Tectonostratigraphic framework and depositional history of the Cretaceous–Danian succession of the Danish Central Graben (North Sea) – new light on a mature area

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Abstract: An integrated tectonic and sequence stratigraphic analysis of the Cretaceous and Danian of the Danish Central Graben has led to significant new insights critical for our understanding of the chalk facies as a unique cool-water carbonate system, as well as for the evaluation of its potential remaining economic significance.

A major regional unconformity in the middle of the Upper Cretaceous chalk has been dated as being of early Campanian age. It separates two distinctly different basin types: a thermal contraction early post-rift basin (Valanginian–Santonian), which was succeeded by an inversion tectonics-affected basin (Campanian–Danian). The infill patterns for these two basin types are dramatically different as a result of the changing influence of the tectonic, palaeoceanographic and eustatic controlling factors.

Several new insights are reported for the Lower Cretaceous: a new depositional model for chalk deposition along the basin margins on shallow shelves, which impacts reservoir quality trends; recognition of a late Aptian long-lasting sea-level lowstand (which hosts lowstand sandstone reservoirs in other parts of the North Sea Basin); and, finally, the observation that Barremian–Aptian sequences can be correlated from the Boreal to the Tethyan domain. In contrast, the Late Cretaceous sedimentation patterns have a strong synsedimentary local tectonic overprint (inversion) that influenced palaeoceanography through the intensification of bottom currents and, as a result, the depositional facies. In this context, four different chalk depositional systems are distinguished in the Chalk Group, with specific palaeogeography, depositional features and sediment composition.

The first formalization of the lithostratigraphic subdivision of the Chalk Group in the Danish Central Graben is proposed, as well as an addition to the Cromer Knoll Group.

Chalks of the NW European and Central Asian realm represent one of the largest carbonate systems that ever occurred in geological history. First appearing in the Late Hauterivian and Barremian of the Central North Sea Basin (Thomsen 1987; Thomsen & Jensen 1989), chalks became the dominant carbonate facies of the northern hemisphere from the Cenomanian to the Danian, representing a time interval of approximately 40 myr (Surlyk *et al.* 2003). The chalk facies classify as a cool-water carbonate system (*sensu* Schlager 2003), and are distinctly different in depositional geometries and skeletal composition from tropical carbonate systems (e.g. Surlyk 1997). Chalks are generally very homogeneous, mainly composed of nannofossils (e.g. coccoliths and nannoconids), with limited admixtures of microfossils and larger bioclasts, and only locally containing clays (Kennedy 1985; citations in Surlyk *et al.* 2003).

Chalks are also of significant economic interest in the Danish and Norwegian sectors of the North Sea Basin, where they contain important hydrocarbon accumulations that have produced since the 1960s (Surlyk *et al.* 2003; Megson & Tygesen 2005). With the current decline in oil production of these chalk fields, there is now a renewed interest in improving our understanding of this prolific petroleum system, both through the acquisition of new data, and in more detailed studies of the stratigraphic organization, depositional processes and the palaeoecology. The key challenges of hydrocarbon exploration and production in chalks include the prediction of regional facies trends and heterogeneities, and their impact on intra-chalk trap creation and hydrocarbon migration pathways.

Much of the sedimentological chalk research has focused on outcrops in quarries and cliff exposures along the coastlines of France (e.g. Quine & Bosence 1991; Lasseur 2007), the UK (e.g. Gale 1996; Jarvis 2006; Gale *et al.* 2013, 2015) and Denmark (e.g. Surlyk *et al.* 2006). Although these studies give important insights into depositional processes and subseismic-scale heterogeneities (basin-floor currents, swells and channels), they are limited in extent and are essentially 2D. Recent seismic stratigraphic work has demonstrated that many depositional features observed in the chalk are beyond the scale of quarries and coastline cliffs, and hence require 3D surveys of several hundreds to thousands of square kilometres for a proper interpretation of the stratigraphic architecture and depositional processes involved (e.g. Surlyk & Lykke-Andersen 2007; Surlyk *et al.* 2008; Back *et al.* 2011; Gennaro *et al.* 2013; Gennaro & Wonham 2014; Smit 2014; Smit *et al.* 2014; van Buchem *et al.* 2014).

The lithostratigraphic subdivision of North European Upper Cretaceous chalk is notoriously difficult, and has a low resolution (e.g. Bailey *et al.* 1999; Surlyk *et al.* 2003, 2006, 2013; van der Molen & Wong 2007). Recently, a number of seismic stratigraphic studies have attempted to increase the stratigraphic resolution by using seismic stratigraphic sequences. In the Norwegian sector of the North Sea, Gennaro *et al.* (2013) proposed seven sequences; in the Dutch sector, van der Molen & Wong (2007) proposed 11 sequences; and in the Danish Basin, Surlyk & Lykke-Andersen (2007) distinguished seven sequences in the Maastrichtian and Danian interval alone.

The purpose of this paper is to follow the examples of a subdivision in seismic sequences, and take this a step further by documenting the evolution of the basin type, palaeogeography and

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depositional processes in high-resolution 3D seismic images. Particular focus is put on the timing of the inversion tectonics, and the impact it had on the chalk depositional system. Instrumental in this study is the availability of a new and reprocessed, high-resolution, regional 3D seismic dataset (6000 km^2) in combination with advanced seismic interpretation software that provides high-quality 3D geomorphological visualizations at the basin, as well as at the facies scale.

The seismic stratigraphic packages are dated using nanno- and micro-fossil biostratigraphic information, which forms the basis for the construction of a chronostratigraphic scheme and led to the proposition of a revised lithostratigraphic nomenclature. Also, selected examples are given of well-log correlations and cutting-based geochemical information to further constrain age dating and facies distribution patterns. The tectonostratigraphic observations made in the Danish Central Graben are subsequently evaluated in the wider context of the North Sea Basin in order to determine the dominance of global or local control mechanisms on the sedimentation patterns. Finally, the consequences of this revised framework for the prediction of the distribution and reservoir quality of the chalk and siliciclastic reservoirs are summarized.

Geological context

The Danish Central Graben is located in the westernmost part of the Danish offshore sector (Fig. 1), and represents the southernmost extension of a complex system of graben that together form the North Sea Central Graben (Ziegler 1990*a*; Japsen *et al.* 2003). The Danish Central Graben is bounded by the Coffee Soil Fault to the east and by the Mid North Sea High in the west, and consists of a set of NNW–SSE-trending half-graben (Fig. 2). The Danish Central Graben was initiated during the Late Jurassic extensional rifting phase, which started at the end of the Callovian and continued until the late Volgian–earliest Berriasian (Møller & Rasmussen 2003). The inherited Upper Jurassic basin morphology persisted during the Early Cretaceous, and was inverted during the Late Cretaceous (Vejbæk 1986; Vejbæk & Andersen 2002; Jakobsen & Andersen 2010). Compared to other basins in the Danish territory, the Central Graben was subjected to the strongest phases of inversion tectonics.

The studied interval is bounded at the base by the Base Cretaceous Unconformity (BCU). The BCU is recognized at the scale of the North Sea Basin, and is a complex, strongly diachronous surface initiated during the late Berriasian–late Ryazanian (Kyrkjebø *et al.* 2004). The lithostratigraphic nomenclature for the Lower Cretaceous succession of the Danish Central Graben was published by Jensen *et al.* (1986). The Lower Cretaceous Cromer Knoll Group (Fig. 3) is composed of the Valhall, Vyl, Tuxen, Sola and Rødby formations, and three members/beds: the carbonate-rich Leek Member at the base of the Valhall Formation, and the organic-matter rich Munk Marl Bed and the Fischschiefer Member in the Tuxen and Sola formations, respectively (Jensen & Buchardt 1987). Biostratigraphic studies have provided the age dating of these formations (Heilman-Clausen 1987; Thomsen 1987). Recent

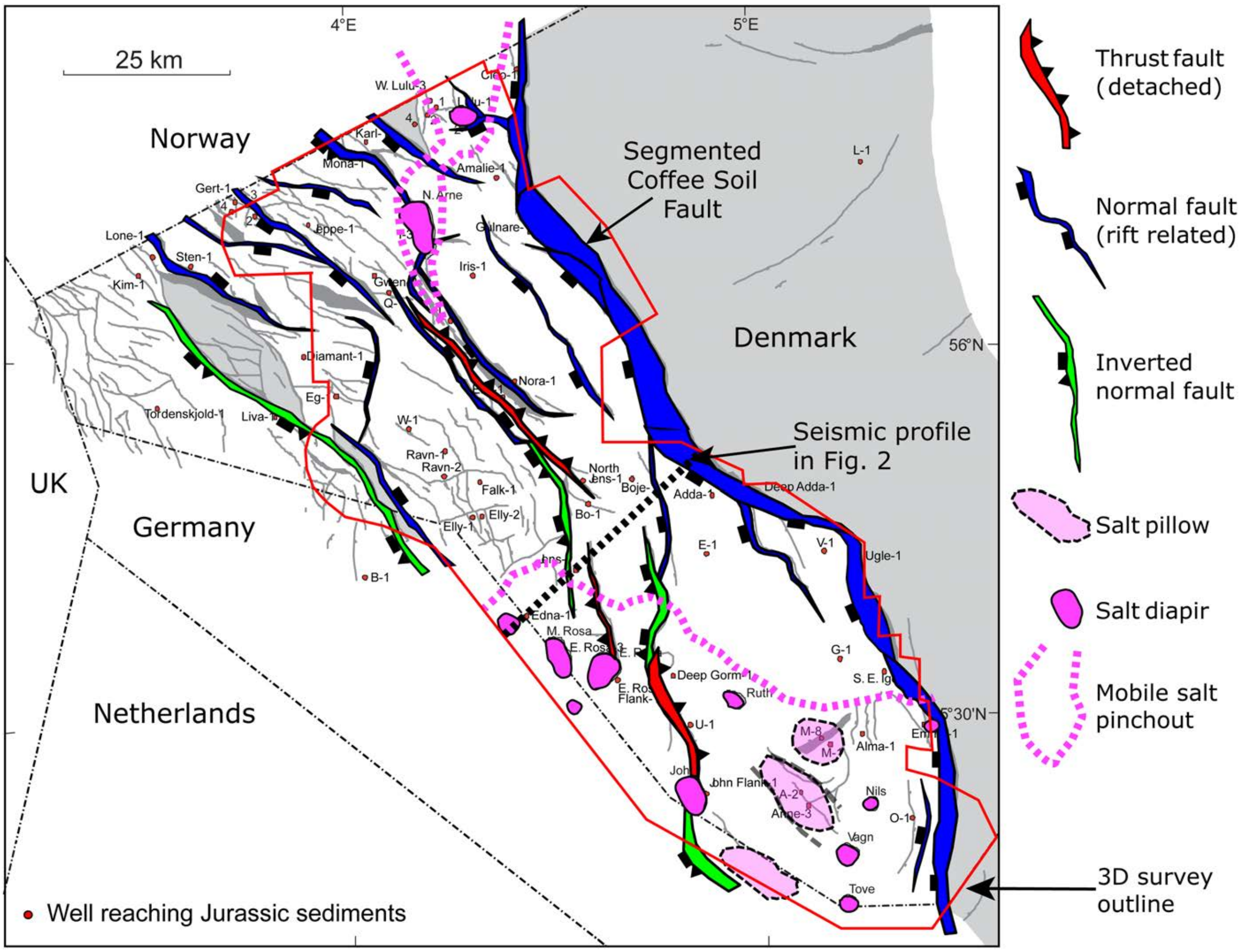

Fig. 1. Structural elements map of the Danish Central Graben (modified after Japsen *et al.* 2003). The aerial extent of the seismic survey used is indicated.

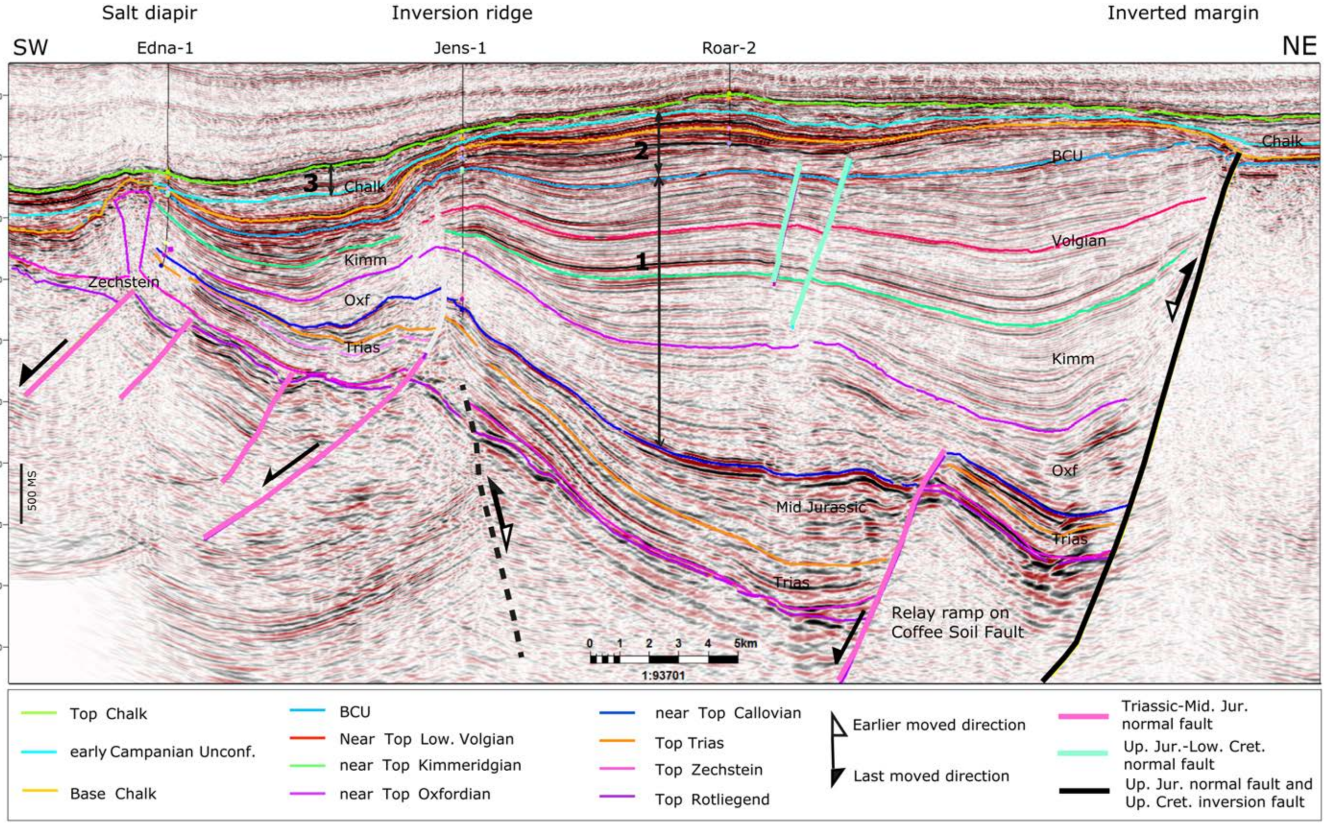

Fig. 2. East–west structural cross-section of the Danish Central Graben illustrating the Late Jurassic rift phase (1), the Cretaceous–Cenozoic thermal subsidence post-rift phase (2) and the Late Cretaceous basin inversion event (3). See Figure 1 for the location map. In this 2D transect, reactivation of a deep-seated normal fault is proposed to explain the inversion-related anticlinal structure in the Jens-1 location.

work by Mutterlose & Bottini (2013) and Sheldon *et al.* (2013) added further detail to the nannofossil palaeoecology of the Tuxen and Sola formations.

Ineson (1993) provided a first sequence stratigraphic interpretation of the Tuxen and Sola formations, based on core and well-log correlations, suggesting a ramp-type morphology. In a seismic stratigraphic study of the Valhall Formation in the southern part of the Danish Central Graben, Vidalie *et al.* (2014) challenged elements of this interpretation, notably through the observation of the presence of clinoforms that provide a proxy of the basin morphology. The broad shelf that developed at this time in the east of the basin formed the substratum for the overlying Tuxen and Sola formations.

In the absence of formal lithostratigraphic nomenclature of the Upper Cretaceous Danish chalk in the North Sea, a nomenclature adopted from the surrounding countries is commonly used: the Hidra, Hod, Tor, Ekofisk and organic-matter rich Plenus Marl formations (Surlyk *et al.* 2003). For the latter formation, Surlyk *et al.* (2003) preferred to use in the Danish Central Graben the Black Band Bed of the Herring Formation in the UK sector (Johnson & Lott 1993). Early attempts to subdivide the Danish chalk into seismic stratigraphic units were published by Lieberkind *et al.* (1982) and Nygaard *et al.* (1989), who distinguished six seismic sequences, whereas Andersen *et al.* (1990) distinguished eight seismic sequences. The first subdivision by Lieberkind *et al.* (1982) has been taken here as the informal reference (Fig. 3). Significant amounts of information on the age dating and faunal composition of the Upper Cretaceous rocks are present in oil company reports, but very little has been published. In the context of the Joint Chalk Research Consortium, nannofossil biostratigraphy has been published for a few wells in the Danish sector of the North Sea (Bailey *et al.* 1999; adopted in Anderskouv & Surlyk 2012). More recently, an integrated biostratigraphic–cyclostratigraphic–isotope stratigraphic approach has been applied to scientific boreholes in the Danish Basin (Ineson *et al.* 2006; Rasmussen & Surlyk 2012; Thibault *et al.* 2012*a*, *b*; Surlyk *et al.* 2013) and a well in the Danish Central Graben (Perdiou *et al.* 2015).

The general palaeogeography of the North Sea Basin in the Early Cretaceous was an enclosed seaway, only open towards the north. During the early Aptian transgression, a connection was established towards the south with the British Wessex Basin, an event that left a basinwide marker bed, the organic-rich Fischschiefer Member (Ziegler 1990*b*; Malkoc *et al.* 2010; Pauly *et al.* 2013). During the next important transgression in the early Cenomanian, the NW European realm was covered by the Chalk Sea that eventually extended towards the east as far as Kazakhstan (Dercourt *et al.* 2000).

The sedimentological interpretation of the Upper Cretaceous Chalk Group has seen a significant evolution over the last 10 years with the recognition in seismic sections of moat and drift systems indicative of persistent bottom currents, which created high relief (100–180 m) on the seafloor in the Danish Basin, and in the German, Danish and Norwegian sectors of the North Sea Basin (e.g. Esmerode *et al.* 2007; Surlyk & Lykke-Andersen 2007; Surlyk *et al.* 2008; Back *et al.* 2011; Gennaro & Wonham 2014; Smit *et al.* 2014) and the Paris Basin (Esmerode & Surlyk 2009), as well as in southern England (Evans *et al.* 2003). The importance of tectonic deformation in shaping the seafloor topography was illustrated for the Norwegian sector of the North Sea Basin by Gennaro *et al.* (2013), and for the Dutch sector by van der Molen & Wong (2007).

The main hydrocarbon-bearing strata in the Cretaceous of the Danish Central Graben are the chalks of the Upper Cretaceous Tor and Danian Ekofisk formations (Hardman 1982; Surlyk *et al.* 2003; Megson & Tygesen 2005). More challenging reservoirs are constituted by the Lower Cretaceous, low-permeability Tuxen and Sola formations (Jakobsen *et al.* 2004). The main source rocks for

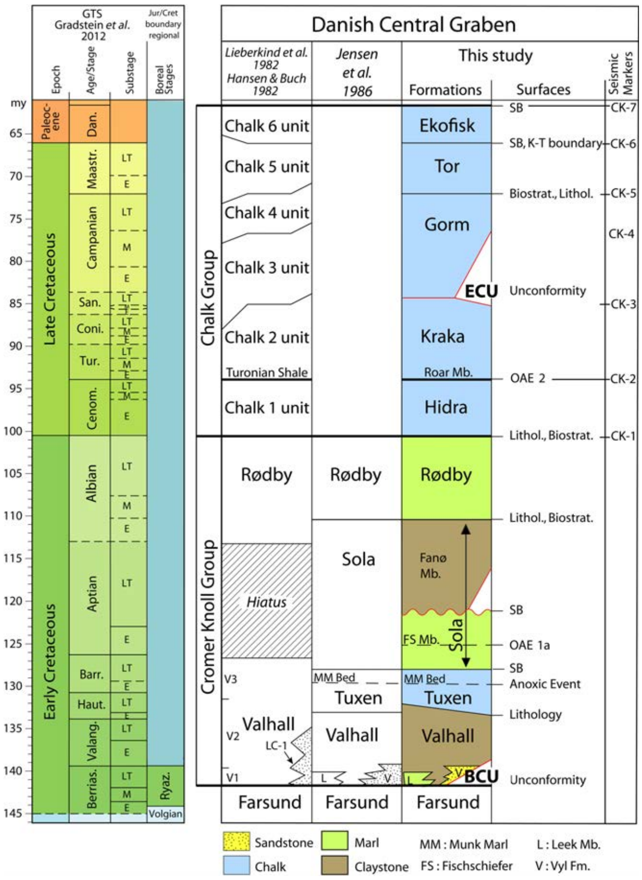

Fig. 3. Lithostratigraphic scheme of the Cretaceous–Danian in the Danish Central Graben presenting the informal lithostratigraphic usage, and the revised and formalized lithostratigraphic nomenclature proposed in Appendix A. The stratigraphic nature of the formation boundaries is indicated. SB, sequence boundary; OAE, Oceanic Anoxic Event; AE, Anoxic Event.

these reservoirs are the organic-rich facies of the Upper Jurassic Farsund Formation (Ineson *et al.* 2003). Within the Cretaceous, there are three organic-matter rich layers (the Munk Marl Bed, the Fischschiefer Member and Black Band Bed/Plenus Marl), but these are thin and generally immature (Jensen & Buchardt 1987).

Material and methods

Seismic data

The study was performed using a recently reprocessed regional seismic dataset consisting of 14 merged smaller surveys (pre-stack depth-migrated) of different vintages (1996–2011). Together, these cover nearly all of the Danish Central Graben (6000 km^2: Fig. 1). The signal to noise ratio is, in general, very good, down to 5 s. The dominant frequency in the Chalk Group is approximately 35 Hz and the average acoustic velocity is around 3400 m s^{-1} (derived by averaging the sonic velocity in the Chalk Group). The vertical and horizontal resolutions are 24.3 and 52.4 m, respectively. The application of a Relative Geological Time (RGT) model interpretation technology (Pauget *et al.* 2009) has been very beneficial for the visualization of both the basin-scale evolution and local geomorphological features.

Biostratigraphy and palaeoecology

A re-evaluation of the Cretaceous biostratigraphic dataset of 39 wells was performed in order to firm up the age control and to deduce palaeoenvironmental information (Barrington 2012). The database comprised microfossils, nannofossils and, locally, palynological observations. Key results of this confidential internal report are presented in this paper, without the extensive datasets. Results from detailed biostratigraphic and palaeontological work carried out on the Tuxen and Sola formations by Petrostrat have also been included.

In addition to the age dating, the palaeontological observations have been used to provide a general overview of the palaeoecology and depositional environment (Barrington 2012). This analysis is based on a semi-quantitative approach, with each sample prepared by a comparable method and specimens counted in abundance categories ranging from rare to super-abundant. Assemblage composition – the overall combination of genera and species – was commonly found to be at least as useful as individual species ranges and, generally, more reliable in being less affected by sediment reworking. Abrupt changes in microfaunas and floras were assessed as potential markers of environmental change and/or stratigraphic break. A positive hiatus was only recognized where at least one biostratigraphic zone was missing, in order for greater confidence in the application of the palaeontological data.

In order to present these observations in a synthetic way, four main faunal assemblages (FA) are defined (Fig. 4), following the work by Leckie *et al.* (1998), Sikora *et al.* (1999), Wilmsen (2003), Hampton *et al.* (2010) and personal observations of D. Barrington. The primary purpose of this classification is to document the variation in the faunal assemblages through time. The next step is the interpretation of these variations in terms of changing depositional environments, which is a topic of much debate owing to the many controlling factors involved, such as water depth, temperature, nutrient supply and salinity (e.g. Wilmsen 2003; Abramovich *et al.* 2003; Hart 2007). In this study, we provide environmental interpretations of these assemblages against the background of the basin evolution of the Danish Central Graben, with emphasis on the relative water depth. The absolute depth indications provided in Figure 4 are approximate. We anticipate that this overall picture will be further refined in future studies that will shed light on the role of other environmental factors, notably temperature and nutrient supply (e.g. recent papers by Mutterlose & Bottini 2013; Sheldon *et al.* 2013; Rasmussen & Sheldon 2016).

Geochemistry

A total of 10 wells were analysed for C and O stable isotopes, and major and trace elements. The results of two of these are presented in this study: the Adda-3 well, where core material was available for the study interval; and the Roar-2 well, where ditch cuttings were used.

Elemental analysis of bulk rock powders was performed at Kingston University, London using procedures presented by Murphy (1998) and Jarvis (2003). A standard suite of 'major' elements consisting of, for example, SiO_2, TiO_2, Al_2O_3, $Fe_2O_3^T$, MnO, MgO, CaO, Na_2O, K_2O, P_2O5 and $CaCO_3$, and a suite of 'trace' elements consisting of Ba, Cr, Sr and Zr, were determined. Results are presented in wt% of oxide for 'major' elements and $\mu g\ g^{-1}$ (ppm) for 'trace' elements.

