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Early Cretaceous stratigraphic and basinal evolution of the Danish Central Graben: a review

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An integrated seismic–stratigraphic study of the Lower Cretaceous Cromer Knoll Group was undertaken as part of a recent comprehensive analysis of the Upper Jurassic – lowermost Cretaceous petroleum system in the Danish Central Graben. This study of the basal group of the post-rift package yielded an updated regional assessment of the distribution of the Valhall, Tuxen, Sola and Rødby Formations. This is documented by four high resolution isochore maps (presented here) that record temporal shifts in subsidence patterns from the latest Ryazanian to the earliest Cenomanian. The distribution and thickness variation of the mud-dominated Valhall Formation (latest Ryazanian – early Hauterivian) at the base of the group attests to the progressive fill of inherited syn-rift morphology. The dominant depositional theme is thus ponding in, and onlap from, the main inherited depocentres, although growth faults and incipient inversion locally controlled stratigraphic architecture, and new depocentres were initiated in the east of the graben (Ål and Outer Rough Basins). The isochores for the succeeding, increasingly chalk-rich Tuxen, Sola and Rødby Formations (Hauterivian – earliest Cenomanian) document the regional weakening of syn-rift patterns but emphasize the shift in sedimentation patterns controlled by accelerating inversion activity in the east (Adda–Tyra area, Søgne Basin) and increased local subsidence. The latter sometimes coincided with syn-rift depocentres, such as the Roar Basin and the Arne-Elin Graben, but was also significant in the new Early Cretaceous depocentres in the west of the graben, particularly the Outer Rough Basin. The evolution of the Early Cretaceous basin recorded by this dataset reveals significant shifts in the subsidence pattern in the late Valanginian – early Hauterivian, in large part due to early inversion in the east, and during the late Aptian – early Albian when subsidence was focussed in central and western sub-basins, probably locally due to salt withdrawal. These events, in combination with sea-level change, had implications for the accumulation and preservation of Barremian and early Aptian reservoir chalks.

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Lower Cretaceous sediments of the Cromer Knoll Group are widely distributed in the Danish Central Graben where the succession has been drilled by numerous exploration wells (Nielsen & Japsen 1991). The sedimentary contrast to the underlying Upper Jurassic – lowermost Cretaceous syn-rift shales of the Farsund and Mandal Formations is striking and characterized by a significant fall in gamma-ray (GR) values (Jensen *et al.* 1986; Petersen & Jacobsen 2021). The lower Ryazanian – Albian post-rift succession though dominated by siliciclastic mudstones records the initial pulses of chalk accumulation (Ineson 1993; Mutterlose & Bottini 2013), heralding the development of the Chalk Sea that dominated NW Europe during the Late Cretaceous (Surlyk *et al*. 2003). The upper Ryazanian – Danian succession in the Danish Central Graben, North Sea, is thus carbonate-dominated overall and includes the highly prolific Upper Cretaceous – Danian chalk play (e.g. Hemmet 2005) (Figs 1, 2). Since production started in 1972, most of the Danish oil and gas production has been from Maastrichtian (Upper Cretaceous) and Danian (lower Paleocene) chalk reservoirs in fields primarily located in the Salt Dome Province in the central–southern part of the Danish Central Graben (Fig. 1). However, hydrocarbon production also occurs from low permeability marly chalk reservoirs in the Lower Cretaceous Tuxen and Sola Formations of the Valdemar Field (Jacobsen *et al*. 2004; Danish Energy Agency 2014; Ponsaing e*t al*. 2020a, b).

As part of an industrial multiclient study ('CRETSYS'; Skaarup *et al*. 2017), seismic mapping was integrated with in-house sedimentological data, a stratigraphic review and petrophysical analysis of the Cromer Knoll Group, and a consistent, well-constrained seismic-stratigraphic framework for the Lower Cretaceous succession was established to improve the regional understanding of the stratigraphy and basin development. The framework was validated with biostratigraphy based primarily on review and update of existing data, both from industrial and published sources.

The aim of this paper is to review the evolution of the Lower Cretaceous Cromer Knoll Group in the Danish Central Graben based on a systematic description of the lithostratigraphy, including an account of the key facies, within the updated seismic architectural framework. High resolution images of the seismic maps that form the basis of this review are included as Supplementary Data files.

Geological setting

The Danish Central Graben constitutes part of the Central Graben in the southern extension of the Jurassic North Sea rift complex, consisting of a series of NNW-SSE trending half-grabens bounded to the east by the Coffee Soil Fault towards the Ringkøbing-Fyn High and to the west by the Mid North Sea High (e.g. Møller 1986; Japsen *et al*. 2003; Møller & Rasmussen 2003) (Fig. 1). Jurassic extensional rifting and half-graben subsidence started in the Middle Jurassic and continued into the earliest Cretaceous (Andsbjerg & Dybkjær 2003; Japsen *et al*. 2003; Møller & Rasmussen 2003; Verreussel *et al*. 2018; Hansen *et al*. 2021). Marine transgression of the developing graben began in the deepest depocentres along the Tail End Graben in the late Middle Jurassic (Andsbjerg 2003; Andsbjerg & Dybkjær 2003), and the seaway expanded episodically during the Late Jurassic, flooding the entire Danish Central Graben and lapping westward onto the Mid North Sea High in Volgian–Ryazanian times (Johannessen 2003; Johannessen *et al*. 2010; Verreussel *et al.* 2018).

The upper boundary of the Upper Jurassic – lowermost Cretaceous syn-rift marine shale succession (Lola, Farsund and Mandal Formations) is defined by the regional seismic surface colloquially termed the 'Base Cretaceous Unconformity' (BCU). Although a true, often composite, unconformity on structural highs and in marginal areas, it is commonly seismically conformable in depocentres and stratigraphic continuity has been proposed in uncored well sections in such basin-centre locations (Rawson & Riley 1982). As indicated by Kyrkjebø *et al.* (2004), the BCU term is thus an over-generalisation but is entrenched in the literature and is retained here for pragmatic reasons. In depocentres in the Central Graben, the BCU seismic horizon marks a basinwide facies change in the latest Ryazanian from black shales deposited under oxygen-deficient/anoxic conditions to open-marine sediments of the Lower Cretaceous Cromer Knoll Group (Rawson & Riley 1982; Copestake *et al*. 2003; Kyrkjebø *et al.* 2004; Ineson *et al.* 2022a). The post-rift Cromer Knoll Group accumulated under early thermal subsidence infilling the basin-floor topography inherited from the Late Jurassic rifting stages in the Danish Central Graben. Although the general Late Jurassic structural basin configuration was maintained during the Early Cretaceous, subsidence along the Coffee Soil Fault at the eastern margin of the basin became less dominant with the development of a number of smaller depocentres, both along the axis of the Tail End Graben and westwards across the Danish Central Graben (Vejbæk 1986; Japsen *et al*. 2003). The total thickness of the Cromer Knoll Group locally exceeds 800 m in depocentres (Britze *et al*. 1995) and thicknesses over a kilometre may be present in undrilled parts of the Outer Rough Basin (Japsen *et al.* 2003).

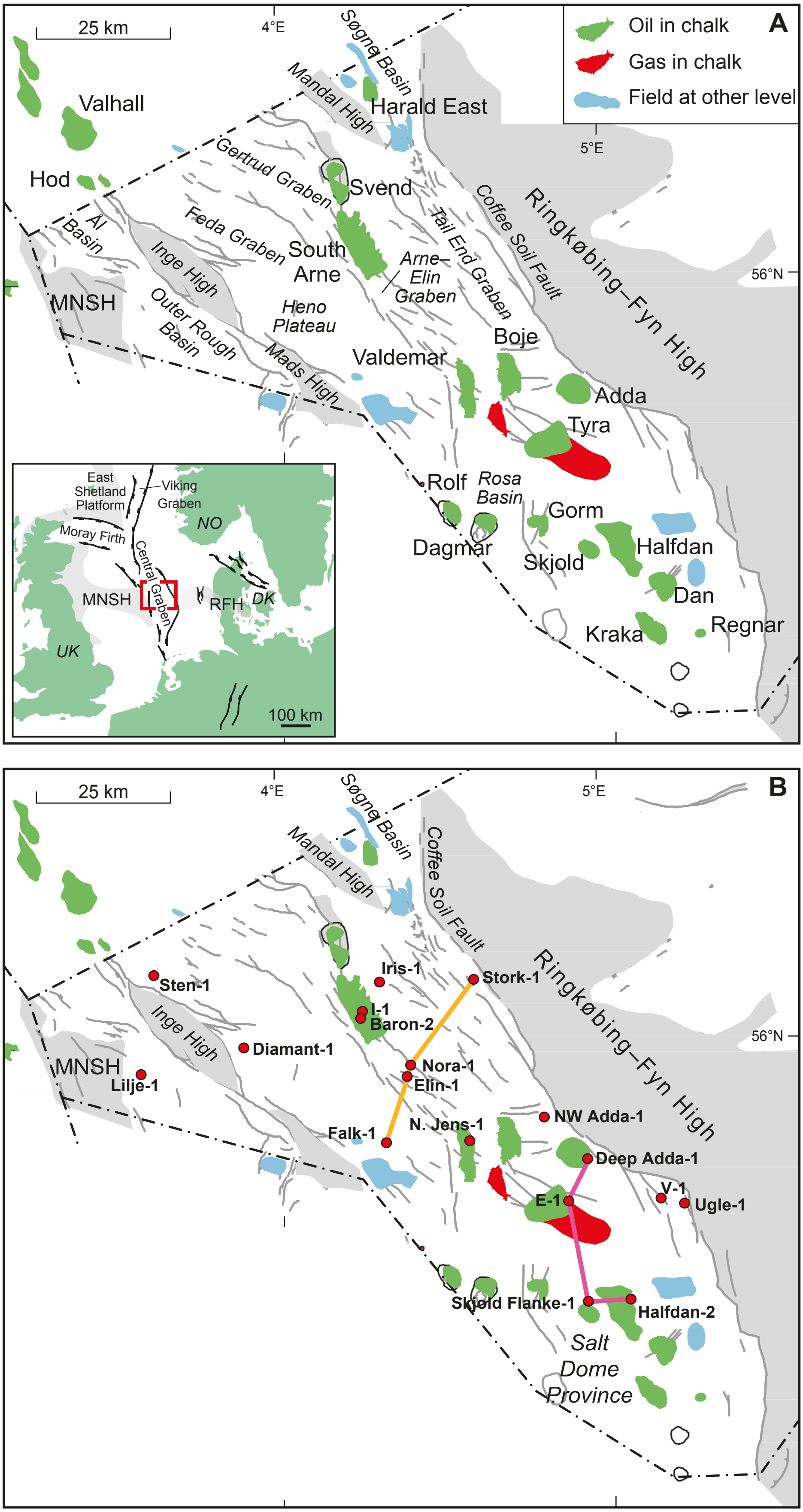

Fig. 1. **(A)** Early Cretaceous structural framework of the Danish Central Graben showing the main structural elements and chalk fields; the latter are concentrated in the Salt Dome Province. Insert map shows the location of the Danish sector within the North Sea rift complex. (**B**) Location of the wells discussed in the text and indicated on figured seismic profiles (Figs 12, 13). MNSH: Mid North Sea High; open circles (southern Danish Central Graben) indicate dry salt-cored structures at Cretaceous level.

Methodology

Seismic mapping

Final migration versions from eight separate 3D surveys of various vintages in the public domain were used. The datasets have an areal overlap of varying size but there is almost full 3D coverage of the entire Danish Central Graben. However, released 3D data is lacking in an area where the Coffee Soil Fault changes direction from NNW–SSE to WNW–ESE, north of the NW Adda-1 well (Fig. 1); structural interpretation and mapping in this area was reliant on vintage 2D data. The line orientations are SW–NE parallel to the general structural dips, apart from the southern surveys in the salt-structure dominated area where the in-line orientation is E–W. The data quality of the surveys in the Cretaceous section is generally fair to very good. A problem exists where a thick high-velocity chalk section directly overlies low-velocity Lower Cretaceous sediments. This gives rise to severe ringing and interbed multiples that mask the imaging of the uppermost Lower Cretaceous section. To mitigate the multiple problem on a couple of the surveys, an FK-filter that removed dips up to 1 ms/trace was applied post-stack on flattened volumes at Base Chalk to remove parallel events immediately below the Chalk Group. This improved the ability to pick dipping events in the upper part of the Lower Cretaceous although this robust treatment was at the expense of removing some of the subsurface data.

