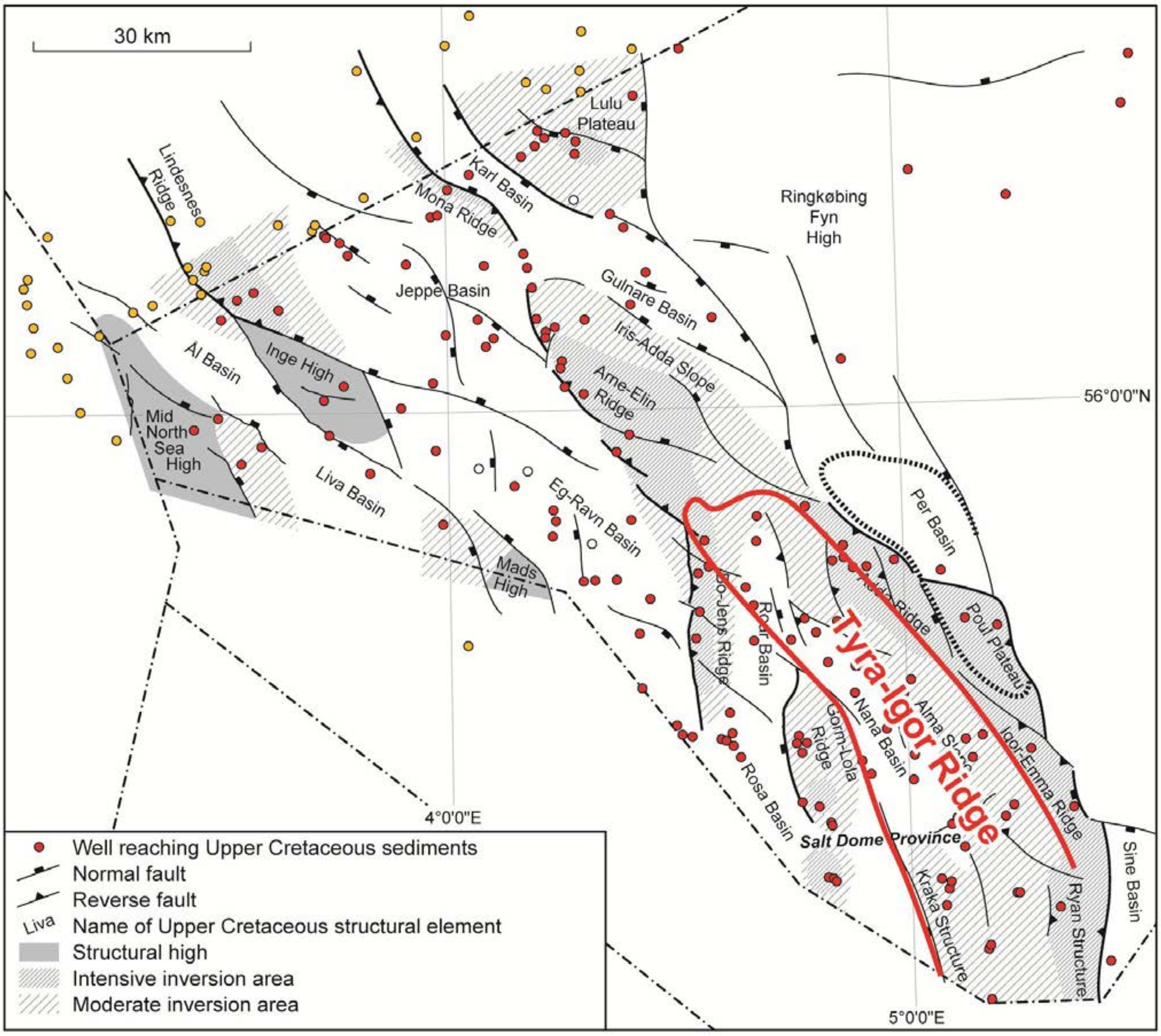


Figure 17. Schematic structure map showing the location of the Tyra-Igor Ridge in relation to the Late Campanian inversion structures.

Porosity distribution in the Upper Cretaceous Chalk

High porosities are encountered in the Maastrichtian Tor and the Danian Ekofisk formations, whereas the chalk related to the Cenomanian-Campanian period generally comprises low porosities. A general porosity versus depth profile through the chalk section shows a gradual but fast decrease in the porosity in the Danian-Maastrichtian package. At the THU a distinct and instant change to lower porosities entering the Campanian Hod units is common.

Japsen *et al.* (2011) associate the pronounced porosity drop from ~20% to less than 10% over a depth interval of less than 300m to a compaction front. The compaction front is closely tied to the effective stress and pore collapse in the chalk section. The modelled depth of the compaction front corresponds at several locations with the depth of the THU, representing the boundary between the general high porosities related to the Maastrichtian – Danian **Upper Chalk** section and the overall low porous Campanian-Cenomanian **Lower Chalk** section. This opens the discussion on the origin and impact of the THU: does the THU reveal a major hiatus separating two different depositional regimes resulting in different reservoir properties or does the THU represent the compaction front in an overall subsiding Chalk Group? The results from this study argue for the first alternative suggesting different depositional regimes while the amalgamating depth of the compaction front and situation of the THU is considered as a coincidence.

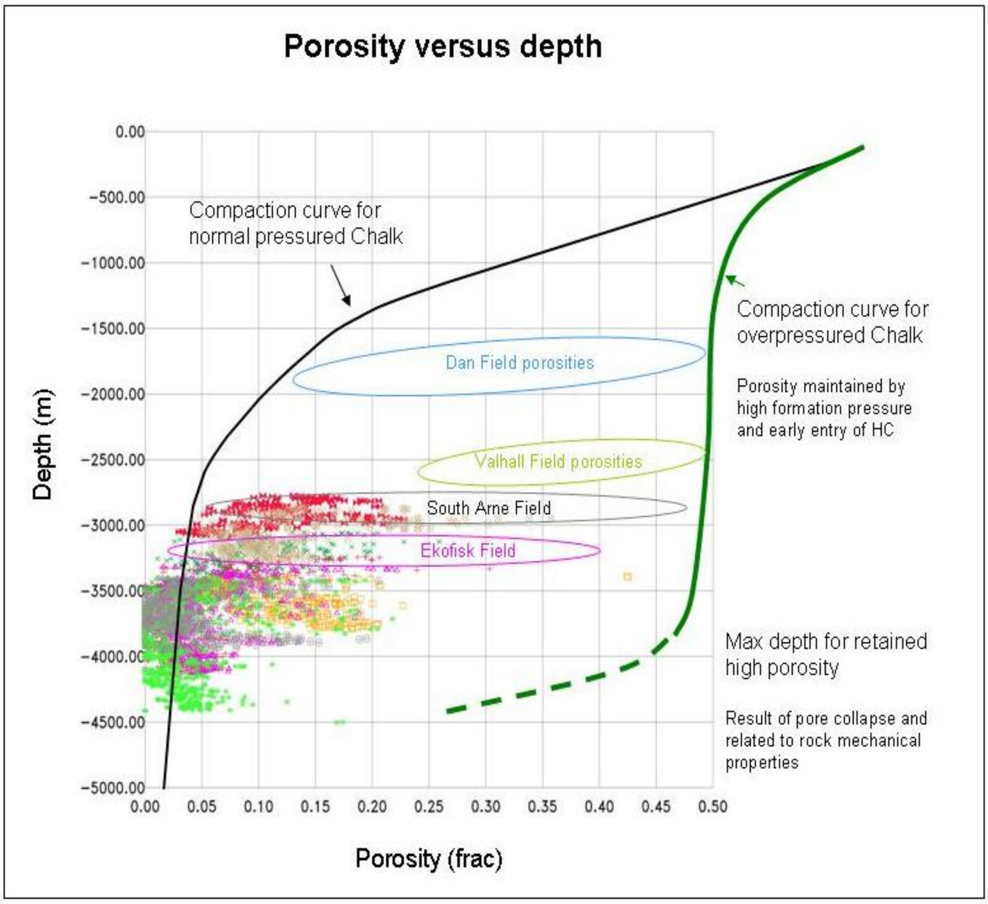


Figure 18. Porosity versus depth diagram. Measured core porosities from Chalk Fields and exploration wells are plotted versus depth. Porosities above 20% are recorded to approximately 4000 m.

A general porosity versus depth of burial trend for chalk is suggested by among others Sclater & Christie (1980). Brasher & Vagle (1996) introduced high pore pressure and hydrocarbon filling for retention in the porosity reduction versus depth. The retention in porosity reduction due to abnormal high formation pressure terminated at the level for pore collapse. Below the level of pore collapse the porosity decrease follows the general depth of burial trend.

Applying porosity data from a large number of chalk fields and exploration wells in the North Sea it is shown that high porosities (> 15%) in the Chalk Group in the Central Graben may be found to a depth of approximately 3500 - 4000 m (Figure 18).

In addition to pore pressure, chalk facies is a controlling factor on the porosity and many observations show that high porosity chalk is more often related to reworked chalk rather than pelagic dominated chalk. The presence of prevailing reworked chalk deposition in the Maastrichtian, due to the bathymetric relief caused by the Late Campanian inversion, combined with pressure buildups, display a situation that favor the interval above the THU with respect to high porosity. The predominance of pelagic deposits below the THU result in a section with relative lower porosity than the overlying and less buried Maastrichtian and Danian chalk.

As a consequence of the above mentioned observations it is apparent that the most prospective part of the Chalk Group is related to the Maastrichtian to Danian succession above the THU. In the Chalk Group below the THU the prospectivity is highly controlled by the structural development and a favorable hydrocarbon filling history as seen in the Bo area.

Reservoir potential and prospectivity

In the Central Graben all structural closures (salt structures and inversion highs) on top Chalk have been drilled and most of the producing Maastrichtian – Danian chalk fields are associated with these structures. The structural closures at Top Chalk are highly controlled by the Eocene inversion. The Eocene inversion involves to some degree the same area involved in the Late Campanian inversion (Figure 17) but does not consume or destroy previous closures related to the intra-Upper Cretaceous inversion. Despite the later tectonic impact of the Eocene inversion, the Late Campanian inversion structures may still encompass intra-Chalk structural traps and a reconstruction of the paleo-topography may reveal internal subtle traps in the Chalk Group.

Discoveries associated with hydrocarbon filled stratigraphic traps are made in the Halfdan area. The discovery is associated with Maastrichtian chalk filled with hydrocarbons in non-equilibrium. The Halfdan discovery is situated within the Eocene Tyra-Igor Ridge area but also located down flank the Late Campanian Adda Ridge. Hydrocarbons are expected to be associated with a pathway in the basin centre with an entry point at the toe of the slope.

It is expected that reworked chalk with proper porosity may be found down flank the inversion ridges but further work is needed on new updated seismic data to outline areas and intervals with reworked chalk. Different types of reworked chalk can be identified from the existing seismic data and a few examples are shown below. Some of the reworked chalk sections are proved non-hydrocarbon bearing because of the lack of migrating hydrocarbons. To complete an evaluation of the prospectivity in the chalk the seismic interpretation require mapping of the migration pathway for hydrocarbons. This aspect will be addressed in a forthcoming project.

Sedimentary features identified from the seismic

Large scale sedimentary features can be identified from the seismic data. These features represent a large variety of depositional processes which again are associated with different porosities. The seismic features are found at different stratigraphic levels but the distribution of the seismic features is closely related to the structural development. A few examples of intervals including reworked chalk are shown below (Figures 20-24; for line location see Figure 19). For a detailed outline of areas with reworked chalk a more comprehensive interpretation is needed.

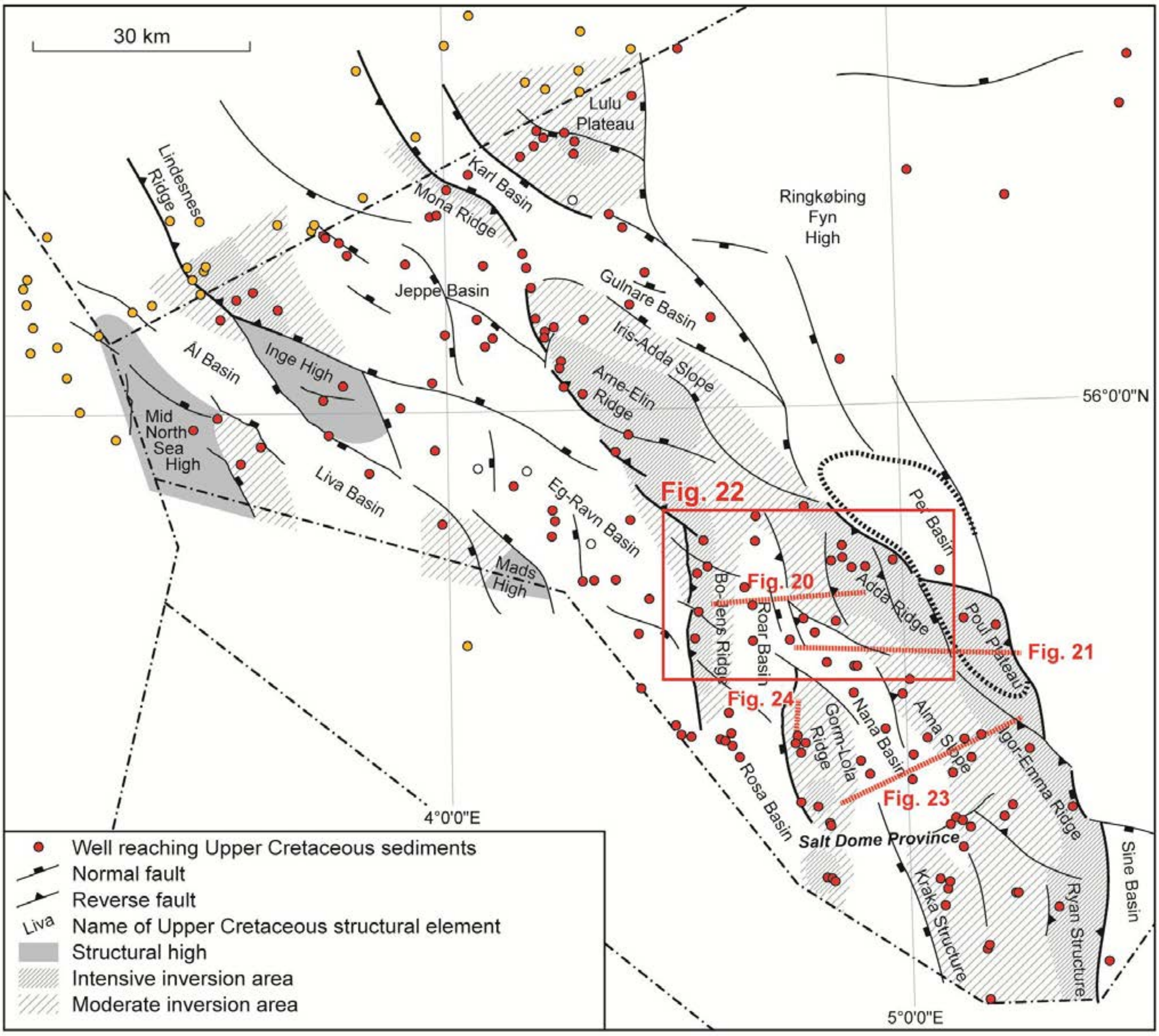


Figure 19. Location of seismic profiles selected for illustration of sedimentary features in the Chalk Group using the inversion structure map as base map.

The Late Campanian inversion gave rise to a number of inversion ridges along major older basement attached faults zones. Within inter-ridge basins channel features, moats etc. are formed (Figure 20).