Carbon and oxygen stable isotope determinations of the carbonate fraction ($\delta^{13}C_{carb}$, $\delta^{18}O$) in powdered samples were carried out at the University of Oxford following the method of Jenkyns *et al.* (1994). Data are reported in standard delta (δ) notation as per mil (‰) relative to the Vienna Peedee belemnite (VPDB) standard.

Revision of the lithostratigraphic nomenclature

Based on the new insights presented in this publication, the first formal lithostratigraphic definition of the Upper Cretaceous

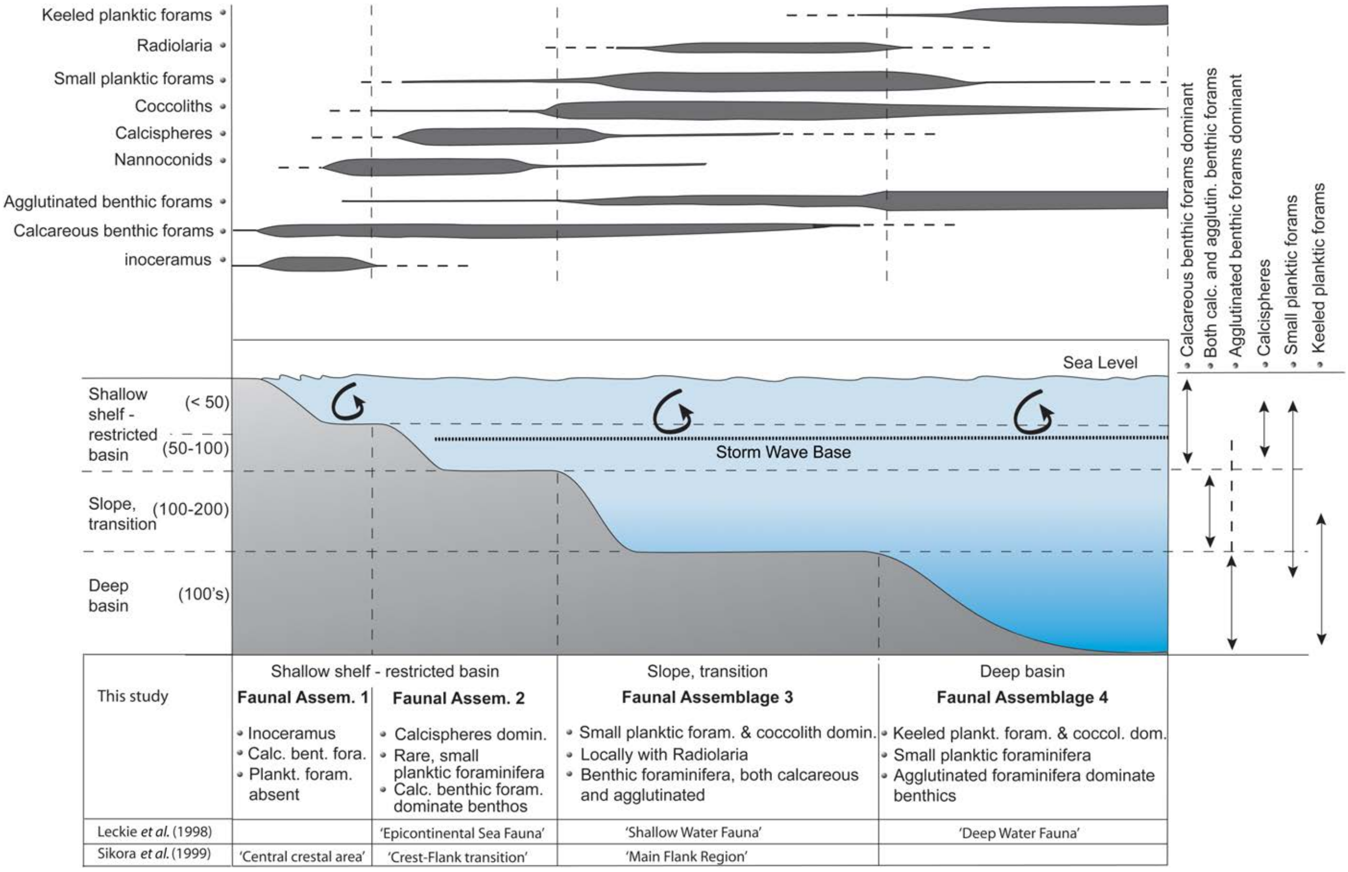

Fig. 4. Faunal assemblages and environmental interpretation of the chalk depositional system in the Central North Sea area (Danish and Norwegian sectors). Absolute depth indications are approximations integrating seismic, facies and palaeoecological considerations.

Chalk Group of the Danish Central Graben is proposed, as well as an addition to the Cromer Knoll Group. These are presented and illustrated in detail in Appendix A, and summarized in Figure 3. In the Chalk Group, three existing formations have been formalized (Hidra, Tor and Ekofisk), two new formations (Kraka and Gorm) replace the informally used Hod Formation, and the new Roar Member replaces the informal Plenus Marl/Black Band Bed. In the Cromer Knoll Group one new member (Fanø) is proposed to replace the informal 'Albian shales'. This revised lithostratigraphic terminology has been used in this paper.

Tectonostratigraphic framework and depositional history

The basin evolution of the Danish Central Graben is illustrated by flattening on two regionally continuous surfaces: the top Chalk Group (Fig. 5a) and the base Chalk Group (Fig. 5b). Although the base Chalk Group is a partly diachronous surface, it is a reasonable choice to eliminate the younger inversion tectonics from the Lower Cretaceous succession. The position of the Early Cretaceous depocentre is a continuation of the Late Jurassic rift basin depocentre (Fig. 5b, c). The tectonic deformation that occurred around the Base Cretaceous Unconformity (BCU) considerably narrowed the basin, probably through rift shoulder uplift, and is interpreted to mark the change from the multiple phases of synrift subsidence to a persistent post-rift phase driven by long-term thermal subsidence (e.g. Kyrkjebø *et al.* 2004). Lower Cretaceous sediments have not been found on the Ringkøbing–Fyn High in the east or on the Heno Plateau in the west. The Lower Cretaceous isochore map (Fig. 5c) is thus interpreted as delineating a marine re-entrant from the north, surrounded by areas of non-deposition for most of that time. The maximum thickness of Lower Cretaceous sediments is approximately 750 m, as observed in the Tail End Graben. Although the top of the Chalk Group was never a flat surface, the flattening does show the shift in depocentres that occurred during the Late Cretaceous inversion (Fig. 5d). Well control shows that the maximum thicknesses in these new depocentres varies from 1000 m in the NW (in the Jeppe-1 well) to 500 m in the southern part of the basin (in the Nana-1XP well), whereas sediment thicknesses in the inverted central part of the basin are of the order of 80–100 m (Fig. 5d). The maximum amount of uplift caused by the inversion during the Cretaceous is several hundred metres over the largest inversion anticlines (Fig. 6).

The Cretaceous and Danian successions have been subdivided into six tectonostratigraphic phases based on differences in structural context, depositional system, palaeogeography and palaeoecology. The results of this analysis are summarized in a chronostratigraphic scheme constructed along an east–west transect across the graben structure and calibrated to 12 wells (Fig. 7). In addition, a stratigraphic distribution chart of the main benthic and pelagic faunal groups in the studied interval is provided (Fig. 8). The interpretation of the depositional environments is based on the results of this integrated study (see also the section on 'Material and methods' earlier in this paper).

Lower Cretaceous

Phase 1. Valanginian–early Hauterivian: prograding claystones of the Valhall Formation. The Valhall Formation is a grey calcareous claystone characterized at the base by the presence of the carbonate-rich Leek Member and siliciclastic Vyl Formation (Jensen *et al.* 1986); these sands are not only siliciclastic, they also contain inoceramid carbonate sands and cherty

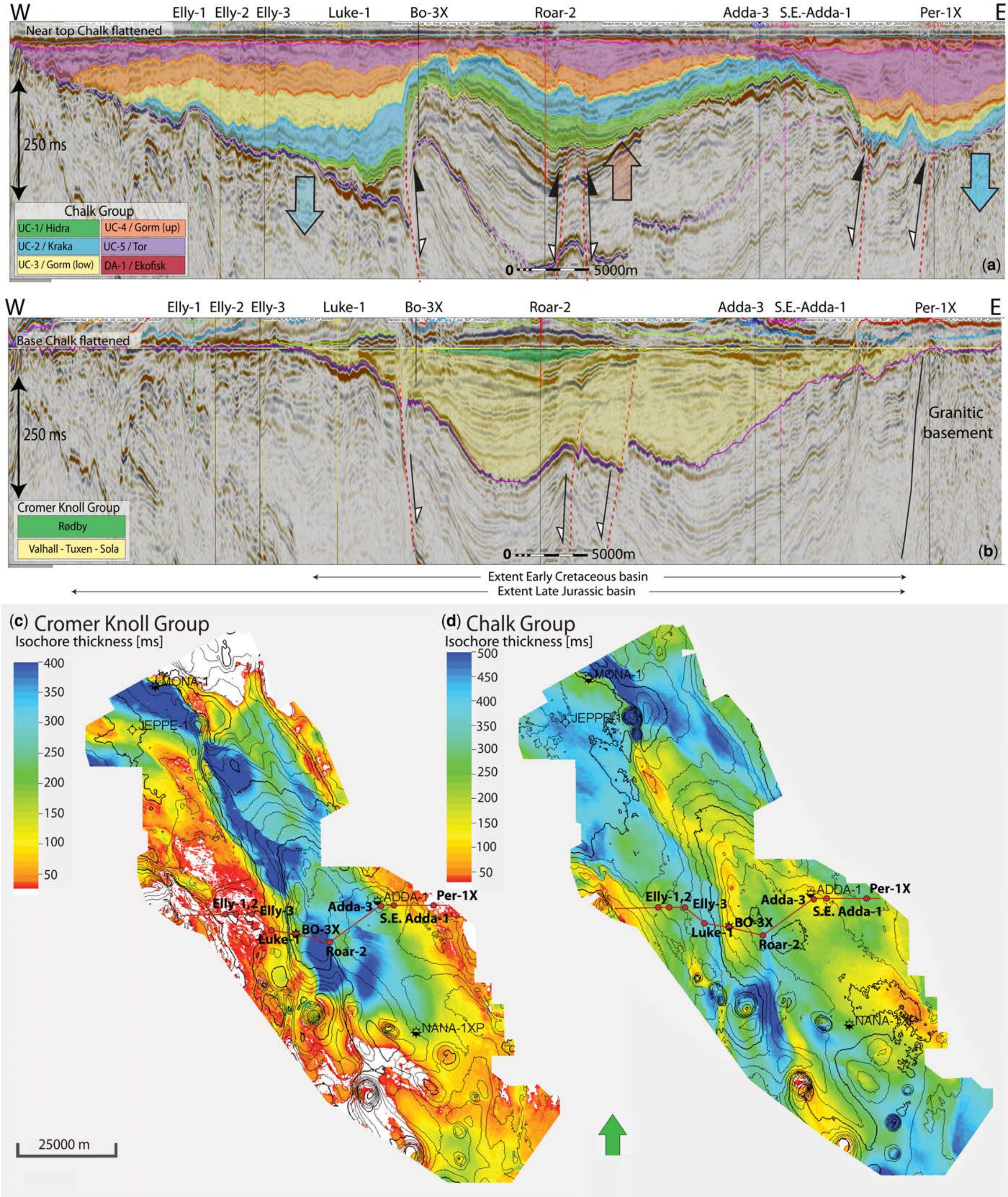

Fig. 5. Thickness variations in the Danish Central Graben of the Lower Cretaceous Cromer Knoll Group and the Upper Cretaceous Chalk Group. (**a**) East–west seismic cross-section flattened on the top Chalk Group reflector. This transect illustrates the effect of the basin inversion uplift and the resulting shift of depocentres. (**b**) East–west seismic cross-section flattened on the base Chalk Group reflector. This transect shows the pre-inversion basin morphology, which was inherited from the Late Jurassic; also note the reduction in basin size across the BCU due to uplift in the west. (**c**) Isochore map of the Cromer Knoll Group, from the BCU to the base of the Chalk Group. (**d**) Isochore map of the Chalk Group. Note the shift in depocentres between the two groups caused by the basin inversion.

'speculite' sands. Examples are from the Elin-1 and NW Adda-l wells and core (Niels Schødt, pers. comm.). Although the Valhall Formation has a generally transparent seismic expression, Vidalie *et al.* (2014) demonstrated the presence of a number of basinwards-dipping reflections with clear topsets, foresets and toesets, which are interpreted as clinoforms prograding towards the basin centre from east to west (Fig. 9a). The maximum topographical relief on these clinoforms is estimated to be of the order of 400 m (360 ms

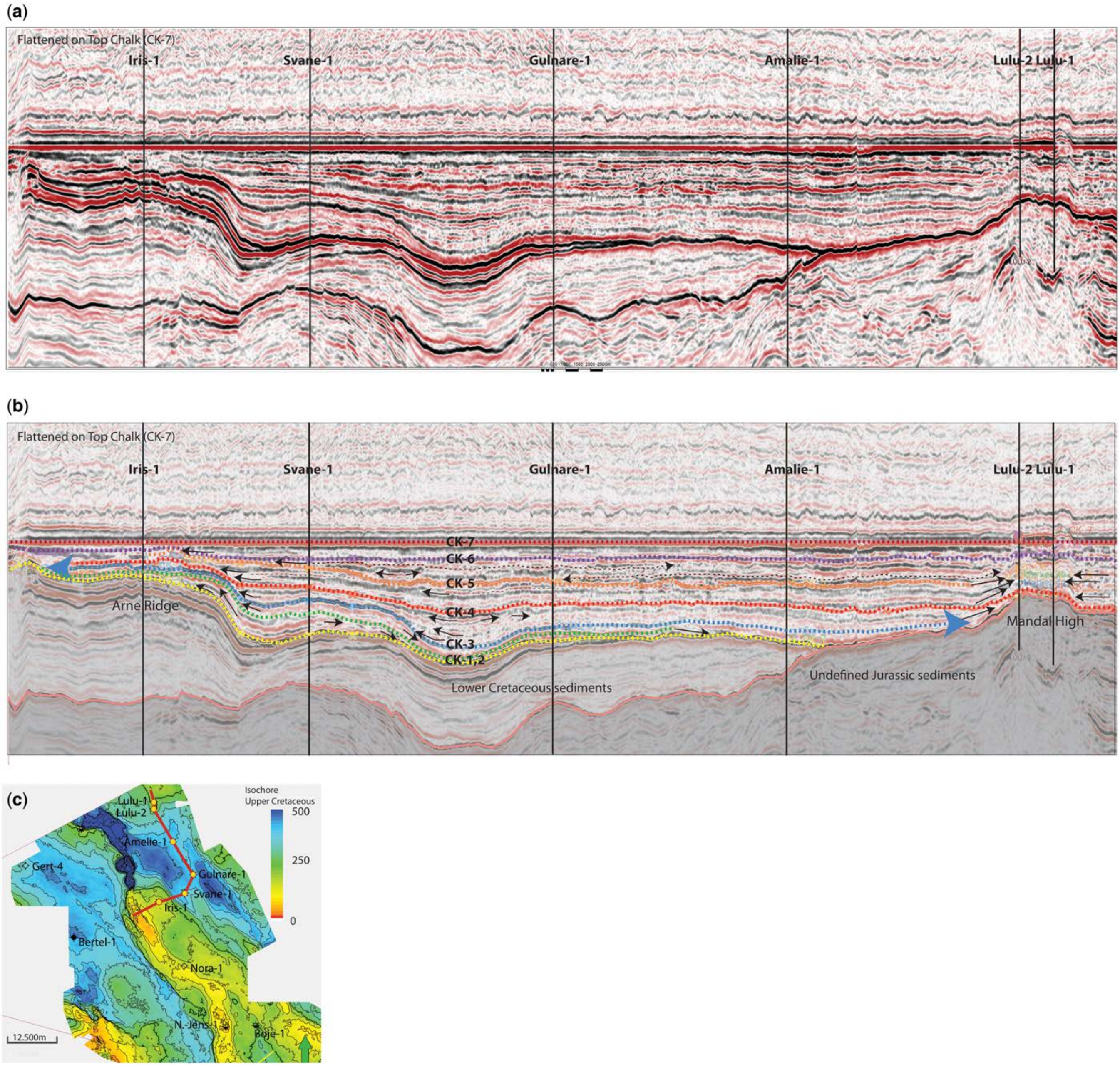

Fig. 6. Seismic cross-section in the northern part of the Danish Central Graben flattened on the top of the Chalk Group. (**a**) Seismic line. (**b**) Interpreted seismic line. Note the onlap of the Campanian and Maastrichtian deposits (between seismic markers CK-3 and CK-6) against the Arne Ridge. (**c**) Position of the seismic transect shown on the Upper Cretaceous isochore map.

two-way time (TWT)), with a foreset angle of 1–2°. In map view (time slice in seismic cube), the clinoform reflectors are intersected and show a pattern of parallel laterally continuous sequences over a distance of approximately 20 km, representing the SW migration of the shelf (Fig. 5) (see also Vidalie *et al.* 2014, fig. 6). Critical for the recognition of these depositional features is the flattening on the Base Chalk Group and the removal of intra-chalk seismic multiples. The clinoforms show the presence of a shelf, shelf-break and deeper basinal area, and are proof of the underfilled nature of the Early Cretaceous basin. The asymmetrical infill pattern is attributed to longshore currents, depositing in the eastern side of the basin and leaving through the western side (see references in Vidalie *et al.* 2014). Seismic stratigraphic analysis shows the presence of two base of slope onlapping packages interpreted as lowstand systems tracts, and distinguishes six seismic stratigraphic sequences (Vidalie *et al.* 2014). Biostratigraphic control is not sufficient to accurately date these sequences. Synsedimentary tectonic control is demonstrated at the base of the Valhall Formation in the middle part of the basin (Adda area), where a fault throw of the order of 120 m is observed locally (Fig. 5) (Vidalie *et al.* 2014).

The faunal associations of this interval show evidence of deepening in the basin centre, with calcareous benthic foraminifera gradually being replaced by the agglutinated foraminifera (Fig. 8). At the same time, a gradual shallowing is observed on the surrounding shelves, with the presence of encrusting foraminifera indicative of shallow waters with high turbulence. These observations are consistent with the seismic interpretation of the establishment and subsequent SW progradation of a (submarine) shelf system.

Phase 2. Late Hauterivian–early Aptian: aggrading/prograding chalks and organic-rich beds of the Tuxen and Sola formations. This interval is characterized by the occurrence of two well-developed, locally oil-bearing, chalk packages (the

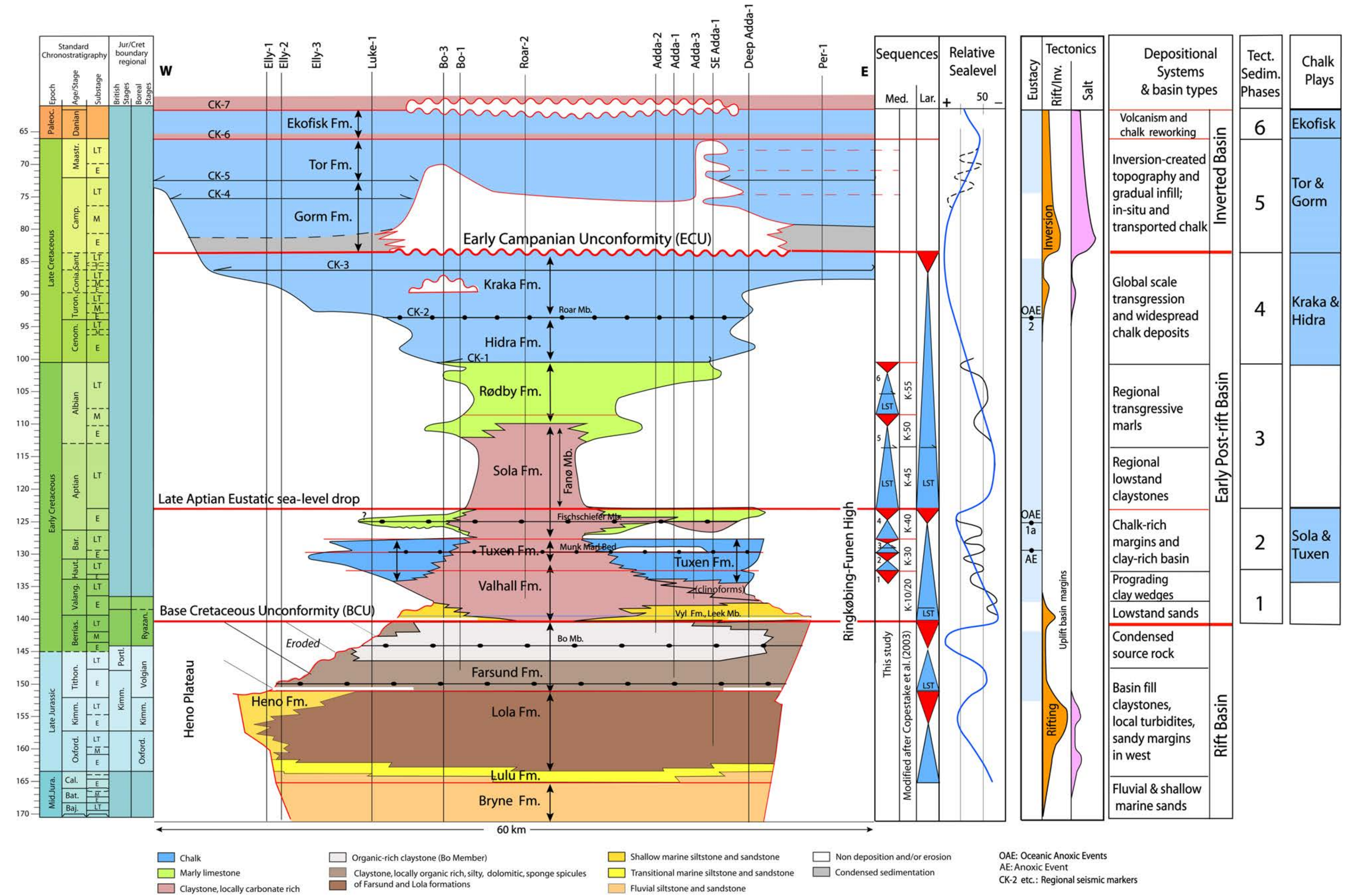

Fig. 7. Chronostratigraphic scheme for the Upper Jurassic, Cretaceous and Danian of the Danish Central Graben along an east–west transect, integrating information from 13 wells and seismic data. Note the importance of the ECU, which occurs in the middle of the Chalk Group separating two very different basinal and depositional settings. Figure 5 shows the seismic expression of this transect and the well locations.

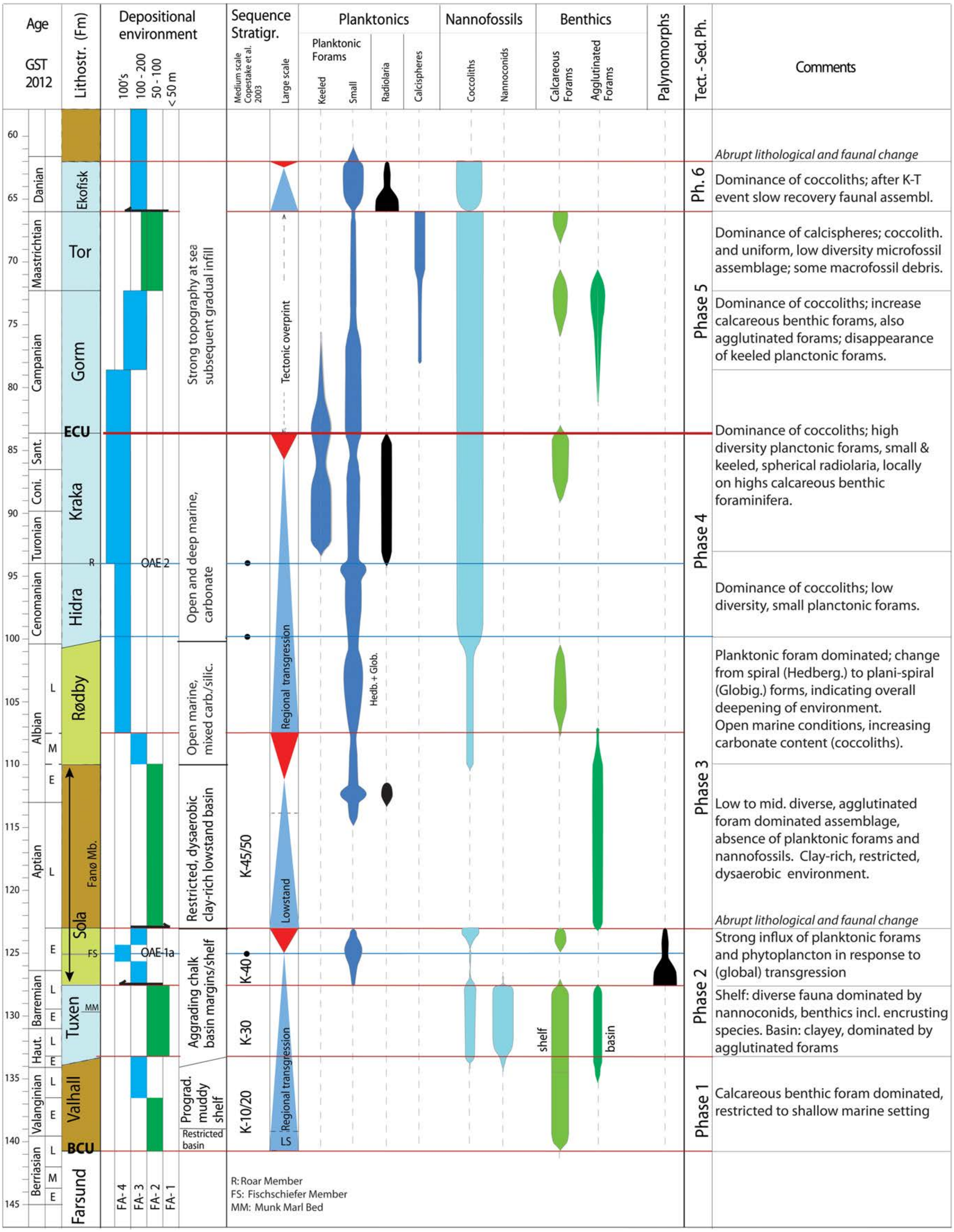

Fig. 8. Stratigraphic evolution of the faunal assemblages in the Cretaceous–Danian succession of the Danish Central Graben. Note the sharp turnover at the Barremian–Aptian sequence boundary. The definition of the Faunal Assemblages (FA-1–FA-4) is summarized in Figure 4. For the legend of the lithostratigraphic column see Figure 3.