Five distinct reflectors that can be traced over most of the Danish Central Graben and tied to well sections were selected for regional interpretation and mapping of the Lower Cretaceous section (see below); an additional surface at top Leek Member – Vyl Formation (Fig. 2, CKG2) is only locally mappable and is not considered further here. The regional reflectors were used to define Lower Cretaceous seismic units with top and base delimited by seismic horizons. Locally, in areas of structural complexity and poor imaging, the interpretation was guided by stratigraphic data from wells. The five regionally interpreted horizons were used to create four time-isochore maps of the Lower

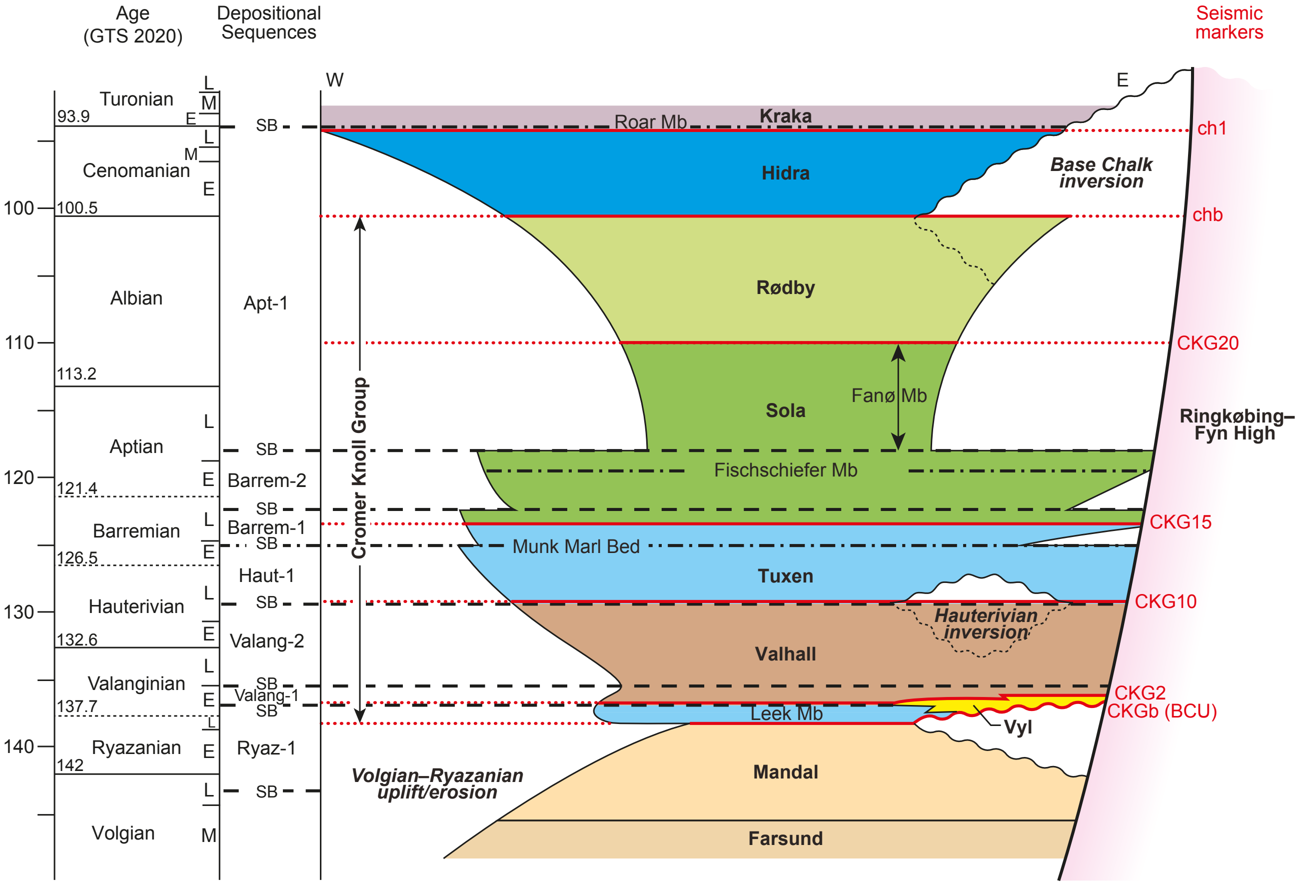

Fig. 2. Schematic representation of the Lower Cretaceous lithostratigraphy showing the relative lateral distribution of the formations in a W–E cross-section of the Danish Central Graben; local stratigraphic variations are not depicted. Key seismic horizons are shown, together with depositional sequences. Chronostratigraphy after Gale *et al.* (2020).

Cretaceous succession by simple subtraction of the relevant horizons. The four isochore maps correspond to the Valhall, Tuxen, Sola and Rødby Formations.

Biostratigraphy

All available biostratigraphic data were reviewed from 65 key wells covering a wide geographic area of the Danish Central Graben in order to provide seismic ties in key locations (see summary in Skaarup *et al.* 2017). The biostratigraphy was mainly based on nannofossils and microfossils (mostly foraminifera with some Radiolaria, diatoms and ostracods). The data were primarily extracted from industrial biostratigraphic consultancy reports but published data and unpublished in-house GEUS data were also incorporated (important published sources include Heilmann-Clausen 1987; Thomsen 1987; Jeremiah 2001; Dybkjær & Jutson 2003; Mutterlose & Bottini 2013; Ineson *et al.* 2022a, 2022b). Key biostratigraphic events (both micro- and nannofossils) were correlated to the current Cretaceous chronostratigraphic scheme (Ogg & Hinnov 2012, subsequently updated to the revised Gale *et al.* 2020 timescale, see Fig.2) and applied to constrain borehole lithostratigraphy (Fig. 2) and regional ties to seismic data.

Seismic stratigraphy and lithostratigraphic development

Seismic stratigraphic framework: key reflectors

The regionally interpreted five key seismic reflectors constituting the seismic stratigraphic framework have been used to delineate and map the distribution and thickness of the different Lower Cretaceous lithostratigraphic formations discussed below (Fig. 2). The reflectivity of the seismic reflectors and the seismic character of the various units vary within the Danish Central Graben.

Base Cretaceous Unconformity

The Base Cretaceous Unconformity (BCU; Fig. 3) marks the base of the Cromer Knoll Group in the Danish Central Graben. As noted above, the BCU

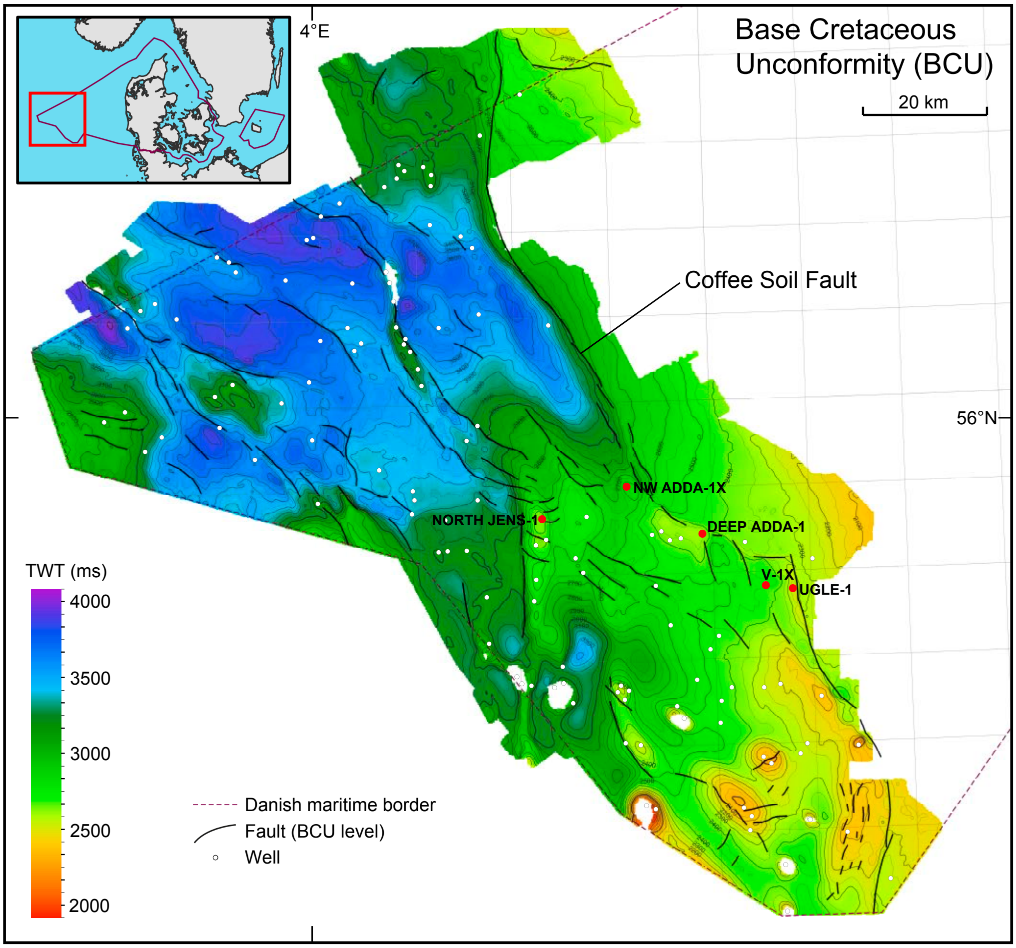

Fig. 3. Time-structure map (TWT, ms) of the Base Cretaceous Unconformity (BCU). Note the deepening of the BCU in the northern part of the Danish Central Graben. Wells discussed in the text specific to this map are named and highlighted in red; see Supplementary Data for high-resolution image, facilitating identification of all wells and detailed contouring.

seismic surface in basin-centre depocentres defines the boundary separating the Jurassic – lowermost Cretaceous syn-rift succession from the Cretaceous post-rift deposits. Regionally, the BCU represents a hiatus and/or a significant facies change that is clearly defined on wireline logs and has a distinct seismic character making it an important marker that can be correlated and mapped in major parts of the North Sea (Copestake *et al*. 2003). A distinct seismic reflector is also observed where Lower Cretaceous successions overlie pre-Jurassic strata.

In large parts of the Danish Central Graben where the BCU seismic horizon corresponds to the lithological change from the low impedance Upper Jurassic – lowermost Cretaceous syn-rift shales to the marly deposits of the lowermost Cromer Knoll Group (the Leek member of the Valhall Formation), the transition is associated with a characteristic distinct positive seismic reflector. In such basinal areas, this reflector corresponds broadly to a distinct shift in the well-log pattern representing the change from the organic-rich Upper Jurassic – lowermost Cretaceous Mandal/Farsund shales to the chalky marlstones of the lowermost Valhall Formation (Figs 2, 4; Petersen & Jacobsen 2021). The boundary is defined at the first significant upwards decrease in gamma ray (GR) response and a corresponding increase in sonic velocity related to the change in lithology (Jensen *et al.* 1986). A cored section in the North Jens-1 well spanning this key surface in a basinal setting was described recently by Ineson *et al.* (2022a).

Along the faulted margin (Coffee Soil Fault) of the Ringkøbing-Fyn High where the Upper Jurassic – lowermost Cretaceous succession includes gravity-flow silt-/sandstone intervals (the Poul Formation), the BCU reflector is less distinct, marking the boundary between Poul Formation sandstones and the overlying Cromer Knoll Group marlstones and shales. In a number of wells located in the fault zone (e.g. V-1, Ugle-1, Deep Adda-1), gravity-flow sandstones referred to the Vyl Formation by Jensen *et al*. (1986) are located above the seismic BCU marker and the sandstone interval is considered as part of the Cromer Knoll Group (Fig. 4). Biostratigraphic data from cored Vyl Formation sandstones in the Deep Adda-1 well suggest an early Valanginian age for these deposits (Fig. 2; Jutson 1997).

Seismic mapping at this level demonstrates the variable degree of stratigraphic truncation in the Danish Central Graben, dependent on the structural position within the basin. Although conformable or para-conformable in many depocentres, stratigraphic truncation increases in magnitude onto the flanks of the graben and on intrabasinal highs where the Cromer Knoll Group progressively overlaps older Jurassic and locally pre-Jurassic strata (Fig 5A). The relief inherited from the late syn-rift phase results in a similar supercrop pattern with basal Cromer Knoll Group sediments present in depocentres and progressive onlap of younger Cromer Knoll Group, and ultimately Upper Cretaceous strata, onto the BCU surface towards the graben flanks and onto intrabasinal highs (Fig. 5B).

CKG10

The top of the mudstone-dominated Valhall Formation, succeeded by Tuxen Formation marly chalks (Fig. 2), is picked in a continuous peak overlying a generally rather transparent interval with few continuous internal reflectors. The top Valhall Formation reflector shows basal onlap to the west but is truncated by the Base Chalk (chb) reflector towards the north in the Søgne Basin and along inversion ridges to the east in the central part of Danish Central Graben. The surface is itself a truncation surface locally in the east of the area, for example in the eastern Adda discovery where the Tuxen Formation unconformably overlies the lower Valhall Formation (Ineson *et al.* 2022b).

