The Danish Hydrocarbon
Research and Technology Centre

DTU

Background study of the Kraka, Dan, and Halfdan Fields.

This document provides geological- and reservoir descriptions of the Southern Salt Dome Province, focusing on the Kraka, Dan and Halfdan Fields.

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Contents

1. Field Summaries

The Kraka, Dan, and Halfdan fields are located in Salt Dome Province of the Danish Central Graben offshore west Denmark (figures 1 and 2). These fields are operated by Maersk, who is a part of the Danish Underground Consortium (DUC): a joint venture between A.P. Møller-Mærsk (31.2 %), Shell (36.8 %), Chevron (12 %) and Nordsøfonden (20 %) cooperating to recover oil from the Sole Concession holder's area of the Danish North Sea. The 500 km long Central Graben, approximately 150 km of which are situated in the Danish North Sea sector, consists of a NNW–SSE-trending complex of half-grabens, and a subordinate N–S-trending segment to the south extending into the German and Dutch sectors. The main bounding fault in the Danish sector is the Coffee Soil Fault, which forms the eastern margin of the Danish Central Graben *(Andsbjerg & Dybkjær, 2003).*

Figure 1. Location map of the Kraka, Dan, and Halfdan fields (ENS, 2014).

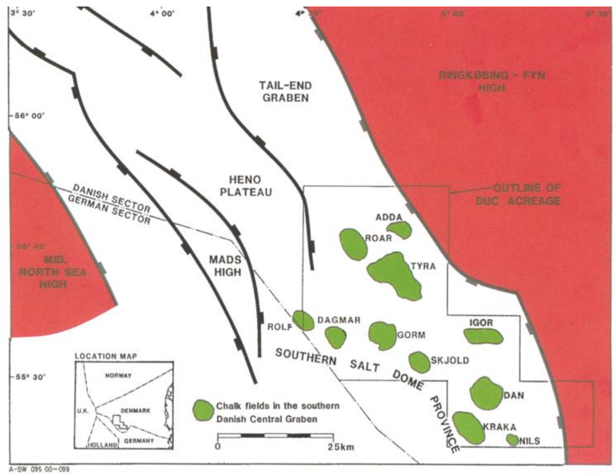

Figure 2. Structural map of the southern Central Graben (Megson, 1992).

1.1 Kraka

Discovery: 1966	Year on stream: 1991	Block: 5505/17	Field delineation: 40km^2	Water depth: 45m
Trap: Anticline	Primary reservoir: Ekofisk Fm	Secondary reservoir: Tor Fm	Reservoir depth: 1800m	

The Kraka Field, located in the Southern Central Graben 9km south of the Dan Field (figure 3), was the first oil discovery in the North Sea. Production was however not enabled by technological EOR advances until 1991. Kraka is an anticlinal structure induced through salt tectonics, which has caused some fracturing in the chalk

(Rasmussen et al., 2005). The Permian salt pillow responsible for the Kraka structure is part of a trend of halokinetic structures known as the Southern Salt Dome Province. The field is areally extensive, stretching more than 8km along its long axis and approximately 5km along the short axis. *(Jørgensen & Andersen, 1991)*.

The main reservoir is the Danian Ekofisk Formation with the Maastrichtian Tor Formation as a secondary reservoir. Porosities in the field are around 30% with a matrix permeability of 1mD and effective permeability due to fracturing of about 8mD. There is a high inverse correlation between impedance and chalk porosity due to the almost mono-mineralic nature of the rock. Chalk porosities decreases with depth, the amount of decrease is however different when hydrocarbons are present, as they tend to preserve porosity *(Rasmussen et al., 2005)*.

The reservoir contains saturated oil beneath a small gas cap. The oil column is thin, with a maximum of 70m and an average of 30m. The overlying gas cap has a thickness of less than 8m. Fluid distributions in the Kraka Field are complex. The thin oil pay zone is in transition zone and is thus characterized by high water saturations of up to 50% in the hydrocarbon bearing zone *(Jørgensen & Andersen, 1991).* The virgin pressure in the field was roughly 6MPa (~900 psi) above hydrostatic in the water zone *(Rasmussen et al., 2005)*. In addition, today this field has an oil-water contact dipping at roughly 10m/km in a SE direction, owing to a lateral water zone pressure gradient in the order of 34.5kPa/km (5psi/km). This pressure gradient fits into a regional pattern of overpressure caused by rapid Neogene burial and reflects the low permeability of the Palaeogene and Cretaceous deposits *(Rasmussen et al., 2005).* Variations in pressures and fluid properties further add to the complexity of the field. Kraka and Dan both have local evidence for a tilted free water level dipping in directions consistent with the regional pressure trend.

Estimates of original STOIIP varies between 200 MMstb *(Rasmussen et al., 2005)* and 300 MMstb *((Jørgensen & Andersen, 1991; ENS, 2014),* depending on the scenario. Cum. oil production at January 1st 2014 was 33.9MMstb *(ENS, 2014).* Ultimate recovery of oil and gas by 2025 is estimated at 36MMstb, resulting in a very low recovery factor of approximately 12% *(Jørgensen & Andersen, 1991)*. Oil is produced through 8 production wells.