Tuxen and Sola formations) and two clayey, organic-rich layers (the Munk Marl Bed and Fischschiefer Member). An initial sequence stratigraphic interpretation of these formations was proposed by Ineson (1993). Recent work by van Buchem *et al.* (2013), integrating new wells (e.g. Roar-2), regional seismic stratigraphy and biostratigraphic information, led to a revised sequence stratigraphic interpretation with considerable implications for the palaeogeography. The biostratigraphy has been calibrated against the LK zonation from Jeremiah (2001) and the GTS 2012 timescale (Gradstein *et al.* 2012), and has been reported by Mutterlose & Bottini (2013) and Sheldon *et al.* (2013).

The subdivision into three sequences of this cool-water carbonate system is based on subtle changes in lithological composition, faunal assemblage and seismic stratal relationships. Distinction is made between the eastern margin of the basin, which represents a shelf area (the Adda Shelf), and the steeper western margin (Figs 9 & 10).

The lowest sequence (sequence 1) covers the lowest part of the Tuxen Formation and the upper part of the Valhall Formation, and thus illustrates the change from clay to chalk deposition (Fig. 10). In the proximal locations, the basal sequence boundary is a hiatus that separates the Valhall and Tuxen formations (Ineson 1993); whereas, in the basin, its expression is more gradational and, therefore, more difficult to pick out. The top sequence boundary in the shelf area in the east is positioned below a green shale bed that marks an abrupt change in the nannofossil faunal assemblage and palynomacerals (documented in the Adda wells), which is interpreted as a relative deepening on the shelf. In the distal locations, the surface is placed with the help of biostratigraphic control (van Buchem *et al.* 2013). The age of this sequence is late Hauterivian (LK 22–LK 24).

The lithological composition of the sequence shows an overall trend, in a basinwards direction, of a decrease in carbonate and an increase in clay content (Fig. 10a). At the finer scale, in proximal areas along the margins, an alternation of limestone beds and shaly interbeds is observed. The carbonates consist of a mixture of nannofossils (coccoliths and nannoconids), encrusting benthic foraminifera (*Patellina*, *Aulotortus*, *Trocholina*, *Marssonella*) and ostracods, whereas agglutinated foraminifera occur abundantly in the marly interbeds and in the basin. This facies association is interpreted as a relatively shallow, eutrophic inner- to outer-shelf environment, bordering a deeper and more clay-rich basin centre.

The top sequence boundary of the second sequence from below is defined in the basin and along the margins by the base of the Munk Marl Bed, and in the most proximal areas by a microfossil facies change or, locally, by a stratigraphic hiatus (Fig. 10). The age of the sequence is late Hauterivian–early Barremian (LK 20 and LK 21). The facies consist mostly of decimetre-scale limestone–marl couplets along the eastern margin, on the shelf, which are red coloured and contain locally reworked intraclasts and levels of transported inoceramid bivalves. The limestone–marl couplets along the western shelf are white to grey in colour and are generally thicker (decimetre to metre scale). These different facies are interpreted as evidence of a difference in accommodation space, less in the east, more in the west. The basinal facies in-between remains more clay-rich. The nannofossil faunal assemblage encountered along both basin margins shows evidence of increased fertility (i.e. runoff) (Sheldon *et al.* 2013) compared to sequence 1. The general depositional environment interpretation is similar to sequence 1. No evidence of subaerial exposure was found.

The third sequence from below comprises the organic-rich Munk Marl Bed and the overlying middle and upper parts of the Tuxen Formation (Fig. 10a). The top sequence boundary corresponds to a sharp change in lithology, from clean chalk of the Tuxen Formation to clayey limestone and marl of the lower part of the Sola Formation, which is clearly expressed in the gamma-ray (GR) log signature and recognized at the scale of the North Sea Basin (e.g. Copestake *et al.* 2003). The lithological change is accompanied

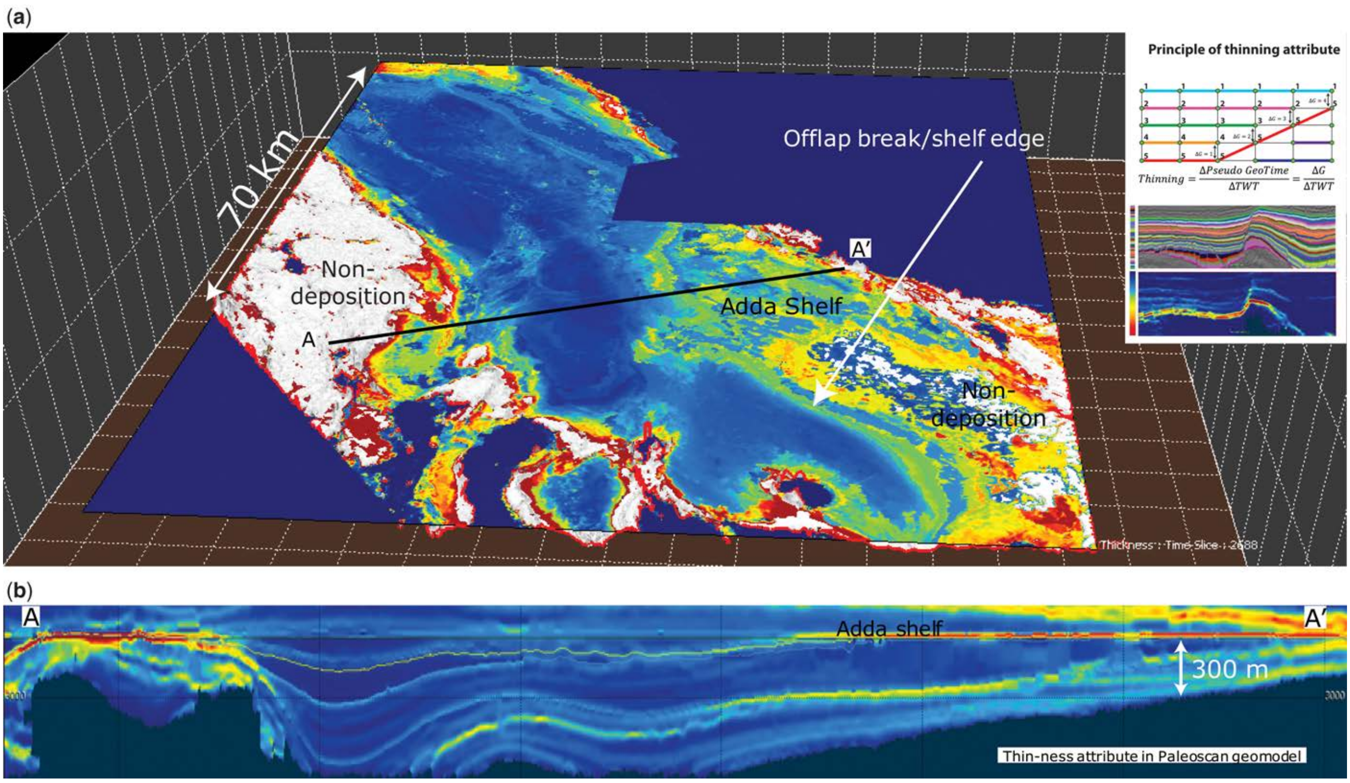

Fig. 9. 2D transect and attribute map of the Upper Tuxen constructed with the ‘thin-ness’ attribute of a Palaeoscan geomodel covering the central part of the Danish Central Graben (see Fig. 1). (**a**) The thin-ness attribute map is used as an approximation of the late Barremian palaeogeography (top Tuxen Formation). Green and warm colours indicate thinning (low accommodation – shallow water) and blues indicate thickening (high accommodation – deeper water). The development of the Adda Shelf in the east is the result of westwards-prograding clinoforms of the clayey Valhall Formation, which acted as the substratum for the deposition of the chalks of the Tuxen Formation in this area. (**b**) 2D transect flattened on the base Chalk Group, in a thin-ness cube; the geomodel surface used in (a) is shown in yellow.

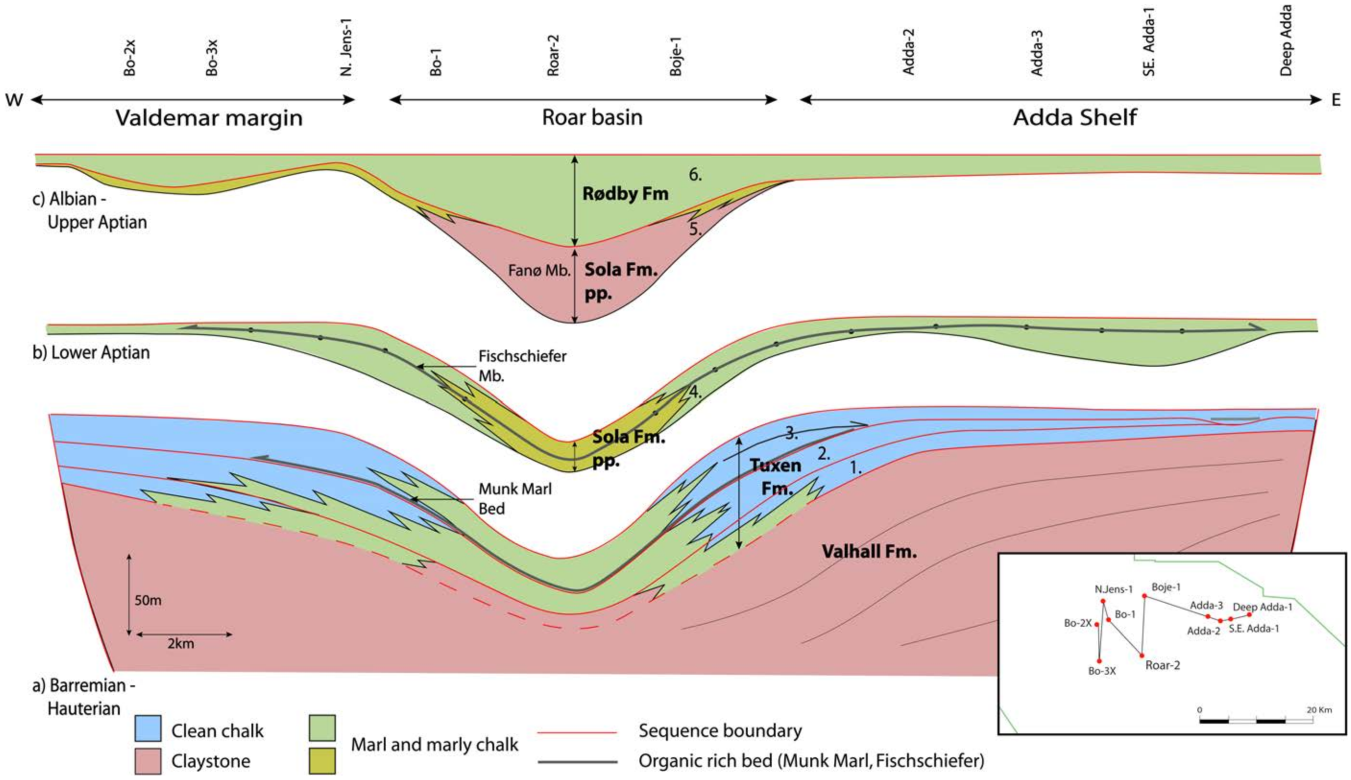

Fig. 10. Sequence stratigraphic models for the Lower Cretaceous of the Danish Central Graben constrained by seismic, log correlations and biostratigraphy. (**a**) The Hauterivian–Barremian interval shows the westwards progradation of the Valhall Formation and the subsequent deposition of the chalks of the Tuxen Formation. In the Tuxen Formation, three sequences are distinguished. The organic-rich Munk Marl Bed was deposited during the sea-level lowstand of sequence 3. (**b**) The lower Aptian part of the Sola Formation is characterized by the presence of the organic-rich Fischschiefer Member. This member corresponds to the maximum flooding surface of sequence 4, and was deposited during a global sea-level rise (OAE 1a). (**c**) The upper part of the Sola Formation, the new Fanø Member, was deposited during a long-lasting, late Aptian sea-level lowstand, recognized at the scale of the North Sea Basin and Neotethys Ocean (see the text). The Albian Rødby Formation was deposited during an overall transgressive phase. The inset shows the location map of the well-log transect.

by a turnover in the microfossil content, with a strong influx of deeper-water fauna, including dinoflagellates, pollen and planktic foraminifera; a change expressed more abruptly on the shallow shelves than in the basin (Fig. 8) (Sheldon *et al.* 2013; van Buchem *et al.* 2013). The Top Tuxen sequence boundary marks the maximum progradation and development of the Lower Cretaceous chalk.

The Munk Marl Bed and middle part of the Tuxen Formation show seismic onlap against the eastern margin, which is confirmed biostratigraphically by the absence of rocks of this age on top of the Adda Shelf (Figs 7 & 10). The onlapping unit is interpreted as a lowstand systems tract, with the organic-rich Munk Marl Bed at the base. Considering the stratigraphic position, anoxic conditions were probably created by a confinement-induced reduction of water circulation, rather than condensation through transgression (Ineson *et al.* 1997). The overlying middle part of the Tuxen Formation consists of open-marine decimetre-scale bedded, grey, limestone–marl couplets. During deposition of both these units, the Adda Shelf was probably a zone of sediment bypass, as no evidence of subaerial exposure has been observed. The upper part of the Tuxen Formation caps the succession, but may not have been deposited over the entire Adda Shelf. Along the western margin, the top of the Tuxen Formation is a diachronous surface, older in the more proximal western position and younger in the more distal position. This unit is interpreted as the prograding highstand/falling stage systems tract of the sequence. The chalk composition of the middle and upper part of the Tuxen Formation is characterized in certain layers by the abundant presence of nannoconids, in addition to the common coccoliths (Mutterlose & Bottini 2013; Sheldon *et al.* 2013).

The palaeogeography at the time of deposition of the middle and upper Tuxen (sequence 3) is represented in Figure 9, using a seismic attribute ('thin-ness' attribute: Pauget *et al.* 2009). It shows shallow-water environments, where clean chalk packages were deposited, bordering a more clay-rich basin centre. Taking into account the seismic-constrained basin morphology and total absence of Lower Cretaceous deposits on the bordering highs, it is considered unlikely that sea level was very high. A water depth in the 50–100 m range is proposed for the Tuxen Shelf, although a shallower water depth cannot be excluded. This interpretation represents a fundamental conceptual change in the depositional model of Lower Cretaceous Tuxen chalk, with a preferred production and accumulation along the shallow basin margins, instead of a uniformly distributed pelagic rain.

The fourth sequence from below covers the Sola Formation, including the Fischschiefer Member (Fig. 10b). The top surface is represented by an increase in the clay content, clearly expressed in the gamma-ray response and a hiatus in the proximal locations. The age is late late Barremian–late early Aptian (top *Simancyloceras pingue* to base *Epicheloniceras martinoides* ammonite Zone). The facies of the lower Sola Formation is characterized by a dramatic increase in deeper water fauna, including dinoflagellates and planktic foraminifera (notably *Hedbergella infracretacea*), and a strong increase in the clay content. The nannofossils decrease upwards in this unit, and the nannoconids temporarily disappear (nannofossil crisis: Mutterlose & Bottini 2013). This lower part of the Sola Formation is interpreted as the transgressive systems tract.

The Fischschiefer Member is rich in organic matter (up to 12% total organic carbon (TOC): Jensen & Buchardt 1987) and is interpreted as including the maximum flooding surface of this sequence. It is the local equivalent of the oceanic anoxic event (OAE) 1a, a worldwide recognized period of organic matter accumulation and transgression (e.g. Pauly *et al.* 2013). The overlying more carbonate-rich part of the Sola Formation is interpreted as the highstand systems tract, and contains abundant small planktic and benthic foraminifera. A diverse and abundant assemblage of species of calcareous benthic genera (*Conorotalites*, *Gavelinella*, *Valvulineria* and *Lenticulina*) is commonly associated with the influx of hedbergellid foraminifera. These genera, in association, point to open-marine conditions (Barrington 2012) and support the interpretation of the Sola Formation as a generally deeper setting than the underlying Tuxen Formation.

Phase 3. Late Aptian–Albian: lowstand of the Fanø Member (Sola Formation) and transgression of the Rødby Formation. The upper part of the Sola Formation has been lithostratigraphically redefined as the Fanø Member (Fig. 3 and Appendix A). This new member is of late Aptian–early Albian age and, in the Roar-2 well, consists of a 40 m-thick package of claystones (Fig. 10c). In seismic profiles, it shows clear onlap against the basin margins; it is absent over the Adda Shelf in the east and is poorly represented in the west. In the northern part of the Tail End Graben, it can locally reach a thickness of more than 90 m (e.g. Baron-2a and Lilje-1). The faunal content shows a disappearance of the planktic foraminifera over most of the area and the appearance of a benthos consisting predominantly of agglutinating foraminifera of low–moderate diversity (Barrington 2012). This combined seismic, lithological and ecological information suggests that the shales of the Fanø Member were deposited during a period of sea-level lowstand, causing basin restriction (reduced water circulation) and dysaerobic conditions.

In seismic profiles, the overlying Albian Rødby Formation shows an overall onlapping trend, overstepping the upper Aptian–lower Albian deposits (Fig. 10). In the Danish Central Graben, the formation consists of greyish, fissile marlstone interbedded with subordinate limestone and claystone layers (Jensen *et al.* 1986). In the upper part of the formation, the depositional environment again becomes more open marine, as testified by the influx of small, simple planktic foraminifera and by the renewed appearance of bottom faunas dominated by calcareous benthic foraminifera (Fig. 8). The change in planktic foraminifera from spiral forms (Hedbergellids) to planispiral forms (*Globigerinelloides*) is interpreted as an indication of increasingly open-marine conditions (Barrington 2012).

Upper Cretaceous–Danian

The key to unravelling the depositional history of the lithologically monotonous Upper Cretaceous–Danian chalk succession in the Danish Central Graben is the relationship between inversion tectonics and the chalk depositional processes. Inversion caused a fundamental change in the basin morphology, which was a determining factor in the distribution of the chalk facies and the creation of intra-chalk heterogeneities (facies changes, hiatuses and hardgrounds).

An integrated approach combining seismic stratigraphic principles, seismic geomorphology and an updated biostratigraphic dataset has been applied to define and date seven, robust and stratigraphically meaningful seismic markers (Fig. 11). Several observations can be made. It is evident that the chalk depositional record is incomplete, owing to the presence of many hiatuses (Fig. 11). A particular event that stands out is the basin-wide absence of lower Campanian rocks that can locally extend up to the late Maastrichtian–Danian, representing a hiatus of approximately 20 myr (Bo-Jens Ridge wells and SE Igor-1 well). The dating of the seismic marker beds gives a reasonable resolution, considering the fact that these have been obtained from cuttings and that the seismic to well tie itself also involves a margin of error. The seismic stratigraphic and biostratigraphic information has been integrated into a chronostratigraphic scheme representing an east–west cross-section over the Adda and Valdemar area, which clearly brings out the importance and variable expression of the early Campanian unconformity (Fig. 12).

Late Cretaceous shifts in depocentres are illustrated in six isochore maps (Fig. 13). An evolution in three stages can be defined: (1) the pre-inversion phase (Cenomanian–Santonian), during which local tectonic uplift occurred, starting in the Turonian, along deeper-seated fault systems flanking the Lower Cretaceous early post-rift basin; (2) the inversion climax phase (Campanian), which marks main uplift and complete inversion of the Early Cretaceous basin centre, with an estimated maximum uplift of the order of 400–500 m and subsequent onlap of thick packages of chalk against the inverted highs; and (3) the post-inversion phase (Maastrichtian–Danian) when uplift slowed, and thermally driven regional subsidence and sedimentation resumed over the entire Danish Central Graben. Sporadic uplift events continued during the deposition of the overlaying siliciclastic Cenozoic strata. The implications of the change in basin morphology on the chalk depositional patterns is presented below, following the three defined tectonostratigraphic phases.

Phase 4. Cenomanian–Santonian: deposition of the chalks of the Hidra and Kraka formations during overall sea-level rise. This phase consists of seismic stratigraphic units UC-1 and UC-2 (Figs 11 & 13). The first unit represents the Hidra Formation and the second one is the Kraka Formation, which includes the organic-rich claystones of the Roar Member at the base (Fig. 3). The base of this phase is represented by seismic marker CK-1, which denotes the locally diachronous lithological transition from the marly Rødby Formation to the chalks of the Hidra Formation. At the top, this phase is bounded by the early Campanian unconformity, located just above or at the CK-3 seismic marker (Fig. 3).

In order to reconstruct the palaeogeography of this phase, a seismic volume flattened on the top of the seismic marker C3 (Santonian age) has been used, eliminating the deformation imposed by the later inversion tectonics (Fig. 14). This image shows the overall transgressive nature of the chalks of the Hidra and Kraka formations, which gradually onlap and overstep the Early Cretaceous basin margins. The seismic reflections show a high continuity and little evidence of structural deformation in this phase (Fig. 14). An exception is the local uplift along the deeper-seated faults inherited from the Late Jurassic rift phase (Arne-Elin Ridge and Bo-Jens Ridge) where stratigraphic thinning is observed (Fig. 13a). In the well-log correlations of Figures 14 and 15, a trend is apparent in the Hidra Formation that ranges from a clay-rich lithology in the centre of the basin (Roar-2 well) to a more carbonate-rich lithology along the basin margins (Adda-3 and Bo wells). This facies distribution is reminiscent of the clay and chalk distribution observed in the Lower Cretaceous Tuxen and Sola formations. Lithological change and stratigraphic thinning are also illustrated in the Roar Member at the base of the Kraka Formation of the Roar-2 and Adda-3 wells (Fig. 15). In the thicker basinal Roar-2 well, a clear expression of the Cenomanian–Turonian Boundary Event (CTBE) is observed in the carbon-isotope curve and gamma-ray spike; whereas, in the thinner, condensed succession of the Adda-3 well, this carbon-isotope excursion is hardly expressed (Fig. 15). At another level, a local diagenetic overprint can be observed in the Adda-3 well where silica precipitation occurred below and just above the early Campanian unconformity, thereby reducing the porosity (Fig. 15).

From a seismic and sequence stratigraphic point of view, at least two regional flooding surfaces can be recognized in this phase.