CKG15

This reflector is generally a strong seismic trough produced by the boundary between the chalks and marly chalks of the Tuxen Formation below and the marls and shales of the Sola Formation above (Fig. 2). The horizon has a more restricted extent than the CKG10 horizon towards the Søgne Basin and along inversion ridges to the east due to truncation by the Base Chalk Group (chb) reflector.

CKG20

This reflector is picked in a peak marking the transition from the mudstones and calcareous mudstones of the upper part of the Sola Formation (Fanø Member of van Buchem *et al*. 2018), to the marlstones and marly chalks of the overlying Rødby Formation (Fig. 2). The reflector can only be traced over restricted areas in the north-west, northernmost, and central-eastern parts of the Danish Central Graben where the overlying Rødby Formation is thick, allowing separation of CKG20 from the distinct Base Chalk reflector.

chb

The base of the Chalk Group (chb) is everywhere represented by a distinct strong amplitude peak marking the break from high impedance chalk above to lower velocity Cromer Knoll Group or older strata beneath.

Lithostratigraphy, facies and distribution

The Lower Cretaceous Cromer Knoll Group lithostratigraphy is based primarily on Jensen *et al.*

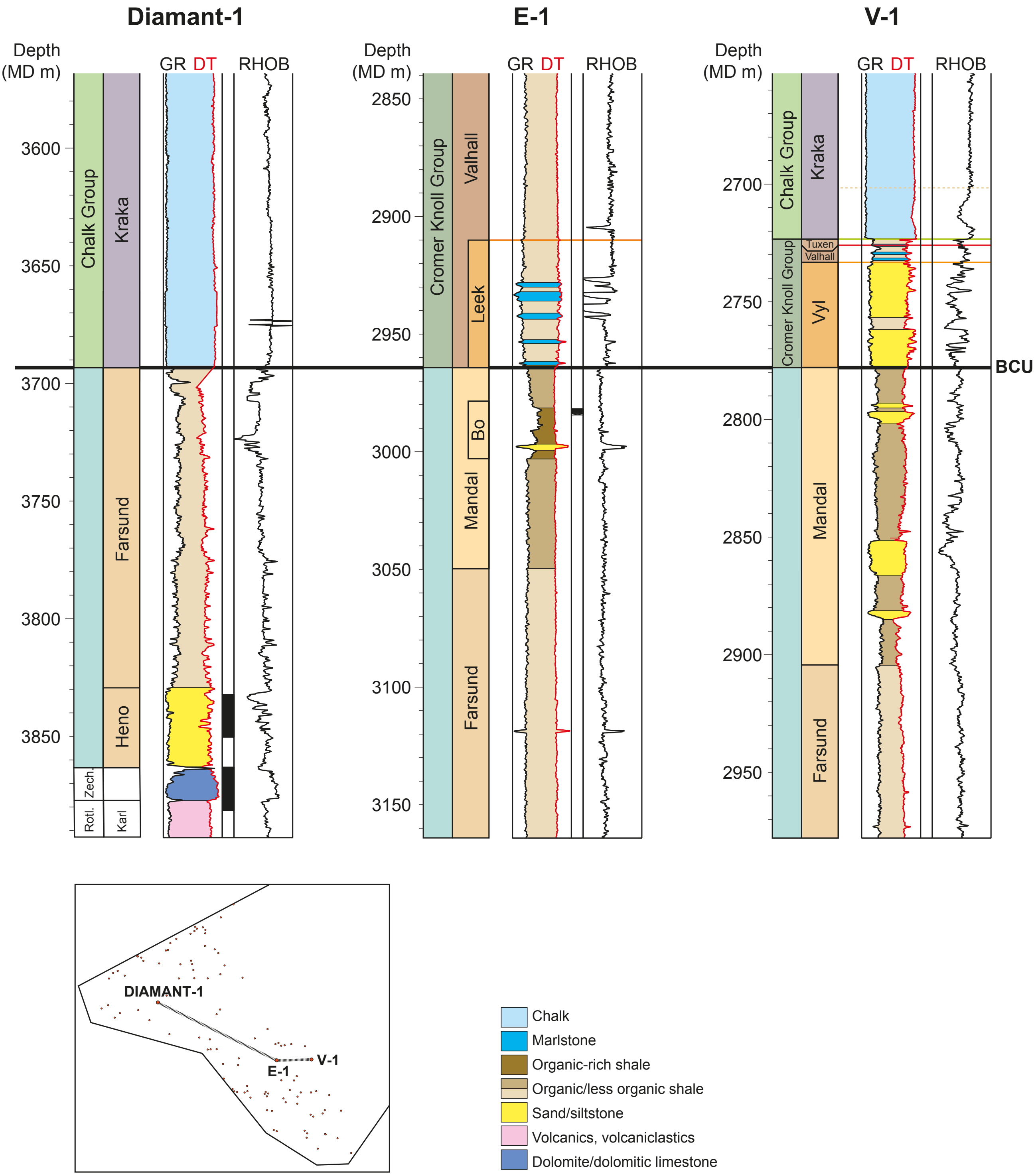

Fig. 4. NW–SE log correlation at the Base Cretaceous Unconformity (BCU) stratigraphic level showing three different scenarios; inset map shows the location of the three illustrated wells in the Danish sector of the Central Graben (see Fig. 1 for enlarged version). The **E-1** well represents a deep depocentre with a probable conformable relationship between the late syn-rift deposits (the Mandal Formation, including the organic-rich mudstones of the Bo Member) overlain by an expanded Leek Member (lowermost Valhall Formation) composed of thin marly chalks – chalky marlstones interbedded with marlstones. Increasing organic richness of the Farsund–Mandal mudstones is indicated by light/medium/dark brown shades. **V-1**, close to the Coffee Soil Fault at the eastern margin of the graben illustrates Vyl Formation gravity-flow sandstones at the base of the Valhall Formation; the indications of Barremian strata (Tuxen Formation) in this well are speculative and may reflect faunal/floral reworking at a base Chalk Group hiatal surface (lowermost Chalk Group absent). The **Diamant-1** well on the north-western Heno Plateau illustrates the western pinch-out of the Cromer Knoll Group on truncated Upper Jurassic syn-rift strata; note that the lowermost Chalk Group is also absent here. GR: Gamma-ray log; DT: Sonic log; RHOB: Density log; Rotl.: Rotliegendes; Zech.: Zechstein.

(1986) with modifications by Riley *et al*. (1992) and more recently by van Buchem *et al*. (2018) (Fig. 2). These modifications included changes to the Sola Formation, whereby the informal Fischschiefer bed was defined as a member (Riley *et al*., 1992) and the new Fanø Member replaced the informal 'Albian Shale' unit in the upper part of the formation (van Buchem *et al*., 2018). Jensen *et al*. (1986) included five formations in the Cromer Knoll Group: Valhall, Vyl, Tuxen, Sola and Rødby. The Valhall Formation contains the carbonate-rich Leek Member. The Tuxen, Sola and Rødby Formations are also used in the Norwegian Central Graben and the formations are largely time-equivalent (Isaksen & Tonstad 1989; Copestake *et al*. 2003; Gradstein *et al*. 2016). The Valhall Formation was defined in the UK North Sea and is time-equivalent to part of the Åsgard Formation in the Norwegian North Sea (Deegan & Scull 1977; Isaksen & Tonstad 1989; Copestake *et al*. 2003; Gradstein *et al*. 2016).

Valhall Formation (uppermost Ryazanian – lower Hauterivian)

In complete sections, the uppermost Ryazanian – lower Hauterivian Valhall Formation is a uniform, mudstone-dominated marine succession; carbonate content in the formation decreases upwards above the basal carbonate-rich Leek Member (<5 m to *c*. 60 m thick) and increases again towards the top of the formation where transitional to the chalk-rich Tuxen Formation. Marlstones and thin argillaceous chalks are recorded in the lower and upper levels. In expanded, complete sections of the Valhall Formation, the GR log pattern reflects these trends, showing an overall upward increase in values to the middle of the formation reverting to a decrease up to the gradational base of the overlying chalk-dominated Tuxen Formation (Fig. 6). In such sections (e.g. E-1 (Fig. 4), Sten-1 (Fig. 6), Iris-1 and I-1 wells; see Fig. 1 for well locations), the spiky log pattern of the Leek Member at the base of the Valhall Formation reflects the interbedding of discrete thin carbonate-rich beds with calcareous shales or marlstones whereas in thinner, more condensed sections the member is commonly carbonate dominated, yielding a blocky GR log pattern.

The distribution and thickness of the Valhall Formation is mapped by the seismic interval BCU – CKG10. The isochore map reveals considerable thickness variations across the Danish Central Graben from

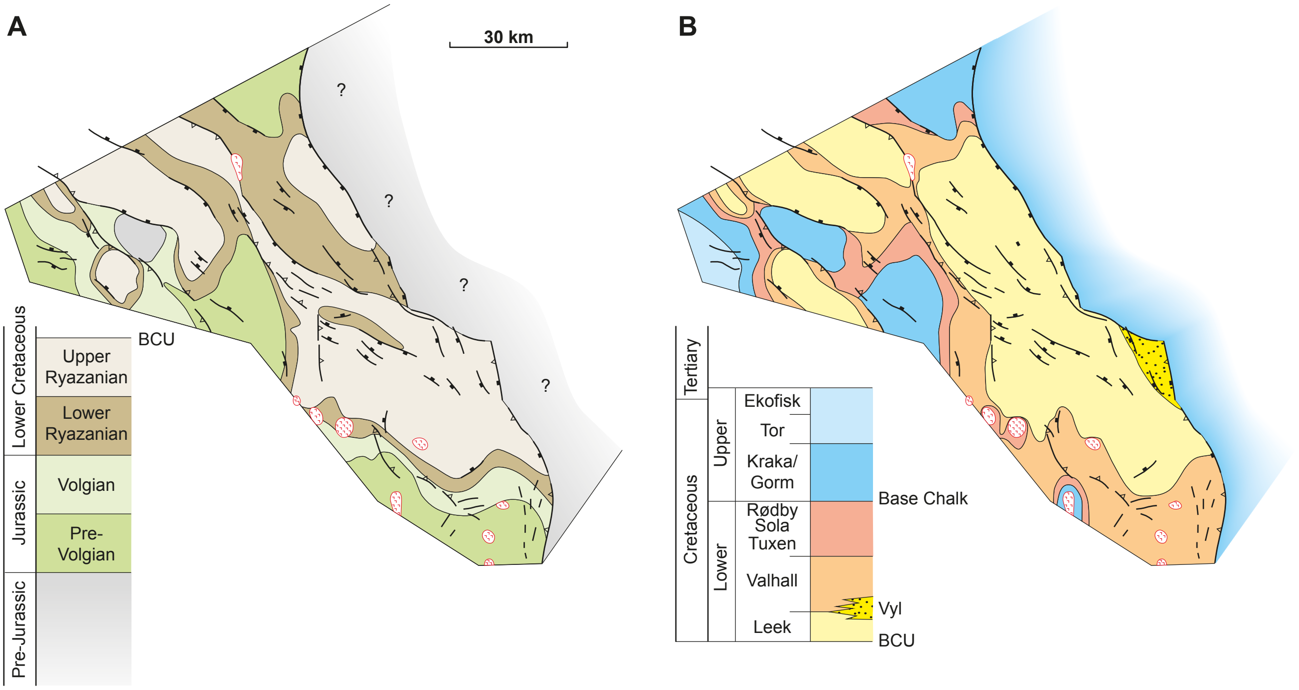

Fig. 5. **(A)** BCU sub-crop map with indications of the degree of truncation of the lowermost Cretaceous, Jurassic and older strata. Gentle truncation is associated with fault activity in the central part of the Danish Central Graben. On structural highs, deep erosion of the Jurassic is recognized. On the Ringkøbing–Fyn High and on the Inge High, the BCU reflector forms the top of Palaeozoic or older rocks (basement). **(B)** BCU super-crop map. Initial Cromer Knoll Group sedimentation (Leek Member) took place in the main depocentres; sandstones of the Vyl Formation were deposited in a narrow zone along the Ringkøbing–Fyn High. The depocentres expanded progressively during the early Cretaceous and prominent intrabasinal highs and the graben flanks were first onlapped in the Late Cretaceous.