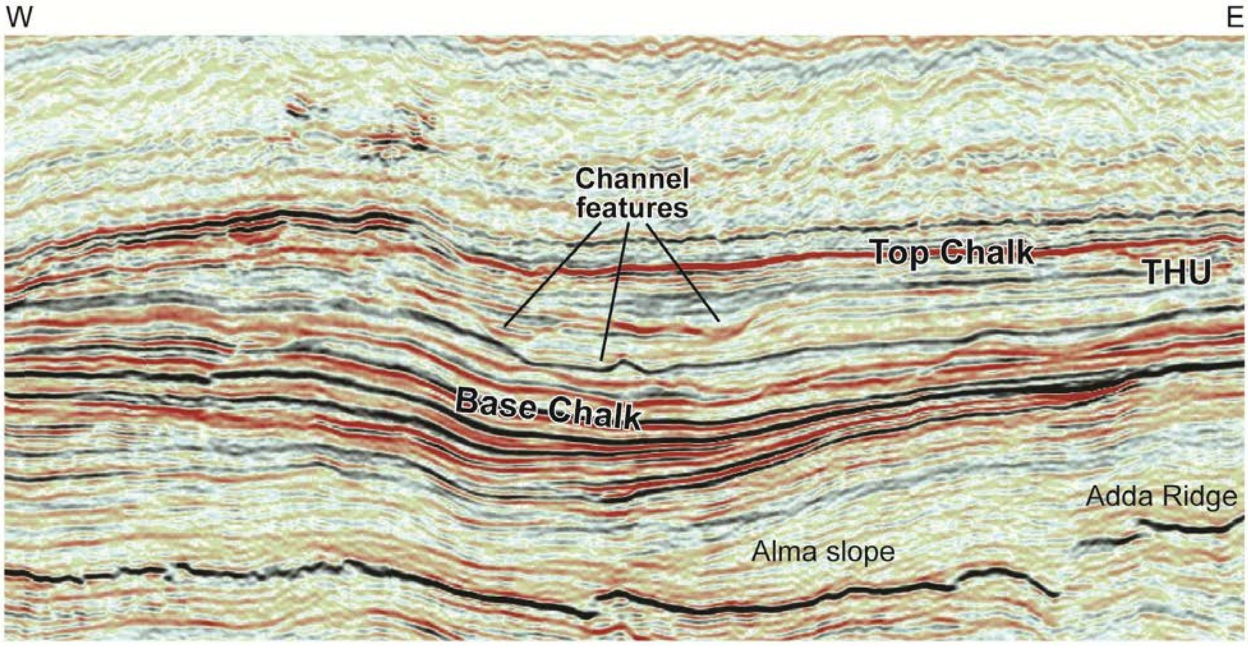


Figure 20. SW-NE trending seismic line crossing the Alma Slope and Adda Ridge showing channel features at several stratigraphic intervals. For location see Figure 19.

Along the eastern flank of the Adda Ridge there is clear evidence of slump and other indications of disturbed chalk within the Maastrichtian to Danian chalk (Figure 21). The Top Chalk surface on the eastern flank is cut by low angle listric faults along the ridge indicating early post-Danian slumping of poorly consolidated caused by the renewed Eocene inversion.

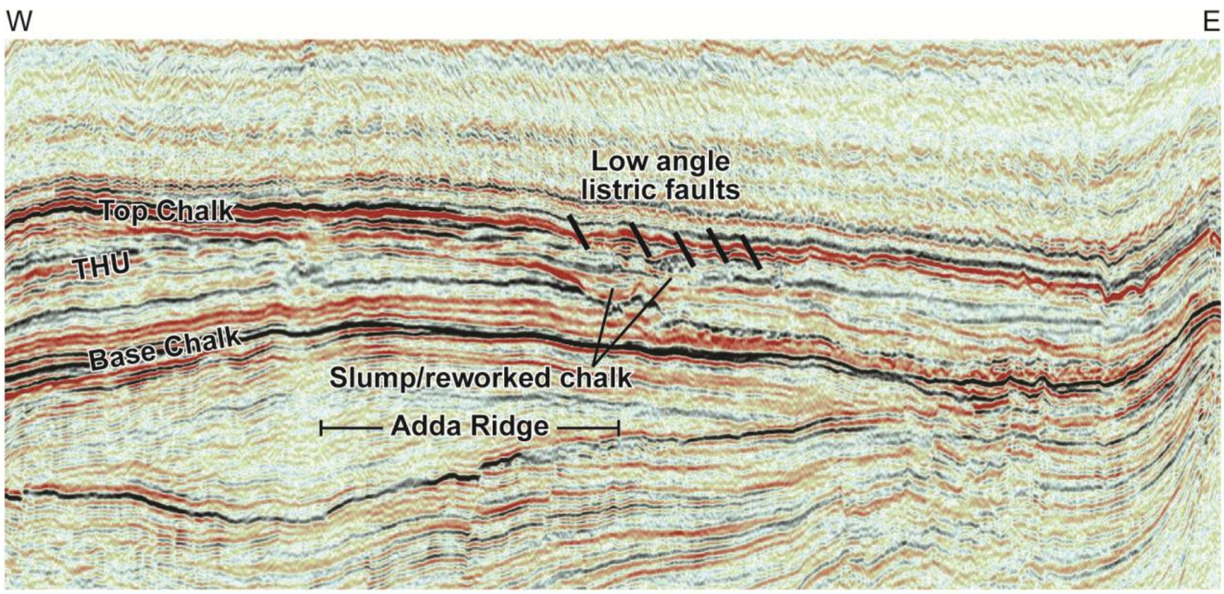


Figure 21. W-E trending seismic line (DUC05 line1850) crossing the Adda Ridge showing slump and channel features at several stratigraphic intervals. For location see Figure 19.

In the area between the Bo-Jens Ridge and the Adda Ridge; Esmerode *et al.* (2008) interpret a number of features as derived from interaction of down-slope mass flow movements (slumps and slides) and along-slope currents.

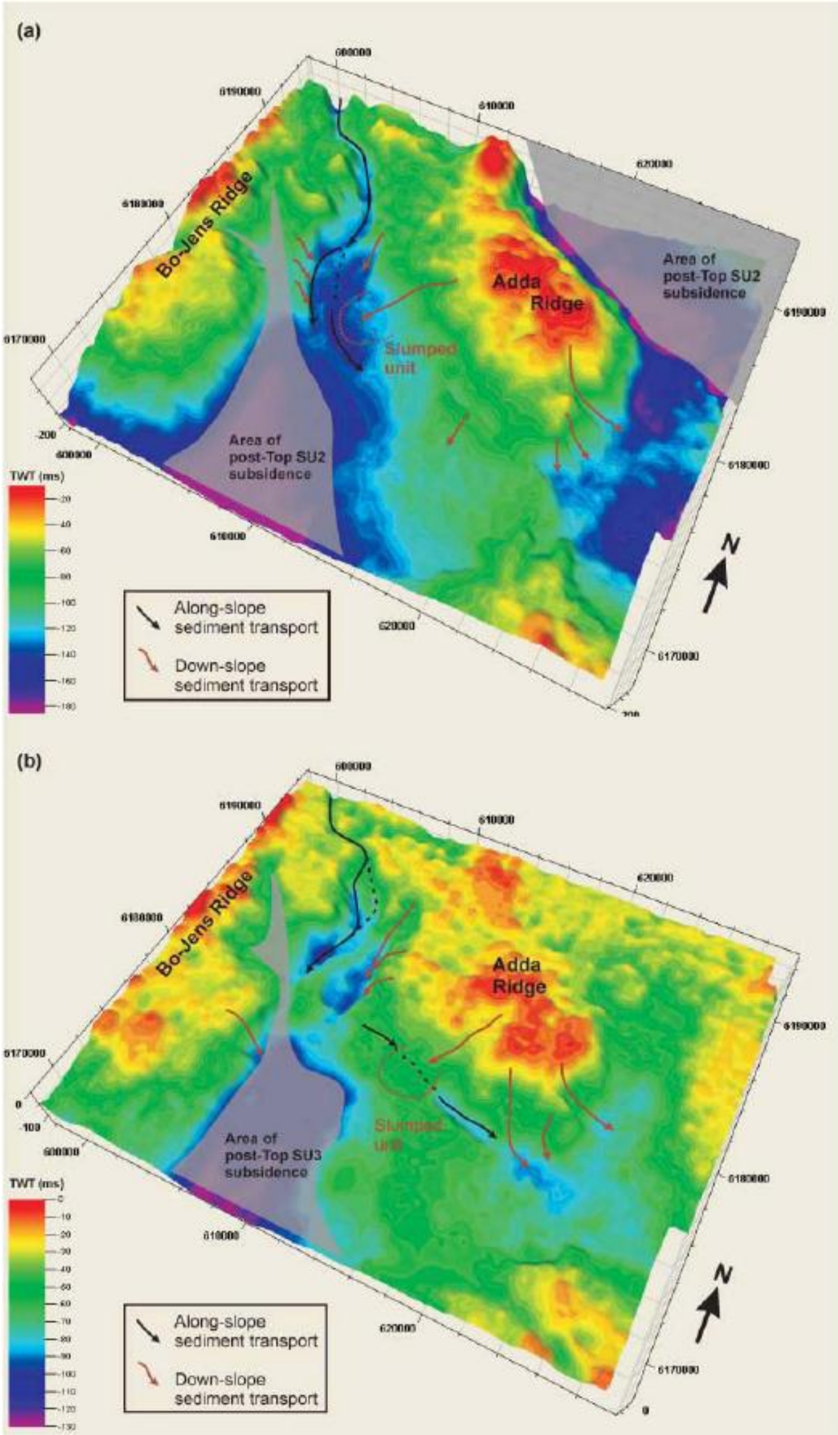


Figure 22. 3D map of the reconstructed bathymetry (of approximately Top Hod) and interpretation of the depositional processes. From Esmerode et al. 2008. For location see Figure 19.

On the western flank of the Igor-Emma Ridge the seismic data indicate the presence of slump, sliding and gravity flow deposition (Figure 23).

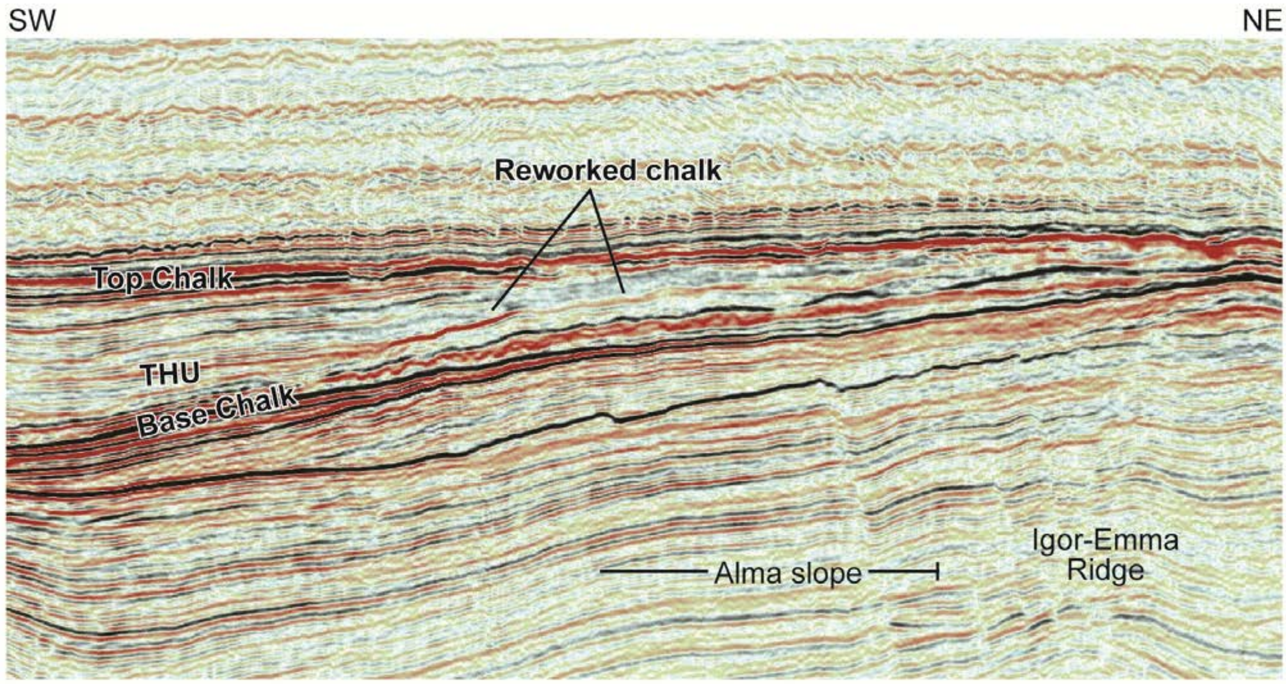


Figure 23. SW-NE trending seismic line crossing the Igor-Emma Ridge. For location see Figure 19. A relative undisturbed and uniform thick chalk succession is found in the basin area to the west. Updip there is a gradual thinning of the uppermost chalk units. The chaotic and disturbed seismic signature in the middle part of the chalk section is interpreted as a result of syn- and post depositional sedimentary processes and may be indicative of down-dip reworking of the Chalk section.

In addition to the structural relief associated with the inversion ridges, salt movements may cause re-activation of the chalk succession. Examples of mega-slides are observed down-flank the Skjold salt diapir (Figure 24) and down-flank the Gorm structure.

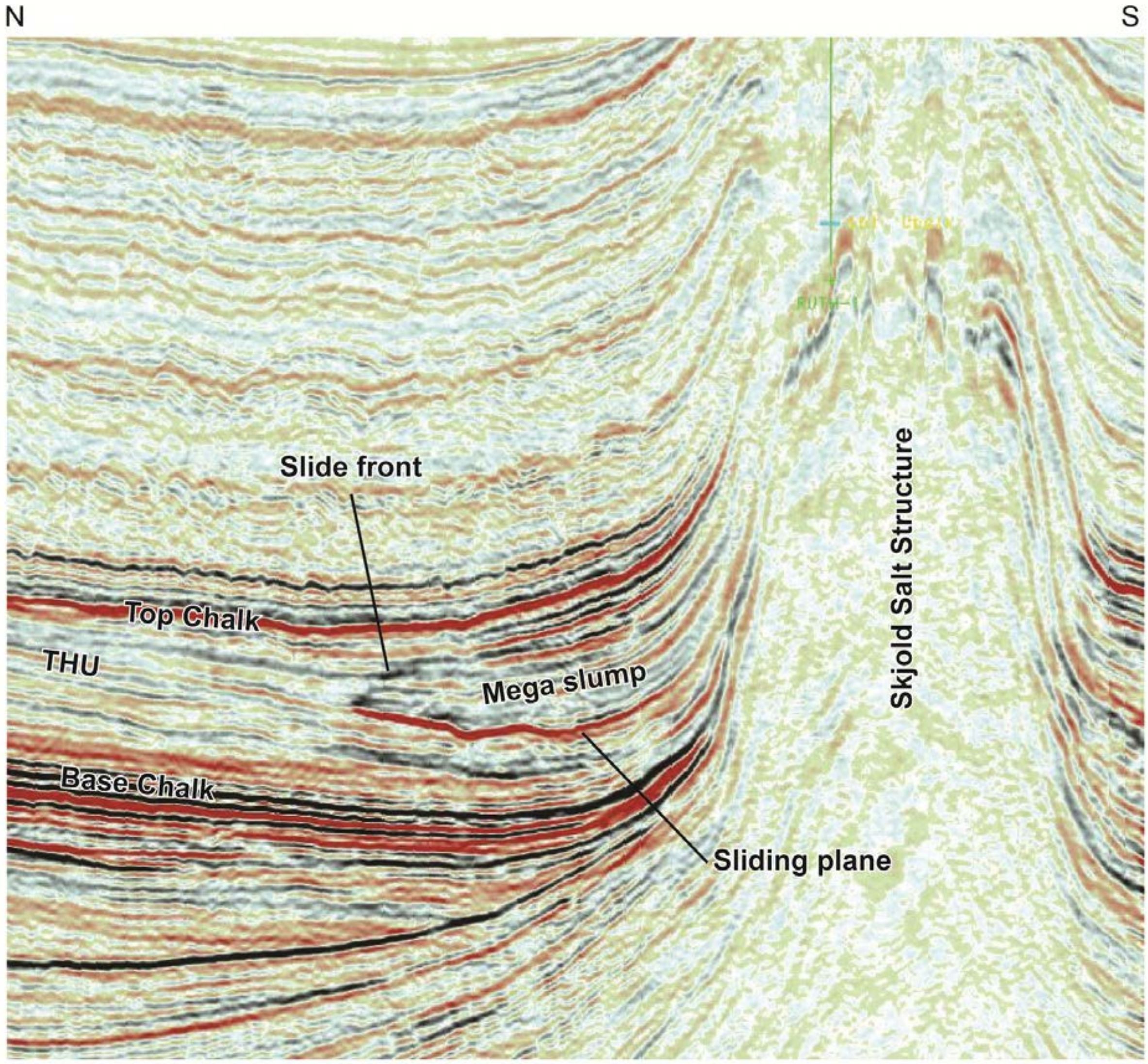


Figure 24. A random NW-SE trending line crossing the Skjold salt structure with clear indication of a mega-slide in the Upper Chalk section down-flank the salt structure. For location see Figure 19.