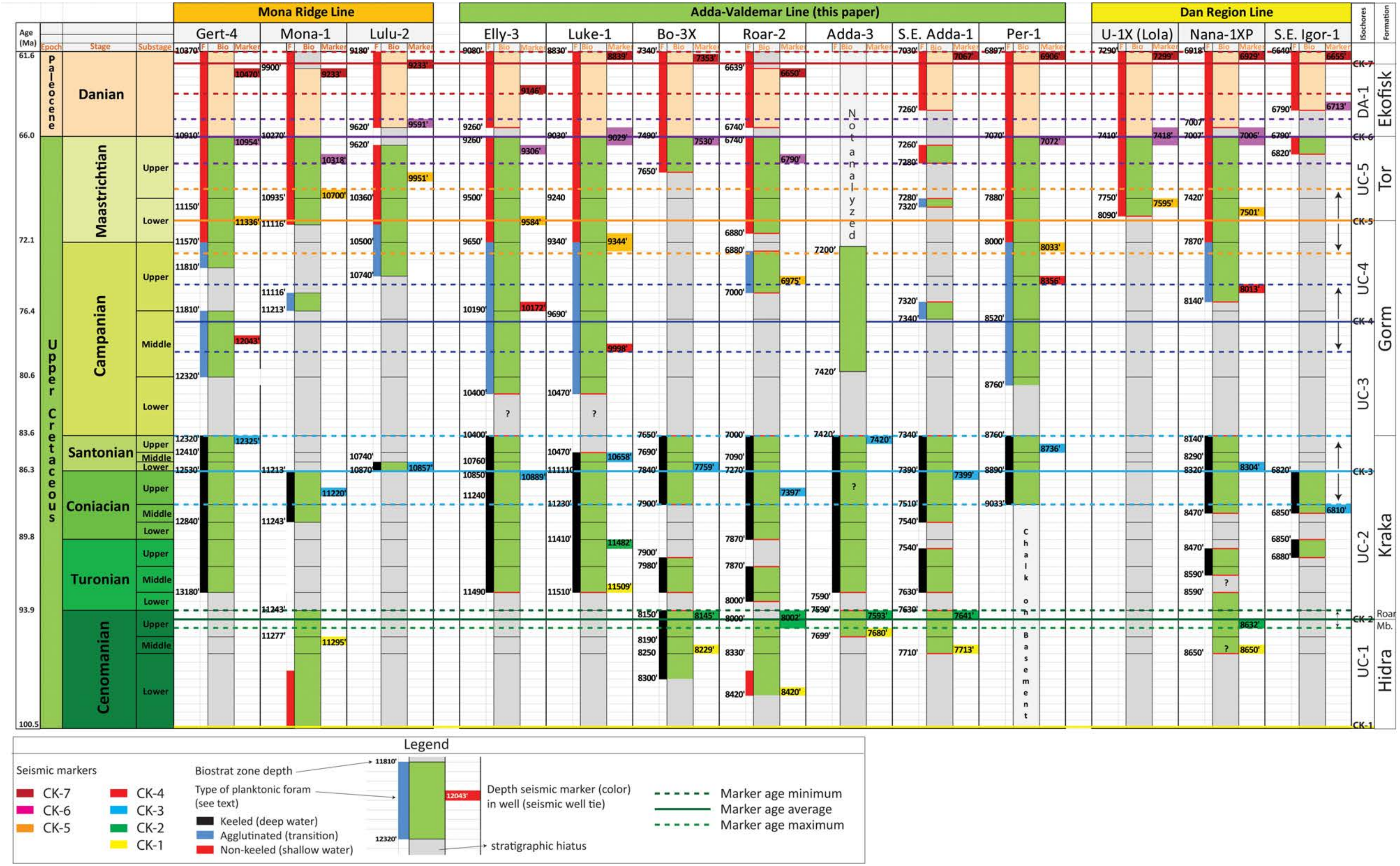

Fig. 11. Upper Cretaceous chronostratigraphic scheme for 13 wells, and calibration of seismic markers CK-1 – CK-7. Green in the well column indicates positive biostratigraphic evidence for the presence of rock of this age, and grey indicates no biostratigraphic evidence for rocks of this age (hiatus). The relative age range for each seismic marker is indicated. Note the regional absence of lower Campanian rocks. For the well locations, see Figures 1 and 12.

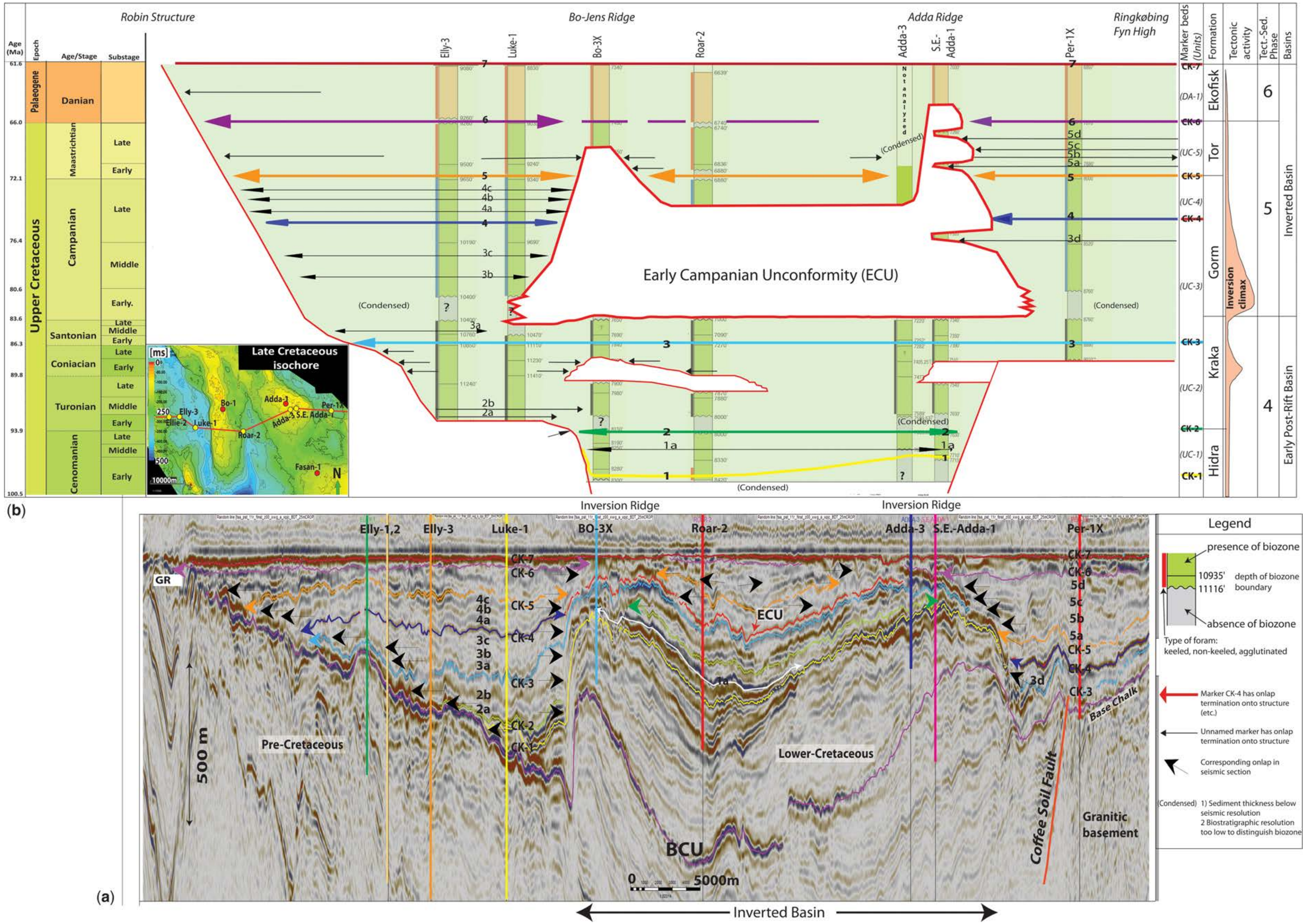

Fig. 12. East–west transect across the Danish Central Graben integrating seismic stratigraphic observations (stratal termination patterns) and biostratigraphic information obtained in the wells: (**a**) seismic section flattened on the top Chalk Group; and (**b**) the Upper Cretaceous chronostratigraphic scheme. Inset: Chalk Group isochore map, and the locations of the well-log and seismic transect.

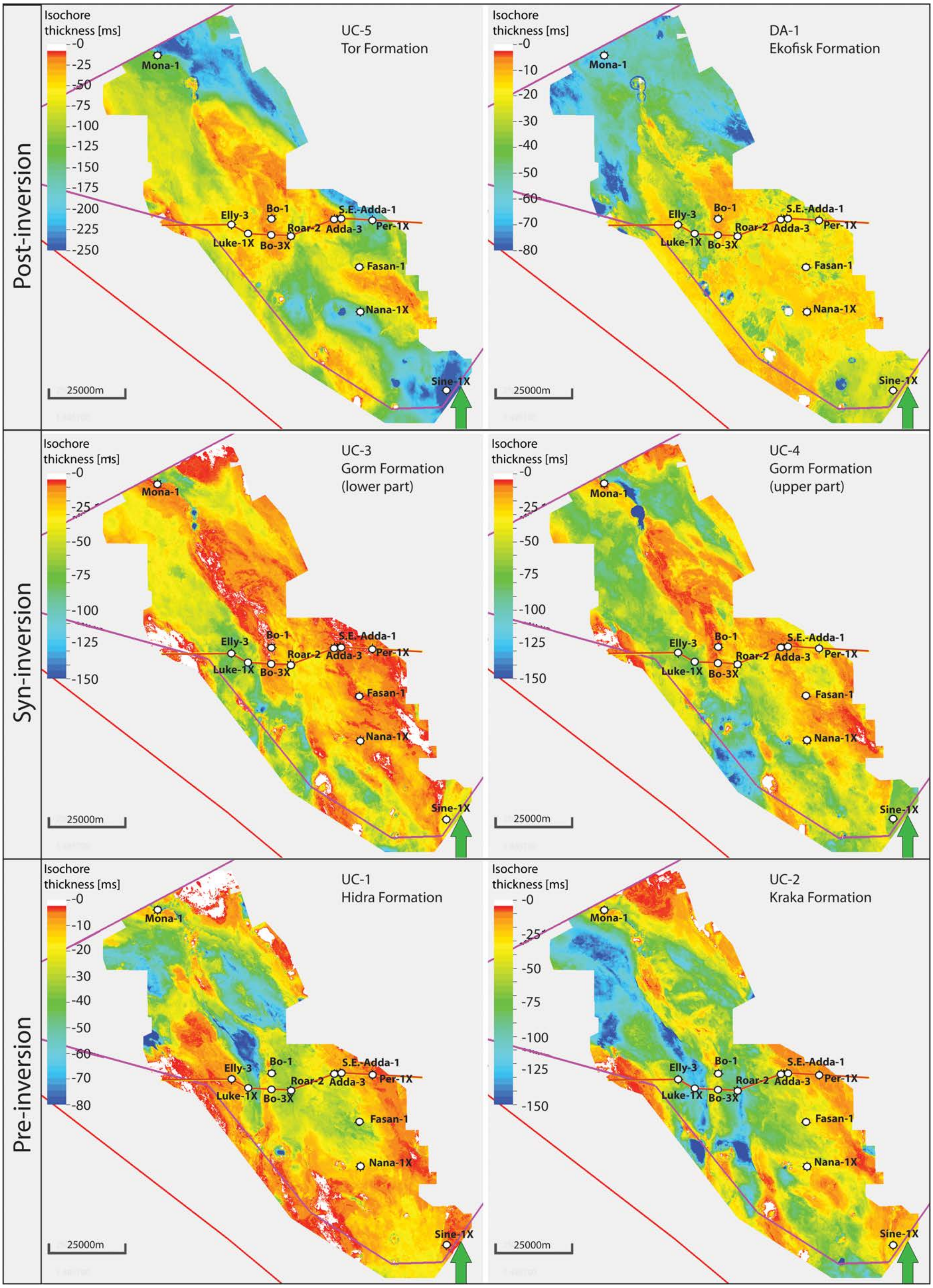

Fig. 13. Upper Cretaceous isochore maps constrained by the seven regionally mapped seismic marker beds (see Figs 11 & 12). Note the shift in depocentres during the evolution from pre-inversion to syn-inversion and post-inversion. Note difference in isochore thickness scale bars.

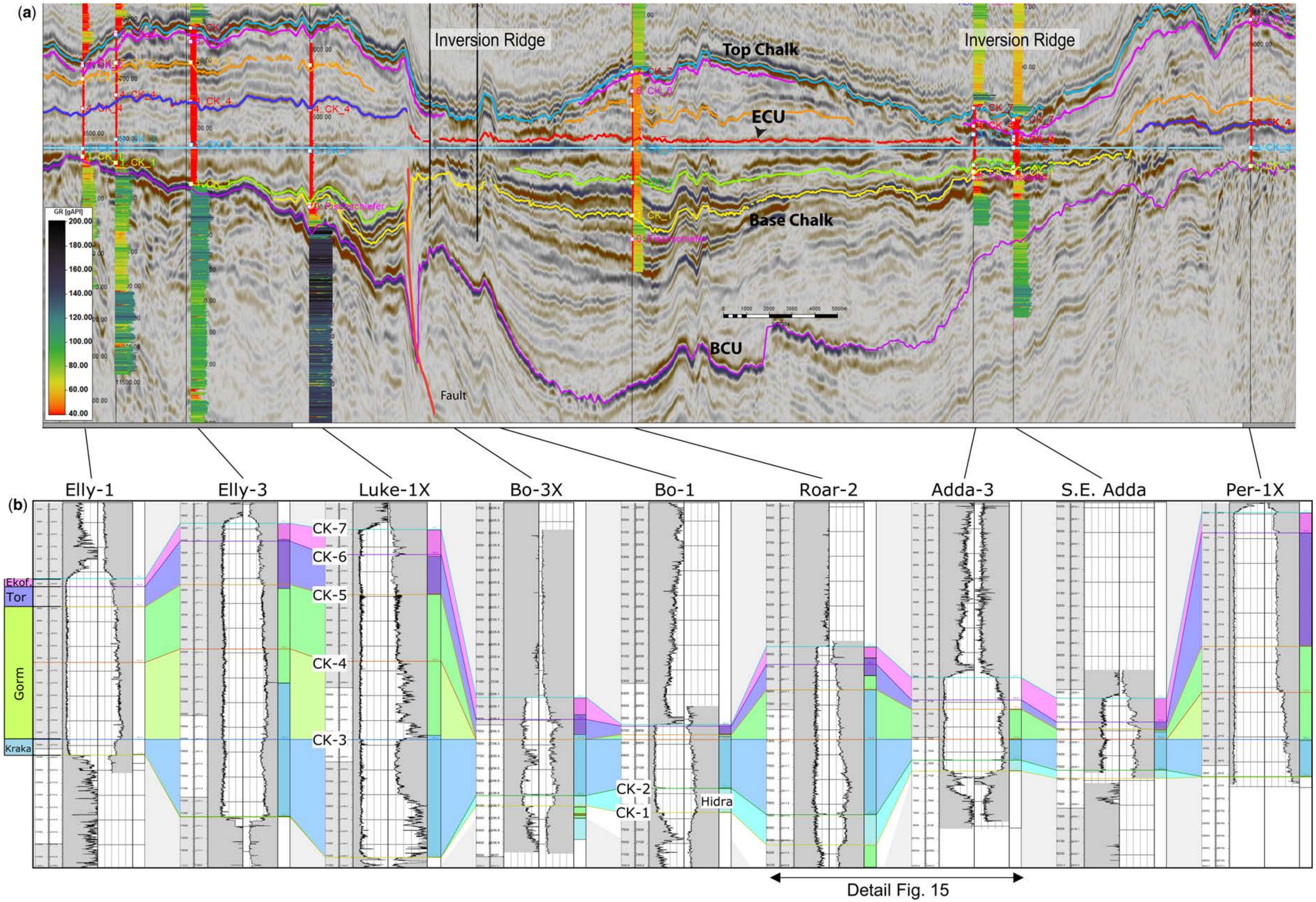

Fig. 14. East–west cross-section flattened on the CK-3 seismic marker, showing the integrated stratigraphic framework of seismic markers, log expression and biostratigraphy. (**a**) Seismic line: note the absence of seismic unit CK-3/CK-4 (Lower Campanian) on the inverted high. (**b**) Well-log correlation with seismic markers and formations (colour fill between wells). The right-hand column of the individual wells shows a biostratigraphy-based definition of the formations. This shows, in general, a good fit, with the notable exception of the Kraka–Gorm boundary in the Elly-3 and Roar-2 wells. A re-evaluation of the biostratigraphy in these wells is recommended. Figure A3 of Appendix A provides a larger image of the well-log correlation. The left-hand curve is gamma ray and the right-hand curve is acoustic impedance (except for Luke-1, where it is resistivity).

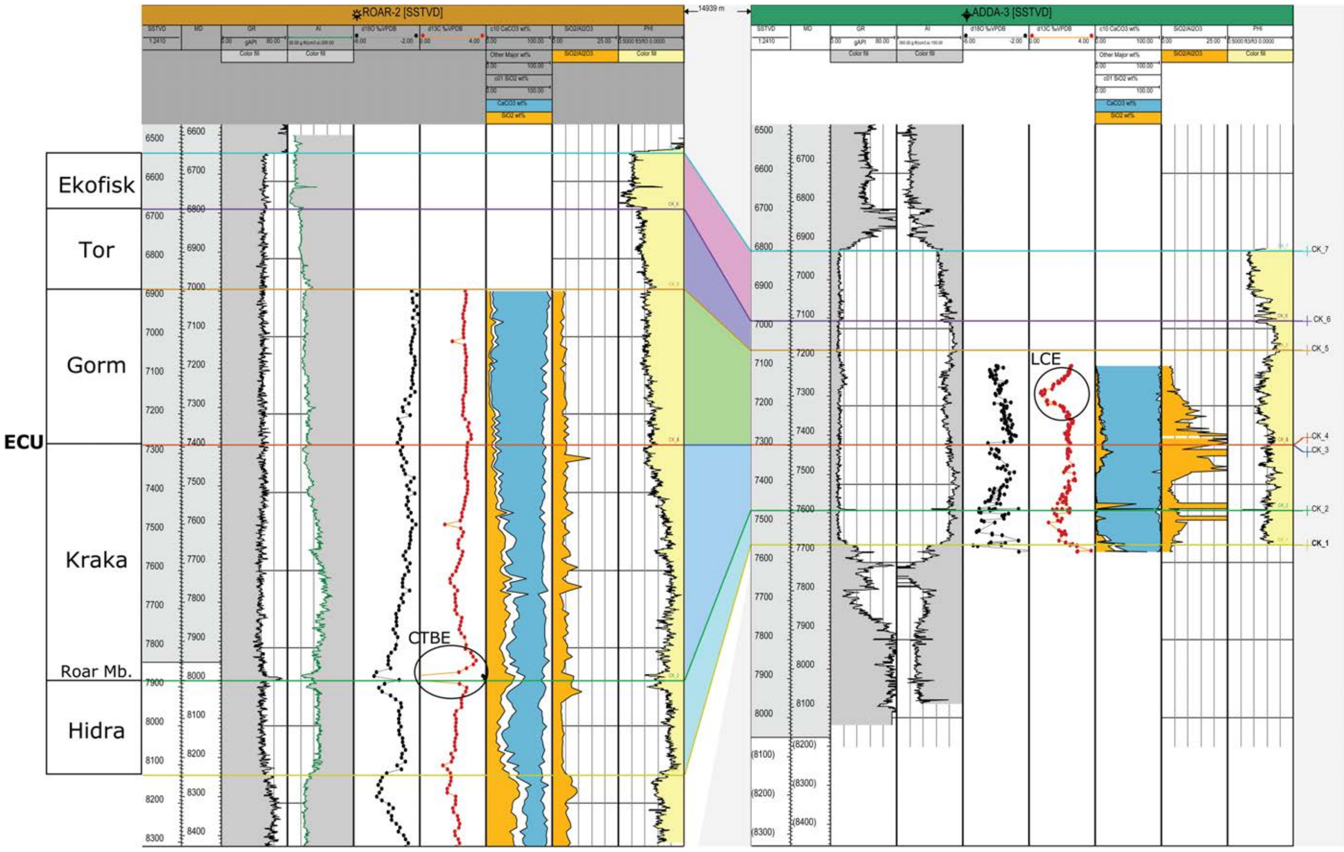

Fig. 15. Correlation panel of the Adda-3 and Roar-2 wells displaying, in this order, gamma-ray and acoustic-impedance logs, O- and C-isotope curves, major element composition, aluminium-normalized SiO_2 content, and an effective porosity log. Chemical analyses were made from core samples in Adda-3 and cuttings samples in Roar-2. The carbon-isotope curves show a well-developed Cenomanian–Turonian Boundary Event (CTBE) in the Roar-2 well, which is very condensed in Adda-3. In the carbonate-isotope curve of Adda-3 the Late Campanian Event (LCE) is well expressed (see Perdiou *et al.* 2015), but it has not been observed in Roar-2. Note the variability in silica content, which in well Roar-2 is mostly related to detrital input, and in the Adda-3 well is related to primary input and diagenetic overprint, which had an overall negative effect on effective porosity. ECU, early Campanian unconformity.

First, the above-described Roar Member, which has an increased clay and organic matter content compared to the surrounding chalk, and is recognizable as a basin-wide expressed seismic marker. This layer corresponds to the worldwide recognized OAE 2 event, which is associated with a global sea-level rise (Arthur *et al.* 1988; Jarvis *et al.* 2011). The other evidence for a phase of maximum sea-level rise has been observed in the Santonian, where seismic reflector CK-3 can be followed throughout the basin overstepping the margins (Figs 7, 11 & 12).

Micropalaeontological observations show evidence of a general deepening of the sea in this phase (Fig. 8). The Cenomanian Hidra Formation is dominated by assemblages of small planktic foraminifera of low diversity (mainly *Hedbergella* spp.), with locally inoceramid-rich facies, and rare occurrences of keeled specimens of the large and complex planktic foraminifera genera. In the Turonian–Santonian Kraka Formation, a change is observed to more diverse assemblages of planktic foraminifera (e.g. *Heterohelix globulosa*, *Globigerinelloides asper*, *Whiteinella* spp. and/or *Hedbergella delrioensis*) including common or abundant keeled planktic foraminifera (e.g. *Marginotruncana marginata*, *M. pseudolinneiana*, *Dicarinella canaliculata* and occasional *Praeglobotruncana* species) and common Radiolaria. Benthic foraminifera are rare throughout this interval, but locally become more common towards the top (e.g. *Stensioeina* spp.).

The combined seismic, lithological and faunal assemblage evidence suggests a progressive deepening of the chalk sea from a possible 100–200 m in the Cenomanian to several hundreds of metres in the Santonian. The additional effect of warmer waters coming in from the south, favouring the proliferation of keeled planktonics, cannot be excluded and, in fact, may well have occurred with maximum sea-level highstands at this time.

Phase 5. Campanian and Maastrichtian: syntectonic chalk deposition of the Gorm and Tor formations. This phase consists of the seismic units UC-3, UC-4 and UC-5, corresponding to the Gorm and Tor formations (Fig. 13). The base of this phase is formed by the early Campanian unconformity, and the top is the hardground marking the Cretaceous–Tertiary (K–T) boundary, as well as the top of the Tor Formation.

The isochore map of seismic unit UC-3 (lower part of the Gorm Formation) highlights the importance of the inverted basin centre and the creation of new depocentres over the previous highs: the Ringkøbing–Fyn High in the east (e.g. Per-1 well) and the Heno Plateau in the west (Fig. 16a). The estimated uplift of the basin centre is of the order of 300–400 m, most of which probably occurred during the early and mid-Campanian. The estimates of the water depths for this time vary from several hundreds of metres in the depocentres to less than 100 m over the new, inverted basin highs. As a result of this tectonically controlled reorganization of the seafloor, chalk sedimentation changed profoundly with condensation and non-deposition on the inverted highs, mass waste deposits along their flanks, and thick accumulations of *in situ* chalks in the new depocentres (Fig. 16). Chalk redeposition is represented by mass flows, debris flows, slumps, olistoliths and channelling, all of which have been reported in the literature (Esmerode *et al.* 2008; Back *et al.* 2011; Smit *et al.* 2014). An additional palaeoceanographical effect of this deformation was the intensification of the bottom currents, as documented by moat and drift systems, and

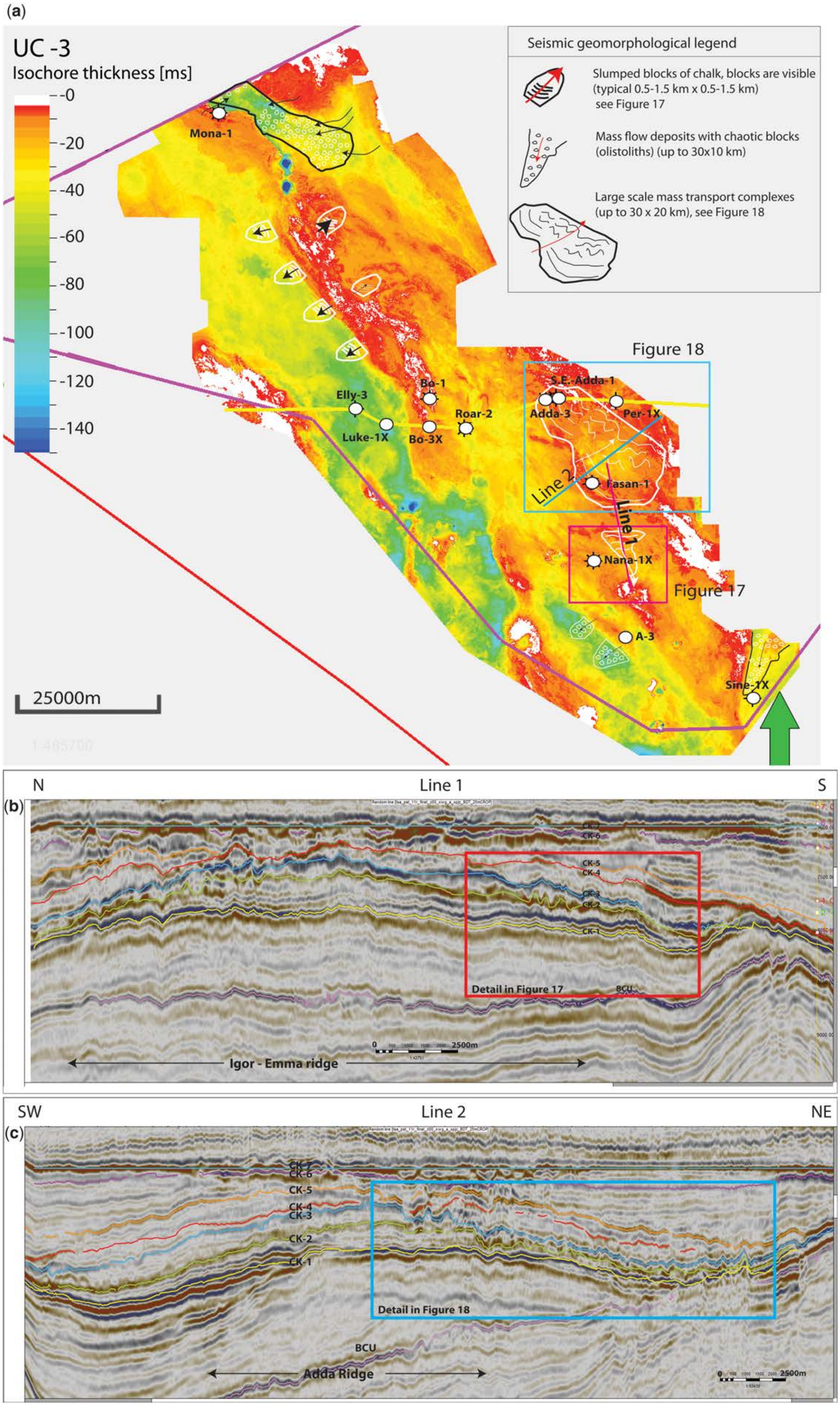

Fig. 16. Early-mid Campanian palaeotopography and gravity deposits: (**a**) Lower–middle Campanian isochore map, and distribution of slump, mass flows and mass-transport complexes; (**b**) seismic line 1, close to Nana-1X, showing slope destabilization in a southwards direction (see in detail in Fig. 17); and (**c**) seismic line 2, close to the Fasan-1 well, showing a large-scale mass-transport complex along the eastern margin of the inverted high (see in detail in Fig. 18).

sediment wave systems (Surlyk & Lykke-Andersen 2007; Esmerode *et al.* 2008; Surlyk *et al.* 2013). During the later part of this phase (upper part Gorm and Tor formations), the basin was gradually filled (Fig. 13).