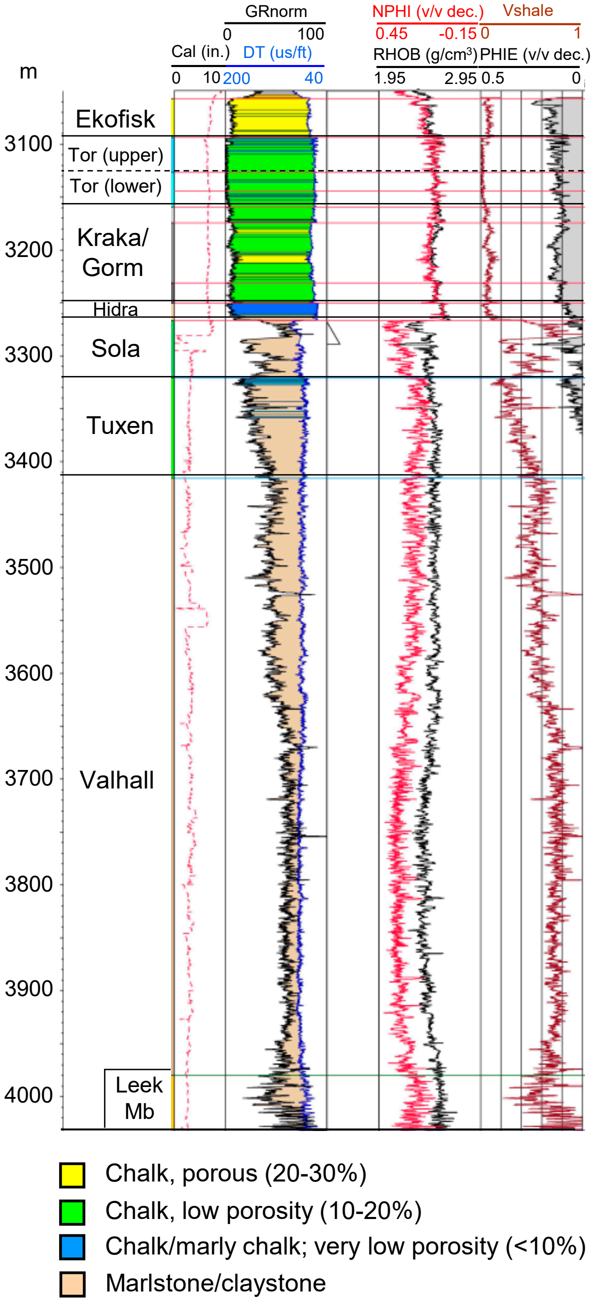

Fig. 6. The Sten-1 well in the Feda Graben illustrating the development of the Valhall, Tuxen and Sola Formations in a major Early Cretaceous depocentre. The low gamma-ray (GR) values at the base of the Valhall Formation correspond to the carbonate-rich Leek Member. The GR readings show an overall upward increase to the middle of the Valhall Formation due to increasing clay content, reverting to a decrease up to the gradational base of the overlying Tuxen Formation that comprises marly chalks and marlstones, displaying lower GR values. The Sola Formation includes clay-dominated intervals indicated by increased GR values, particularly in the lower half and upper levels of the formation. GRnorm: normalised Gamma-ray log; DT: Sonic log; NPHI: Neutron porosity log; PHIE: Effective porosity; RHOB: Density log; Vshale: Calculated shale volume.

absence on the Mid North Sea High, Inge High, Heno Plateau and in the Søgne Basin to thick sections in depocentres (Fig. 7A). The main depocentres with the thickest Valhall Formation are the Feda, Gertrud and Arne-Elin Grabens, and the Iris, Gulnare and Roar Basins (Fig. 7A). Drilled Valhall thicknesses range from less than 30 m to hundreds of meters with a maximum drilled thickness of 614 m in the Sten-1 well located in the Feda Graben (Fig. 6); thicknesses of up to a kilometre may be attained in the deepest subbasins (Jensen *et al.* 1986). Although largely representing the primary distribution of the formation, the distribution and thickness variation depicted on Fig. 7A are locally influenced by erosional truncation, either at base Tuxen (e.g. easternmost Adda discovery and Tyra Field) or at base Chalk Group (e.g. Søgne Basin area).

Vyl Formation (lower Valanginian)

Based on well penetrations, the lower Valanginian Vyl Formation is apparently restricted to a narrow zone adjacent to the Coffee Soil Fault against the Ringkøbing-Fyn High, particularly in the breached transfer zone intersected by the V-1, Deep Adda-1 and Ugle-1 wells in the south-eastern Danish Central Graben (Figs 1, 4). The distribution of the formation was not mapped seismically. This formation represents gravity-flow sandstones located stratigraphically above the BCU while comparable sandstones assigned to the upper Volgian – Ryazanian Poul Formation occur below the BCU (Petersen & Jakobsen 2021). Stratigraphic data suggest that the Vyl Formation may post-date much of the carbonate-dominated Leek Member of the Valhall Formation (Jutson 1997; Fig. 2). Deposition of the Vyl Formation may have been linked to active tectonism along the fault zone, as inferred for the Poul Formation by Petersen & Jakobsen (2021), suggesting that extensional fault activity along the Coffee Soil Fault zone persisted into the early Valanginian.

The formation comprises silty fine-grained sandstones and interbedded siltstones (Jensen *et al.* 1986); in the Deep Adda-1 core section through the upper Vyl Formation, the siltstones and silty fine sandstones are intensely bioturbated and contain bioclasts (Nielsen *et al.* 2015; succession erroneously referred to the uppermost Farsund Formation by these authors). Cuttings in the Ugle-1 well suggest that coarser, texturally and mineralogically immature facies are represented in the most proximal settings, close to the fault zone (Michelsen *et al.* 2003; Nielsen *et al.* 2015).

Tuxen Formation (Hauterivian – upper Barremian)

The Tuxen Formation is an important chalk reservoir unit in the producing Valdemar Field and in the Adda–Tyra area (Jakobsen *et al.* 2004; Fig. 1) but is recognized throughout the Danish Central Graben and extends

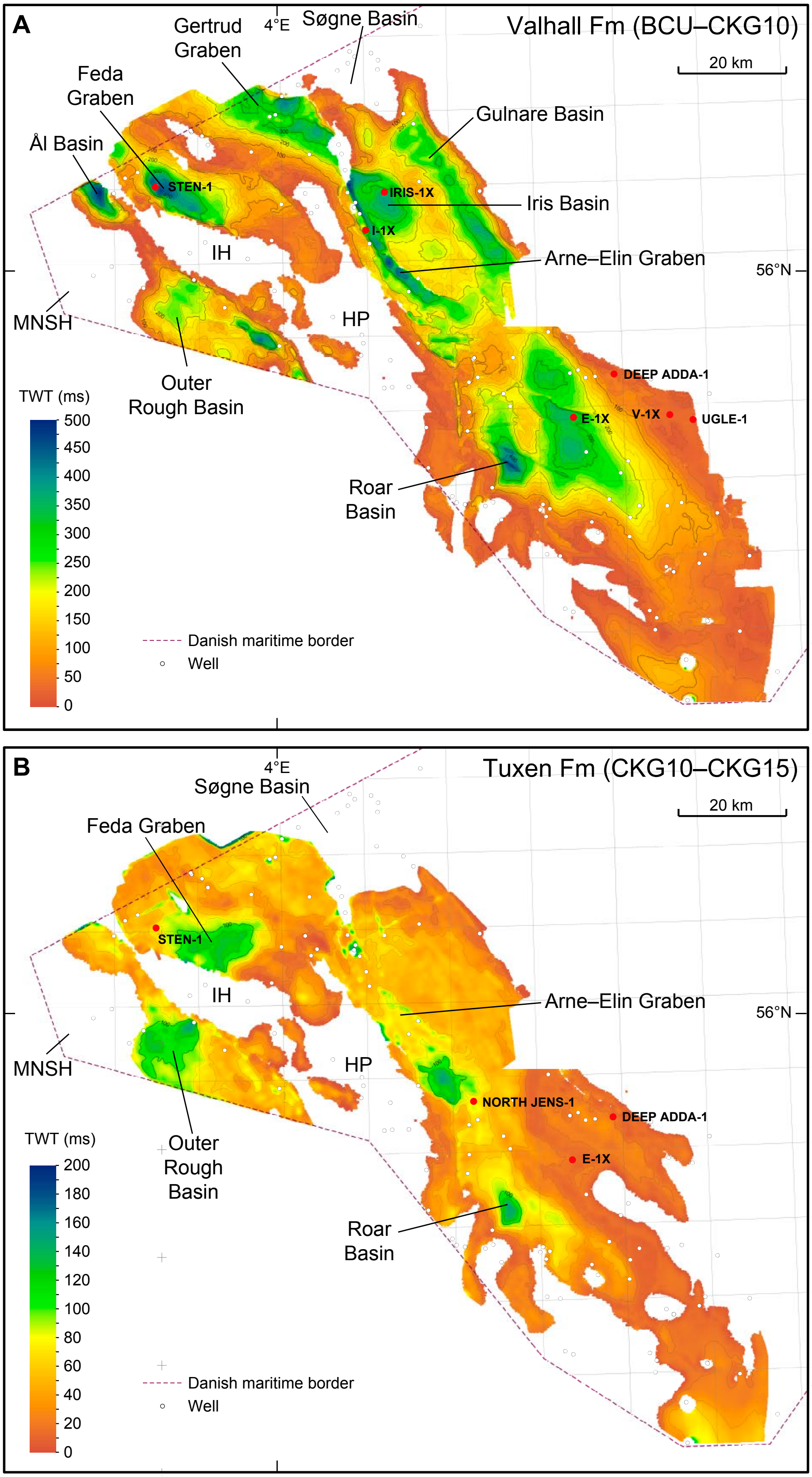

Fig. 7. Time-isochore maps (TWT, ms) of Lower Cretaceous formations with indication of the key structural highs and depocentres; wells discussed in the text specific to the mapped unit are named and highlighted in red. See Supplementary Data for high-resolution images to identify all wells and enlarge contouring details. **(A)** Valhall Formation (seismic interval BCU–CKG10). **(B)** Tuxen Formation (seismic interval CKG10–CKG15). **(C)** Sola Formation (seismic interval CKG15–CKG20). **(D)** Rødby Formation (seismic interval CKG20–chb). HP: Heno Plateau; IH: Inge High; MNSH: Mid North Sea High.

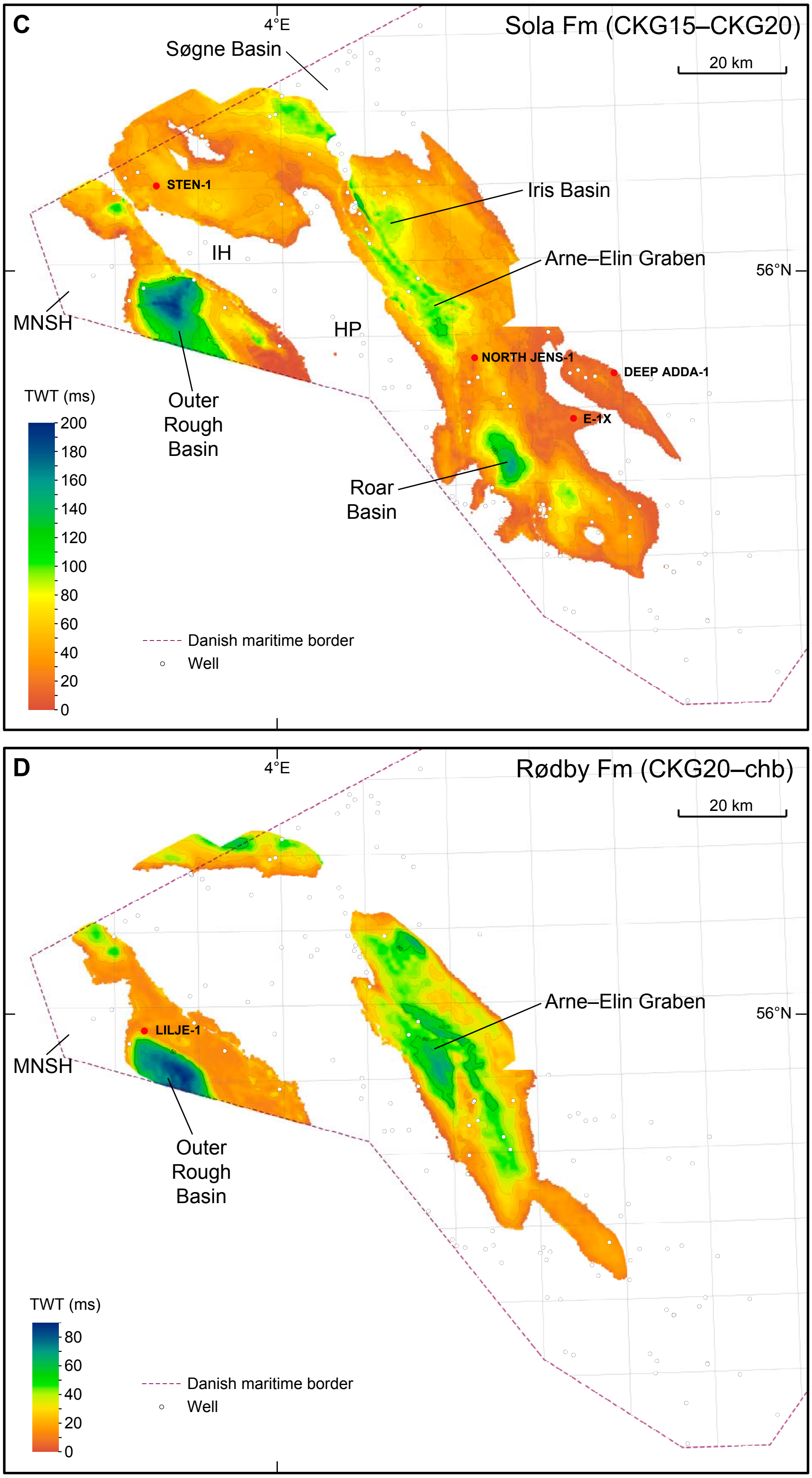

Fig. 7. Continued.

northwards into the southern Norwegian Central Graben. The formation is generally of late Hauterivian to late Barremian age, though the lowermost beds in the Adda area extend down into the lower Hauterivian due primarily to condensation and the earlier onset of carbonate-dominated sedimentation on the evolving Adda High.