The present study proposes a close relation between allochthonous/reworked chalk and the inversion structures. A large variety in type of reworked chalk related to different structural settings can be observed. A detailed study for determination and delineation of the allochthonous chalk is recommended for better prediction of porous intervals in the chalk. At the same time this evaluation may be used to decipher the possibility of a relief as a result of one single event (the Late Campanian inversion) or if the sustained distinct relief was a result of reactivations related to new inversion phases during Maastrichtian and Danian times.

Conclusions

The Chalk Group in the Central Graben can be divided into 10 lithostratigraphic units with a more or less regional distribution. The distribution of the various units depends on the structural setting with the inversion ridges related to the Late Campanian inversion tectonism as the most import features. The presented model subdivides the Chalk Group in the Central Graben into two successions (**Lower Chalk** and **Upper Chalk**) divided by the distinct and regional Top Hod Unconformity (THU).

Deposition of the Chalk Group in the study area took place during a phase of regional post-rift subsidence associated with a generally transgressive period following Late Jurassic rifting. The period for deposition of the **Lower Chalk** was marked by generally high-sea-level, high-surface temperature and a peak in production of organic matter and comprises of prevailing pelagic chalk. The deposition generally took place in a continuously subsiding basin setting above the depocentres of Lower Cretaceous. A moderate relief inherited from the Lower Cretaceous is partly wiped out or modified in importance in connection with the Cenomanian-Early Campanian sea level rise.

Compressional tectonism in Late Campanian gave rise to inversion in major parts of the Central Graben. The main inversion was bounded by the Coffee Soil Fault to the east and the fault lineament including the Baron-Elin Fault, the Jens-Bo Fault and the Gorm-John Fault to the west. Major ridges were formed associated with reverse faulting along these fault systems. Less severe inversion in the central area resulted in intervening sub-basins.

The Late Campanian inversion phase was accompanied with a relative sea level fall and in large areas the inverted **Lower Chalk** section was situated above the wave base level which gave rise to severe erosion of the succession. The hiatus associated with the THU exhibits varying time gap depending on the degree of truncation into the Lower Chalk section.

The deposition of the **Upper Chalk** is highly controlled by the relief created during the Late Campanian inversion. Initially, the eroded material from the ridges was delivered to the basin centres outside the inversion zone. The following sea level rise endorsed pelagic deposition in the inverted area but the thinning of the chalk interval from the basins towards the inversion areas are indicative of a condensed chalk packages within the inverted area. It is assumed that high energy may have been sufficient for sweeping the sediment away from the crest of the inversion ridges.

During Late Maastrichtian relative thick deposits covers the entire Chalk basin, but the section reveals a high amount of reworked chalk. The reworked chalk is closely related to the flanks of the inversion structures and is often associated with down dip gravity processes. The reactivation and reworking of the chalk is closely related to the instability developed on a dipping slope. It is still uncertain if the relief generated during the Late Campanian inversion was a static situation during Maastrichtian and Danian time or was renewed during new inversion phases in the Maastrichtian. The hiatus and hardground formation at the K/T boundary identified in the southern part of the Central Graben suggests some tectonic activity during this period and most likely new inversion phases throughout Maastrichtian time may have triggered the reworking processes on the flanks.

The **Upper Chalk** encounters high porosity chalk due to the prevalence of reworked chalk and represents the most prolific interval in the Chalk Group. Because all structural closures on Top

Chalk have been drilled new chalk prospects need to be related to stratigraphic traps and therefore it is necessary to outline areas and intervals with reworked chalk.

It is therefore suggested to carry out a more detailed study on the basin development including biostratigraphy, lithostratigraphy combined with mapping of sedimentary features. Based on the close relationship between erosion, re-deposition (deposition of reservoir chalk) and structural development the basin development can be used as guide for prediction of hitherto unrecognized reservoir intervals.

The presented basin model for the Chalk Group is based on well and seismic data of varying quality and an adjustment of the model is required. For a new evaluation a detailed biostratigraphic analysis in selected intervals and seismic interpretation of modern 3D seismic surveys of comparable quality is needed.

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ENCLOSURES

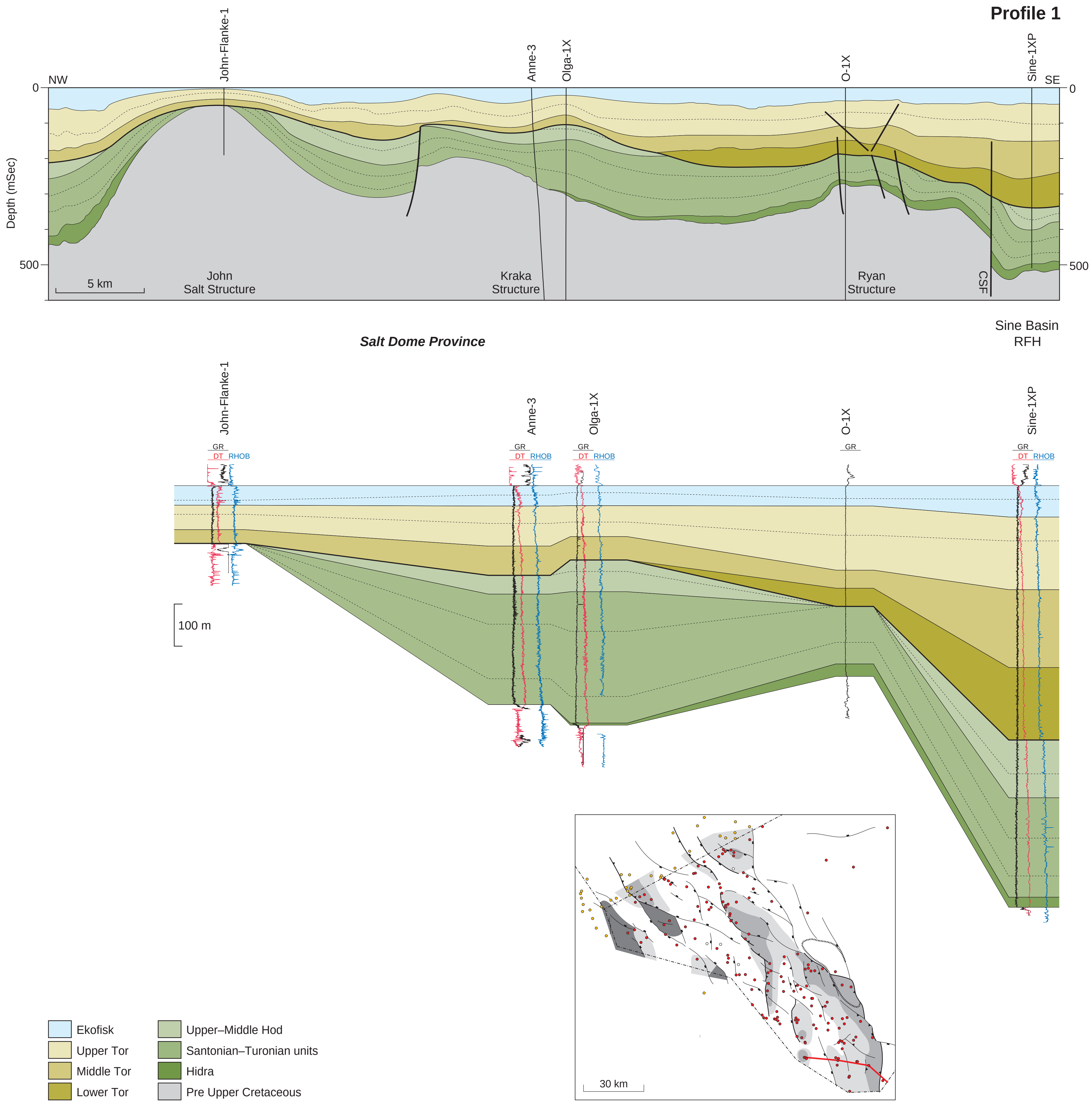
ENCLOSURE 1

Geological profiles

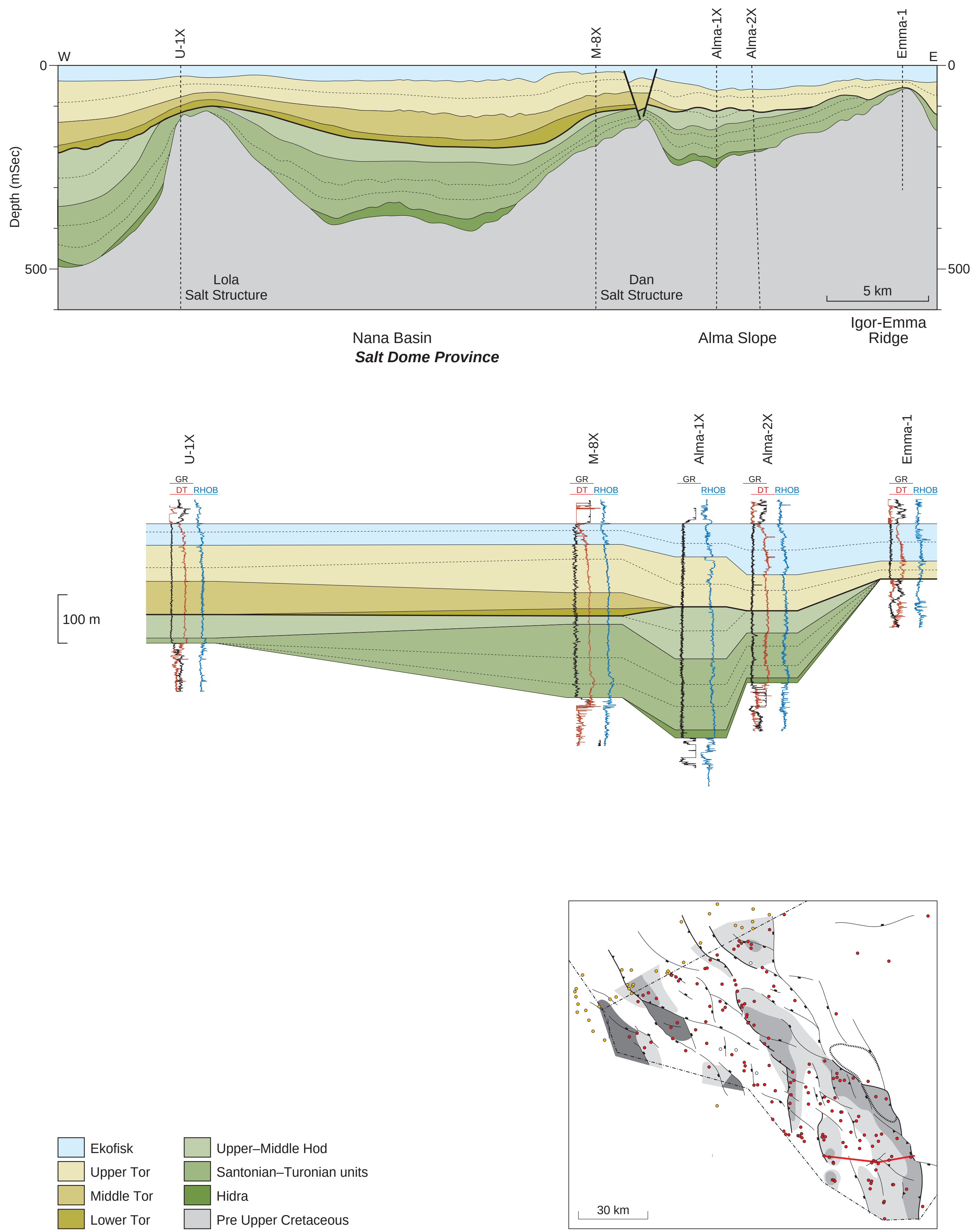
10 W-E trending profiles across the Central Graben have been generation for illustrating the basin development in the Central Graben area during Upper Cretaceous.

The profiles are based on seismic data which have been flattened at Top Chalk to downgrade the visible distortion caused by post-Cretaceous structuring. There is full awareness on the fact that the Top Chalk was not an even surface but may have displayed a minor bathymetric relief. The relief, however, is considered to be too insignificant to disrupt the overall understanding of the basin development.

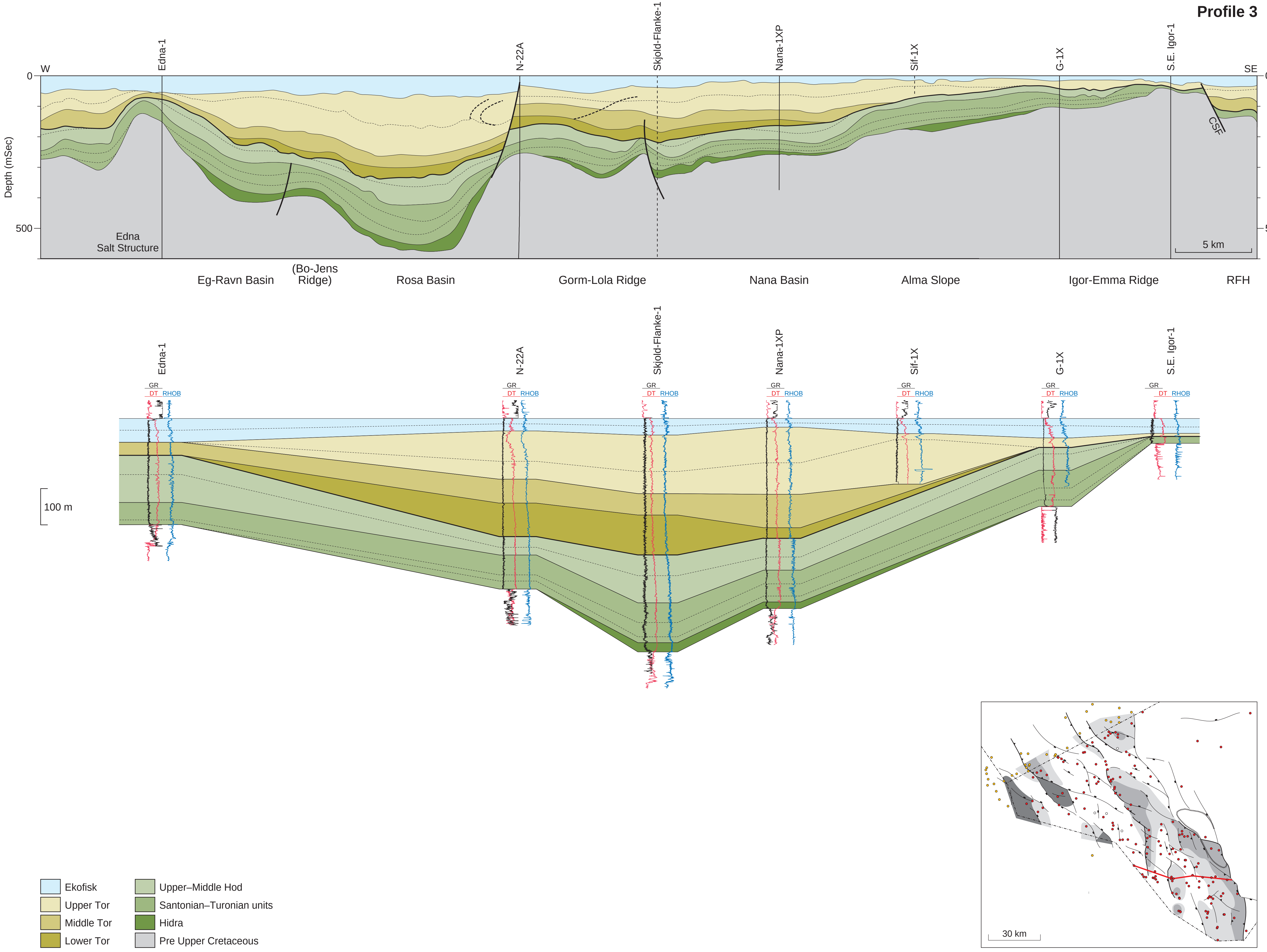
The profiles tie a number of wells and the seismic profiles are supplemented with a log correlation panel.