Owing to the exceptional quality of the seismic data, the 3D geomorphological context of large-scale slope failures can be illustrated. A first example shows an area affected by creep (Figs 16b & 17). In a 2D seismic line, subtle discontinuities are observed in the CK-1–CK-3 interval (Fig. 17b). Placed in a geomorphological context, the interpretation of these features becomes self-explanatory, as an early phase of slope failure (creep) at the head of a seafloor valley (Fig. 17a). The affected sediment is of Cenomanian–Santonian age, and the deformation occurred in the early Campanian. A good example of a fully developed mass-transport complex is shown in Figures 16c and 18. The 2D seismic line provides clear evidence of discontinuity, an erosional surface, disturbed beds and a younger healing phase. Put in the geomorphological context, the different elements of this large depositional feature (17 × 10 km) can be identified, such as the head scarp, slump blocks and compressed toe sediments (Fig. 18a). The deposition of this mass-transport complex also took place in the early Campanian, probably when strongest inversion-controlled relief was created. The cross-sections in Figure 16b & c show that sediment displacement preferably and repeatedly occurred along the flanks of the inverted basin centre. These features have been observed at the scale of the Danish Central Graben (Fig. 16a).

Towards the end of the Campanian, the keeled planktic foraminifera decreased in numbers, whereas the contribution of calcipheres increased (Fig. 8). This trend continued during the Maastrichtian with the appearance of a more uniform, low-diversity faunal assemblage, dominated by calcispheres and small planktic foraminifera, and local occurrences of macrofossil debris. Keeled planktonic foraminifera are virtually absent at this time (Fig. 8). This trend in the faunal assemblages occurred when a gradual infill of the basin is observed (Fig. 13), and is thus interpreted as support for a gradual shallowing. Ecological factors, such as nutrient supply, have also been evoked as being important for calcisphere

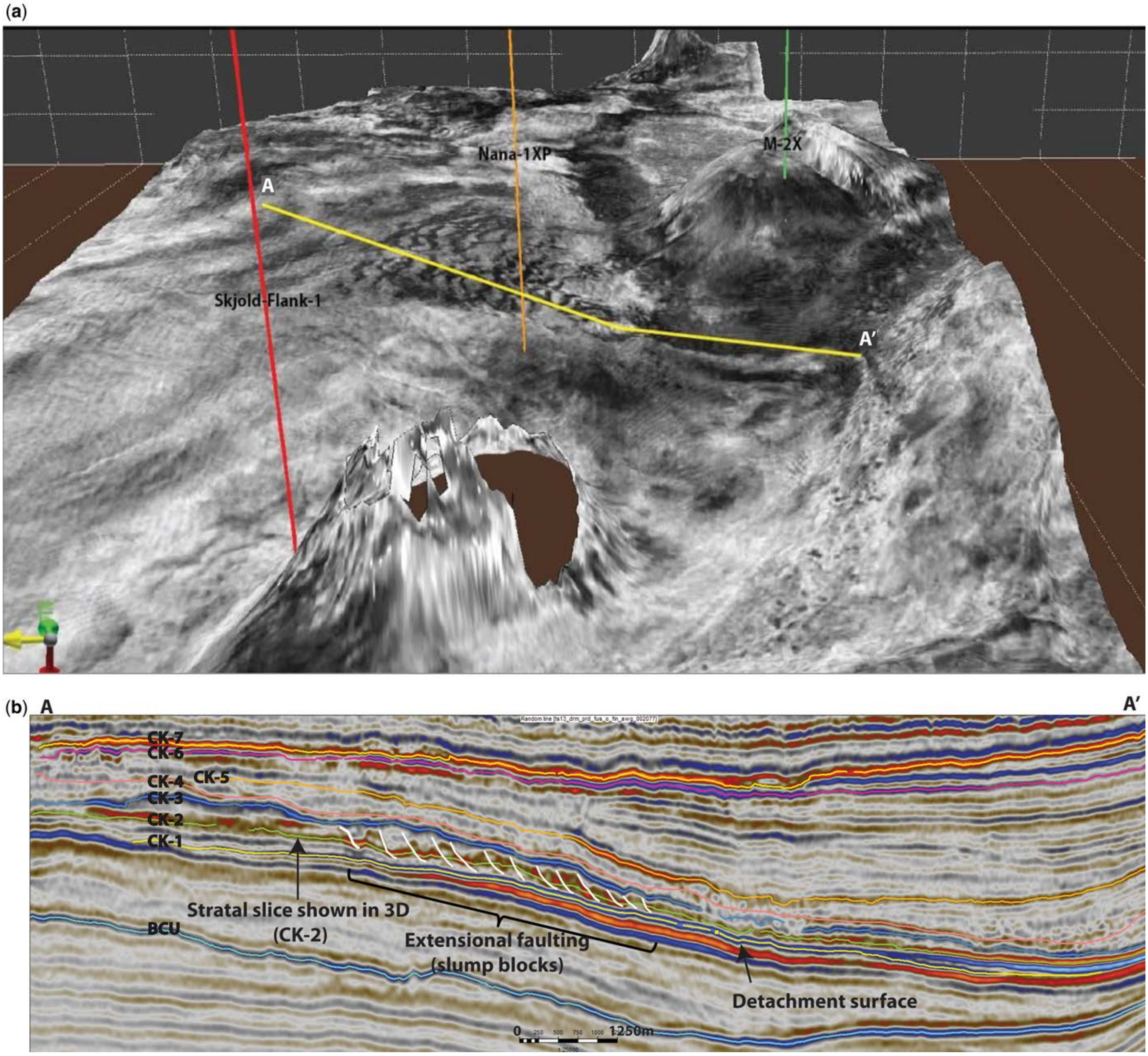

Fig. 17. Creep features in the Nana-1XP area. See Figure 16 for the location map: (**a**) 3D reconstructed geomodel horizon slice using a RMS amplitude, the position of the 2D line in (b) is indicated; and (**b**) 2D seismic line.

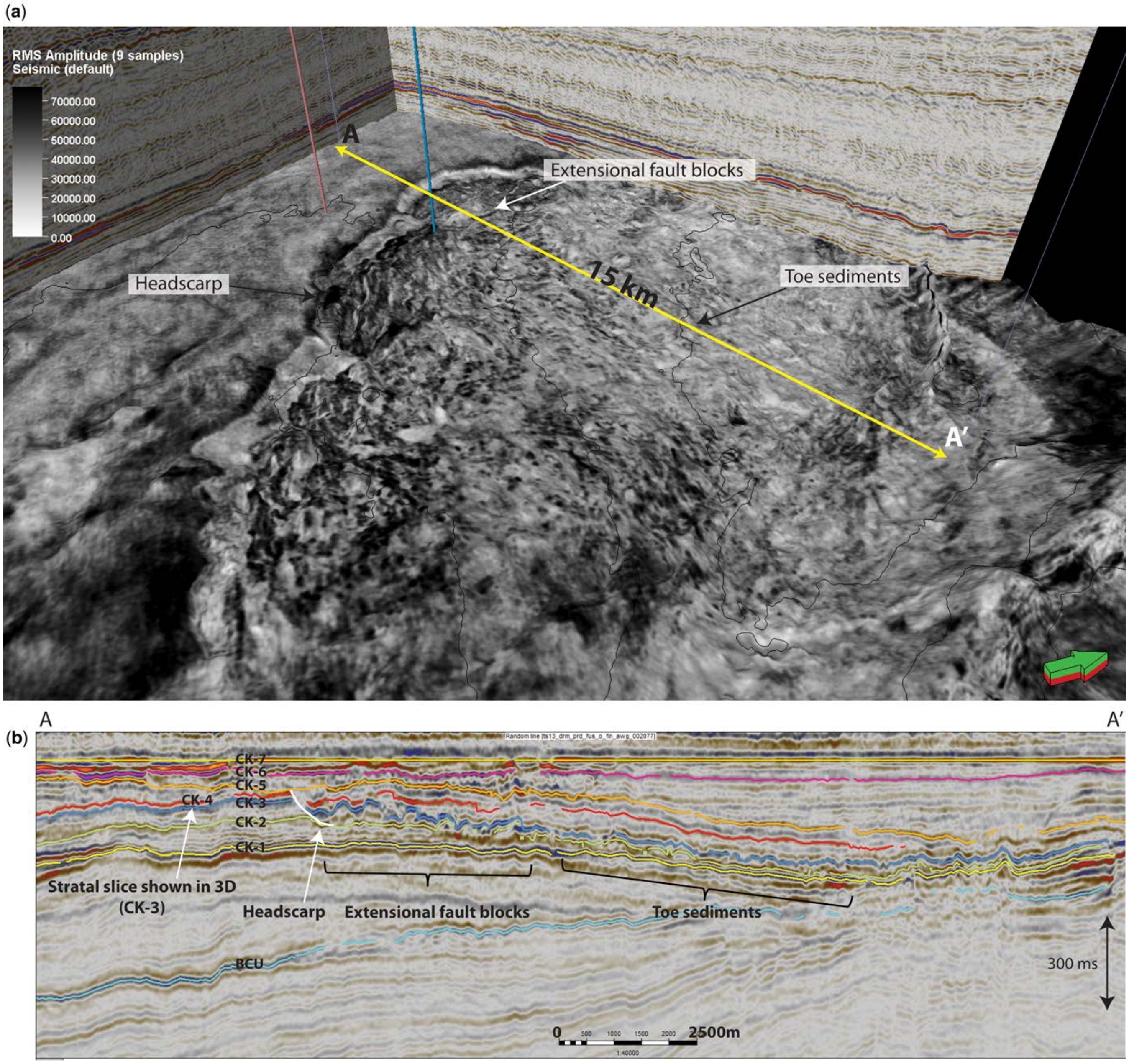

Fig. 18. Mass waste deposit in the Fasan-1 area. See Figure 16 for the location map: (**a**) 3D reconstructed horizon slice using RMS amplitude, the position of the 2D line used in (b) is indicated; and (**b**) 2D seismic line.

blooms (Wilmsen 2003), and it is, indeed, possible that both factors – shallowing and nutrient supply – acted together.

Phase 6. Danian: marl, volcanic ash layers and chalk deposition of the Ekofisk Formation. This phase consists of seismic unit DA-1 and corresponds to the Danian Ekofisk Formation (Fig. 13). It is marked at the base by the hardground at the K–T boundary and at the top by the sharp transition to the fine-grained siliciclastics of the Rogaland Group.

Important global, as well as local, events influenced sedimentation in this phase. The hardground marking the K–T boundary is locally associated with a stratigraphic hiatus. In addition, the early Danian was characterized by a period of volcanic activity in the North Sea Basin, related to the doming of the Shetland area (Coward *et al.* 2003), which led to the deposition of multiple volcanic ash layers that are evident in the GR logs as low-porosity clay streaks (Simonsen & Toft 2006). The later Danian chalk deposits are present over most of the Danish Central Graben and mark a period of renewed sedimentation. The palaeo-water depth in Danian times is estimated, based on seismic and palaeoecological evidence, to have been less than 100 m. The end of the Danian chalk sedimentation was abrupt, and probably related to a combination of a high-amplitude eustatic sea-level fall and local siliciclastic influx (Clemmensen & Thomsen 2005).

The faunal assemblage in the Danian is dominated by small planktic foraminifera associated with common spherical radiolaria and rare benthonic foraminifera (Fig. 8). It needs to be taken into account that keeled planktonic foraminifera became extinct at the K–T boundary. The nannofossil faunal assemblage re-established itself after the K–T event.

Discussion

The interpretation of the Lower Cretaceous as a post-rift, early thermal subsidence succession filling in inherited basin-floor topography is also supported in the wider North Sea Basin (Erratt *et al.* 1999; Gabrielsen *et al.* 2001), although locally deviations from this model may have occurred (see Copestake *et al.* 2003). Campanian–Maastrichtian basin inversion is an equally widespread phenomenon observed in Denmark (Vejbæk & Andersen 2002), Norway (e.g. Hampton *et al.* 2010; Gennaro *et al.* 2013), The Netherlands (Bless *et al.* 1986; van der Molen & Wong 2007) and further afield in the Harz Mountains in northern Germany (Stille 1924; Riedel 1942; Niebuhr *et al.* 2000; Pharaoh *et al.* 2010). This fundamental subdivision in two basin styles is followed here for an evaluation of the local or regional expression of the Danish tectonostratigraphic framework, and the implications for the chalk depositional models and the related play types.

The base of the studied succession, the BCU, is a North Sea Basin-wide observed seismic marker that commonly represents a hiatus and/or a change in facies. The fact that it separates the dysaerobic to anoxic sedimentation below (Kimmeridge Clay and Farsund formations) from the oxic depositional conditions above this surface testifies to its profound influence on the regional sedimentation patterns (Rawson & Riley 1982; Copestake *et al.* 2003; Kyrkjebø *et al.* 2004). The top of the succession is the top Chalk Group surface, which is an equally widespread marker bed corresponding to the Danian–Selandian boundary, and marks the cessation of 40 myr of continuous Upper Cretaceous chalk deposition in the North Sea Basin with a return to clastic sedimentation (Clemmensen & Thomsen 2005).

The early thermal subsidence basin (latest Ryazanian–late Santonian)

For the Lower Cretaceous of the North Sea Basin, a number of sequence schemes have been proposed over the years, most of which were established for a particular region (e.g. Crittenden *et al.* 1997; Ineson *et al.* 1997; Jeremiah 2000; Jeremiah *et al.* 2010). Here we compare our subdivisions in tectonostratigraphic phases and sequences to the scheme proposed by Copestake *et al.* (2003), which was intended to provide a framework for the Northern North Sea Basin, and the study by Jeremiah *et al.* (2010), which deals with the southern, siliciclastic margin of the North Sea Basin in The Netherlands. The sequences defined by Copestake *et al.* (2003) follow mostly the methodology of Galloway (1989), defining a sequence by maximum flooding surfaces, but for some intervals Vail *et al.* (1977) is followed using the sequence boundaries.

Phase 1 (latest Ryazanian–Valanginian–early Hauterivian). This phase corresponds to sequences K10 and K20 of Copestake *et al.* (2003), which consist of coarse- and fine-grained marine siliciclastic sediments, interpreted in the UK and Norwegian sectors as being overall transgressive and deposited in an aerobic environment. In the Danish Central Graben, coarser-grained siliciclastic sediments only occurred at the base of the succession (Vyl Formation: Fig. 7), and are subsequently overlain by mudstones of the Valhall Formation. An overall relative rise in sea level was also concluded for the Danish sector. Particular to the Danish Central Graben is the asymmetrical infill pattern with westwards-prograding clinoforms that created a shelf along the eastern margin adjacent to the Ringkøbing–Fyn High, and condensed sedimentation along the western margin and in the northern part of the graben (Vidalie *et al.* 2014). The invoked depositional processes are longshore currents in this re-entrant of the North Sea Basin, processes that may also have influenced mudstone sedimentation in other parts of the North Sea Basin at this time. This interpretation explains the previously reported absence of Valanginian strata (Copestake *et al.* 2003) as a result of condensation on the toesets of clinoforms.

Phase 2 (late Hauterivian–Barremian–early Aptian). Phase 2 corresponds to sequences K30 and K40 of Copestake *et al.* (2003), and has a very characteristic sequence stratigraphic pattern expressed in different depositional environments throughout the North Sea Basin (Fig. 19). Based on our work in the Danish sector, the following regional correlation is proposed:

- The base K30 sequence boundary corresponds to the base of our sequence 2, which marks a small hiatus in the proximal domain. The oldest Cretaceous chalks occur in this sequence.
- The top K30 sequence boundary here is put at the top of the Tuxen Formation, which corresponds to the top of our sequence 3. This surface marks a sharp lithological change from clean carbonates to marls, expressed as a clear break in the log patterns recognizable throughout the North Sea Basin as far north as the Utsira High in the Viking Graben in Norway (e.g. Copestake *et al.* 2003). On the shelf, it is also associated with an abrupt faunal and floral change from a shallow platform top assemblage ($<$50 m) to a fully open-marine assemblage. This surface is a combined sequence boundary and transgressive surface, and is dated as being of late to latest Barremian age (top *S. pingue* Zone), which is slightly older than the Barremian–Aptian boundary reported by Copestake *et al.* (2003). The K30 sequence has been subdivided into two smaller-scale sequences (2 and 3: Fig. 19) separated by the Munk Marl Bed. This organic-rich marker bed is interpreted as a lowstand systems tract based on seismic and biostratigraphic data, in agreement with the original interpretation by Ineson *et al.* (1997). The age of the Munk Marl Bed is late early Barremian (base *Hoplocrioceras fissicostatum* Zone), which is younger than the earliest Barremian age reported by Copestake *et al.* (2003).
- The top K40 sequence boundary is put at the base of the new Fanø Member. This surface is characterized by an abrupt change in the faunal composition, from calcareous benthic and planktonic foraminifera below to almost exclusively agglutinated foraminifera above, and a change in lithology from marlstones to claystones. The surface is locally erosional, onlapped along the basin margins and represents a hiatus on the shelves, where the Fanø Member is thin or absent. It is interpreted to be the result of a significant drop in sea level, causing exposure and erosion along the basin margins. This surface is dated as latest early Aptian–earliest late Aptian (top *Tropaeum bowerbanki* Zone) and is in agreement with Copestake *et al.* (2003). The K40 MFS equates to the marker bed of the Fischschiefer Member, which is interpreted as the local expression of the OAE 1a event (e.g. Ineson *et al.* 1997; Copestake *et al.* 2003; Mutterlose *et al.* 2009; Pauly *et al.* 2013). It is associated with a eustatic sea-level rise (Arthur *et al.* 1988), and is here dated to be of *Deshayesites forbesi* Zone age (cf. Copestake *et al.* 2003).

Based on the biostratigraphic control, a correlation can be proposed at the scale of the North Sea Basin, including the siliciclastic-dominated, coastal succession of the Dutch sector studied by Jeremiah *et al.* (2010). The Munk Marl Bed (base sequence 2 in K30: Fig. 19) is also recognized in the Norwegian sector and in Germany (Hauptblatterton: Copestake *et al.* 2003) as an organic-rich layer, and is time-equivalent to the Berkel Sandstone Member (*H. fissicostatum–Paracrioceras elegans* ammonite zones), interpreted as a lowstand systems tract (Jeremiah *et al.* 2010). In sequence K40, the transgressive facies below the Fischschiefer Member is correlated with the condensed, glauconitic De Lier Sandstones and the Valhall-4 Member (Copestake *et al.* 2003) in the UK (Fig. 19). The organic-rich Fischschiefer Member is present in Norway and Germany, and is time-equivalent to the organic-rich part of the

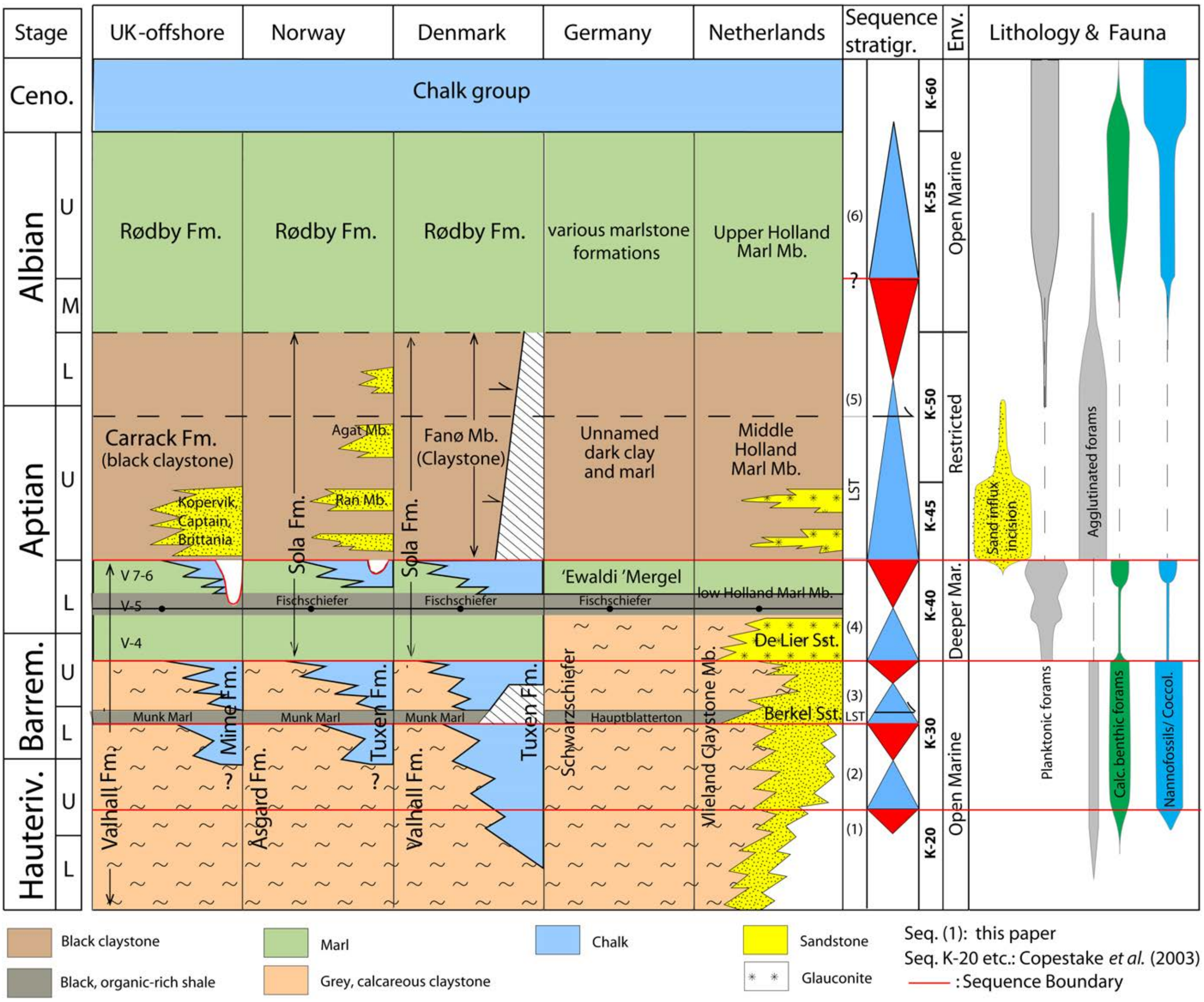

Fig. 19. Chronostratigraphic scheme for the upper part of the Lower Cretaceous in the North Sea Basin. Note the regional expression of depositional sequences with clear lithological and faunal assemblage changes across sequence boundaries. Literature references – Danish sector: Larsen (1966), Jensen *et al.* (1986) and this study; the UK: Deegan & Scull (1977), Johnson & Lott (1993) and Copestake *et al.* (2003); Norway: Isaksen & Tonstad (1989) and Copestake *et al.* (2003); Germany: Voigt *et al.* (2008); The Netherlands: Jeremiah *et al.* (2010).

lower Holland Marl Formation. The organic-poor part of the Sola Formation, between the Fischschiefer Member and the Fanø Member, is time-equivalent to the organic-poor part of the lower Holland Marl Formation, the Valhall-6 and Valhall-7 members in the UK, and the German Ewaldi facies, all of which mark the return to more oxic conditions (Fig. 19) (Crittenden *et al.* 1991; Garrett *et al.* 2000; Jeremiah *et al.* 2010). The top K40 sequence boundary in all locations is a sharp surface marking a lithological, as well as a faunal, change (Fig. 19). To summarize, the facies patterns of the K40 sequence have a supra-regional expression with the transgression, culminating in the OAE 1a event, recognized as a regional onlap across NW Europe (Jeremiah *et al.* 2010). At this time, connections were established between the Boreal and Tethyan domains.

The occurrence of the chalks in the Tuxen and Sola formations is a unique and geographically limited phenomenon that occurred along the margins of the Early Cretaceous highs in the North Sea Basin (Danish sector, central and SW Norwegian sector, and SE UK sector). One explanation for this occurrence may be the distance from the siliciclastic-shedding source areas along the margins onshore of the UK, The Netherlands and Germany. This made the shelves in the centre of the North Sea Basin a nutrient-poor (oligotrophic) environment, the preferred setting for both coccoliths and nannoconids, which are the main components of the Lower Cretaceous nannofossil assemblage.