In expanded sections, such as in the Valdemar Field (Ineson 1993: Jakobsen *et al.* 2004), the formation is subdivided by a prominent organic-rich marker bed, the Munk Marl Bed (MMB; Jensen *et al.* 1986), which forms a distinctive 'forked' GR peak recognized widely in the subsurface of the North Sea (Fig. 8; Crittenden *et al.* 1991; Copestake *et al.* 2003). The chalk-rich lower and upper Tuxen Formation units show similar 'cleaning-upward' trends, the cleanest, clay-poor chalks (with the lowest GR values) occurring at the top of the units (Figs 6, 8). The formation comprises a heterogeneous layered succession of bioturbated chalks and marly chalks interbedded with greenish grey (locally reddish) or dark grey-black marlstones; a detailed description of the lithofacies of the Tuxen and Sola Formations is presented by Jelby *et al.* (2022). Marly chalk constitutes nearly 75% of the Tuxen Formation in the Valdemar Field (Fig. 9A; Jakobsen *et al.* 2004) but marlstones dominate the lowermost Tuxen Formation. The dominant marly chalk facies is characterized by mid-grey to light yellowish-fawn chalk with a clear marl content in the form of burrow fills, marlstone flasers, solution seams and laminae; biogenic fabrics dominate and the definition of the trace fossils can be striking, particularly adjacent to darker marlstone beds (Fig 9A). *Chondrites* burrows are abundant and the best-defined trace, and clearly represent the last component of a tiered ichnofabric that includes *Planolites*, *Asterosoma*, and less commonly *Zoophycos*, *Teichichnus* and *Thalassinoides*.

At certain levels, particularly immediately beneath the MMB and at the top of the Tuxen Formation, off-white, pale yellow or cream-coloured chalk is prominent and forms the most important reservoir facies in the Valdemar Field. Although this facies contributes only 9% to the gross Tuxen Formation in this field, it forms 50% of the uppermost Tuxen Formation – the 'Upper Tuxen-1' reservoir zone of Jakobsen *et al.* (2004). It comprises chalk without significant marl content, with the exception of rare isolated marlstone flasers. The chalk is typically homogeneous and essentially structureless; faint bio-mottling may be recognized locally, and a diffuse pelleted fabric is evident in places. In the Adda–Tyra area, the Tuxen Formation is thin and stratigraphically condensed or incomplete; pebbly chalk beds occur locally in association with nodular chalks and hardgrounds (Jensen & Buchardt 1987; van Buchem *et al.* 2018; Jelby *et al.* 2022; Ineson *et al.* 2022b).

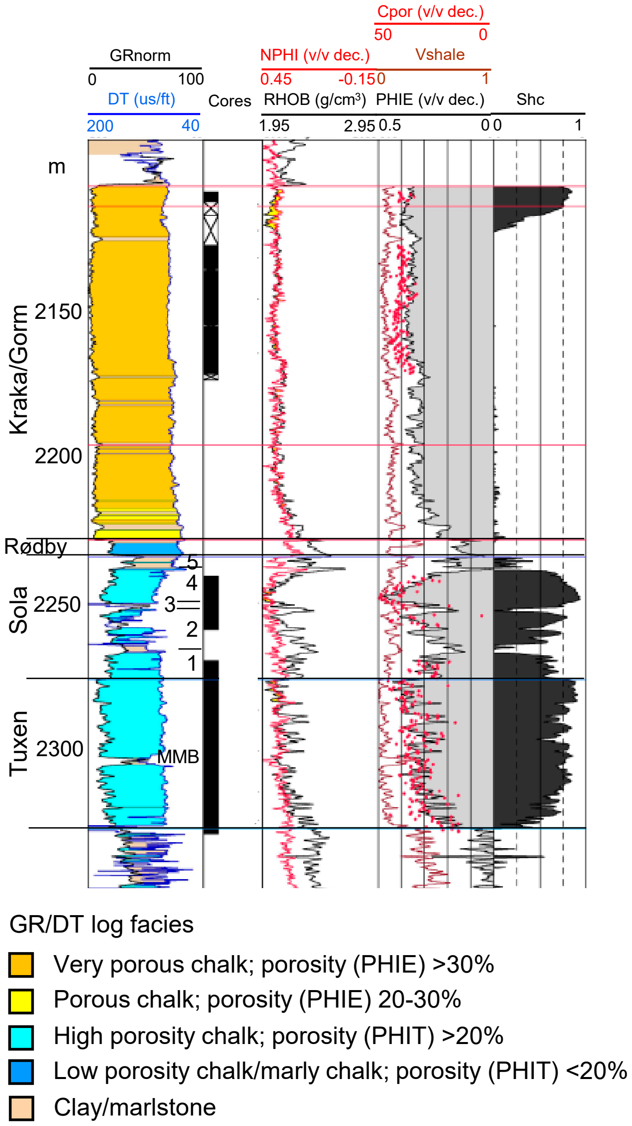

Fig. 8. Computer-processed interpretation (CPI) log of the North Jens-1 well (Valdemar Field; see Fig. 1 for location) showing high oil saturations exceeding 75% in high porosity chalk reservoirs of the Lower Cretaceous Tuxen and Sola Formations. Note minor oil saturations in the lower part of the Chalk Group (lower Kraka Formation) above the Tuxen and Sola accumulations. The five units (1–5) of the Sola Formation described in the text are indicated; MMB: Munk Mark Bed. Semi-quantitative log evaluation of reservoir facies (first column) utilized different parameters for the clay-poor Upper Cretaceous – Danian Chalk Group (PHIE, effective porosity) and the clay-rich Cromer Knoll Group chalks (PHIT, total porosity; for full methodology, see Skaarup *et al.* 2017). Cpor: core porosity, GRnorm: normalised Gamma-ray log; DT: Sonic log; NPHI: Neutron porosity log; PHIE: Effective porosity; RHOB: Density log; Shc: Hydrocarbon saturation. Vshale: Calculated shale volume.

The MMB, bisecting the Tuxen Formation (Figs 2, 8), is an interval of dark grey to black, finely laminated, organic-rich marlstone up to 2 m thick; the bed is locally absent or condensed on structural highs (e,g, Adda-2, Jensen & Buchardt 1987). The organic matter contains diagenetic bituminite and late-oil solid bitumen (Rudra *et al.* 2021). The lamination is commonly defined by an alternation of lighter-coloured carbonate-rich and darker clay-rich laminae (Fig. 9B; see also Jelby *et al.* 2022). As reported in detail by Thomsen (1989a, b), the carbonate-rich laminae are dominated by nannofossils and the coccoliths are spectacularly preserved. The lamination is typically parallel and undisturbed but weakly bioturbated levels (*Chondrites*) are recognized locally. Pyrite is common in this lithofacies, both disseminated and forming framboidal pyrite nodules up to ~2.5 cm across (Rudra *et al.*, 2021). The marlstones are rich in organic carbon and Jensen & Buchardt (1987) recorded an average TOC value of 11.5 wt.% for the MMB in the E-1 well (Fig. 1 for location). Matrix-rich conglomerate beds up to 0.4 m thick, of debris flow origin, and thin graded marlstone turbidites occur interbedded with laminated marlstones in the MMB in the Deep Adda-1 well; these redeposited facies were probably derived from the fault-controlled eastern margin of the Danish Central Graben (Ineson *et al.* 2022b).

Log definition of the base of the formation is variable. In expanded sections, the apparently conformable boundary is transitional and picking a significant fall in GR values (increase in carbonate content) can be subjective (Fig. 6); in other cases, for example in the eastern Adda area, the boundary is abrupt and associated with seismic truncation at seismic marker CKG10 and a significant biostratigraphic hiatus (Ineson 1993; Copestake *et al.* 2003; Ineson *et al.* 2022b). The top of the formation is defined at a significant increase in GR values marking the incoming of the shale-dominated facies of the overlying Sola Formation (Figs 6, 8).

The preserved Tuxen Formation is somewhat less widespread than the underlying Valhall Formation, as indicated by the mapped seismic interval CKG10 – CKG15 (Fig. 7B), due to truncation in the Søgne Basin and in the southern part of the graben. The thickness of the Tuxen Formation in well penetrations generally ranges from ~10–90 m but the formation can exceed 100 m in thickness in depositional depocentres such as the Feda Graben (e.g. Sten-1 well; Fig. 6). As illustrated in Fig. 7A and B, discrete depocentres were more localised than during Valhall times, being restricted to the Feda Graben, the southern part of the Arne-Elin Graben and the south-western part of the Roar Basin (Fig. 7B), the latter depocentre possibly the result of salt withdrawal. The depositional depocentre in the Outer Rough Basin (Fig. 7B), which was initiated in Valhall Formation times, shows more definition in the Tuxen Formation isochore, a trend that developed strongly during deposition of the Sola and Rødby Formations (Fig. 7C, D). The eclipse of the Valhall depocenter east of the Roar Basin in the Hauterivian and Barremian

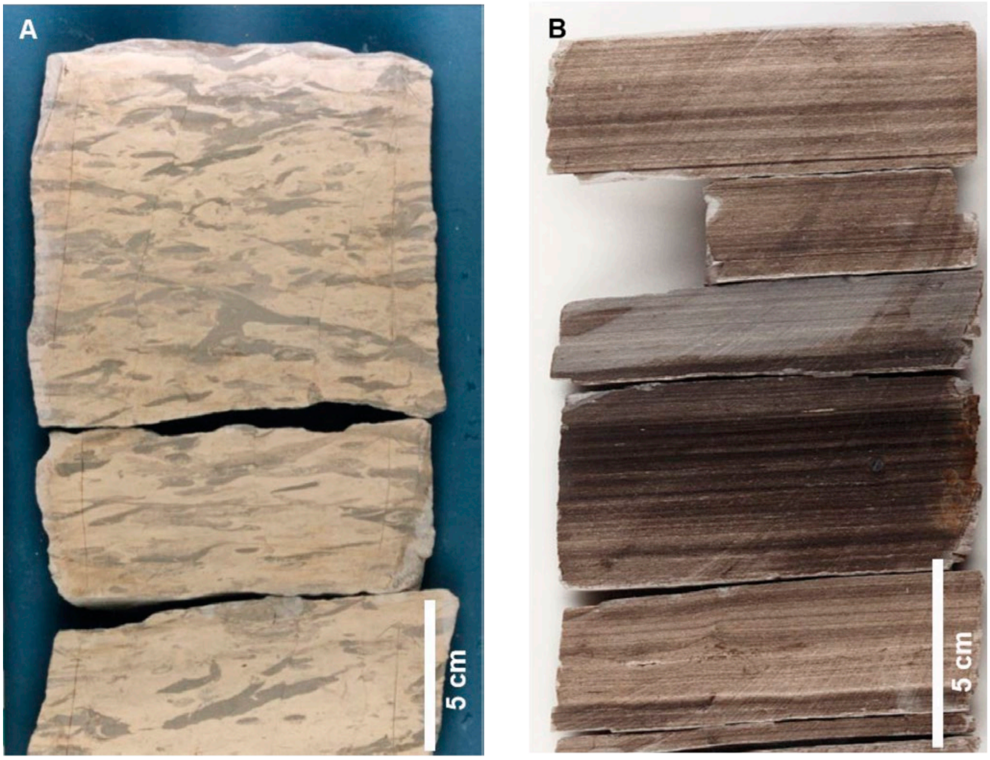

Fig. 9. (A) Bioturbated marly chalk, the typical facies in the central portion of the upper Tuxen Formation (North Jens-1 well, 7944 ft/2421.3 m), **(B)** Finely laminated marlstones of the Munk Marl Bed in the Tuxen Formation (North Jens-1 well, 7560 ft/2304.3 m). Note the absence of bioturbation, the delicate dark–light laminae and the superimposed gradual transitions from darker more clay-rich intervals to lighter chalkier intervals. Minor truncation and drape (lower left) is attributed to slope creep.

reflects beginning uplift along the trend of the subsequent Late Cretaceous Tyra–Igor and Adda inversion ridges (Vejbæk & Andersen 2002).