Profile 1
NW
SE
John-Flanke-1
Anne-3
Olga-1X
O-1X
Sine-1XP
Depth (mSec)
0
500
5 km
John
Salt Structure
Kraka
Structure
Ryan
Structure
CSF
Sine Basin
RFH
Salt Dome Province
GR
DT
RHOB
100 m
30 km
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper–Middle Hod
Santonian–Turonian units
Hidra
Pre Upper Cretaceous

Profile 2

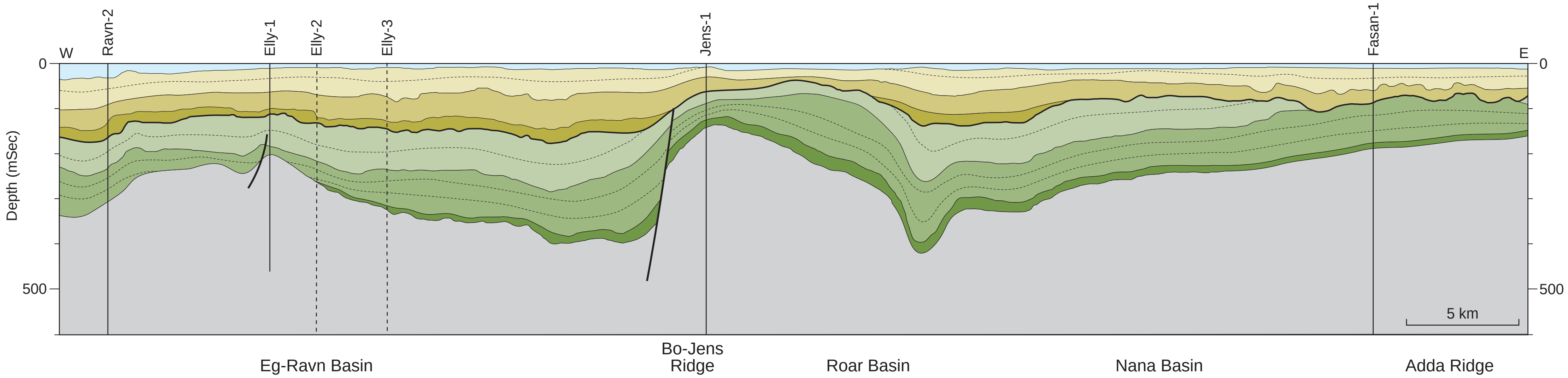


W
E
U-1X
M-8X
Alma-1X
Alma-2X
Emma-1
0
500
Depth (mSec)
Lola
Salt Structure
Dan
Salt Structure
5 km
Nana Basin
Salt Dome Province
Alma Slope
Igor-Emma
Ridge
GR
DT
RHOB
100 m
30 km
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper–Middle Hod
Santonian–Turonian units
Hidra
Pre Upper Cretaceous

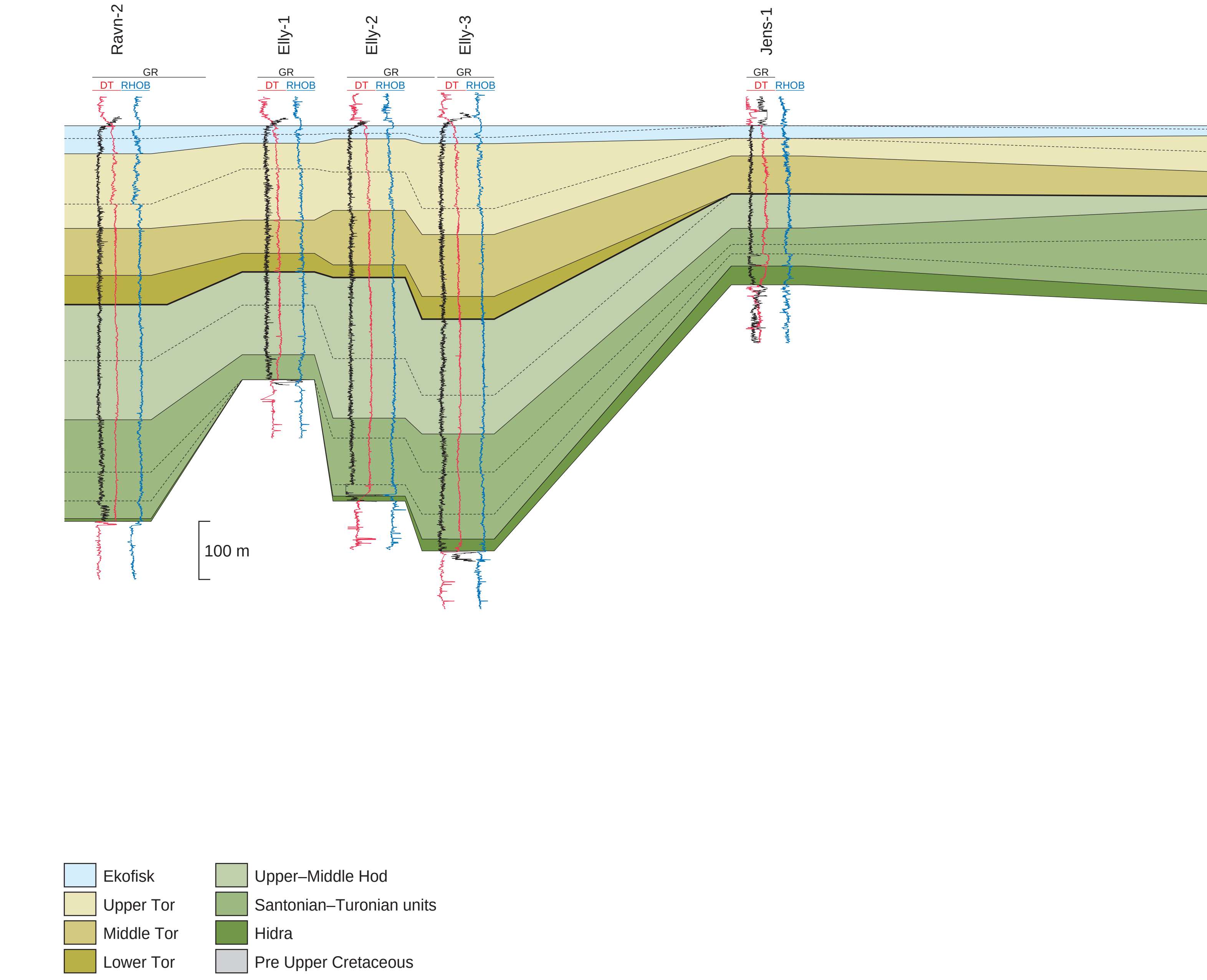


Profile 3
W
SE
Edna-1
N-22A
Skjold-Flanke-1
Nana-1XP
Sif-1X
G-1X
S.E. Igor-1
Depth (mSec)
0
500
CSF
Edna
Salt Structure
5 km
Eg-Ravn Basin
(Bo-Jens Ridge)
Rosa Basin
Gorm-Lola Ridge
Nana Basin
Alma Slope
Igor-Emma Ridge
RFH
GR
DT
RHOB
100 m
30 km
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper–Middle Hod
Santonian–Turonian units
Hidra
Pre Upper Cretaceous

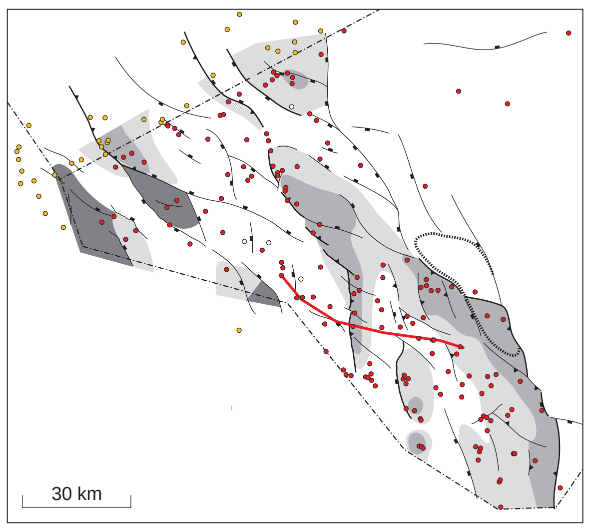
Profile 4



W
E
Ravn-2
Elly-1
Elly-2
Elly-3
Jens-1
Fasan-1
0
500
Depth (mSec)
5 km
Eg-Ravn Basin
Bo-Jens Ridge
Roar Basin
Nana Basin
Adda Ridge

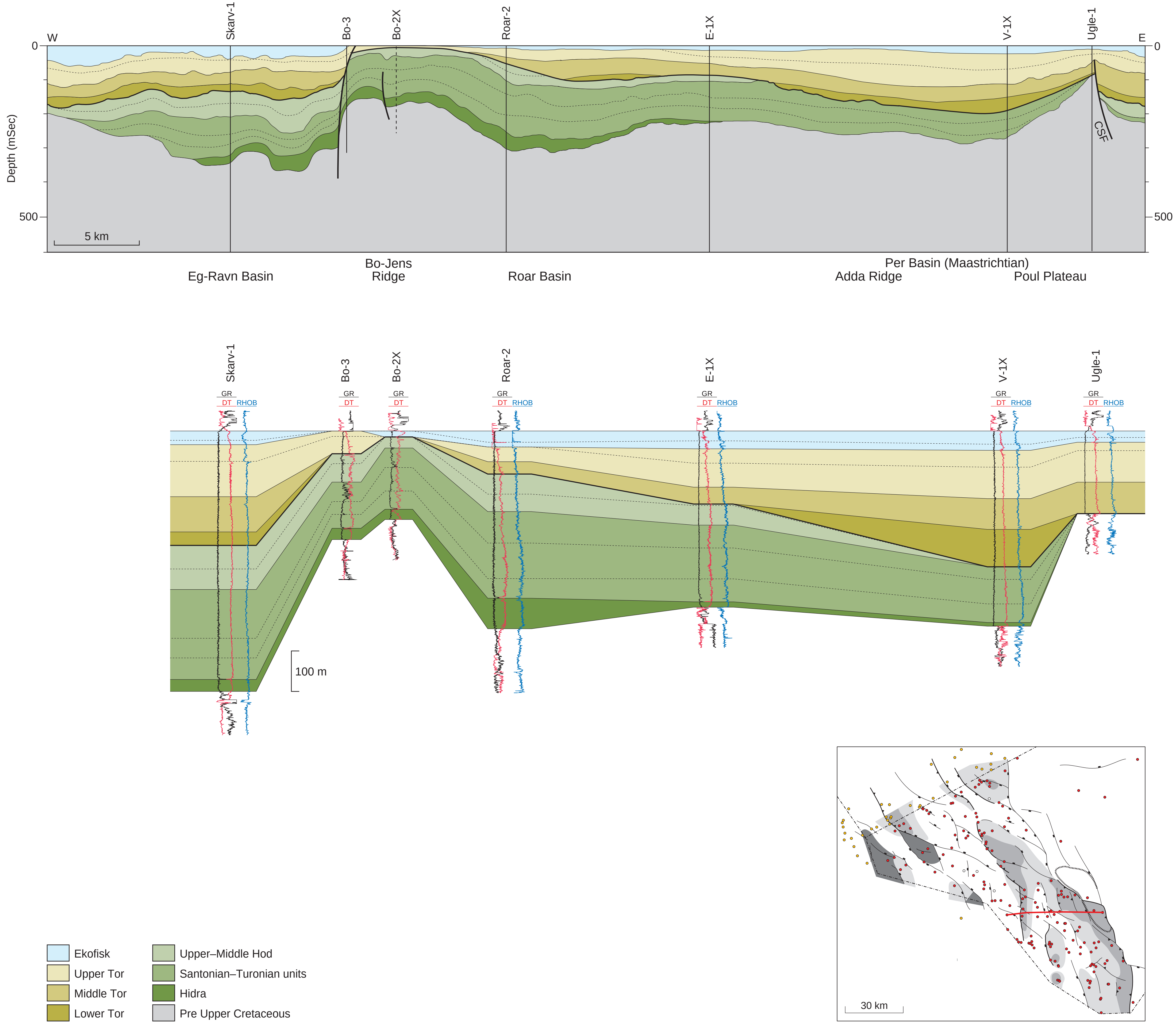


Ravn-2
Elly-1
Elly-2
Elly-3
Jens-1
Fasan-1
GR
DT
RHOB
100 m
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper–Middle Hod
Santonian–Turonian units
Hidra
Pre Upper Cretaceous