Phase 3 (late Aptian–Albian). Phase 3 can be lithologically subdivided at the scale of the North Sea Basin into a lower part, which consists of claystones and locally sandstones and which corresponds to upper Aptian–lower Albian units K45 and K50, and an upper part, which consists of marlstones and corresponds to middle–upper Albian unit K55 (Copestake *et al.* 2003) (Fig. 19).

The lower claystone unit corresponds to the Fanø Member in the Danish sector, the Carrack Formation in the UK sector, the 'unnamed dark clay and shales' in Germany, and the middle Holland Marl Formation in The Netherlands (Fig. 19). This unit has a typical faunal content of exclusively agglutinated benthic foraminifera, and it shows seismic onlap against the basin margins. Another characteristic observed in the UK, Norwegian and Dutch sectors of the North Sea, but not in the Danish sector, is the significant increase in clastic supply to the basins at this time (e.g. the Kopervik trend, the Britannia upper members, the Agat Member and the Ran sandstone Member: see e.g. Crittenden *et al.* 1997, 1998; Ainsworth *et al.* 2000; Copestake *et al.* 2003). These sandstone deposits are locally associated with incised channel systems and non-deposition on the basin highs.

We support the interpretation of this regional sedimentation pattern as the result of an earliest late Aptian drop in relative sea level, which led to the isolation of intrashelf basins (restricted environments, faunal change), and the mobilization and deposition of coarse siliciclastics into the basinal lows (Crittenden *et al.* 1997, 1998). A late Aptian, high-amplitude, long-lasting sea-level drop has also been documented in a number of sites in the Neotethys domain, such as the Arabian Plate (van Buchem *et al.* 2010; Maurer *et al.* 2013), Spain (Bover-Arnal *et al.* 2014) and Siberia (Medvedev *et al.* 2011). In these locations, evidence was found of large incised valley systems, that were backfilled during the latest Aptian and earliest Albian. The global expression of this sea-level fluctuation supports a glacio-eustatic origin rather than a local tectonic overprint (e.g. Maurer *et al.* 2013; Rodriguez-Lopez *et al.* 2016). In this context, the K45 and K50 units of Copestake *et al.* (2003) are interpreted as lowstand deposits associated with the late Aptian, long-lived global sea-level lowstand.

The middle and upper Albian rocks show a gradual, regional transgression at the scale of the North Sea Basin (e.g. Crittenden 1987; Jeremiah *et al.* 2010). Uniform depositional conditions existed, as expressed in the regionally defined Rødby Formation (K55 unit of Copestake *et al.* 2003), which is characterized by transgressive onlap along the margins, the gradual increase in carbonate content (in particular, coccoliths) and the reappearance of a deeper, open-marine faunal assemblage (Fig. 19).

Phase 4 (Cenomanian–early Santonian). In Phase 4, the overall transgressive trend continued during the Cenomanian when the chalk depositional system was established at the scale of NW Europe (e.g. Dercourt *et al.* 2000; Surlyk *et al.* 2003; Voigt *et al.* 2006). The dominant seismic facies patterns during this phase are laterally continuous seismic reflections with relatively small differences in thickness and an overstepping of the basin margins, which are interpreted as evidence of a parallel-bedded, autochthonous chalk deposition (Fig. 20). Around the Cenomanian–Turonian boundary, a basin-wide, organic-rich marker bed is observed (variously named the Black Band Bed, Plenus marl, Blodøks and the new Roar Member: Fig. 20), which is interpreted as the local expression of the OAE 2 event (e.g. Surlyk *et al.* 2003; Jarvis *et al.* 2011). Tectonic deformation at this time was minor, and local and eustatic sea-level fluctuations were the dominant factors controlling sedimentation. A study of Turonian and Coniacian coastal outcrops in northern France led Quine & Bosence (1991) to propose that strong bottom currents occurred, possibly as a result of eustatic sea-level fluctuations. Lasseur *et al.* (2008), in outcrop studies of the Cenomanian–middle Coniacian chalks in the Paris Basin, suggested that chalk sedimentation in this area took place on a wide shelf, with a water depth within or around the storm wave base (<100 m). Compared to these observations, depositional conditions in the Central Graben of the North Sea Basin were probably deeper (several hundreds of metres), as suggested by the deep-water planktic faunal assemblage, the scarcity of shallow-water facies and the basin-scale context (Fig. 8).

The inverted basin (late Santonian–Danian)

Phase 5 (late Santonian–Campanian–Maastrichtian). A summary of literature data shows that the late Santonian–early Campanian interval marks a dramatic change in basin configuration and sedimentation styles at the scale of NW Europe (Fig. 20). This was caused by two related factors: a compressional tectonic deformation phase, which caused basin inversion in the Norwegian, Danish and Dutch sectors of the Central Graben, and the contemporaneous intensification of the sea-bottom current systems.

The onset of the tectonic deformation in the North Sea Central Graben occurred in all locations during the mid–late Santonian (Fig. 20). The climax of this deformation is, however, slightly diachronous: latest Santonian in the Norwegian sector (Sikora *et al.* 1999; Hampton *et al.* 2010; Gennaro *et al.* 2013), early Campanian in the Danish sector (Vejbæk & Andersen 2002; this study) and, eventually, at the beginning of the middle Campanian in the Dutch sector (van der Molen 2004). The impact of the deformation was greatest in the Dutch sector, where on reactivated fault blocks most of the Chalk Group was eroded (van der Molen 2004; van der Molen *et al.* 2005), followed by the Danish sector, where the large-scale basin inversion led to significant condensation over the inverted highs; in the Norwegian sector, however, the uplift was particularly focused along the more restricted Lindesnes and Josephine highs, that follow deeper-seated fault systems inherited from the Late Jurassic rift phase (Gennaro *et al.* 2013). The estimated amount of uplift varies from up to 1000 m in The Netherlands to several hundreds of metres in Denmark, which is matched on local highs in the Norwegian sector.

Contemporaneous with the tectonic uplift, a change in the sedimentation processes occurred. This can be partly attributed to instability created along the flanks of the uplifted areas, which led to mass-transport complexes, slumps and olistoliths, and partly to an intensification of bottom currents as a result of the increased topography of the seafloor. Sedimentological expressions of these changes in the oceanographic conditions include the formation of crestal hardground, moat and drift systems, sediment wave complexes, and channel incisions (Fig. 20). Interestingly, good evidence of bottom-current intensification has also been found outside the zone of structural deformation, with common hardgrounds and seismically mapped channel incisions of up to 120 m in the Paris Basin (Esmerode & Surlyk 2009), and seismically expressed channels in combination with phosphate-rich and current-resistent fauna paved hardgrounds in southern England (Jarvis 1980; Jarvis & Woodroff 1981; Evans *et al.* 2003; Gale *et al.* 2013, 2015). These observations imply that the relatively local deformation of the North Sea Central Graben area had an effect on the sedimentation patterns across a much larger area through its influence on the current systems of the NW European intra-cratonic basins. The interplay of the reconfiguration of the basin-floor topography, with newly created highs and lows, and the circulation patterns in the sea, caused strong currents that controlled sediment distribution and was a typical phenomenon of the Late Cretaceous seas of NW Europe.

Seismic analysis of the upper Campanian and Maastrichtian deposits show an overall infill pattern of the previously created topography, accompanied in the Danish sector by the occurrence of a more homogeneous and shallower-water faunal assemblage (Fig. 8). Moat and drift systems, channel incision, and hardground surfaces that developed around the Campanian–Maastrichtian boundary and during the mid-Maastrichtian are interpreted by several authors as a probable result of eustatic sea-level fluctuations (e.g. Esmerode *et al.* 2008; Gennaro *et al.* 2013; Gennaro & Wonham 2014). A large-scale channel system that developed in the Danish Basin, as well as in the German and Dutch sectors of the North Sea, persisted from the late Maastrichtian into the Danian and may have been a marine connection that survived the K–T boundary events (van der Molen 2004; Surlyk & Lykke-Andersen 2007; Surlyk *et al.* 2008).

For the Eldfisk Field region, in the Norwegian sector, Hampton *et al.* (2010) linked their depositional sequences to different tectonic pulses defined in the Harz Mountains in central Germany. The literature compilation presented in this study suggests there is evidence for a climax in the tectonic inversion in the early and

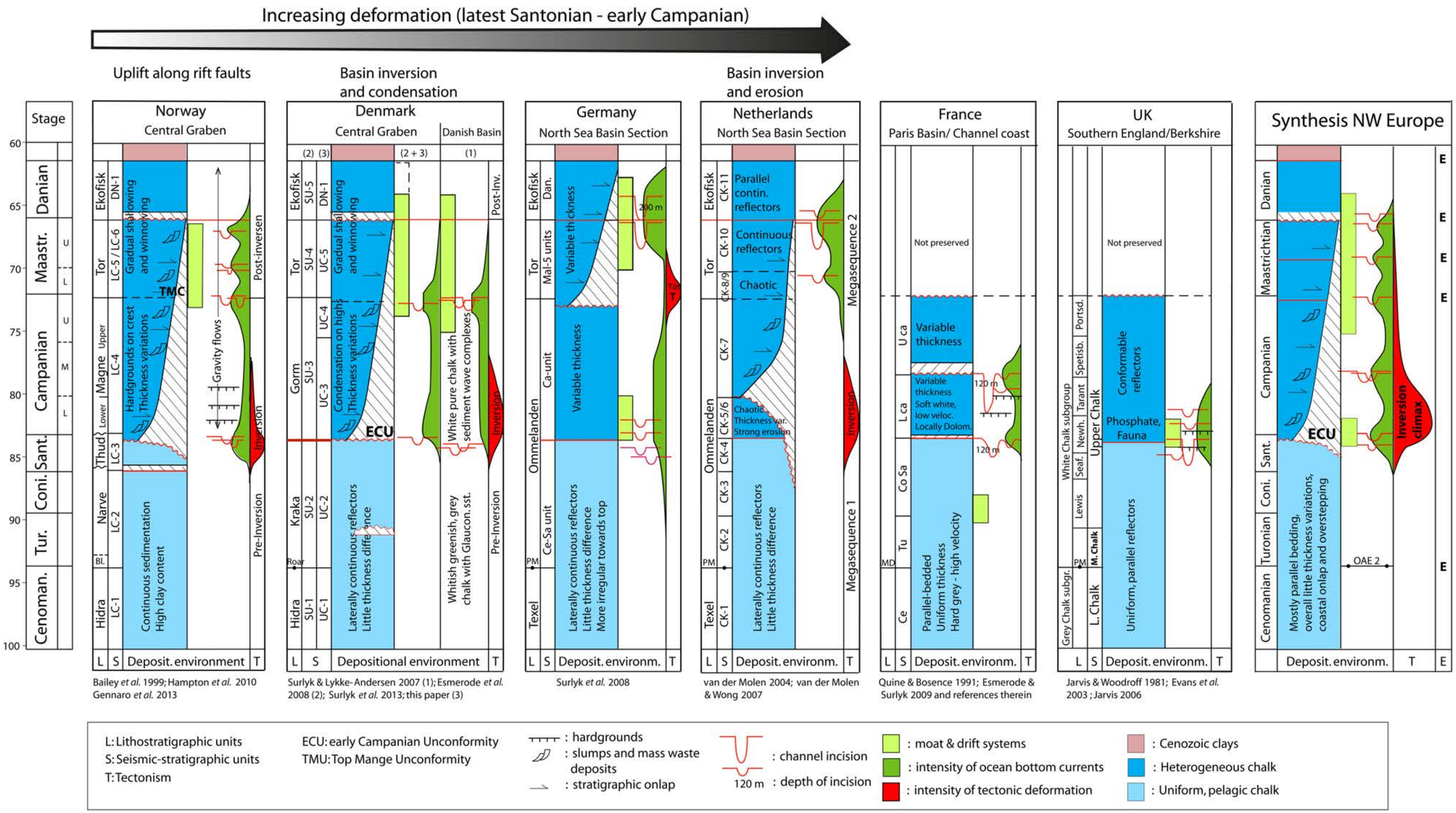

Fig. 20. Chronostratigraphic scheme for the Chalk Group in the North Sea Basin showing the timing of tectonic deformation (inversion) and the depositional patterns. Note the synchronous occurrence of the basin inversion tectonics and the regional intensification of the bottom-current systems. The climax of both is reached in the early Campanian. The ECU thus separates two distinctly different phases in the Upper Cretaceous chalk depositional history.

mid-Campanian, after which the deformation gradually waned (Fig. 20). In addition, the overall shallowing as a result of the infill, and substantiated by the faunal assemblage of the Tor and Ekofisk, suggests that there may have been a gradual shift from tectonically dominated to eustatically dominated sedimentation in the Maastrichtian and Danian. Clearly separating the relative influence of tectonic uplift and eustatic sea-level fall in the late Campanian and Maastrichtian deposits is difficult. We therefore prefer to stress the importance of the early Campanian climax of deformation, which has been reported throughout northern Europe, but are doubtful about the shorter deformation phases of earlier authors (e.g. Stille 1924; Riedel 1942; Bless *et al.* 1986; Mortimore *et al.* 1998). In a wider sense, the early Campanian compressional event can be placed in a plate tectonic context of closure of the Tethyan Ocean through collision of the African Plate (and associated micro-plates) with the Eurasian Plate (see the overview in Pharaoh *et al.* 2010). The resultant Alpine and Pyrenean orogenies led to intra-plate shortening across the NW European foreland, with the possibility that some of the intra-plate deformation was also associated with spreading in the North Atlantic.

Phase 6 (Danian). The Danian stands out as a separate phase for several reasons: (a) the global impact of the K–T boundary event on the marine fauna and flora, with the extinction of most planktonic foraminifera and a gradual recovery of the coccoliths (Brasher & Vagle 1996): (b) the early Danian volcanic activity, with the basin-wide deposition of ash layers (Simonsen & Toft 2006); and (c) in comparison to the Campanian and Maastrichtian, the depositional patterns are more laterally continuous with limited thickness changes, although local deformation and non-deposition did occur.

Implications of Cretaceous hydrocarbon play types

Within the presented tectonosedimentary history, four different chalk depositional models can be distinguished in the Danish Central Graben that differ in faunal assemblage, basin configuration and dominant depositional processes, affecting chalk composition, distribution and heterogeneities. Support for this subdivision is also provided by the differences in the reservoir characteristics (porosity–permeability relationships) of the Danian (Ekofisk Formation), Maastrichtian (Tor Formation) and Lower Cretaceous (Tuxen and Sola formations) chalks that are independent of current burial depth, and should thus be related to the primary depositional conditions (see Jakobsen *et al.* 2004, fig. 8). Clay content has been identified early on as one of the key factors controlling reservoir quality, notably in the Lower Cretaceous (Kennedy 1987). At the scale of the North Sea Basin, siliciclastic lowstand deposits represent another important Cretaceous play. A short summary of these different play types is presented below.

Barremian–Aptian chalk (Tuxen and Sola formations). The Tuxen and Sola formations contain oil in the Danish Central Graben, where the Valdemar Field has been in production since 1993. The determining factor for reservoir quality in both of these formations is the insoluble residue (mostly clay), which varies from 6 to 50% and correlates negatively with porosity and permeability (porosity range 10–48%; matrix permeability range 0.01–4 mD: Jakobsen *et al.* 2004). In light of this, the revised sequence stratigraphic interpretation and the chalk depositional model of the Tuxen and Sola formations gain importance, since they introduce a clay-rich basin centre and preferred deposition of the clean chalks around the basin margins. As a result, an understanding of the palaeogeography becomes an essential input for the prediction of reservoir quality trends within fields, and for the identification of other sweet spots in this stratigraphic interval in the basin.

Cenomanian–Santonian chalk (Hidra and Kraka formations). Although oil has been found in the Hidra and Kraka formations (e.g. the Adda wells), no producing fields exist as of today in these formations in Denmark. In Norway and the UK, several fields produce from the Kraka equivalent formations: the Eldfisk, Hod and Valhall fields produce from the chalks of the Magne Formation; and in the Bruce Field (UK Quadrant), the Turonian chalk is a gas condensate reservoir (Beckly *et al.* 1993).

Deposition of the Cenomanian Hidra Formation occurred during a period of tectonic quiescence, resulting in a high lateral continuity of sedimentary facies. Since the reservoir quality of the Hidra Formation is mainly controlled by the clay content, an understanding of the palaeogeography plays an important role in the prediction of the variations in reservoir quality, similarly to that for the Tuxen and Sola formations.

In the upper part of the Kraka Formation, more stratigraphic heterogeneities are observed (thickness changes, channels, hardgrounds and slumps) owing to the beginning of tectonic deformation in the mid–late Santonian. During the early Campanian inversion climax, parts of the Kraka Formation were redeposited (Fig. 17); in other locations, however, a long-lasting hiatus developed with the formation of hardgrounds and associated silica precipitation that decreased the porosity, and thus created intra-chalk permeability barriers (Figs 14 & 15).

Campanian–Maastrichtian chalk (Gorm and Tor formations). By far, the majority of the North Sea chalk fields have reservoirs in the Tor Formation, including: the fields of the greater Ekofisk area in Norway; the Dan, Halfdan and Tyra fields in Denmark; the Banff, Joanne and Machar fields in the UK; and the Harlingen and Hanze fields in The Netherlands (e.g. Surlyk *et al.* 2003; Megson & Tygesen 2005). Chalk of the Tor Formation reservoirs has typically the highest porosities and permeabilities of all chalk reservoirs (e.g. Jakobsen *et al.* 2004). Although less common, the Campanian chalks can be a reservoir in Norway, typically in addition to reservoirs in the Tor and Ekofisk formations, and especially in the larger fields and in fractured chalk fields (e.g. the Ekofisk, Hod and Valhall fields).

The depositional characteristics of the Tor and Gorm formations are broadly comparable, both having been deposited during a phase of active tectonic uplift and increased in bottom-current intensity, which caused significant stratigraphic heterogeneity (moats, drifts and channels; condensed, hardground-crested highs, flanked by slumps and mass-transport complexes). A good example of the influence of bottom currents on primary facies and porosity distribution was presented by Surlyk *et al.* (2008), who demonstrated that the best effective porosity was observed in updip parts of channel flanks and not in the main channels. Anderskouv & Surlyk (2012) demonstrated that reservoir characteristics can also be predicted by taking into account both the primary depositional chalk facies and the amount of post-depositional transportation and slumping.

Danian chalk (Ekofisk Formation). The majority of oil and gas fields in the Danish sector has a producing Danian reservoir interval (Ekofisk Formation), including the Dan, Halfdan and Tyra fields in the Danish sector, and the fields in the greater Ekofisk area in the Norwegian sector (Surlyk *et al.* 2003). Many fields have a tight zone in the lower Danian (bentonite clay deposits), which separates the Maastrichtian reservoir layers from the Danian reservoir layers, and locally this zone may act as a baffle or even a seal (e.g. the Ekofisk, Kraka, Halfdan and Dan fields).

The stratigraphic architecture and depositional environment of the Danian chalks in the Danish sector appear more continuous. Reservoir characteristics of the Danian chalks are poorer than the Cretaceous chalks (Jakobsen *et al.* 2004). For low-porosity chalks, the permeability of Danian chalk may be up to a factor of 10 lower than the permeability of the otherwise similar Maastrichtian chalk. For high-porosity chalks, this difference diminishes (Surlyk *et al.* 2003).

The chalk depositional models presented above are defined based on primary facies composition and stratigraphic architecture, which have had a fundamental influence on the reservoir architecture. In order to get a full picture of the reservoir characteristics and trap configuration, early and burial diagenesis, as well as structural deformation and hydrodynamic aspects, also need to be taken into account (e.g. Surlyk *et al.* 2003; Megson & Tygesen 2005; Vejbæk *et al.* 2012). In this context, the tectonostratigraphic subdivision and applied methodology will be helpful in directing further work to elucidate the complexity and remaining potential of the chalk reservoirs in the North Sea Basin.

Lower Cretaceous siliciclastic lowstands. This study has drawn attention to the presence of upper Aptian lowstand deposits in the central part of the Danish Central Graben through the definition of the new Fanø Member. So far, no evidence of coarse siliciclastics has been found in this claystone interval, probably owing to the distance from available sand sources. However, in the UK and Norwegian sectors, this play contains a number of oil fields in the Britannia, Captain, Kopervik and Ran sandstones (e.g. Crittenden *et al.* 1997, 1998) (Fig. 19). The Lower Cretaceous Valanginian sandstone reservoirs in the UK sector (e.g. the Punt Sandstone in the Golden Eagle Field) are also interpreted as lowstand deposits. In the claystones of the Valhall Formation in the Danish sector, lowstand deposits of approximately that age were also found but showed no evidence of the presence of sandstone (Vidalie *et al.* 2014).

Conclusions

The following conclusions are drawn from this study:

- The Cretaceous–Danian depositional history of the Danish Central Graben is characterized by two basin styles: (a) an early thermal subsidence basin, for the late Ryazanian–late Santonian, inherited from Late Jurassic rifting with minor tectonic deformation and with eustatic sea level acting as a dominant controlling factor on sedimentation; and (b) a basin influenced by inversion tectonics for the Campanian, Maastrichtian and Danian, with active uplift and synsedimentary tectonic deformation having a major impact on the sedimentation processes (e.g. increased intensity of bottom currents, slope failures along flanks of highs and hardground crested highs).
- The transition from one basin style to another occurred in the middle of the Chalk Group in the North Sea Basin and is associated with a compressional tectonic deformation phase that affected NW Europe. The climax of this tectonic deformation is dated as being of late Santonian–early Campanian age, and it created a basin-wide unconformity, here called the early Campanian unconformity (ECU). This is the most prominent stratigraphic surface in the Chalk Group; in the Danish Central Graben, it is clearly recognizable in seismic data and is associated with a hiatus that varies in duration from the early Campanian to the entire Campanian, Maastrichtian and Danian interval.
- A new depositional model is proposed for the Barremian–lower Aptian Tuxen and Sola chalks, with a preferred production and deposition of the nannofossils along the basin margins on shallow shelfal areas, and the presence of a more clay-rich basin centre. The seismic stratigraphic work on the underlying Valhall Formation was instrumental in documenting the Lower Cretaceous basin morphology, which formed the substratum for the deposition of these Lower Cretaceous chalks.
- The sequence stratigraphic importance of the upper Aptian sea-level lowstand is emphasized in the Danish Central Graben by the introduction of the new Fanø Member. Although sand-poor in the Danish Central Graben, upper Aptian lowstand deposits are sand-prone and hydrocarbon-bearing in the UK and Norwegian sectors of the North Sea Basin.
- The stratigraphic distribution and palaeoenvironmental implications of the main Cretaceous chalk faunal assemblages in the Danish Central Graben have been integrated into the tectonostratigraphic history. These have helped to identify basin-wide environmental changes important for sequence stratigraphic analyses, as well as local variations due to seafloor topography.
- Six tectonostratigraphic phases are distinguished in the Danish Central Graben, based on variations in basin configuration, dominant lithologies, depositional processes and faunal assemblages. These are:
  (1) Valanginian–early Hauterivian: prograding claystones of the Valhall Formation;
  (2) Late Hauterivian–early Aptian: aggrading/prograding chalks of the Tuxen and Sola formations along basin margins, and organic-rich marker beds of the Munk Marl Bed and the Fischschiefer Member;
  (3) Late Aptian–Albian: lowstand claystones of the Fanø Member and the overall transgressive marlstones of the Rødby Formation;
  (4) Cenomanian–late Santonian: transgressive chalk deposition of the Hidra and Kraka formations;
  (5) Campanian–Maastrichtian: syntectonic chalk deposition, and intensified bottom currents in the Gorm and Tor formations;
  (6) Danian: Cretaceous–Palaeogene boundary extinction, volcanic activity and last chalk deposition (Ekofisk Formation).
- These tectonostratigraphic phases and their particular stratigraphic expressions can be followed across the wider North Sea area. The Barremian–Aptian sequences observed in the Boreal domain can also be correlated to well-established sequences in the Neotethys domain, whereas the Campanian–Maastrichtian sedimentation pattern, with its strong local tectonic overprint, is a particular feature of the Boreal domain.
- This study proposes four chalk play types for the Danish Central Graben that differ in reservoir quality and architecture due to tectonic context, palaeoecology and palaeoceanography, and sediment and faunal composition, in addition one siliciclastic play type is distinguished:
  (1) Tuxen–Sola chalk play: distribution along basin margins, decimetre-scale bedded clay–limestone couplets, a mixture of nannoconids and coccoliths;
  (2) Hidra–Kraka chalk play: distribution evolved from basin margins to regional blanket, and from decimetre-scale bedded clay–limestone couplets to clean chalk and coccoliths dominated;
  (3) Gorm–Tor chalk play: significant heterogeneity caused by synsedimentary tectonic deformation (mass-transport complexes) and intensification of bottom currents (channels, moat and drift systems), coccoliths dominated in the Valdemar, and calcispheres dominated in the Tor;
  (4) Ekofisk chalk play: less heterogeneity, coccoliths dominated;
  (5) Fanø siliciclastic lowstand play: proven in the UK and Norwegian sectors but not yet proven in the Danish sector.
- Based on an integration of seismic response, log character and age determination, the first formal definition of the lithostratigraphy of the Chalk Group in the Danish Central Graben is proposed, as well as an addition to the Lower Cretaceous lithostratigraphic nomenclature.