Sola Formation (upper Barremian – lower Albian)

The Upper Barremian – Lower Albian Sola Formation is dominated by fine-grained calcareous siliciclastics but also includes marly chalk interbeds; a discrete thin reservoir-quality chalk unit (*c.* 5–8 m thick) of late early Aptian age is present locally, notably in the Valdemar Field (Figs 1, 8).

Where fully developed (e.g. northern Valdemar Field; Ineson 1993; Jakobsen *et al.* 2004; Fig. 8), the formation comprises five units:

(1) The basal unit of late Barremian age (Lower Sola-1 of Jakobsen *et al.* 2004) is up to 8 m thick, although often absent or thinly developed. Lithologically it resembles the underlying Tuxen Formation, comprising thoroughly bioturbated chalky marlstones and marly chalks.

(2) Dark grey to black bioturbated or laminated marlstones dominate this interval (Middle Sola-1 to -3 of Jakobsen *et al.* 2004), though interbedded bioturbated chalky marlstones and marly chalks are represented in the upper levels. This upper Barremian to lowermost Aptian unit is *c.* 15 m thick in the northern Valdemar Field and up to 25 m thick in eastern Adda discovery wells.

(3) Black, finely laminated, organic-rich marlstones of the lower Aptian Fischschiefer Member, typically 2–5 m thick, create a distinctive log marker that is recognized widely in the North Sea region (see below),

(4) This unit (Upper Sola-1, -2 of Jakobsen *et al.* 2004) varies lithologically in the Danish Central Graben, being dominated by marlstones with subordinate marly chalk interbeds in most areas but forming a secondary chalk reservoir body in the northern Valdemar Field (Fig. 8) where it is *c.* 13 m thick and includes clay-poor chalk of reservoir quality in the lower half.

(5) The uppermost Sola Formation consists of a mid-Aptian – lower Albian variably calcareous claystone succession that varies in thickness from a few metres to nearly 100 metres in late Aptian – Albian depocentres. Previously referred to informally as the 'Albian Shale' (Jakobsen *et al.* 2004), this unit was defined formally as the Fanø Member of the Sola Formation by van Buchem *et al.* (2018) and interpreted to record lowstand deposition in a restricted, dysaerobic basin with reduced water circulation. The lower boundary is locally erosional, truncating the Aptian chalk reservoir beneath (e.g. southern Valdemar Field).

Complete sections including all five of these units are relatively scarce in the Danish Central Graben. The lower two units may be absent such that the Fischschiefer Member rests directly on the Tuxen Formation, exemplified by the Adda-2 well (Jensen & Buchardt 1987), whilst the upper Sola Formation (and the succeeding Rødby Formation) is typically only well developed in the central depocentres (e.g. the Roar Basin, Arne Elin Graben) and is more commonly highly condensed or absent.

The laminated organic-rich marker bed in the Sola Formation, the lower Aptian Fischschiefer Member, is recognized widely in the North Sea subsurface (Crittenden *et al.* 1991; Ainsworth *et al.* 2000; Riley *et al.* 1992; Copestake *et al.* 2003) and is commonly correlated with the globally recognized early Aptian anoxic event, OAE 1a (van Buchem *et al.* 2018; Blok *et al.* 2022). Although overtly resembling the MMB within the Tuxen Formation, Thomsen (1989b) demonstrated that the light-coloured, carbonate-rich laminae in the Fischschiefer Member are commonly composed of discrete coccolith-rich pellets, contrasting with the pristine, often monospecific nannofossil-rich laminae in the MMB (Thomsen 1989a, b). The Fischschiefer Member contains bitumen from migrated oil, degraded lamalginite and abundant framboidal pyrite (Rudra *et al.* 2021).

The areal extent and thickness variation of the Sola Formation is illustrated by the seismic interval CKG15–CKG20 (Fig. 7C). The formation has a reduced lateral extent in the south-south-eastern part of the Danish Central Graben due to truncation but otherwise the time-isochore map shows similarities to that of the Tuxen Formation with regard to the location of the main depocentres, i.e. the Arne-Elin Graben – Iris Basin and the south-eastern Roar Basin. Contrasts include the decrease in importance of the Feda Graben and the evidence of marked subsidence of the central part of the Outer Rough Basin during Sola Formation times, where based on seismic data the formation has a maximum thickness of more than 200 m (150 ms). In most wells the drilled thickness of the Sola Formation is ~10–60 m but exceeds 100 m in the Arne-Elin Graben and Iris Basin depocentres (Fig. 7C; Nielsen & Japsen 1991; van Buchem *et al.* 2018). It is deemed likely that much of the enhanced thickness in undrilled depocentres is attributable to the Fanø Member, recording centres of Late Aptian – Albian subsidence (see also Rødby Formation, Fig 7D; van Buchem *et al.* 2018).

Rødby Formation (early Albian – earliest Cenomanian)

The Lower Albian – lowermost Cenomanian Rødby Formation represents the upward transition from the mud-rich facies of the Sola Formation to the chalks of the Upper Cretaceous Chalk Group above, as reflected by the overall upward decrease in GR values. The formation typically consists of greyish marlstones with subordinate calcareous shales and chalky limestones (Jensen *et al*. 1986).

The CKG20 – chb seismic interval comprising the Rødby Formation is generally thinly developed and there is poor separation between the CKG20 and the distinct Base Chalk chb seismic horizon (Fig. 7D); the limited extent of this formation relative to those beneath (compare Fig. 7D with 7A–C) may thus be in part an artefact due to seismic resolution. The Outer Rough Basin is anomalous showing extraordinary thicknesses, but it is stressed that the central part of this basin is without well control, the only direct seismic tie being that of the Lilje-1 well, located at the western basin margin. In many wells, the Rødby Formation is condensed and in most wells the formation is <25 m thick or absent, but thicknesses over 60 m have been recorded in mid-Cretaceous depocentres (e.g. Nielsen & Japsen 1991) where the R1–R3 subdivisions of Crittenden *et al.* (1991) are often recognisable. In such expanded sections, where the succeeding chalks of the Hidra Formation are thickly developed and argillaceous, defining the location of the upper boundary of the Rødby Formation can be difficult. Compared to the underlying uppermost Sola Formation (Fanø Member) the sediments and microfossils of the Rødby Formation indicate a return to more open marine depositional conditions (van Buchem *et al*. 2018).

Discussion

The new stratigraphically well-constrained isochore maps presented here (Fig. 7, Supplementary Data) document the regional Early Cretaceous evolution of the Danish Central Graben in unprecedented detail; this is particularly the case for the Hauterivian–Albian portion of the basin fill that is the focus of much industrial and academic interest (e.g. Mutterlose & Bottini 2013; van Buchem *et al.* 2018; Blok *et al.* 2022; Ineson *et al.* 2022b). The shifting subsidence history revealed by these maps, and the interaction with eustatic sea-level events, have important implications for the stratigraphic development and lateral distribution of mid-Cretaceous chalk reservoirs, as stressed below, a subject relevant to optimizing ongoing hydrocarbon production and future storage potential.

Basin evolution and reservoir development

The depth to the base of the Cromer Knoll Group, the BCU surface, in the Danish Central Graben increases from south to north from about 2000 ms (equivalent to about 2340 m) to more than 3800 ms (equivalent to about 4800 m; Fig. 3). The southern area is dominated by Zechstein salt piercement structures and pillows giving rise to rather dramatic relief (Fig. 10). It is noteworthy that the BCU is shallower in the graben area along the south-eastern segments of the Coffee Soil Fault Zone than on the adjoining part of the stable Ringkøbing-Fyn High. This is the result of intra-Cretaceous compressional tectonism with minor thrust faults that propagate from the tips of former extensional basement-attached faults in the substrate. The major faults (both normal and reverse) affecting the BCU are highlighted in Fig. 11A.

The Cromer Knoll Group sediments were deposited during a post-rift thermal subsidence phase, and the main depocentres are mapped as elongate troughs or sub-basins parallel to the basin axis (Fig. 11B). The Roar Basin to the south was separated by a NE–SW trending threshold (Pollerne Ridge of Vejbæk 1986) from the northern sub-basins. The post-rift Valhall Formation depocentres are to a large extent coincident with the major depocentres of the late-rift deposits referred to the middle Volgian – upper Ryazanian Farsund/Mandal Formations, i.e. the Feda Graben, Gertrud Graben, Arne-Elin Graben and major parts of the former Tail End Graben (Fig. 11B). The Outer Rough Basin and Ål Basin developed as new structural elements that accumulated thick Lower Cretaceous sections (Fig. 10). The Cromer Knoll Group is, however, more limited in extent than the underlying Upper Jurassic – lowermost Cretaceous syn-rift deposits, being absent on the Mid North Sea High and the Heno Plateau, and in the Søgne Basin and the south-western part of the Salt Dome Province (Fig. 11B).

The lower Cromer Knoll Group basin-fill geometry in the northern sub-basins (e.g. Feda Graben, Arne-Elin Graben, Gulnare Basin) shows that the uppermost Ryazanian to lower Hauterivian Valhall Formation (rather seismically transparent BCU–CKG10 interval) onlaps onto the BCU along the basin margins (Fig. 12). The basin-fill geometry differs in the southern part of the Roar Basin where oblique reflectors dipping gently (1–2°) basinwards (westwards) have been interpreted to represent clinoforms that prograded towards the basin centre from east to west (Vidalie *et al.* 2014); these workers estimated that the maximum topographical relief on these gently dipping reflectors was in the order of 400 m.. Based on flattening at the Base Chalk Group, Vidalie *et al*. (2014) mapped a pattern of laterally continuous sequences over more than 20 km and suggested that this records south-westward migration of a shelf, into the underfilled Early Cretaceous basin. An alternative interpretation, however, is that the dipping surfaces in this area represent gently tilted strata due to a progressive westward shift in the depocentre accompanying incipient inversion in the Adda–Tyra area, the latter being testified by hiatal surfaces at base Tuxen Formation and within both the Tuxen and Sola Formations (Jensen & Buchardt 1987; Copestake *et al.* 2003; van Buchem *et al.* 2018; Ineson *et al.* 2022b). Synsedimentary tectonic control during deposition of the interval is demonstrated in the Adda–Tyra area by a system of WNW–ESE oriented normal faults that show a vertical displacement of up to 150 m at BCU level (Fig. 13; Vidalie *et al.* 2014). Syndepositional growth on these faults peaked in the Valanginian,

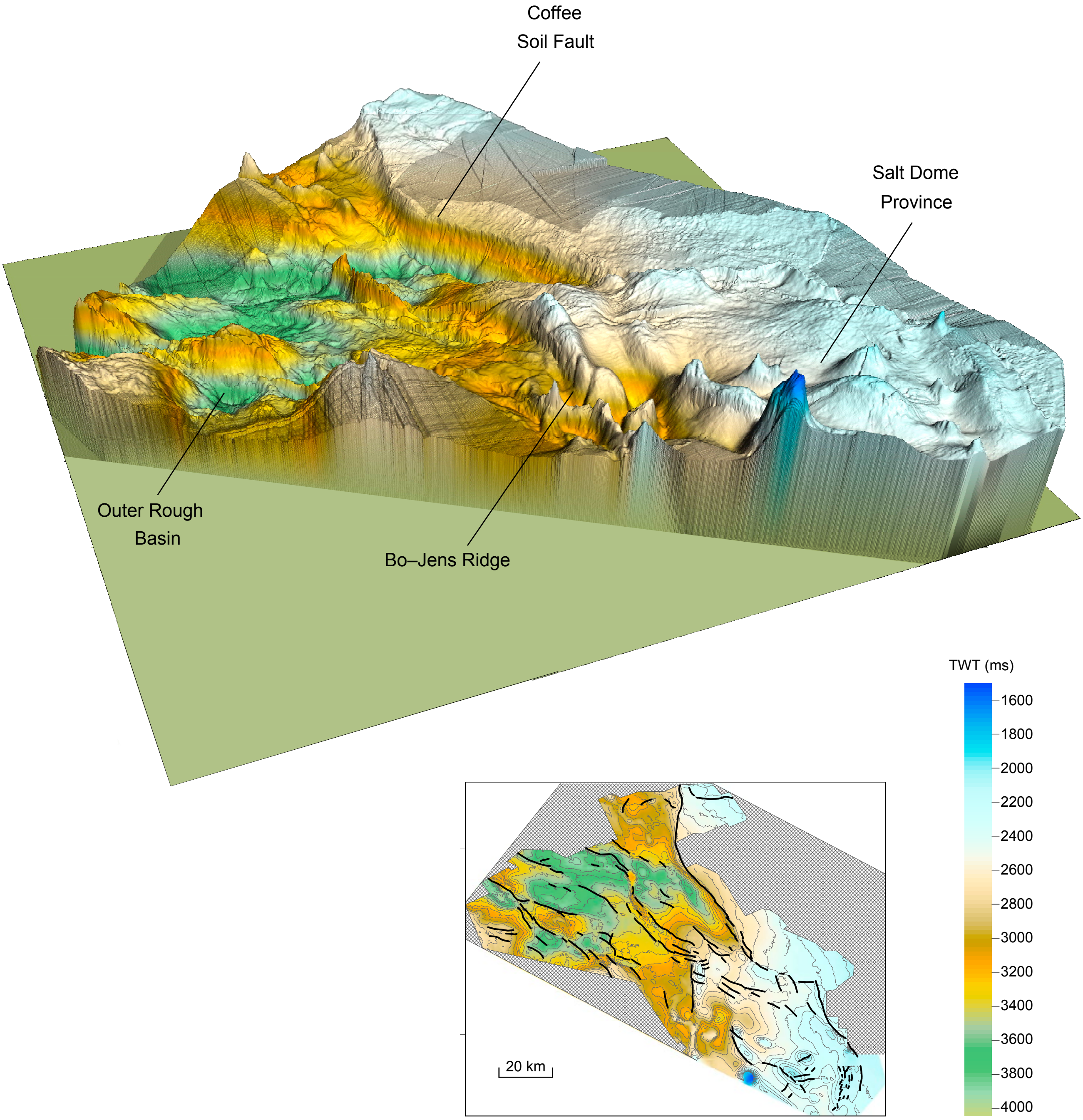

Fig 10. 3D presentation of the time-structure map of the BCU as viewed from the south towards the NNE; key features are indicated for reference. Insert map shows the BCU time-structure map of the Danish Central Graben to aid orientation (see also Fig. 3). 3D image produced by Christian Brogaard Pedersen (GEUS).