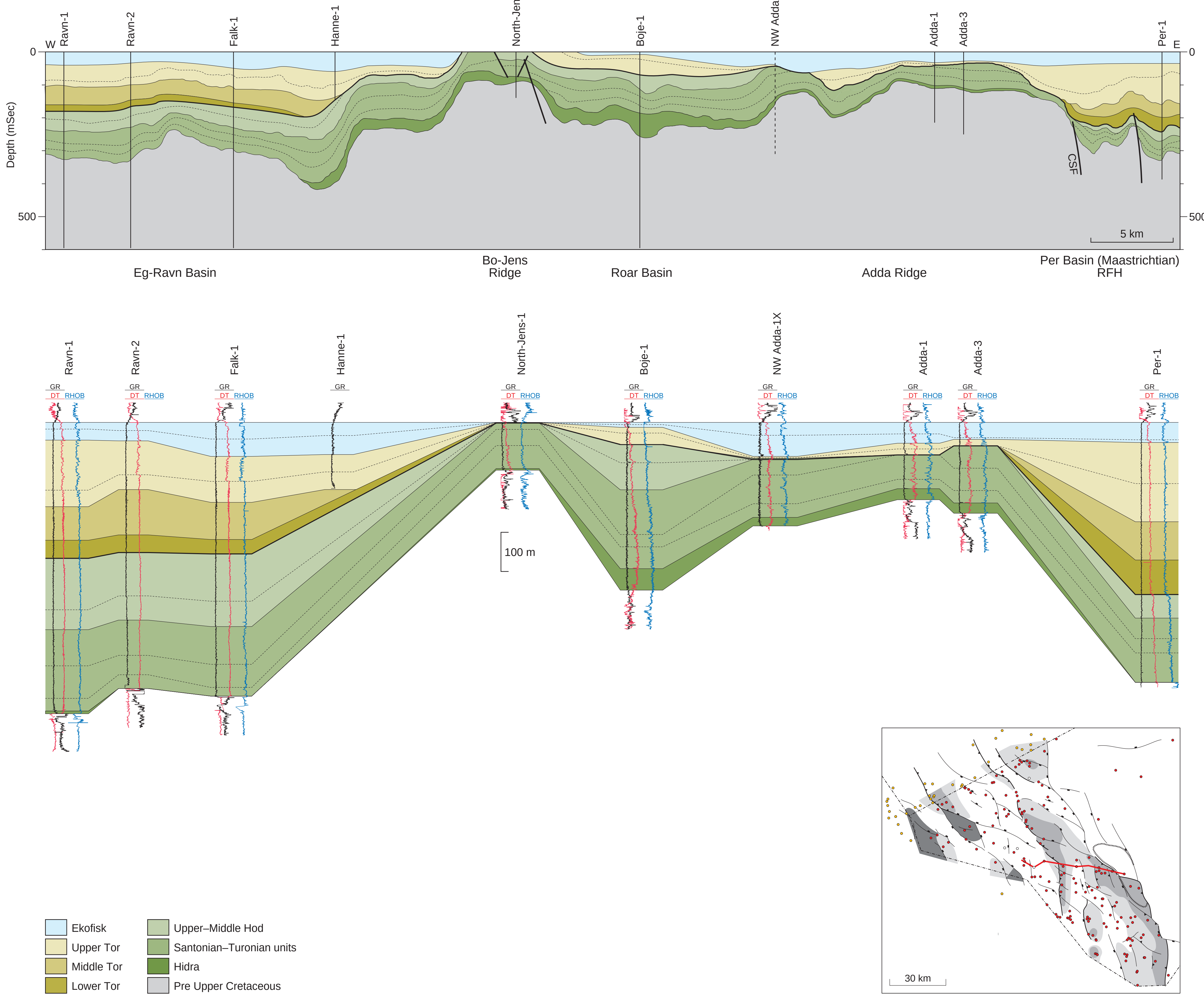
30 km

Profile 5

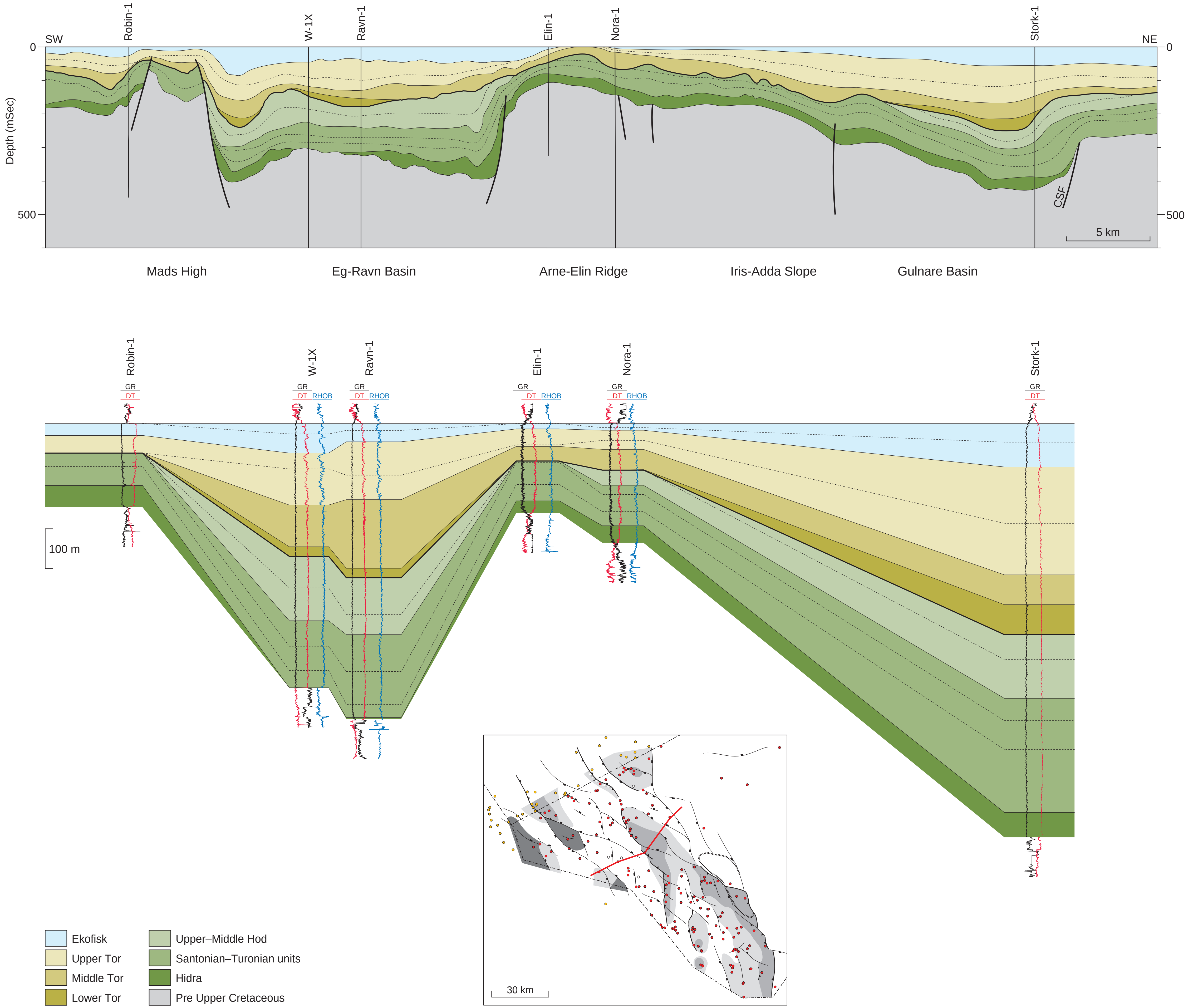


W
E
Skarv-1
Bo-3
Bo-2X
Roar-2
E-1X
V-1X
Ugle-1
0
500
Depth (mSec)
5 km
CSF
Eg-Ravn Basin
Bo-Jens Ridge
Roar Basin
Per Basin (Maastrichtian)
Adda Ridge
Poul Plateau
GR
DT
RHOB
100 m
30 km
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper–Middle Hod
Santonian–Turonian units
Hidra
Pre Upper Cretaceous

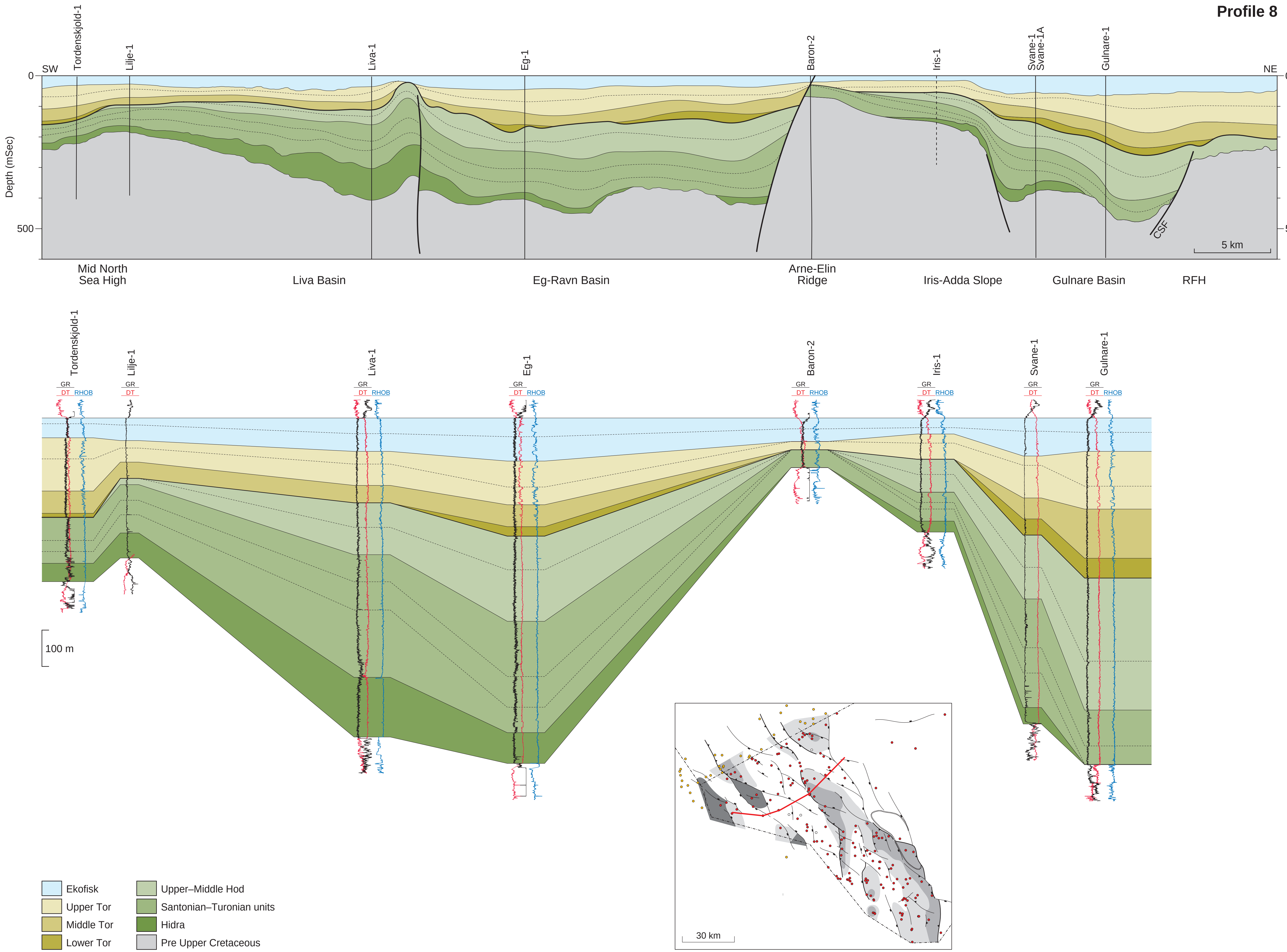
Profile 6


W
Ravn-1
Ravn-2
Falk-1
Hanne-1
North-Jens-1
Boje-1
NW Adda-1X
Adda-1
Adda-3
Per-1
E
Depth (mSec)
0
500
CSF
5 km
Eg-Ravn Basin
Bo-Jens Ridge
Roar Basin
Adda Ridge
Per Basin (Maastrichtian)
RFH
100 m
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper–Middle Hod
Santonian–Turonian units
Hidra
Pre Upper Cretaceous
30 km

Profile 7

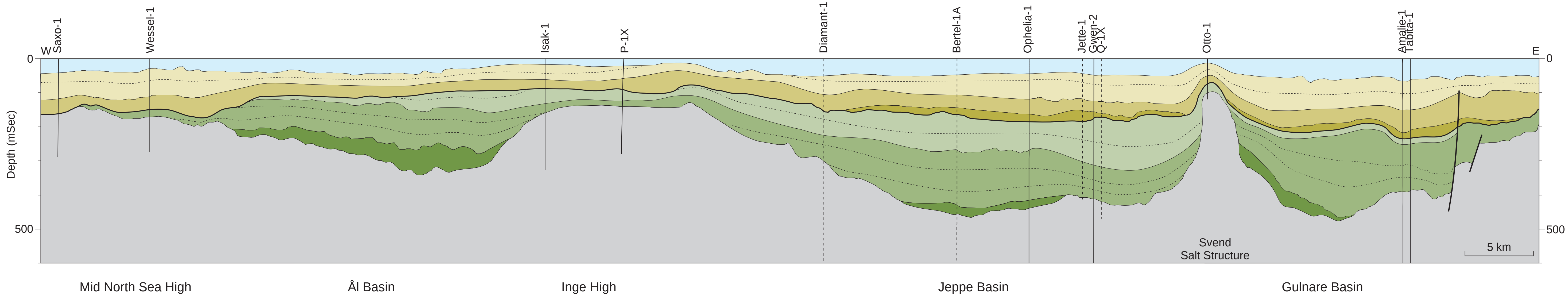


SW
NE
Robin-1
W-1X
Ravn-1
Elin-1
Nora-1
Stork-1
Depth (mSec)
0
500
5 km
CSF
Mads High
Eg-Ravn Basin
Arne-Elin Ridge
Iris-Adda Slope
Gulnare Basin
GR
DT
RHOB
100 m
30 km
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper–Middle Hod
Santonian–Turonian units
Hidra
Pre Upper Cretaceous

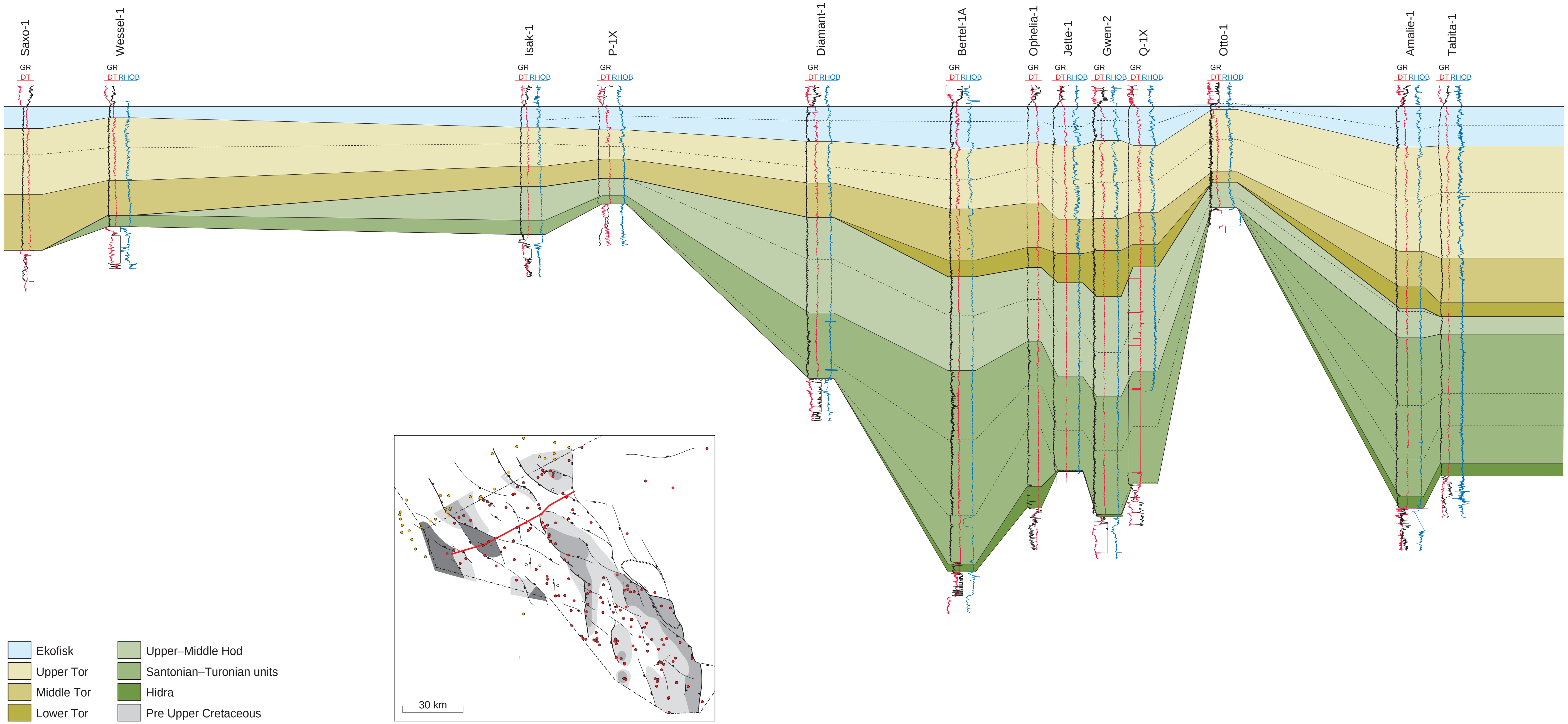


Profile 8
SW
NE
Tordenskjold-1
Lilje-1
Liva-1
Eg-1
Baron-2
Iris-1
Svane-1
Svane-1A
Gulnare-1
Depth (mSec)
0
500
CSF
5 km
Mid North Sea High
Liva Basin
Eg-Ravn Basin
Arne-Elin Ridge
Iris-Adda Slope
Gulnare Basin
RFH
GR
DT
RHOB
100 m
30 km
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper–Middle Hod
Santonian–Turonian units
Hidra
Pre Upper Cretaceous