This paper summarizes the results of work carried out over the years in the exploration and production departments of Maersk Oil, and has benefited much from work sessions and discussions with our colleagues. We would like to acknowledge in particular: Teddy Fuzeau, Maiwenn Herpe, Ulla Hoffmann, Charles Jourdan, John Karlo, Helle Krabbe, Esbern Møller Nielsen, Alessandro Sandrin, Ingelise Schmidt, Niels Schødt and Marie Vidalie. In addition, Jon Ineson and Emma Sheldon (GEUS), Jurg Mutterlose (Bochum University), Finn Surlyk (Copenhagen University) and Ian Jarvis (London Polytechnic) are acknowledged for sharing their insights of the Cretaceous of NW Europe. We are particularly grateful to Dave Barrington for his feedback on the palaeoecological part of the paper. The Upper Cretaceous part of this paper is partly based on the MSc thesis of Florian Smit (2014), Aarhus University. The constructive comments of journal reviewers Jon Ineson (GEUS) and Andrea Gennaro helped to improve this paper. The partners of the Danish Underground Consortium (Maersk Oil, Shell, Chevron) are gratefully acknowledged for granting permission to publish this paper and for financing the cost of the colour figures.

Appendix A: Cretaceous–Danian lithostratigraphy of the Danish Central Graben, North Sea

Based on the detailed tectonostratigraphic and sequence stratigraphic study of the Danish Central Graben described earlier, we propose the first formal lithostratigraphic nomenclature of the Upper Cretaceous–Danian Chalk Group since the introduction of the informal seismic units by Lieberkind *et al.* (1982) and an addition to the lithostratigraphy of the Lower Cretaceous Cromer Knoll Group as defined by Jensen *et al.* (1986).

The distinction of different lithostratigraphic units in the Chalk Group of the Danish Central Graben has always been difficult owing to the very homogeneous response of the chalks in well logs. Here we have adopted a multi-disciplinary approach to define chronostratigraphically meaningful lithostratigraphic units by combining seismic response, log character and age dating. Three established formations from the UK and Norwegian sectors of the North Sea are formally extended into the Danish sector (the Hidra, Tor and Ekofisk formations) and two new formations (the Kraka and Gorm formations) are proposed to replace the informally used Hod Formation, and one new member (the Roar Member) is proposed to replace the informal Plenus marl–Black Band Bed (Fig. A1).

In the Lower Cretaceous Cromer Knoll Group, a new member is introduced in the upper part of the Sola Formation (Fanø Member) to replace the informal 'Albian shales' (Fig. A1). The justification is that it represents a specific lithological unit and is an important interval in terms of sea-level history and basin evolution.

Cromer Knoll Group

Jensen *et al.* (1986) adopted the Cromer Knoll Group in the Danish Central Graben as defined by Rhys (1974), including the later extension proposed by Deegan & Scull (1977) (Fig. A1). They subdivided the Group into five formations, four of which were adopted from earlier work in the Norwegian and UK sectors, namely the Vyl, Valhall (including the Leek Member), Sola and Rødby formations, and added the Tuxen Formation, which includes the organic-rich Munk Marl Bed (Jensen *et al.* 1986). The Tuxen Formation is time-equivalent to the Mime Formation in the Norwegian and UK sectors (Copestake *et al.* 2003; Gradstein *et al.* 2016) (Fig. A1).

*Sola Formation (*redefined*)*

History. The Sola Formation was first named and described by Hesjedal & Hamar (1983) in the Norwegian sector. It represented the upper, mid Aptian–lower Albian part of the Valhall Formation, as defined by Deegan & Scull (1977) (Fig. A1). The formation was, however, not formally defined in a type section by these authors. Jensen *et al.* (1986) formally introduced the Sola Formation in the Danish Central Graben, but with a different age (middle Barremian–Albian). Gradstein *et al.* (2016) adopted the shorter age range of Hesjedal & Hamar (1983) in the Norwegian sector, but also indicated the longer age range for the formation in the Danish sector (Fig. A1).

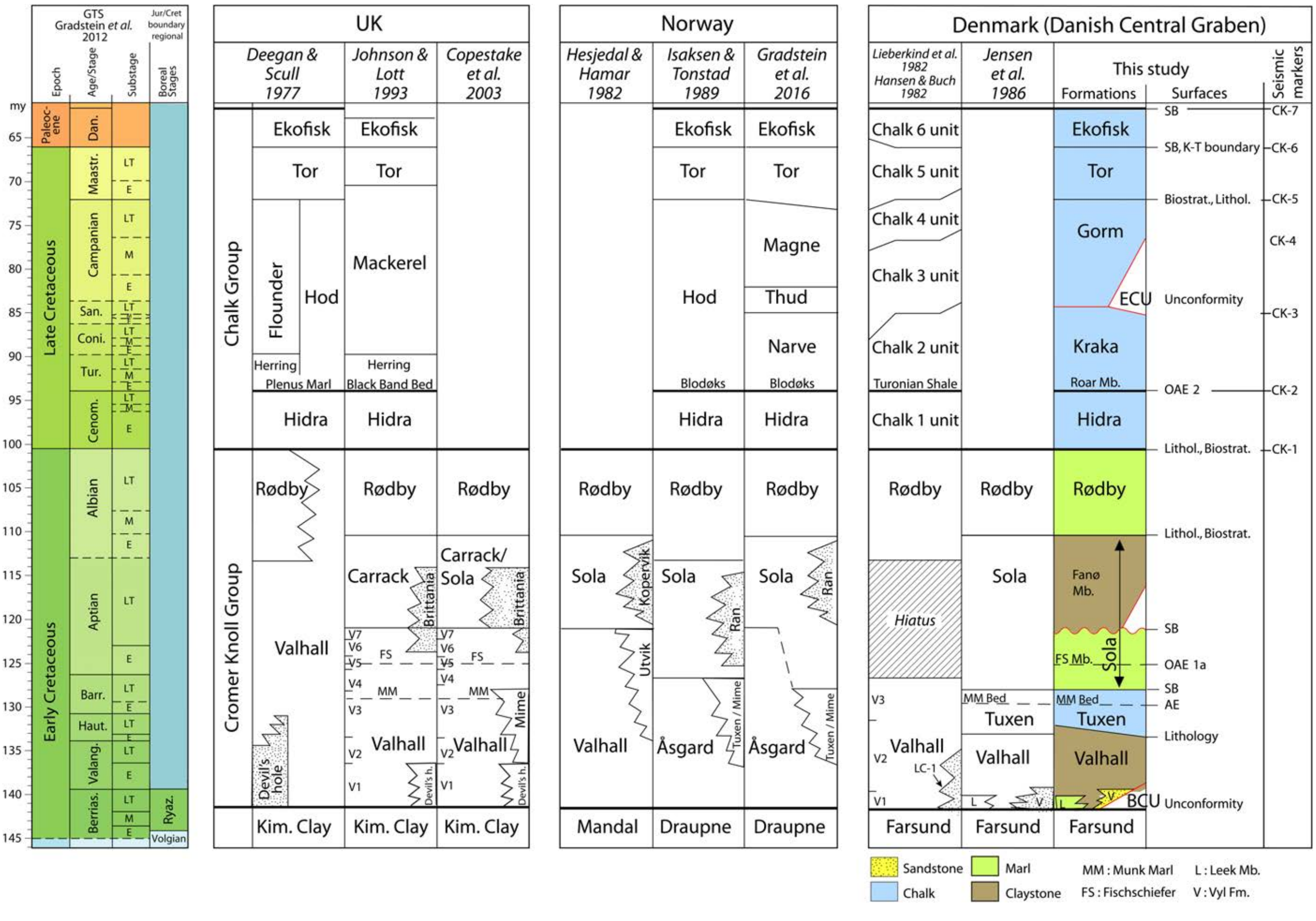

Fig. A1. Comparative lithostratigraphic summary table showing the nomenclature for the Cretaceous–Danian interval of the Danish Central Graben defined in this study, and those for the UK and Norwegian sectors of the North Sea Basin. The stratigraphic nature of the formation boundaries is indicated. SB, sequence boundary; OAE, Oceanic Anoxic Event; AE, Anoxic Event.

The Sola Formation includes the Fischschiefer Member, which was first named and described by Kemper (1976) in Germany. Subsequently, Riley *et al.* (1992) adapted the name and defined the Fischschiefer Member in the Scapa Field in the UK sector, which was followed by Johnson & Lott (1993). In the Danish Central Graben, Jensen & Buchardt (1987) and Ineson (1993) also adapted this nomenclature.

Here we introduce a new member for the Sola Formation in the Danish Central Graben, the Fanø Member, which corresponds to its upper clay-dominated part (Fig. A1).

*Fanø Member (*new member*)*

History. The upper part of the Sola Formation in the Danish Central Graben is locally characterized by a claystone unit, informally called 'Albian shales'. Considering the importance of this unit in the sequence stratigraphic analysis of the Lower Cretaceous (this paper) and its economic importance in other parts of the North Sea Basin, this unit is now raised to formal member status.

Name. From the 56 km^2 large island Fanø in the North Sea, just off the city of Esbjerg on the SW coast of Denmark.

Well type section and reference wells. Type well: Elin-1, 9843–10.065 ft (measured depth (MD)). Reference wells Baron-2, Nora-1, Roar-2 and Boje-1 (Fig. A2).

Thickness. The formation has an irregular distribution, mostly absent along the margins of the Danish Central Graben, and is well preserved in the basin centre, where it reaches a considerable thickness (e.g. 280 ft (92 m) in the Baron-2a well) (Figs 10 & A2).

Lithology. The formation consists of non-calcareous grey, millimetre-laminated claystones with little bioturbation. The faunal content is dominated by agglutinated benthic formanifera. The Fanø Member is fully cored in the Valdemar-1 well (7390–7447 ft MD).

Log characteristics. In the depocentres, the gamma-ray (GR) log of this formation shows a typical upwards-increasing/upwards-decreasing trend. Where present along the margins, it is recognized as a thin higher gamma-ray spike or interval (Fig. A2).

Boundaries. The base of the member is put at the change from reddish, calcareous mudstones and marls to grey laminated claystones (7447 ft MD: Valdemar-1 well), this is expressed in the log pattern by a clear and gradual increase of the GR log. The upper boundary corresponds to the change from the grey, laminated claystones of the Fanø Member to the overlying whitish grey marls of the Rødby Formation, expressed by a clear upwards decrease in the gamma-ray values owing to the increase in the carbonate content.

Depositional environment. Based on the lithological composition, the virtual absence of bioturbation and the paucity of the fauna, the depositional environmental is interpreted as a restricted basin. In a sequence stratigraphic context, this is interpreted as a lowstand systems tract that was deposited during a late Aptian sea-level lowstand (this paper).

Chronostratigraphy. Middle/upper Aptian–lower Albian.

Distribution. Upper Aptian–Lower Albian claystone units are recognized at the scale of the North Sea Basin (Figs A1 & 19). In the UK sector, it corresponds to the upper Aptian–lower Albian Carrack Formation (see fig. 12.1 in Copestake *et al.* 2003), which is time-equivalent to the clay-rich Sola Formation as defined in the Britannia Field by Ainsworth *et al.* (2000). In the Dutch sector, a time-equivalent claystone unit is named the middle Holland Marl Member; in the German sector, it corresponds to the 'Unnamed clay and marl' unit. In a recent revision of the Norwegian lithostratigraphic nomenclature, Gradstein *et al.* (2016) defined the Sola Formation as of mid-Aptian–early Albian age; in their figures 4.4 and 4.5, a sequence stratigraphic interpretation of this interval is provided that is consistent with the interpretation proposed here (Fig. 19). This unit is well developed in the basin centre, where it contains sandstones embedded in claystones that are often hydrocarbon-bearing in the Norwegian and UK sectors (e.g. the Britannia, Kopervik and Captain formations, and the Ran sandstones: Fig. 19).

Chalk Group

The formally introduced lithostratigraphic subdivision of the Upper Cretaceous of the North Sea region by Deegan & Scull (1977) still forms the basis for much of the current terminology. Later additions were proposed by Isaksen & Tonstad (1989) for the Norwegian sector and by Johnson & Lott (1993) for the UK sector (Fig. A1). The Chalk Group was erected for the southern carbonate-dominated part of the North Sea Basin, and the Shetland Group for the northern siliciclastic-dominated part. Surlyk *et al.* (2003) suggested that this distinction on group level between two regionally significant and markedly different facies tracts should be upheld, despite the proposition by Isaksen & Tonstad (1989) to include the chalk succession in the Shetland Group of Deegan & Scull (1977). The viewpoint of Surlyk *et al.* (2003) is followed here (Fig. A1).

Lieberkind *et al.* (1982) described the Chalk Group in the Danish Central Graben, and subdivided the group into six informal seismic units (Chalk units 1–6), which were tentatively correlated with the formations of Deegan & Scull (1977) (Fig. A1). This paper formally extends the definitions by Deegan & Scull (1977) of the Hidra, Tor and Ekofisk formations into the Danish Central Graben, replacing the informal units of Lieberkind *et al.* (1982). In addition, we erect two new formations: the Kraka and Gorm formations to replace the Hod Formation of Deegan & Scull (1977) (the Chalk units 2–4 units of Lieberkind *et al.* 1982); and the Roar Member as the equivalent of the informal 'Turonian shales' of Lieberkind *et al.* (1982) at the base of the Kraka Formation (Fig. A1).

Owing to the homogeneity of the chalk facies, the definitions of the Chalk formations are based on an integration of seismic, well-log (lithological) and biostratigraphic information, and take into account new insights about the depositional history presented in this study. In Figure A3, a regional correlation panel integrating GR logs, acoustic impedance (density × sonic) and biostratigraphy is presented. In addition, Figures A4–A6 provide seismic to well ties for three key wells in the Danish Central Graben (E-1, Elly-3 and Roar-2).

Hidra Formation

The Hidra Formation was erected by Deegan & Scull (1977). The formation is named after the Hidra High in Norwegian blocks 1/3 and 2/1, which derived its name from the island of Hidra on the SE coast of Norway. The formation spans the Cenomanian, and consists of fine-grained white to light grey, strongly bioturbated hard and dense chalky limestone with interbedded dark grey to reddish mudstones (Surlyk *et al.* 2003). Isaksen & Tonstad (1989) and Johnson & Lott (1993) maintained the definitions of the Hidra Formation after their revisions of the Chalk Group lithostratigraphy in Norway and the UK, respectively. Lieberkind *et al.* (1982) defined the informal Chalk unit 1 within the Central Graben of the Danish North Sea and correlated this unit with the Hidra Formation as defined by Deegan & Scull (1977) (Fig. A1).

In this paper, we formally adopt the Hidra Formation for this lowermost lithostratigraphic unit of the Chalk Group in the Danish Central Graben. The formation overlies the Rødby Formation of the Lower Cretaceous Cromer Knoll Group and is overlain by the Roar Member of the Kraka Formation (new member and new formation).

Kraka Formation (new formation)

History. This formation corresponds to the informal seismic Chalk unit 2 of Lieberkind *et al.* (1982), who correlated it with the lower part of the Hod Formation of Deegan & Scull (1977). Lieberkind *et al.* (1982) included the 'Turonian shales' as an informal basal unit in the Chalk unit 2 (Fig. A1).

Name. The name Kraka is taken from the Danish oil and gas field discovered in 1966 and put into production in 1972. The Kraka Field is located some 200 km west of the Danish town of Esbjerg on the west coast of Jylland, and was the first hydrocarbon discovery offshore in the entire North Sea area. The field was named after Kraka, who was a queen in the Norse mythology married to Ragnar Lodborg.

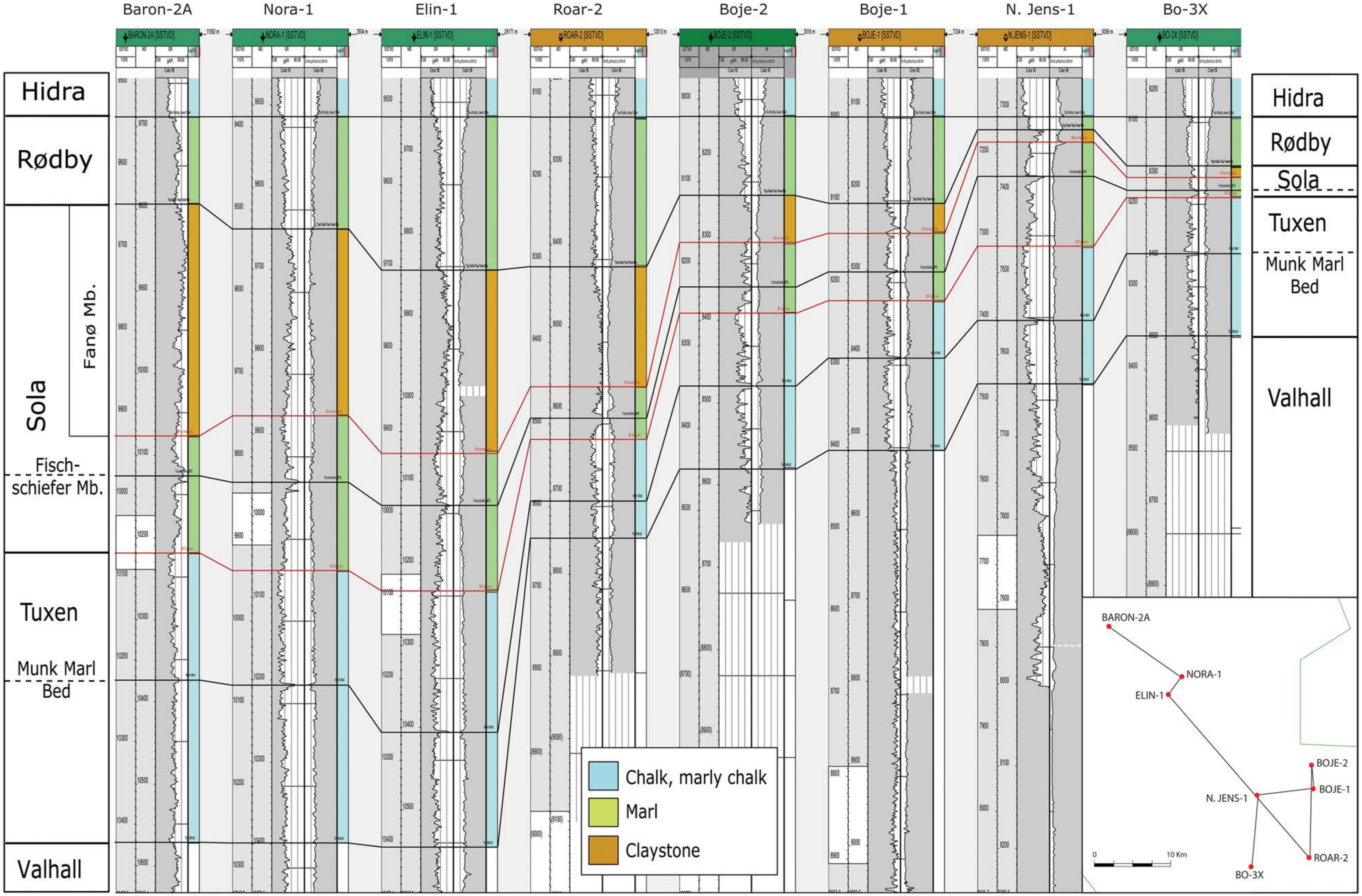

Fig. A2. Well-log correlation of the Lower Cretaceous displaying the lithostratigraphic units of the Cromer Knoll Group in the Danish Central Graben, including the new Fanø Member. Note the lateral variations in thickness of the Fanø Member, which is best developed in the centre of the basin. The red lines are sequence boundaries.

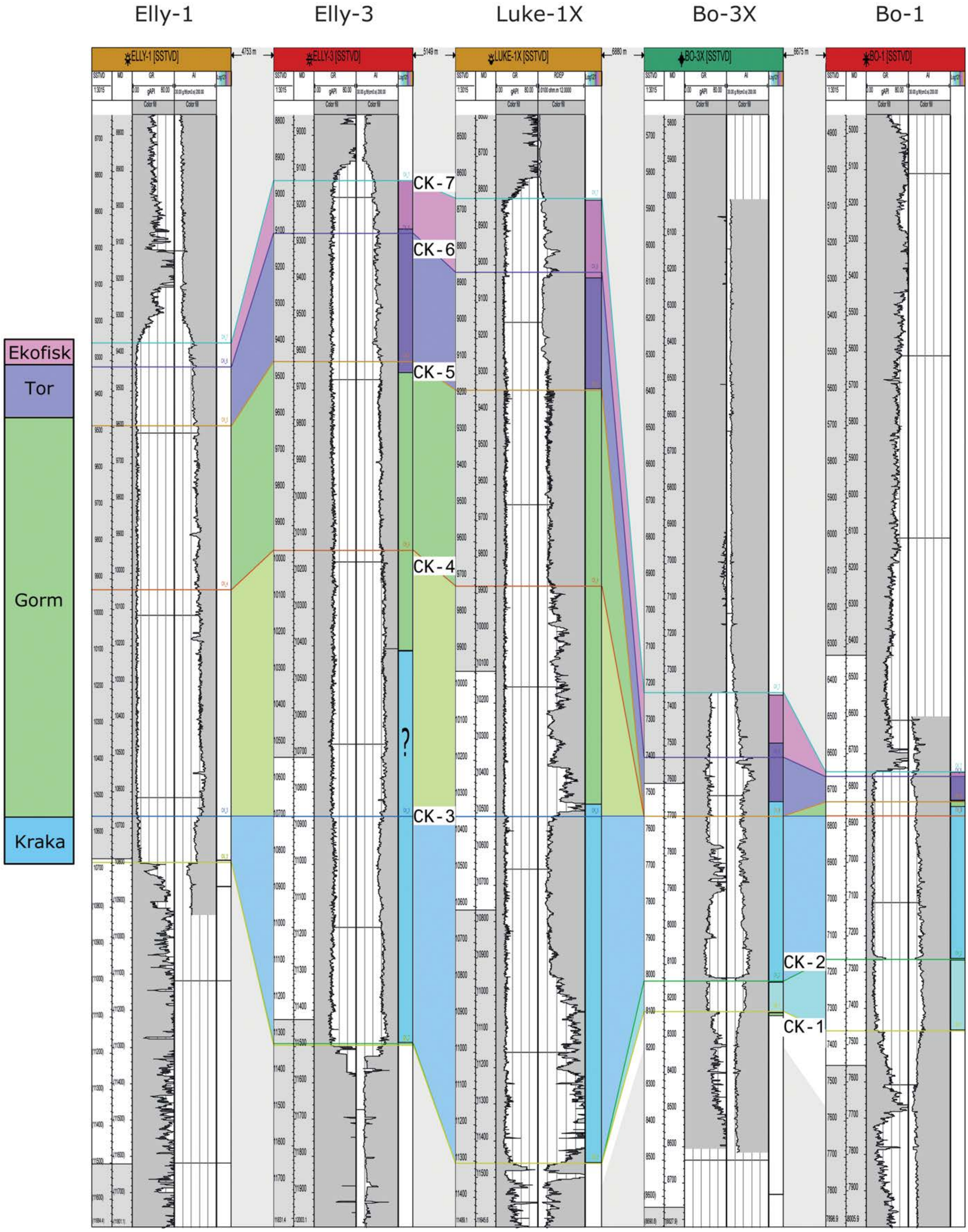

Fig. A3. Well-log correlation of the Upper Cretaceous displaying the lithostratigraphic units of the Chalk Group in the Danish Central Graben as formally defined in this paper. Seismic markers CK-1–CK-7 are regionally mapped and tied to the wells (see Figs A4–A6). Colour fill between the wells follows the most consistent seismic marker/log pick/biostratigraphic-controlled formation boundaries. The last well column on the right-hand side of each individual well display shows the formation boundaries placed using the biostratigraphy. These are generally in good agreement with the seismic markers, with the notable exception of the CK-3 marker (Kraka–Gorm boundary) in the Elly-3 and Roar-2 wells. The consistency of the seismic markers and log picks for this boundary in the other wells suggests a potential problem with biostratigraphic age dating. The Hidra Formation and Roar Member are absent in the Elly-1 and Elly-3, Luke-1X and Per-1X wells as a result of non-deposition (proximal, basin-margin position).