waned during the Hauterivian–Albian and the faults were apparently inactive by the Cenomanian (base Chalk Group level).

During deposition of the Tuxen Formation (seismic interval CKG10–CKG15) the basin configuration changed with pronounced subsidence in the Outer Rough Basin in the NW Danish Central Graben (Figs 7B; 10). The Tuxen Formation also marks a change from clay- to chalk-dominated deposition. The depositional setting of the Tuxen Formation is a subject of some debate. Although the chalks that dominate this formation are generally overwhelmingly dominated by nannofossils of pelagic origin, van Buchem *et al.* (2018) suggested a model of areally differentiated carbonate production comprising relatively shallow settings (50–100 m or less) where carbonate-rich sections accumulated separated by mud-dominated deeper water environments. Detailed consideration of this model will be presented elsewhere though regional well and seismic data document the persistence of the chalk-rich Tuxen Formation throughout the Danish Central Graben, albeit being thicker and marlier in depocentres (e.g. Fig. 6; Jakobsen *et al.* 2005). It is likely, however, that relatively shallow 'shelf-like' conditions prevailed locally on uplifted Early Cretaceous inversion structures such as the Adda–Tyra high – the site of the main 'Tuxen shelf' of van Buchem *et al.* (2018). The structural evolution of the basin in the Valdemar and Adda–Tyra areas during the late Hauterivian – Barremian strongly influenced both the facies development and the distribution and preservation of Tuxen Formation reservoir chalks (Ineson 1993; Jakobsen *et al.* 2004, 2005; Jelby *et al.* 2022; Ineson *et al.* 2022b). Protracted subsidence in the Valdemar area ensured the accumulation of continuous chalk–marl successions whereas early inversion of the Adda–Tyra structure resulted in thin, stratigraphically incomplete, condensed chalk deposits.

The succeeding Sola Formation records a significant shift in sedimentation style, being dominated by fine-grained siliciclastic sediment, the influx of mud probably resulting in part from two relative falls in sea level (Ineson 1993; Jakobsen *et al.* 2004; van Buchem *et al.* 2018). In stratigraphically complete sections (e.g. North Jens-1, see Ineson 1993; Copestake *et al.* 2003; Fig. 8), the organic-rich Fischschiefer Member marks the transition from dark bioturbated and laminated marlstones to chalk-rich facies, and has been interpreted to represent a maximum flooding surface that is equivalent to the global oceanic anoxic event OAE 1a characterized by transgression and the accumulation and preservation of organic matter (van Buchem *et al.* 2018; Blok *et al.* 2022). In contrast, the mud-rich upper part of the Sola Formation (the Fanø Member) was deposited under lowstand conditions in a more restricted basin and is considered to reflect a global sea-level fall in the latest Aptian – earliest Albian (van Buchem *et al.* 2018). The absence of the Aptian chalk reservoir (unit 4 of the Sola Formation, Fig. 8) in the southern Valdemar Field probably resulted from sub-

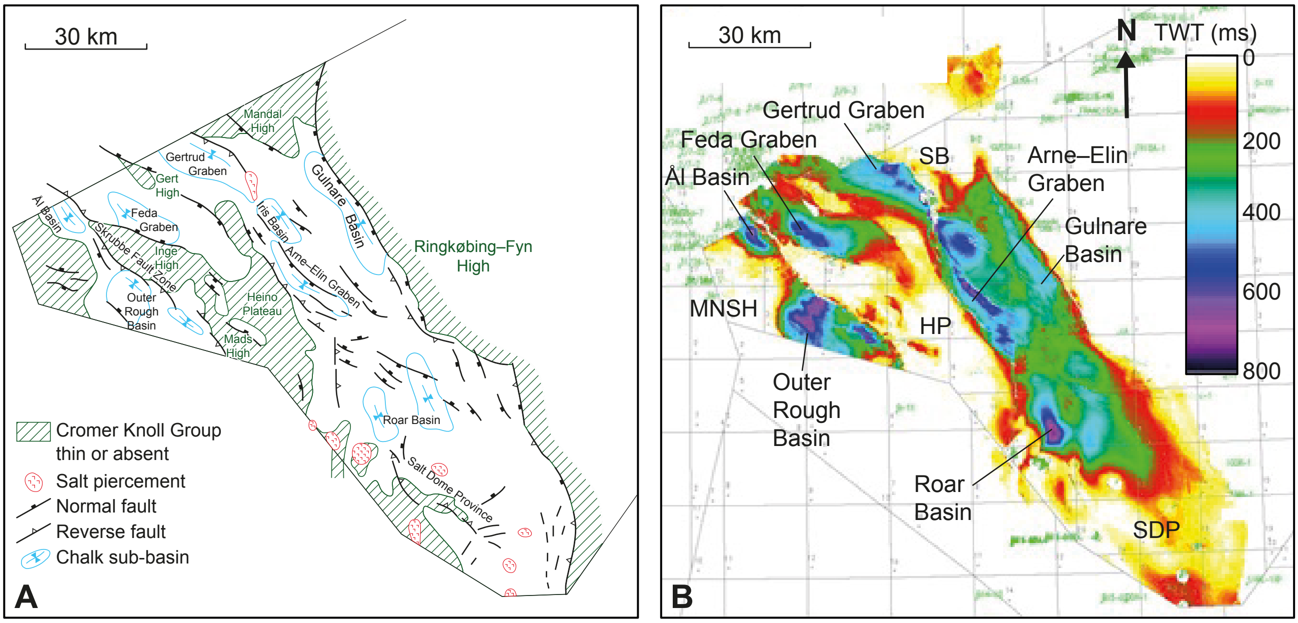

Fig. 11. (A) Lower Cretaceous structural elements with fault traces at the BCU level. Lower Cretaceous sub-basins are shown together with areas where the Cromer Knoll Group is thin or absent. Structural nomenclature partly after Britze *et al.* (1995) **(B)** Time-isochore map (TWT, ms) of the Lower Cretaceous Cromer Knoll Group. HP: Heno Plateau; MNSH: Mid North Sea High; SB, Søgne Basin; SDP: Salt Dome Province.

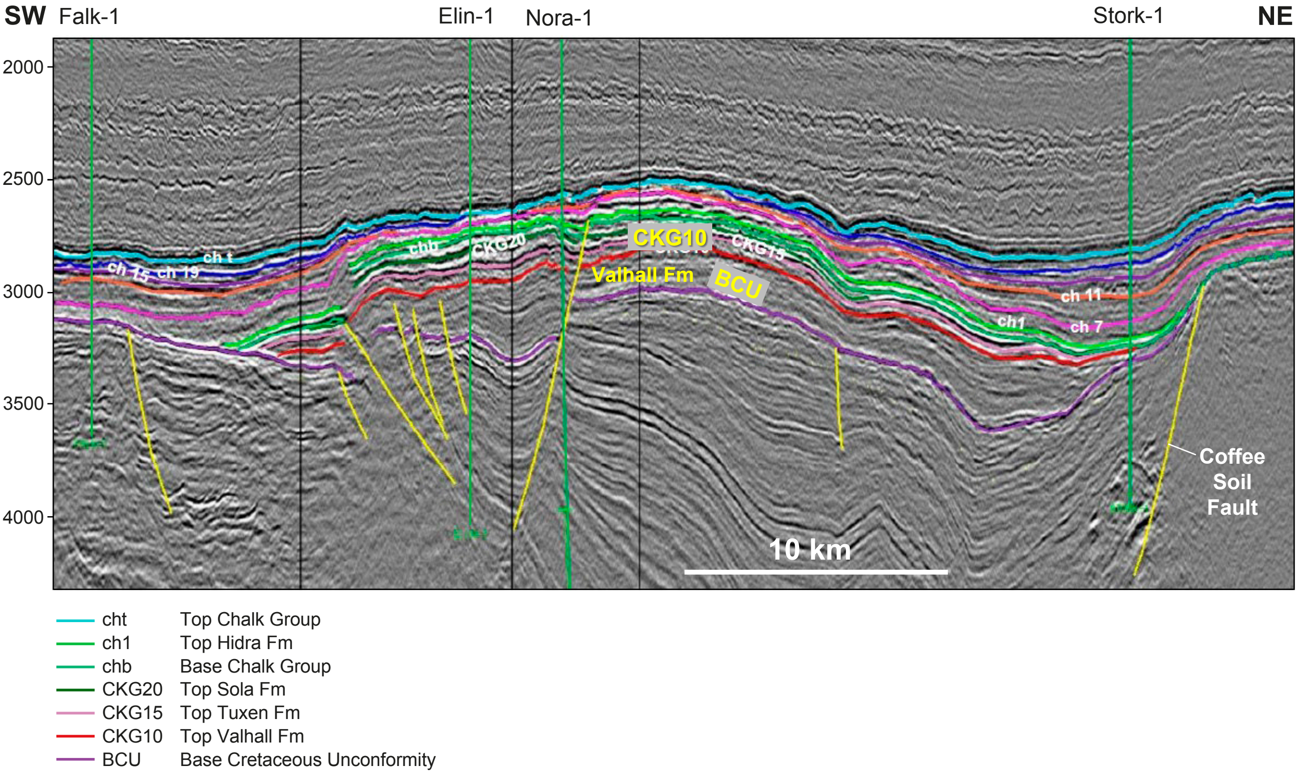

Fig. 12. SW–NE seismic structural profile across the Arne–Elin Graben and the Gulnare Basin (Early Cretaceous sub-basin of the Tail End Graben) to the east showing basal onlap of the lowermost Cretaceous Valhall Formation (seismic interval BCU–CKG10) onto the BCU. See Fig. 1 for location of seismic profile.