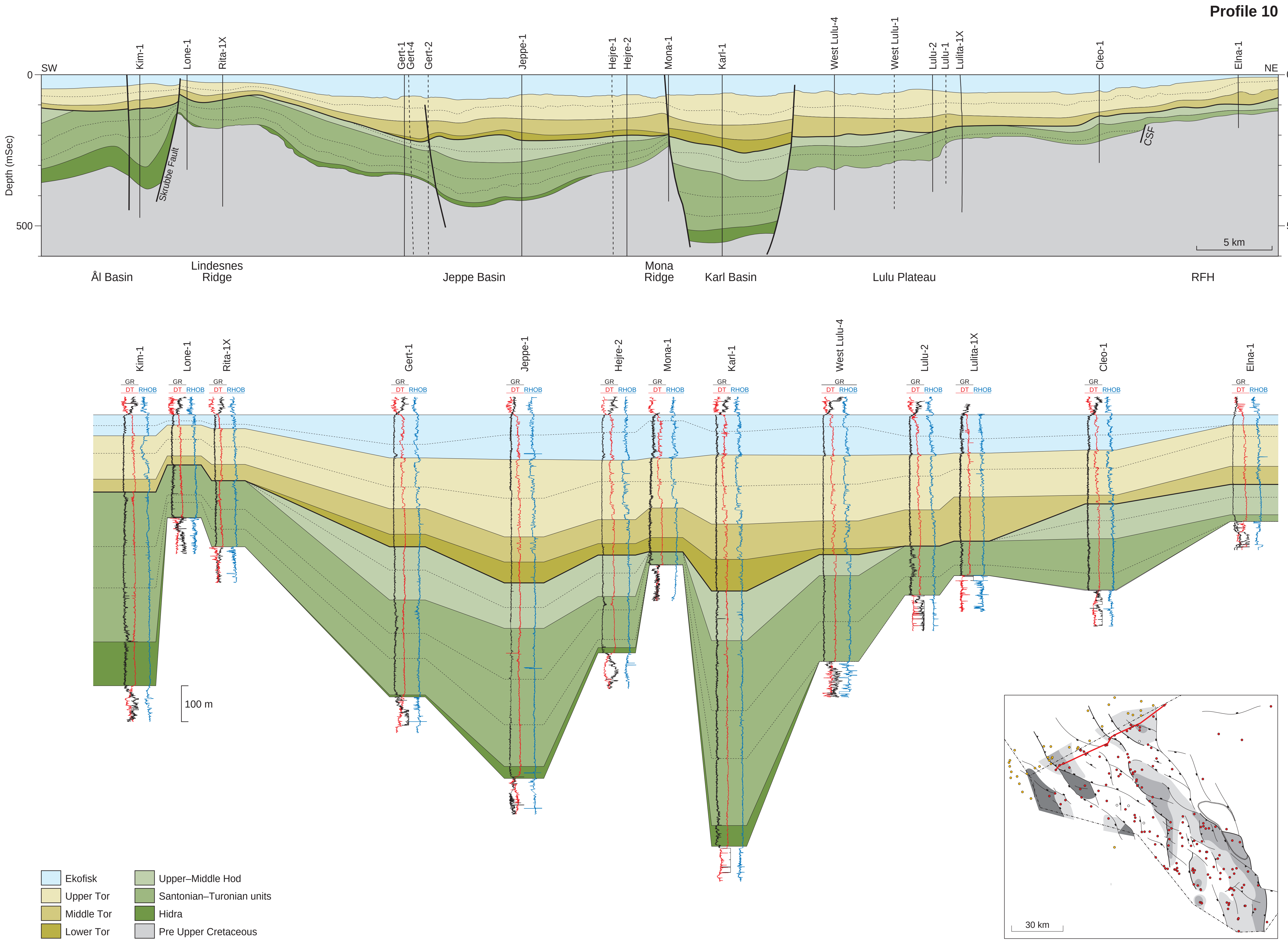
Profile 9



Saxo-1
Wessel-1
Isak-1
P-1X
Diamant-1
Bertel-1A
Ophelia-1
Jette-1
Gwen-2
Q-1X
Otto-1
Amalie-1
Tabita-1
W
E
0
500
Depth (mSec)
Svend
Salt Structure
5 km
Mid North Sea High
Ål Basin
Inge High
Jeppe Basin
Gulnare Basin



Saxo-1
Wessel-1
Isak-1
P-1X
Diamant-1
Bertel-1A
Ophelia-1
Jette-1
Gwen-2
Q-1X
Otto-1
Amalie-1
Tabita-1
GR
DT
RHOB
30 km
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper–Middle Hod
Santonian–Turonian units
Hidra
Pre Upper Cretaceous



Profile 10
SW
NE
Kim-1
Lone-1
Rita-1X
Gert-1
Gert-4
Gert-2
Jeppe-1
Hejre-1
Hejre-2
Mona-1
Karl-1
West Lulu-4
West Lulu-1
Lulu-2
Lulu-1
Lulita-1X
Cleo-1
Elna-1
Depth (mSec)
0
500
Skrubbe Fault
CSF
5 km
Ål Basin
Lindesnes Ridge
Jeppe Basin
Mona Ridge
Karl Basin
Lulu Plateau
RFH
GR
DT
RHOB
100 m
30 km
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper–Middle Hod
Santonian–Turonian units
Hidra
Pre Upper Cretaceous

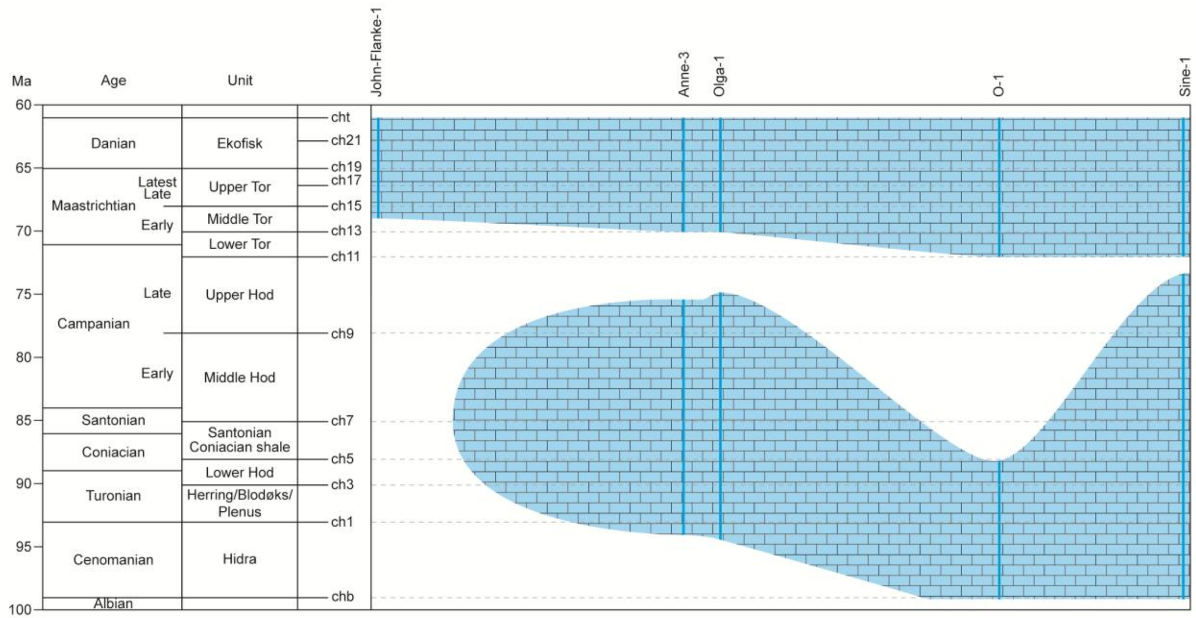
ENCLOSURE 2

Chalk stratigraphy in explorations wells drilled in the Danish Central Graben

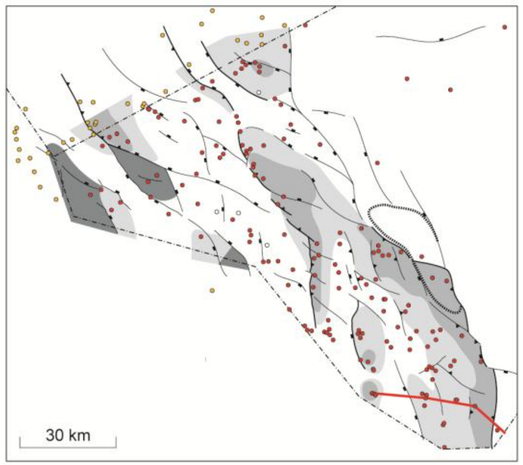
A stratigraphic breakdown of more than 100 exploration wells in the Central Graben has been carried out by integration of biostratigraphy, log stratigraphy and seismic data.

The biostratigraphic subdivision of the Upper Cretaceous has been established utilizing the zonations used by the various contractors assessing the biostratigraphy in the wells. Formation tops are defined by combining the biostratigraphy, the log motif and information from the seismic data.

The stratigraphic coverage and distribution of hiatii in the various wells are illustrated by a number of Wheeler diagram panels organised in the same way as the geosections shown in Enclosure 1.

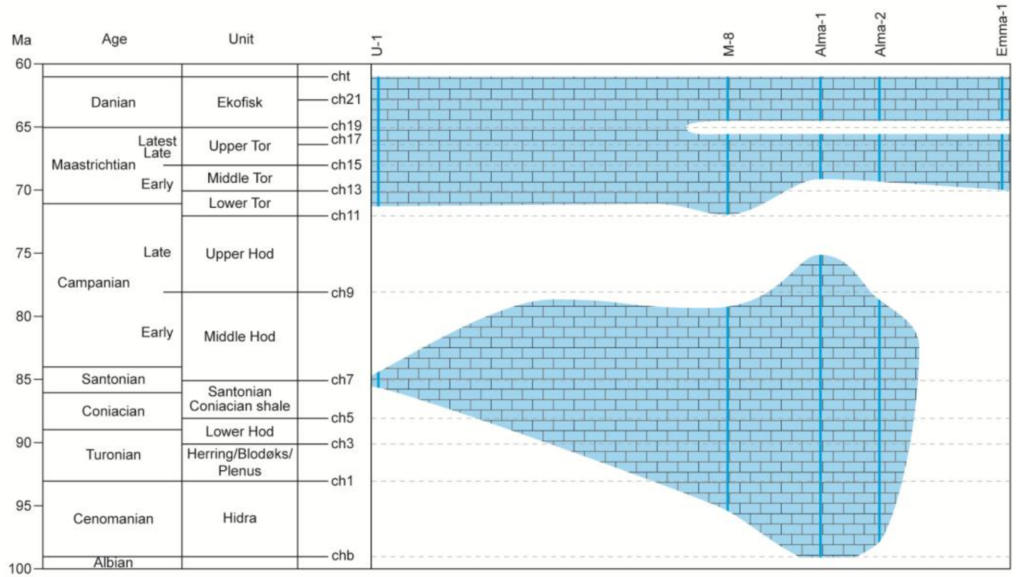


Ma
Age
Unit
John-Flanke-1
Anne-3
Olga-1
O-1
Sine-1
60
65
70
75
80
85
90
95
100
Danian
Maastrichtian
Latest
Late
Early
Campanian
Late
Early
Santonian
Coniacian
Turonian
Cenomanian
Albian
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper Hod
Middle Hod
Santonian Coniacian shale
Lower Hod
Herring/Blodøks/ Plenus
Hidra
cht
ch21
ch19
ch17
ch15
ch13
ch11
ch9
ch7
ch5
ch3
ch1
chb

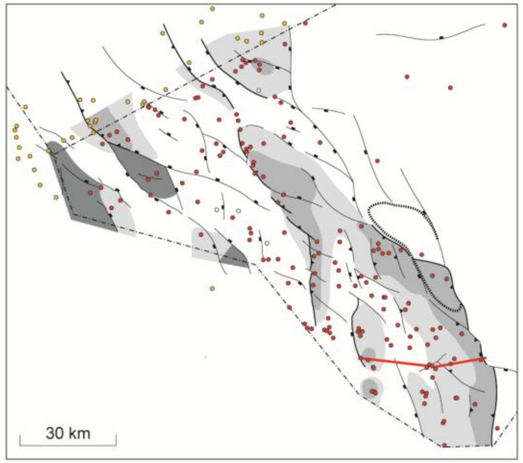


30 km

Panel 1

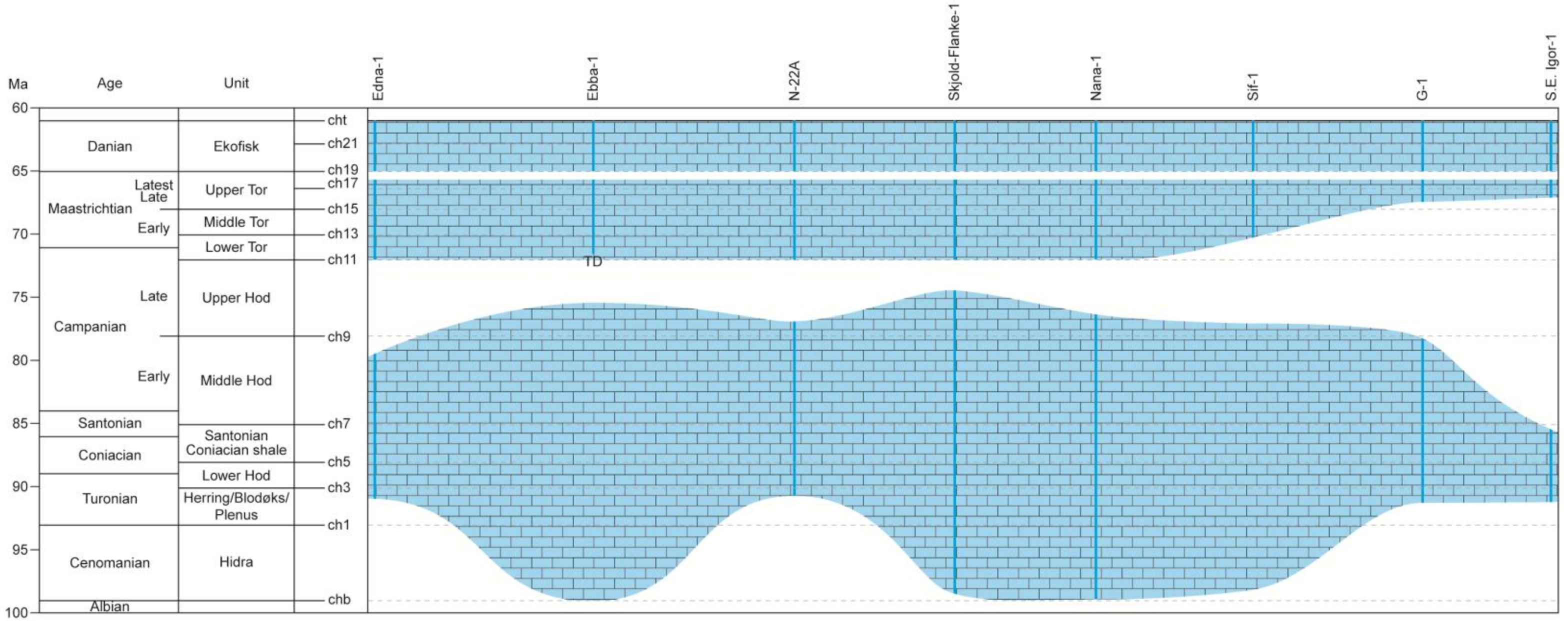


Ma
Age
Unit
U-1
M-8
Alma-1
Alma-2
Emma-1
60
65
70
75
80
85
90
95
100
Danian
Maastrichtian
Latest
Late
Early
Campanian
Late
Early
Santonian
Coniacian
Turonian
Cenomanian
Albian
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper Hod
Middle Hod
Santonian Coniacian shale
Lower Hod
Herring/Blodøks/ Plenus
Hidra
cht
ch21
ch19
ch17
ch15
ch13
ch11
ch9
ch7
ch5
ch3
ch1
chb