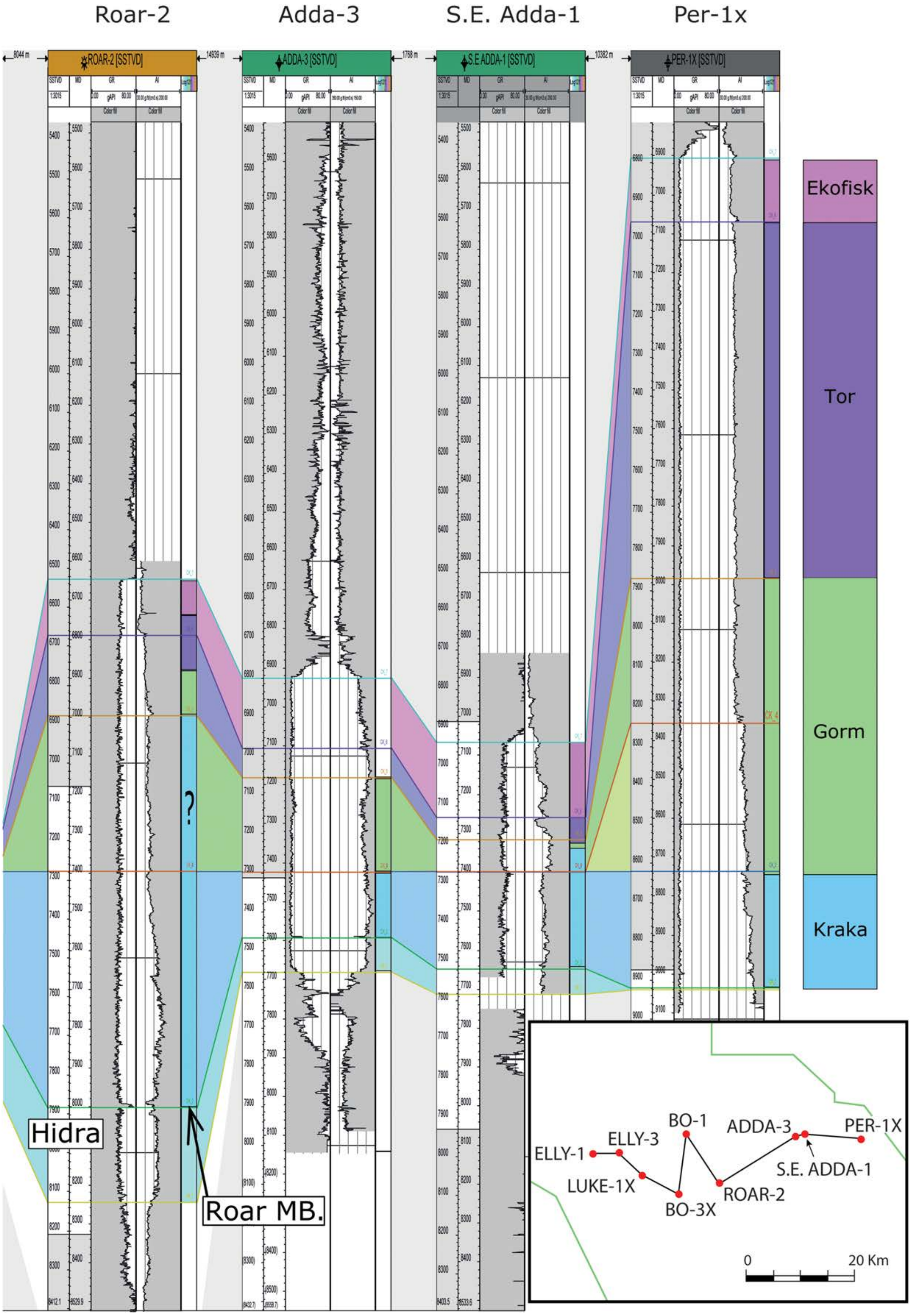

Fig. A3. *Continued.*

Well type section and reference wells. Type well: Luke-1, from 10.513 to 11.482 ft (MD) (Fig. A3); reference wells E-1 (Fig. A4) and Adda-3 (fully cored in this well; Fig. A3).

Thickness. The thickness of the formation varies significantly from very thin to a thickness of 1049 ft true vertical depth (TVD) (346 m) in the Luke-1 well located in the depocentre (Fig. A3).

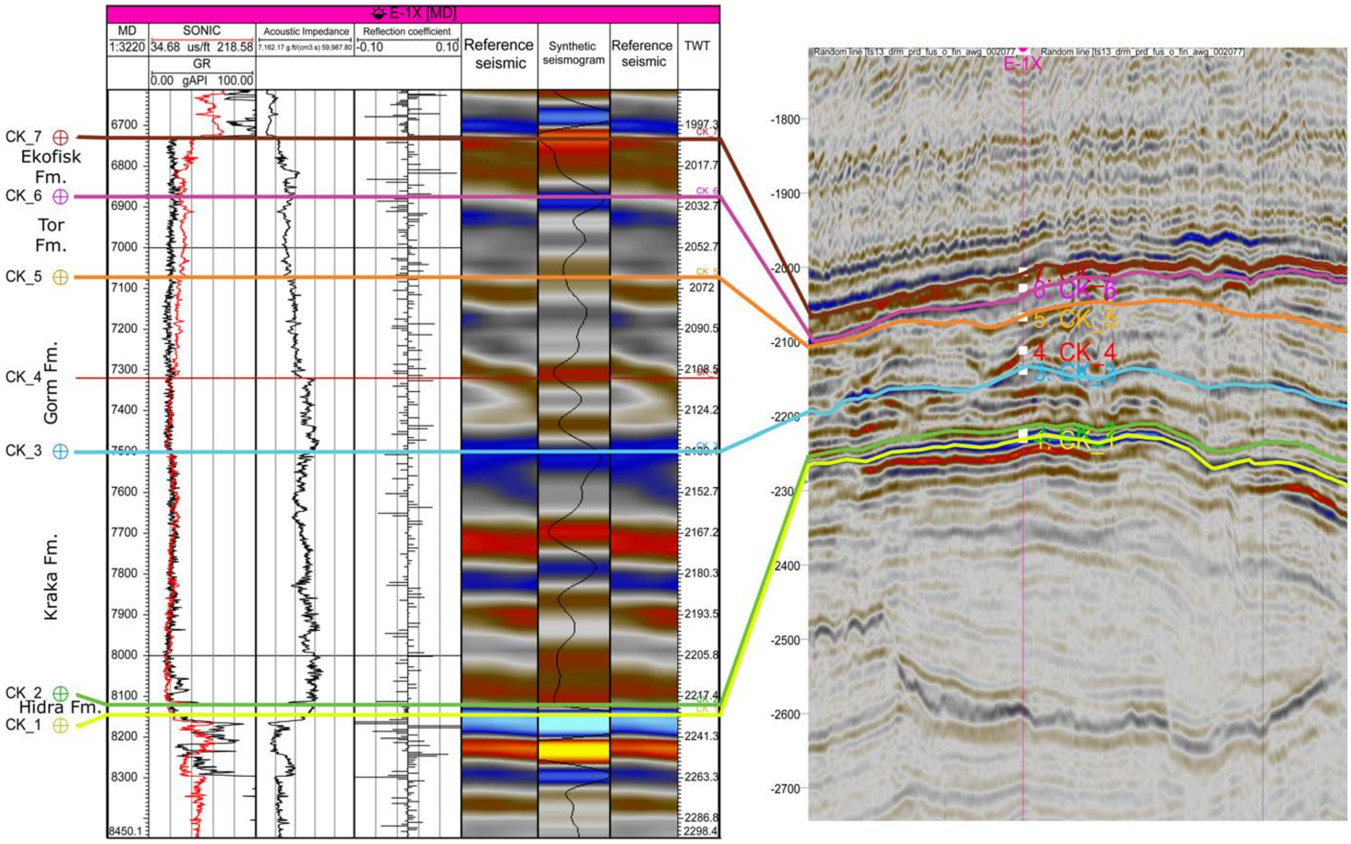

Fig. A4. Well log to seismic tie for the E-1 well. CK, seismic markers.

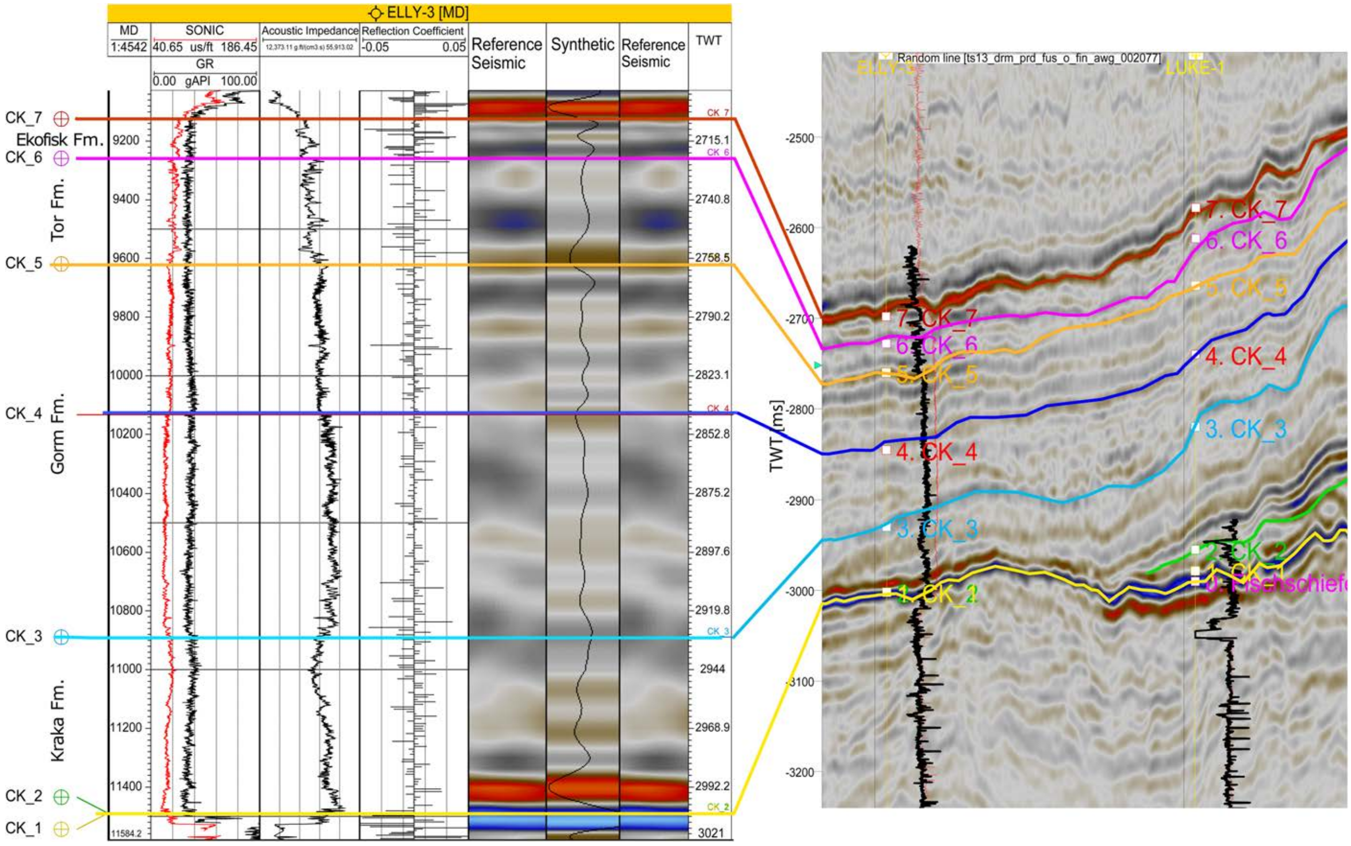

Fig. A5. Well log to seismic tie for the Elly-3 well. Note that the Hidra Formation and Roar Member are absent in this well. CK, seismic markers.

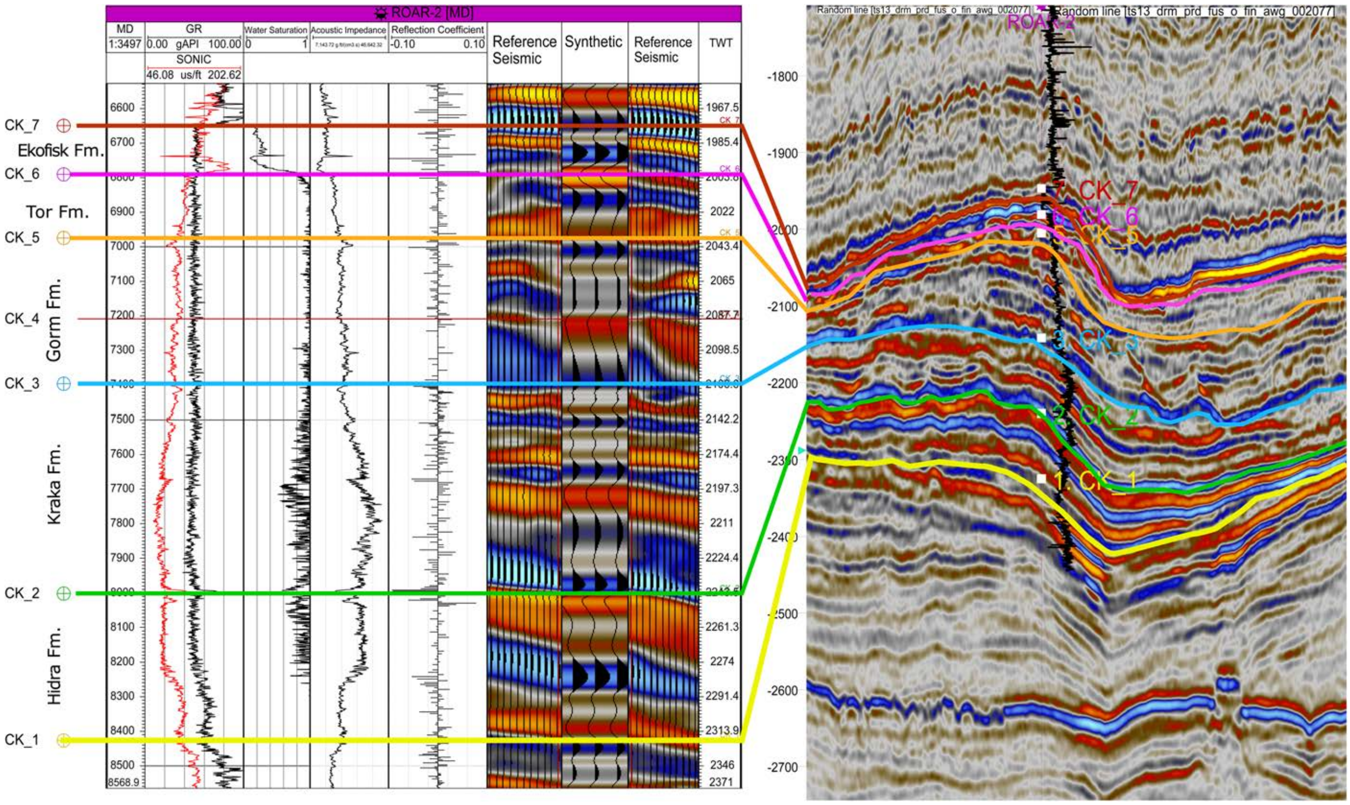

Fig. A6. Well log to seismic tie for the Roar-2 well. CK, seismic markers.

Lithology. The formation consists predominantly of white to grey chalk. Locally, marly intervals or fine clay laminae are present in the chalk (e.g. Bo-3X and E-1 wells: Figs A3 & A4).

Log characteristics. The GR logs in most wells show constant low values in the lower part of the formation above the Roar Member; whereas, in the upper part, higher values are recorded locally owing to the presence of thin clay–marl interbeds (e.g. Bo-3X and E-1: Figs A3 & A4). The acoustic impedance logs always show more elevated values in the lower part of the formation, and lower values in the upper part (higher porosity) (Fig. A3).

Boundaries. The lower boundary of the Kraka Formation is placed at the base of a gamma-ray spike that represents an organic-rich interval that is named here the Roar Member, formerly referred to as 'Turonian Shales', Plenus Marl or Blodøks (Fig. A1). The upper boundary is formed by a regional unconformity, defined in this paper as the early Campanian unconformity (ECU). In seismic sections, this unconformity is clearly expressed and can be followed at the scale of the Danish Central Graben (Figs 12 & 13). Biostratigraphic analysis in most locations has recorded a hiatus at this level that spans the early Campanian, but which may locally range into the Maastrichtian and Danian (Fig. 11).

In some wells the biostratigraphic dating is not consistent with the regionally mapped seismic marker that defines the top of this formation, such as in the Elly-3 and Roar-2 wells (Fig. A3). Recent high-resolution biostratigraphic and carbon-isotope stratigraphic work on the Adda-3 well showed that the original age dating reported in the final well report was incorrect (Perdiou *et al.* 2015). We expect this may also be the case in the dating in the Elly-3 well, considering the very robust nature of the seismic reflectors in that area and the consistent age dates obtained in the nearby Elly-1 and Luke-1X wells (Fig. A3). However, it cannot be excluded that in the stratigraphically complex, structurally inverted areas, in particular, a local diagenetic overprint may have influenced the expression of the seismic reflectors (e.g. in the Roar-2 well). Further work is needed to elucidate these questions.

Depositional environment. The depositional environment was an open-marine setting during an overall transgressive episode. Deepest water conditions of the chalk succession were probably reached during this phase, as testified by the faunal associations and, notably, the common occurrence of keeled planktonic foraminifera (Fig. 8).

Chronostratigraphy. Turonian–uppermost Santonian.

Distribution. The Kraka Formation is a correlative of the Narve Formation in the Norwegian sector, of the seismic units CK-2–CK-4 in the Dutch sector (van der Molen & Wong 2007), and of the Herring and lowest part of the Mackerel formations in the UK sector (Johnson & Lott 1993) (Figs 20 & A1).

Roar Member (new member)

History. The rock unit represented by this member was informally referred to as 'Turonian shales' by Lieberkind *et al.* (1982). Following usage in the surrounding countries, it has also been named the Plenus Marl Formation (Deegan & Scull 1977), the Blodøks Formation (Isaksen & Tonstad 1989) and the Black Band Bed (Johnson & Lott 1993; Surlyk *et al.* 2003) (Fig. 3). There is a consensus in the above-cited literature that these units are all approximately time-equivalent and correspond to OAE 2, which led to the deposition of organic-rich deposits worldwide (e.g. Voigt *et al.* 2006; Jarvis *et al.* 2011). Some work on the precise dating and characterization of this event and its relationship to the variously applied lithostratigraphic units in the North Sea Basin has been carried out, but further work is needed to better understand the lateral variation in the preservation of the organic matter (e.g. Dodsworth 1996; Jarvis pers. comm.). Here we have chosen a pragmatic option and limited the definition of this member to the organic-rich interval expressed in the GR logs. In this way, the member can later be incorporated into a definition of a formation that will also include the organic-poor rocks of the OAE 2 (Fig. 15).

Name. The name is taken from the Roar-2 well, where the Roar Member is well developed. Roar (Hroar, Ro) was, according to Norwegian sagas, a legendary Danish king from the sixth century, possibly son of Halvdan (Halfdan).

Well type section and reference wells. Type section: Roar-2 well, interval 7993, 24–8001, 84 ft MD (Fig. 15). Reference wells: E-1 (interval

8113–8115 ft MD), Bo-1 (interval 7268–7274 MD; cored) and Adda-3 (interval 7588–7592 ft MD) (Fig. 15).

Thickness. The member is generally thin (from 1 ft to a few feet), but can reach approximately 10 ft, for instance in the Roar-2 well (Fig. 15).

Lithology. This member consists of black, laminated, non-calcareous shale and is enriched in organic matter.

Boundaries and log characteristics. This member in most locations is represented by a thin gamma-ray and sonic (acoustic impedance) spike that can be thicker (up to 14 ft, Roar-2) in the centre of the basin. The organic-rich interval occurs in the middle of the Cenomanian–Turonian Boundary Event of the carbon-isotope curves measured in the Roar-2 and Adda-3 wells (Fig. 15). We include it in the Kraka Formation.

Depositional environment. The depositional environment is interpreted as dysaerobic to anoxic owing to a combination of reduced mixing of the water column and increased productivity of organic matter.

Chronostratigraphy. Straddles the Cenomanian–Turonian boundary.

Distribution. The Roar Member corresponds to part of the Blodøks Formation in the Norwegian sector, and part of the Plenus Marl and Black Band Bed succession in the UK sector (Fig. A1).

Gorm Formation (new formation)

History. This formation corresponds to the informal seismic Chalk units 3 and 4 of Lieberkind *et al.* (1982), which represent the upper part of the Hod Formation of Deegan & Scull (1977) and Isaksen & Tonstad (1989) (Fig. A1). It has been given formation status because it was formed during a time of very different depositional conditions, both tectonic and oceanographic, compared to the underlying Kraka Formation (Chalk unit 2), which had an effect on the rock composition and stratigraphy. In addition, the two formations are separated by a major regional unconformity (the ECU).

Name. The name Gorm is taken from the Danish oil and gas field discovered in 1971 and put into production in 1981. The Gorm Field is located some 200 km west of the Danish town of Esbjerg on the west coast of Jylland. The field was given the name after the Danish Viking king Gorm den Gamle (Gorm the Old), who reigned from AD 935 to approximately AD 950.

Well type section and reference wells. Type well: Luke-1, 9342–10.510 ft (MD) (Fig. A3); reference wells: Elly-3 and Per-1 (Figs A3 & A5).

Thickness. The thickness of this formation varies considerably as a result of the inversion tectonics that reached their climax during the early Campanian (this paper). A maximum thickness of up to 1171 ft (TVD: 386 m) is found in the Luke-1 well, which is situated in the depocentre next to the inverted high (Fig. A3). On the top of the inversion structures, this formation can locally be reduced to a few metres (e.g. Bo-1 well: Fig. A3).

Lithology. The lower part of the formation consists of white to light grey hard chalk with a very low clay content (<2%, Chalk unit 3: Lieberkind *et al.* 1982). The white chalk of the upper part of the formation (Chalk unit 4 of Lieberkind *et al.* 1982) is sometimes referred to as ‘Calcisphere Chalk’, as allochems of calcispheres can make up 20–30% of the rock (see also Fig. 8). Stylolites are common, and flint and chert beds and clays are unevenly distributed.

Log characteristics. This formation has a very consistent low gamma-ray signature. The acoustic impedance log shows more character, notably in the well-developed successions of the new depocentres (Elly-1, Elly-3, Luke-1X and Per-1X: Fig. A3) where the lower part has slightly higher values (also compared to the underlying Kraka Formation), and the upper part has slightly lower values. This halfway change in acoustic impedance character corresponds to seismic reflector CK-4, which is present in the depocentres and absent over the inverted structures (Fig. A3).

Boundaries. The lower boundary is formed by a regional unconformity, named in this paper as the early Campanian unconformity (ECU). This unconformity is expressed in the seismic and is the result of a tectonic inversion of the basin centre (Figs 12 & 13). Owing to the syntectonic activity, the nature of the lower boundary of this formation is very variable. In the newly created depocentres, the contact can be conformable; whereas it is an onlap termination against the inverted basin centre where the underlying Kraka Formation was uplifted. The ECU in most locations represents a stratigraphic hiatus that spans the early Campanian, the climax of the deformation phase, but can locally range up into the Maastrichtian and Danian (Figs 6, 11 & 12).

The Upper boundary is subtle and not easy to pick out in GR logs, where it is locally marked by a slight increase (Lieberkind *et al.* 1982). It is more characteristically expressed in the acoustic impedance log, which systematically shows an upwards change to lower values in the overlaying Tor Formation. Biostratigraphic control and seismic marker correlation are also used here to pick out the boundary.

Depositional environment. The depositional environment shows an overall shallowing trend, culminating in the upper part in the widespread occurrence of calcisphere-rich chalk (Fig. 8).

Chronostratigraphy. Campanian.

Distribution. The tectonic deformation that occurred during the late Santonian and early Campanian in the Danish, Dutch and Norwegian sectors created significant hiatuses and heterogeneities. We consider that the upper Santonian–lower Campanian Thud Formation in the Norwegian sector (Gradstein *et al.* 2016) is a local expression of the climax of this deformation phase, and we have chosen not to separate this phase out as an individual formation. The Norwegian Thud and Magne formations are thus considered as the time-equivalent of the Gorm Formation. In the UK sector, this formation corresponds to the upper part of the Mackerel Formation (Fig. A1).

Tor Formation

The Tor Formation was introduced by Deegan & Scull (1977) and retained in the Central North Sea by Johnson & Lott (1993). The definition in the type area of the Norwegian Central Graben was recently updated in Gradstein *et al.* (2016) following the unpublished work by Fritsen & Riis (2000). The Mona-1 well was chosen by Gradstein *et al.* (2016) as the Danish reference well. Although Surlyk *et al.* (2006) provisionally adopted the Tor Formation in their definition of the Upper Cretaceous chalk lithostratigraphic scheme in the onshore area, this was abandoned by Surlyk *et al.* (2013) with the definitions of new formations for the Danish Basin. Following Surlyk *et al.* (2003) in the offshore Danish sector, the Tor Formation equates approximately with the informal seismic Chalk unit 5 from Lieberkind *et al.* (1982). The formation is here formally introduced for the Danish Central Graben.

The Tor Formation is Maastrichtian, but may locally reach down into the uppermost Campanian. It consists typically of homogeneous, white or pale grey chalk and is generally less than 150 m thick, but reaches more than 250 m in the Central Graben (Surlyk *et al.* 2003). In spite of its apparently uniform nature, it comprises a wide spectrum of facies (e.g. Scholle *et al.* 1998; Damholt & Surlyk 2004). Resedimented chalk is common in the uppermost part, especially in the Norwegian sector (Sikora *et al.* 1999; Anderskouv & Surlyk 2012).

Ekofisk Formation

The Ekofisk Formation was introduced by Deegan & Scull (1977), and retained in the Central North Sea by Johnson & Lott (1993) and Surlyk *et al.* (2003). The definition in the Norwegian sector was updated by Gradstein *et al.* (2016), and correlated to the UK and Danish sector based on Isaksen & Tonstad (1989), Fritsen *et al.* (1999) and Fritsen & Riis (2000) (Fig. A1). The Gradstein *et al.* (2016) definition of the Ekofisk Formation is followed here. It corresponds to informal seismic Chalk unit 6 of Lieberkind *et al.* (1982). The Ekofisk Formation is of Danian age, although locally the formation may only cover the lower part of the Danian stage and can also be absent owing to local erosion or non-deposition (e.g. in the UK and Danish sectors of the North Sea Basin). The formation here is formally introduced in the Danish Central Graben.

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