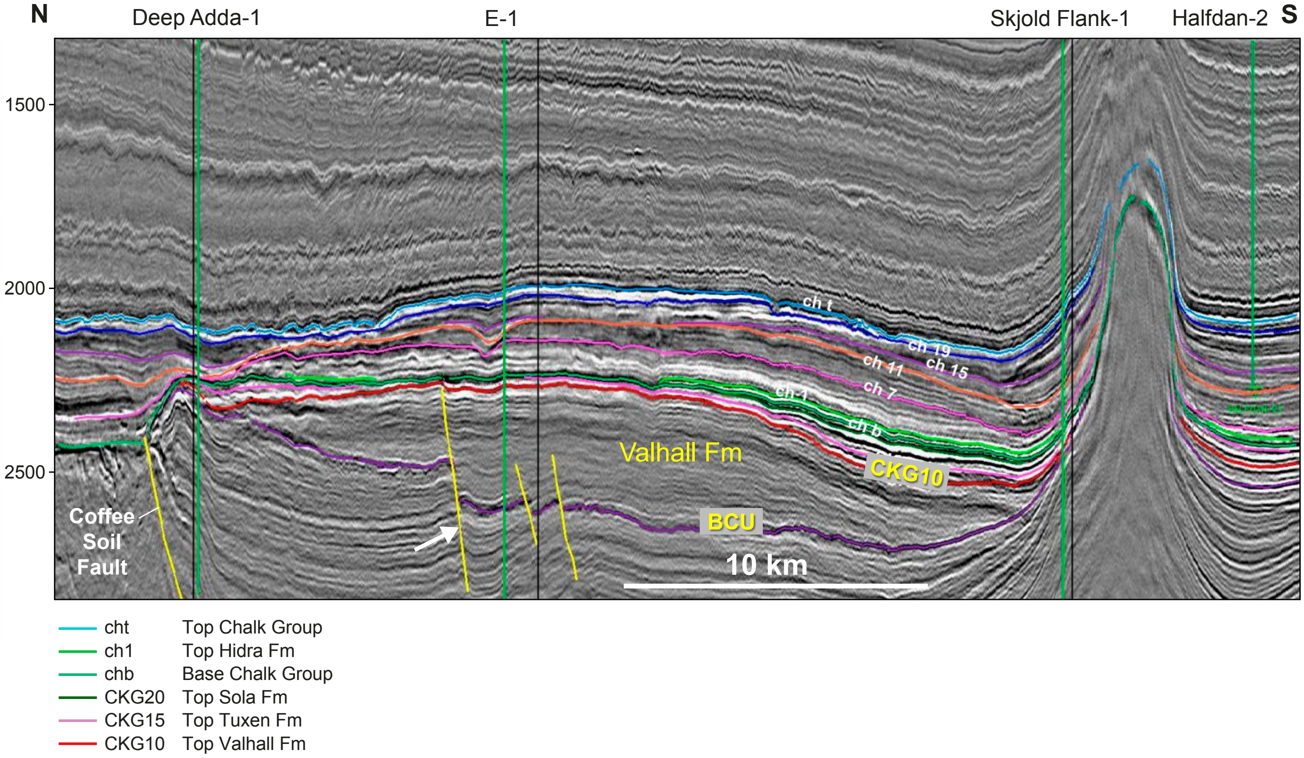

Fig. 13. N–S seismic structural profile showing faults active during the deposition of the Valhall Formation (seismic interval BCU–CKG10). An important Valanginian growth fault is arrowed. See Fig. 1 for location of seismic profile.

marine erosion accompanying this sea-level excursion.

The uppermost unit of the Cromer Knoll Group, the Rødby Formation (seismic interval CKG20 – chb; Fig. 7D), comprises a succession of marlstones and marly chalks that becomes increasingly carbonate-rich upwards, and represents a return to more open marine depositional conditions. It oversteps underlying deposits but is typically relatively thinly developed in the Danish Central Graben, often being beneath seismic resolution, though thickening to up to 60 m in local depocentres (e.g. Roar Basin, Outer Rough Basin). In such expanded sections, the fluctuating carbonate:clay content yields a distinctive log pattern that matches the 'type North Sea' development described by Crittenden *et al.* (1991) suggesting regional/global controls on facies development.

Hydrocarbon aspects

The Danish Central Graben is a mature petroleum producing basin in which the vast majority of the oil can be correlated to source rock facies of the Upper Jurassic – lowermost Cretaceous marine shales of the Farsund and Mandal Formations, i.e. Kimmeridge Clay Formation equivalents (Petersen *et al.* 2016; Petersen & Hertle 2021; Petersen & Jakobsen 2021). The source rock quality varies through space and time, but generally it increases through time and attains the best quality in the upper Volgian – Ryazanian Mandal Formation that includes the organic-rich 'hot shales' of the Bo Member (Ineson *et al.* 2003; Ponsaing *et al.* 2020a, b, 2021; Petersen & Hertle 2021; Petersen & Jakobsen 2021). Today, this upper, rich part of the source rock section is only mature in the northern part of the Danish Central Graben while the deepest buried part is gas mature to overmature. In contrast, in the southern part of the basin, the source rock section is thermally immature with regard to oil generation due to insufficient burial depth, thus suggesting a complex filling history of the chalk fields in the Salt Dome Province. The Upper Cretaceous – Danian Chalk Group contains the most successful and economically important play in the Danish Central Graben. Since the first discovery in 1966 and the initiation of production some years later, substantial amounts of hydrocarbons (oil and gas) have been produced from the Upper Cretaceous Tor and Danian Ekofisk Formations but also from the Tuxen (and Sola) Formations of the Cromer Knoll Group (e.g. Danish Energy Agency 2014). Hydrocarbon production started to decline in 2004, mainly due to gradual exhaustion of recoverable reserves in the ageing fields.

The chalk fields are mostly structural traps formed by salt halokinesis but other trapping mechanisms exist, including the inversion structures of the South Arne and Valdemar Fields and the large non-structural, stratigraphic/dynamic trap of the Halfdan Field (Albrechtsen *et al*. 2001; Megson & Tygesen 2005; Vejbæk & Rasmussen 2005; Fig. 1). The Halfdan Field illustrates the validity of more complex dynamic trapping mechanisms of hydrocarbons. In addition to the prolific chalk play, multiple sandstone plays exist in the Danish North Sea as shown by fields and discoveries in sandstone reservoirs in the Middle and Upper Jurassic (e.g. Søgne Basin fields and Hejre discovery; Petersen & Hertle 2018, 2021), Paleocene (e.g. Siri Fairway fields; Ohm *et al*. 2006) and Miocene (Lille John discovery; Danish Energy Agency 2015).

Recoverable hydrocarbons in the Lower Cretaceous Cromer Knoll Group are considered to be restricted to the chalk reservoirs of the Tuxen Formation, and locally the Sola Formation. Present production is primarily from the Valdemar Field though the Tuxen Formation reservoir is also present in the Adda discovery and across the Tyra Field (Jakobsen *et al*. 2004, 2005; Ponsaing *et al*. 2020a, b; Schovsbo *et al*. 2020; Figs 1, 8). (). Structurally trapped oil has been recorded in both the Hidra and Hod Formations in the lower part of the Chalk Group above accumulations in the Tuxen Formation (e.g. North Jens-1 well, Valdemar Field), either because the top-seal has leaked/breached or the hydrocarbons have migrated in porous layers from entry points outside the structural trap. These discoveries show that the chalk can act both as a reservoir and as a seal. The siliciclastic sediments of the Vyl Formation at the base of the Cromer Knoll Group, flanking the eastern margin of the Danish Central Graben (Fig. 2), have been the focus of some exploration interest though without success to date.

The Tuxen/Sola interval has traditionally been considered as a secondary, deeper exploration target below structural traps identified in the overlying Chalk Group. The reservoirs consist of pelagic chalk and marly chalk in the Tuxen Formation and to a lesser extent in the overlying Sola Formation. The interval is located above the rich Upper Jurassic source rocks and below the Upper Cretaceous hydrocarbon-bearing chalk reservoirs and is thus favourably positioned on the migration route via fractures and faults (Ponsaing *et al*. 2020a, b; Rudra *et al*. 2021). The highest porosity and hydrocarbon saturations in the Tuxen Formation are recorded in the central parts of the Danish Central Graben concentrated on the Bo-Jens and Adda inversion highs (Valdemar Field and Adda discovery, respectively) (Fig. 1); the northward decline in reservoir properties illustrated in Fig 14 supports the inverse relationship between chalk porosity and burial depth proposed by Jakobsen *et al*. (2005). The best reservoir properties in the Valdemar Field are obtained in chalk-dominated intervals with less than

20% clay (Jakobsen *et al.* 2004); the porosity in the chalk units is locally very high, up to 35–40% at *c.* 2500 m depth (Schovsbo *et al.* 2020; Fig. 8). The effective porosity decreases with increasing burial depth and clay content, and due to the very low permeability of the layers in the Lower Cretaceous (0.1–4 mD; Jakobsen *et al.* 2004), chalk production is challenged in some parts of the Valdemar Field where internal baffles also result in compartmentalization of the reservoir (Jakobsen *et al.* 2005; Danish Energy Agency 2014). The distribution of sub-seismic faults and natural fractures is considered an important factor in the productivity of these tight reservoirs (Glad *et al.* 2022; Lorentzen *et al.* 2022) though the difficult production conditions are mitigated by the use of horizontal wells and sand-propant fracture stimulation. Since the onset of hydrocarbon production about 50 years ago, the exploitation efficiency of such low permeability chalk reservoirs has significantly improved following the introduction in the mid-1980s of long horizontal wells and for some fields water or gas injection, which maintains the pressure and forces the oil towards the production wells. These technologies have increased the hydrocarbon recovery factor in tight chalk reservoirs from 5–10% to about 30% (Danish Energy Agency 2009).

Conclusions

The comprehensive seismic mapping program undertaken during an integrated petroleum system study incorporated all available 3D seismic data, constrained by lithostratigraphic and biostratigraphic review of 65 key boreholes. Although the lithostratigraphic framework and broad depositional evolution of the Cromer Knoll Group in the Danish Central Graben is well-established, this seismic–stratigraphic re-evaluation resulted in documentation of the regional subsidence history and depositional patterns in the Danish Central Graben at a scale previously unattained. This is especially pertinent for the mid-Cretaceous, where the Tuxen and Sola Formations command particular interest both in view of their productive chalk reservoirs and their palaeoceanographic significance as harbingers of the Chalk Sea of the Late Cretaceous (Mutterlose & Bottini 2013).

The time isochore maps illustrate the interplay between the dynamic subsidence history of the Early Cretaceous – due to inherited basin morphology, the development of new depocentres and incipient inversion uplift – and regional/global sea-level change. Significant shifts in the subsidence pattern can be

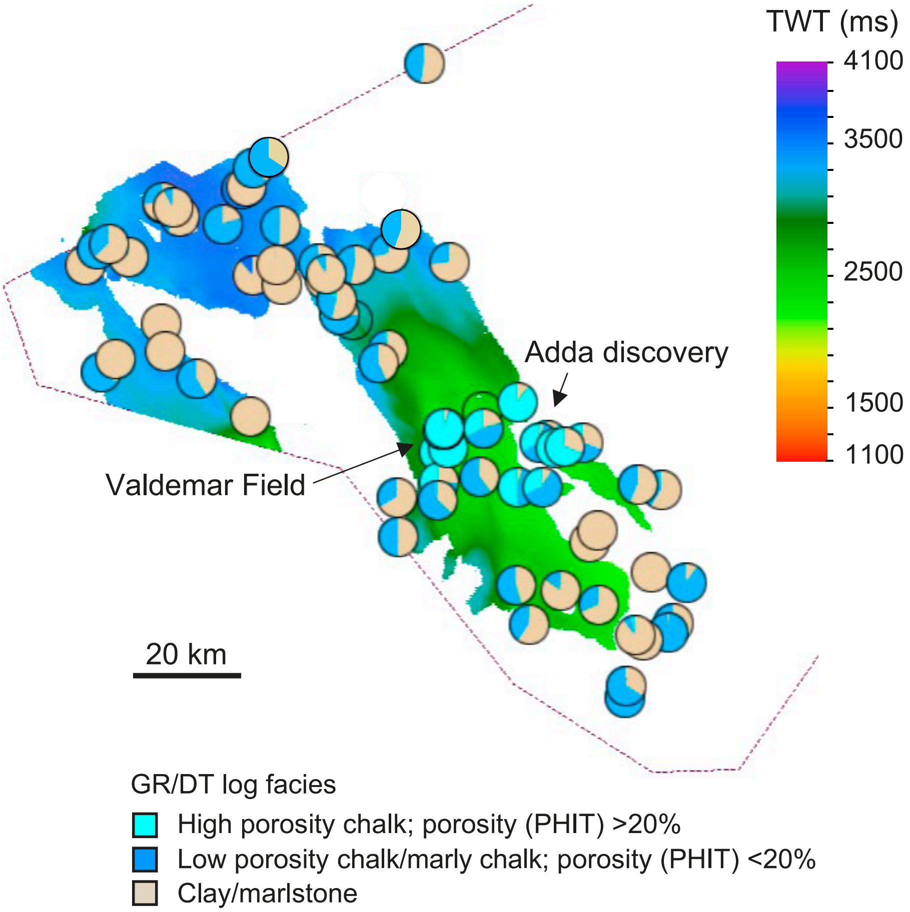

Fig. 14. Top Tuxen structure map (CKG15 reflector) overlain with pie diagrams showing the relative proportions of the main reservoir facies in the Tuxen Formation, based on semi-quantitative log evaluation (GR/DT facies, see Skaarup *et al.* 2017). The optimum chalk reservoir in the Tuxen Formation (highest porosity and net chalk) is recorded in the central parts of the Danish Central Graben concentrated on the Bo–Jens and Adda inversion ridges (Valdemar Field and Adda discovery, respectively; see Fig. 1 for location).

detected in the late Valanginian – early Hauterivian and the late Aptian – early Albian, the former due to the initiation of inversion in the east and the latter resulting from accelerating subsidence in central and western sub-basins. In concert with sea-level changes, these events influenced the facies development and gross thicknesses of the Barremian and lower Aptian chalk reservoirs.

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