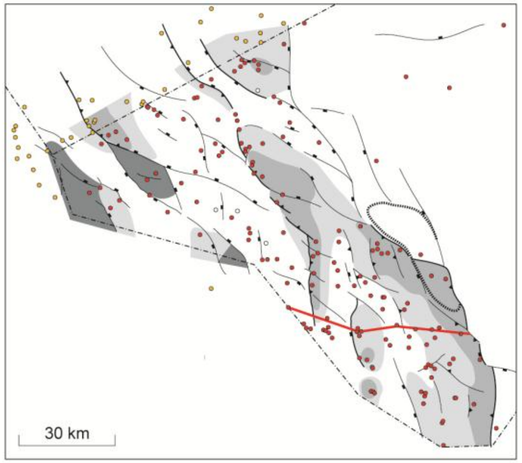


30 km

Panel 2

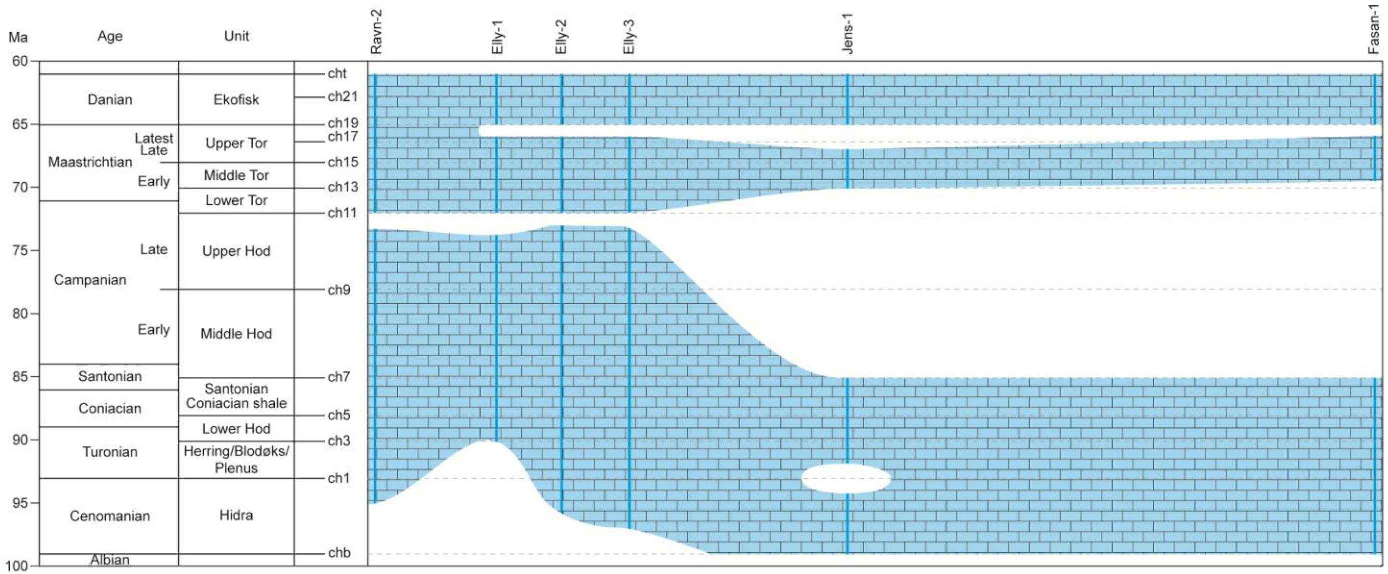


Ma
Age
Unit
Edna-1
Ebba-1
N-22A
Skjold-Flanke-1
Nana-1
Sif-1
G-1
S.E. Igor-1
60
65
70
75
80
85
90
95
100
Danian
Maastrichtian
Latest
Late
Early
Campanian
Late
Early
Santonian
Coniacian
Turonian
Cenomanian
Albian
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper Hod
Middle Hod
Santonian Coniacian shale
Lower Hod
Herring/Blodøks/ Plenus
Hidra
cht
ch21
ch19
ch17
ch15
ch13
ch11
ch9
ch7
ch5
ch3
ch1
chb
TD

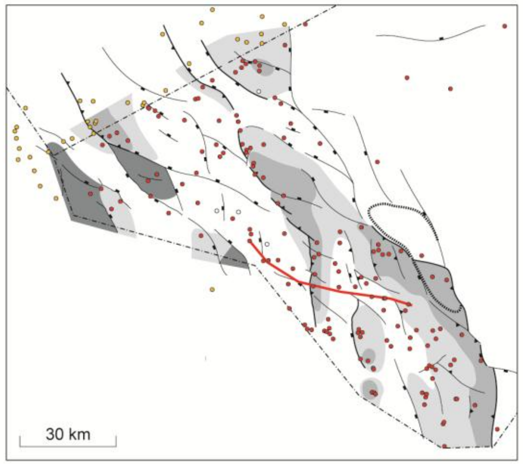


30 km

Panel 3

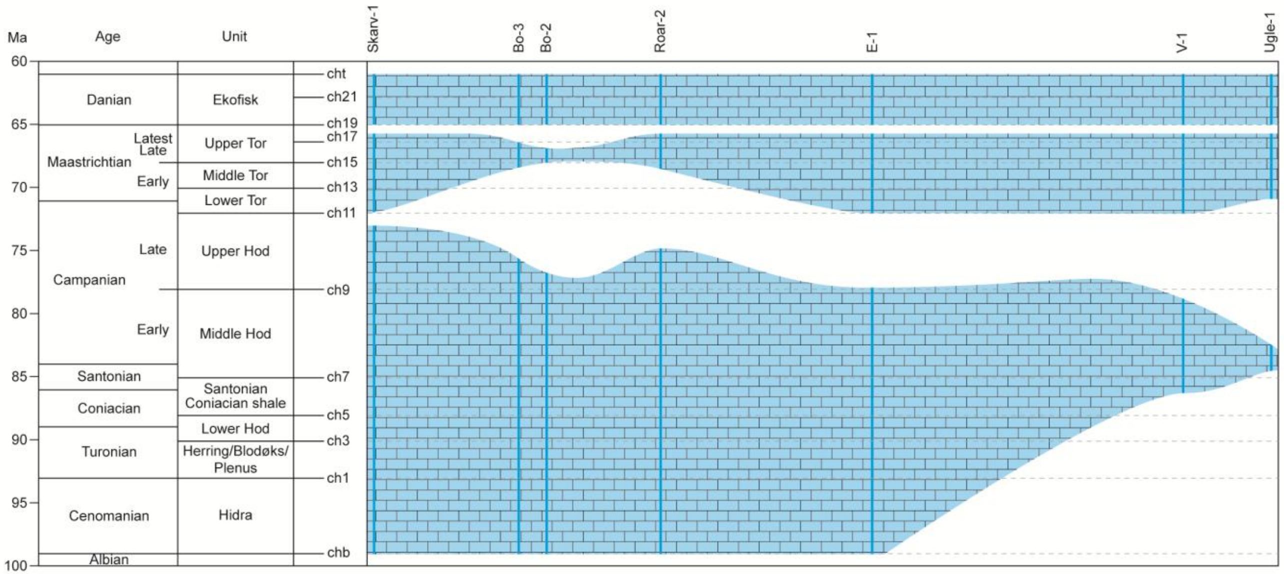


Ma
Age
Unit
Ravn-2
Elly-1
Elly-2
Elly-3
Jens-1
Fasan-1
60
65
70
75
80
85
90
95
100
Danian
Maastrichtian
Latest
Late
Early
Campanian
Late
Early
Santonian
Coniacian
Turonian
Cenomanian
Albian
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper Hod
Middle Hod
Santonian Coniacian shale
Lower Hod
Herring/Blodøks/ Plenus
Hidra
cht
ch21
ch19
ch17
ch15
ch13
ch11
ch9
ch7
ch5
ch3
ch1
chb



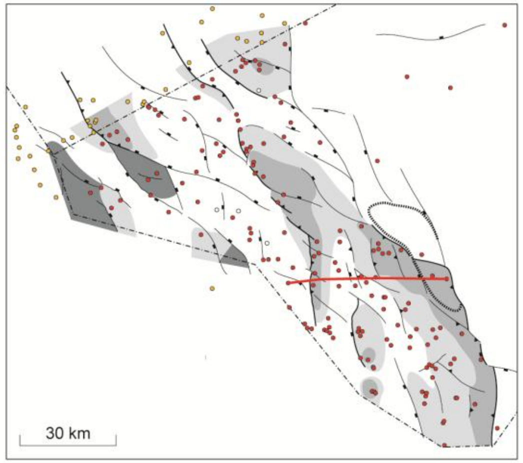
30 km

Panel 4

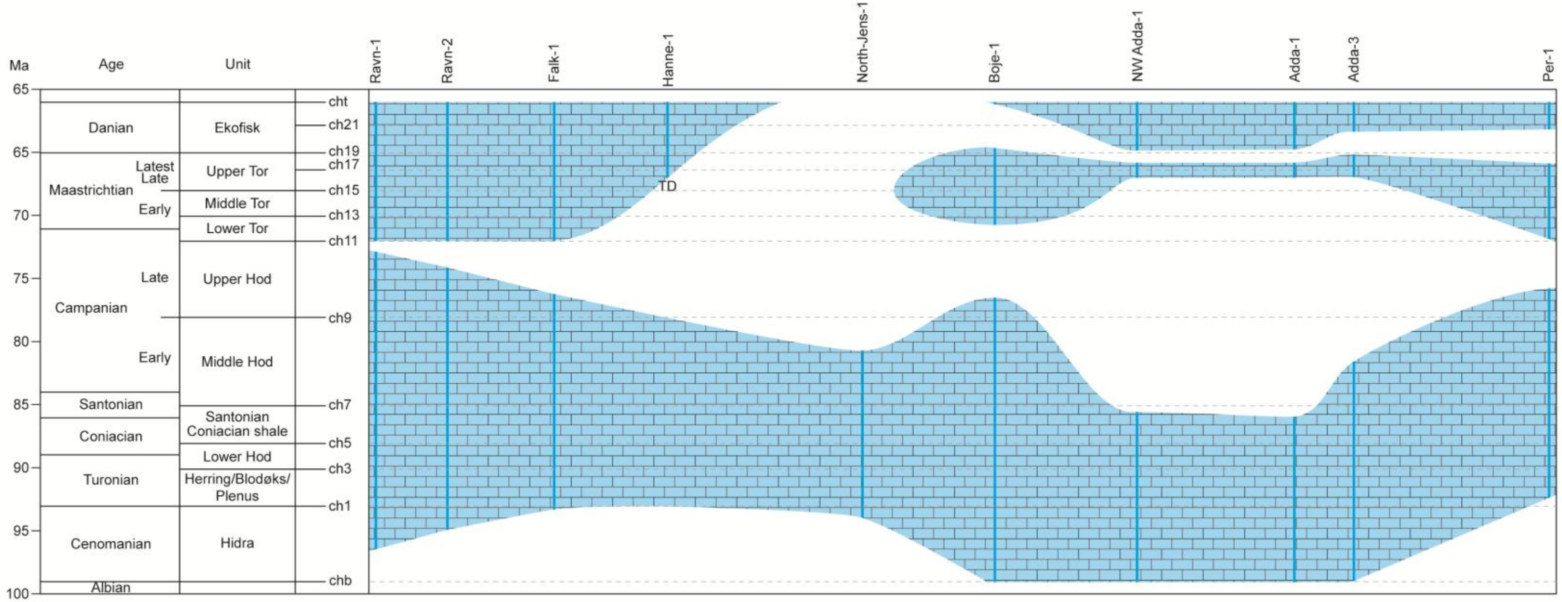


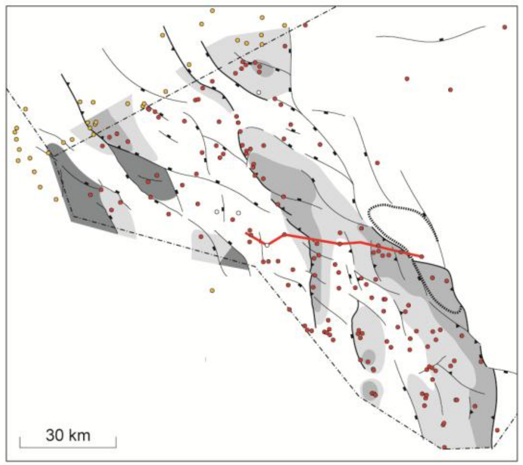
Ma
Age
Unit
Skarv-1
Bo-3
Bo-2
Roar-2
E-1
V-1
Ugle-1
60
65
70
75
80
85
90
95
100
Danian
Maastrichtian
Latest
Late
Early
Campanian
Late
Early
Santonian
Coniacian
Turonian
Cenomanian
Albian
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper Hod
Middle Hod
Santonian Coniacian shale
Lower Hod
Herring/Blodøks/ Plenus
Hidra
cht
ch21
ch19
ch17
ch15
ch13
ch11
ch9
ch7
ch5
ch3
ch1
chb

Panel 5

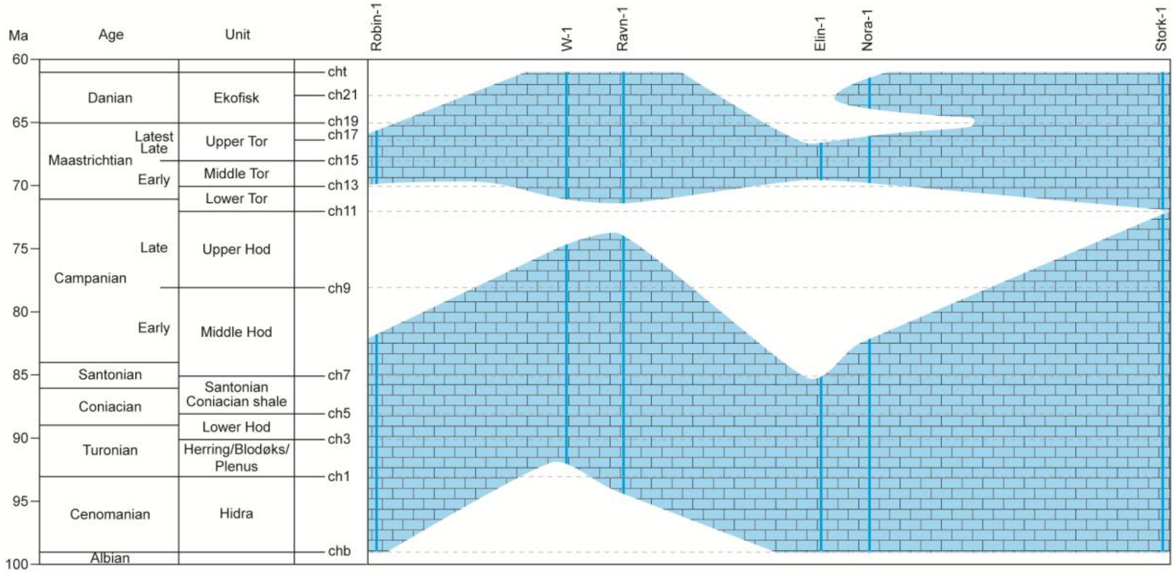


30 km


Ma
Age
Unit
Ravn-1
Ravn-2
Falk-1
Hanne-1
North-Jens-1
Boje-1
NW Adda-1
Adda-1
Adda-3
Per-1
65
65
70
75
80
85
90
95
100
Danian
Latest
Late
Maastrichtian
Early
Campanian
Late
Early
Santonian
Coniacian
Turonian
Cenomanian
Albian
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper Hod
Middle Hod
Santonian
Coniacian shale
Lower Hod
Herring/Blodøks/
Plenus
Hidra
cht
ch21
ch19
ch17
ch15
ch13
ch11
ch9
ch7
ch5
ch3
ch1
chb
TD


30 km

Panel 6



Ma
Age
Unit
Robin-1
W-1
Ravn-1
Elin-1
Nora-1
Stork-1
60
65
70
75
80
85
90
95
100
Danian
Maastrichtian
Latest
Late
Early
Campanian
Late
Early
Santonian
Coniacian
Turonian
Cenomanian
Albian
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper Hod
Middle Hod
Santonian
Coniacian shale
Lower Hod
Herring/Blodøks/
Plenus
Hidra
cht
ch21
ch19
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ch15
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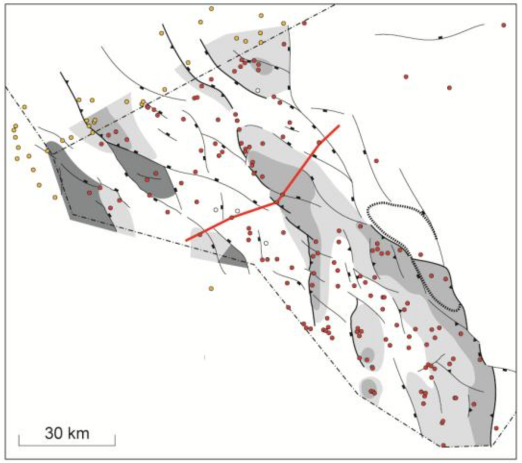
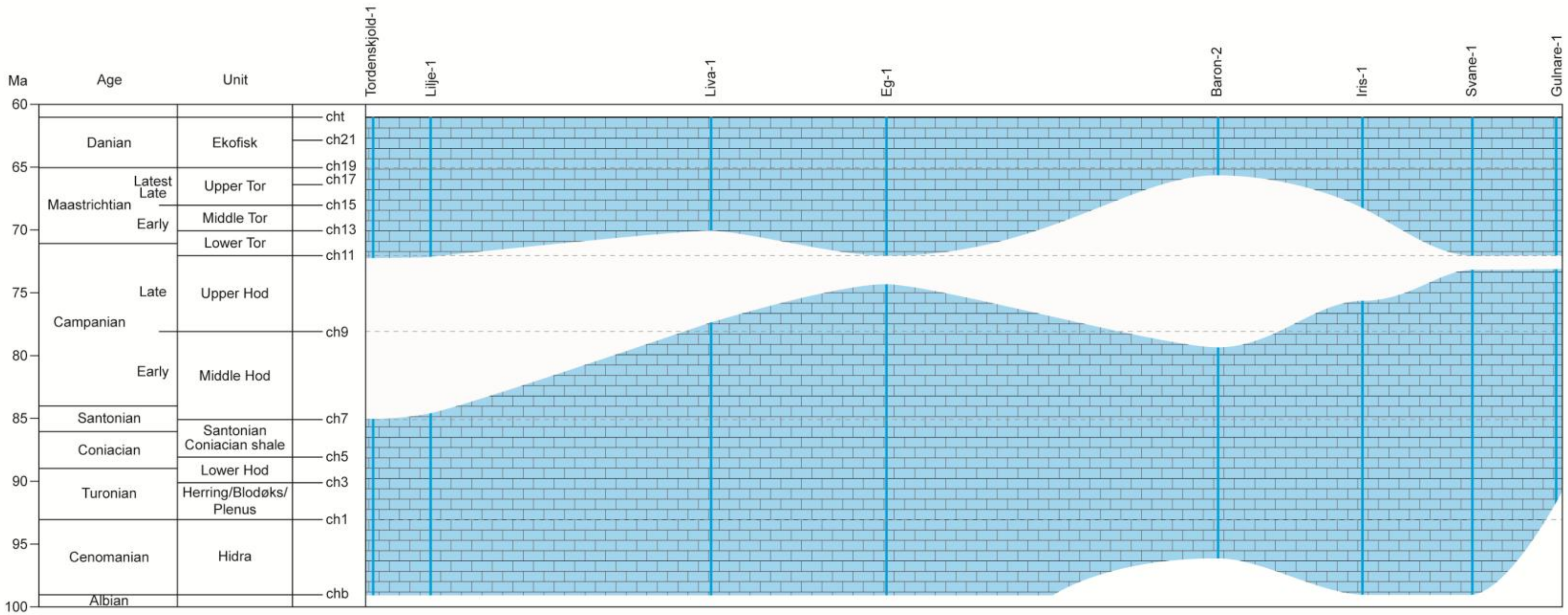
ch5
ch3
ch1
chb

Panel 7



30 km


Ma
Age
Unit
Tordenskjold-1
Lilje-1
Liva-1
Eg-1
Baron-2
Iris-1
Svane-1
Gulnare-1
60
65
70
75
80
85
90
95
100
Danian
Maastrichtian
Latest
Late
Early
Campanian
Late
Early
Santonian
Coniacian
Turonian
Cenomanian
Albian
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper Hod
Middle Hod
Santonian
Coniacian shale
Lower Hod
Herring/Blodøks/
Plenus
Hidra
cht
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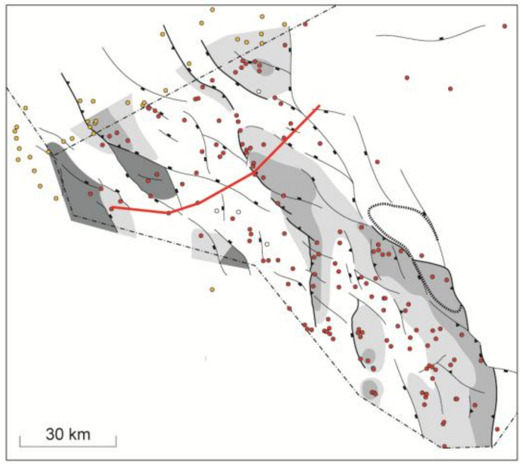
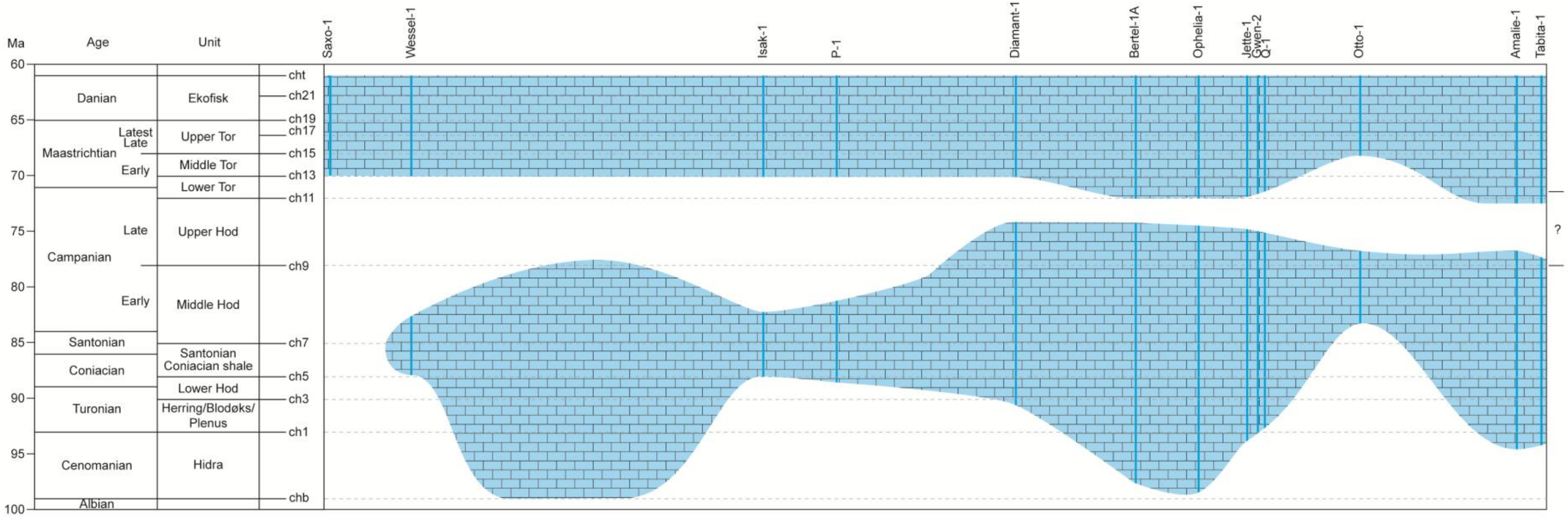
ch13
ch11
ch9
ch7
ch5
ch3
ch1
chb


30 km

Panel 8


Ma
Age
Unit
Saxo-1
Wessel-1
Isak-1
P-1
Diamant-1
Bertel-1A
Ophelia-1
Jette-1
Gwen-2
Q-1
Otto-1
Amalie-1
Tabita-1
Danian
Ekofisk
Maastrichtian
Latest
Late
Early
Upper Tor
Middle Tor
Lower Tor
Campanian
Late
Early
Upper Hod
Middle Hod
Santonian
Coniacian
Santonian Coniacian shale
Lower Hod
Turonian
Herring/Blodøks/Plenus
Cenomanian
Hidra
Albian
cht
ch21
ch19
ch17
ch15
ch13
ch11
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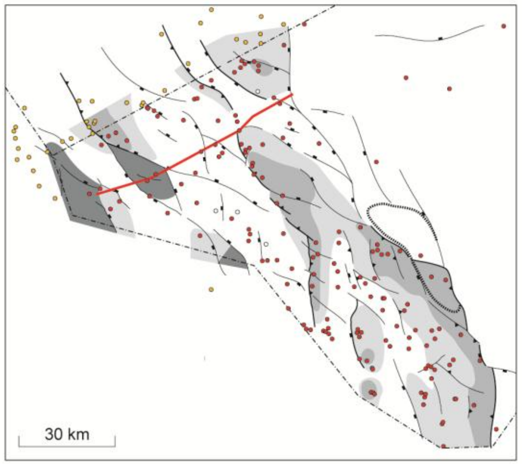
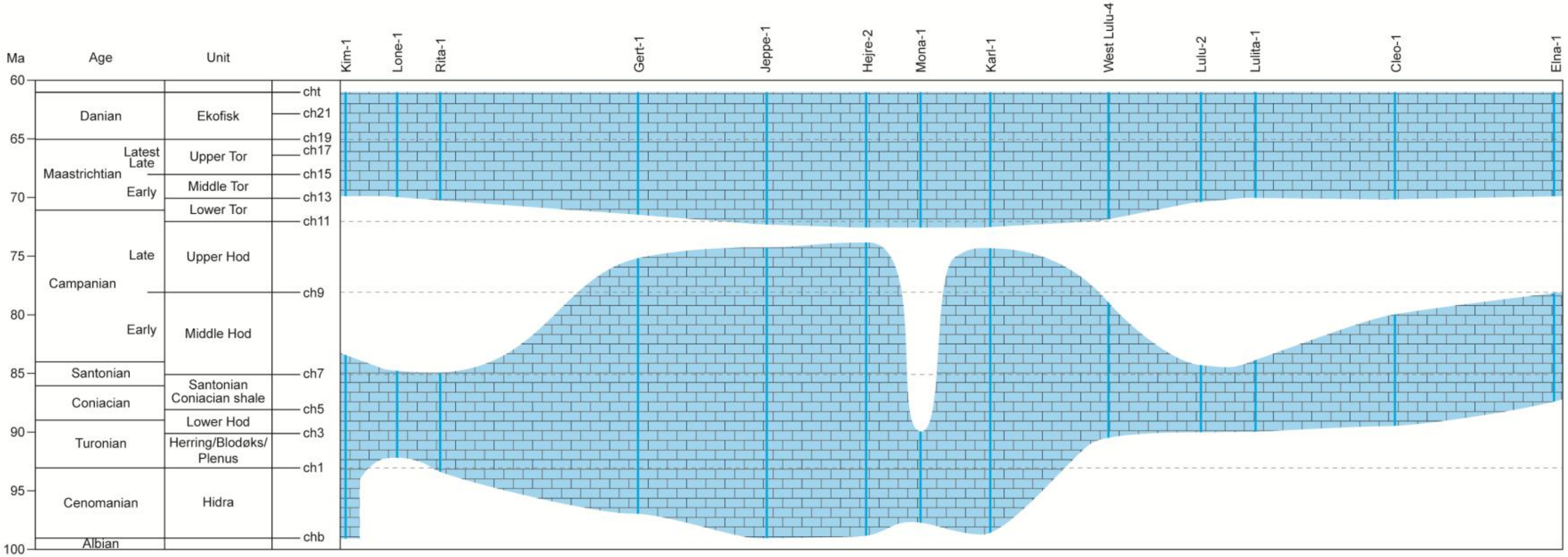
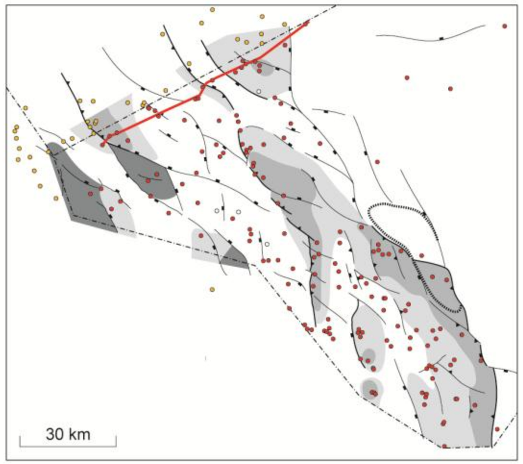
ch5
ch3
ch1
chb
60
65
70
75
80
85
90
95
100
?


30 km

Panel 9



Ma
Age
Unit
Kim-1
Lone-1
Rita-1
Gert-1
Jeppe-1
Hejre-2
Mona-1
Karl-1
West Lulu-4
Lulu-2
Lulita-1
Cleo-1
Elna-1
60
65
70
75
80
85
90
95
100
Danian
Latest
Late
Maastrichtian
Early
Late
Campanian
Early
Santonian
Coniacian
Turonian
Cenomanian
Albian
Ekofisk
Upper Tor
Middle Tor
Lower Tor
Upper Hod
Middle Hod
Santonian
Coniacian shale
Lower Hod
Herring/Blodøks/
Plenus
Hidra
cht
ch21
ch19
ch17
ch15
ch13
ch11
ch9
ch7
ch5
ch3
ch1
chb



30 km

Panel 10