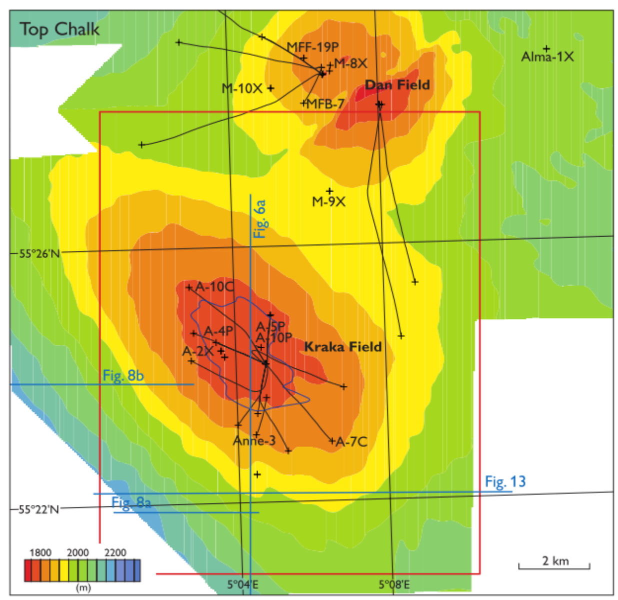

Figure 3. Top Chalk Group depth structure map of the Kraka–Dan area in the southern Danish Central Graben (Klinkby et al., 2005).

1.2 Dan

Discovery: 1971	Year on stream: 1972	Block: 5505/17	Field delineation: 104km^2	Water depth: 40m
Trap: Anticline	Primary reservoir: Tor Fm	Secondary reservoir: Ekofisk Fm	Reservoir depth: 1850m	

The Dan Field is located in the Southern Central Graben, northeast of the Kraka Field and southeast of the Halfdan Field. Production began in 1972, making the Dan Field the oldest producing oil field in the entire North Sea. Like the Kraka Field, Dan is an anticlinal structure induced through salt tectonics. The small Permian salt pillow (7km in diameter), which is connected to the Kraka salt pillow structure to the SW (figure 4), intruded through two sills into the layer beneath the chalk, causing faulting and natural fractures in the Upper- and lower Cretaceous, Jurassic and Triassic layers *(Clausen et al., 2014).* A major NE-SW oriented fault intersects the Dan reservoir, splitting it into two blocks that in turn are intersected by minor faults. Tectonic fracturing however is restricted to the volume close to the major fault *(Larsen et al., 1997; Ovens et al., 1998).* The western flank of the field is unfaulted and unfractured, and is geologically similar to the adjacent Halfdan Field. The presence of oil in the western flank was not confirmed until 1998 with the drilling of the MFF-19C well, which also established the existence of Halfdan *(ENS, 2014).*

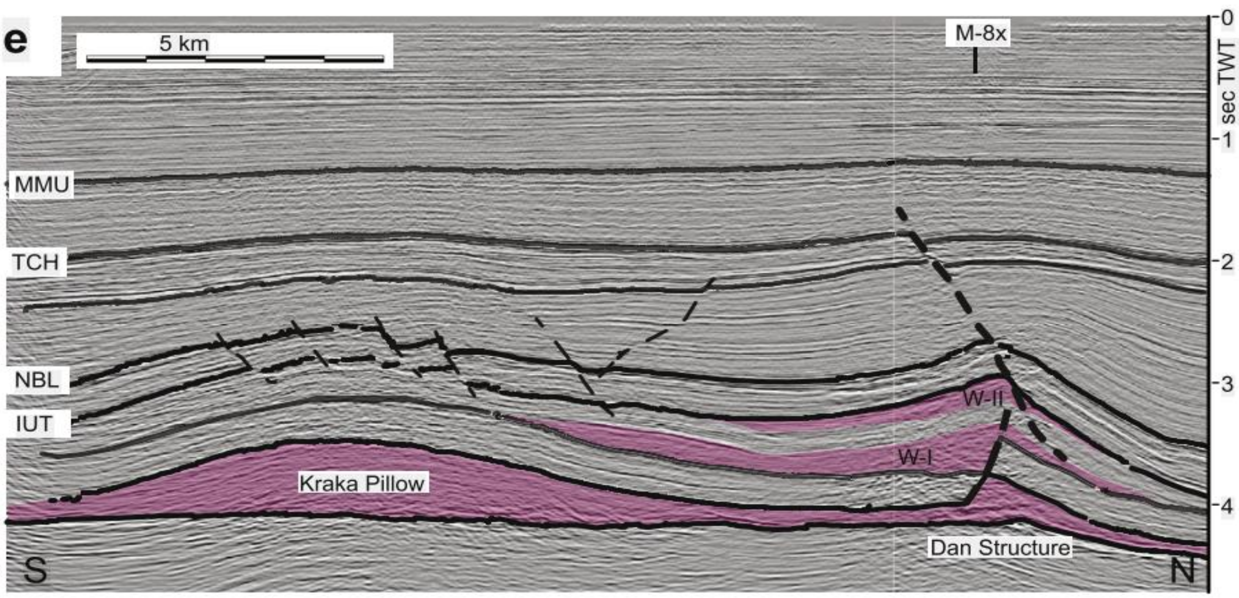

Figure 4. Cross section of the Dan-Kraka area showing the position of evaporite layers in purple and the major faults in the area (Clausen et al., 2014).

The main reservoir is the Maastrichtian Tor Formation, with the Danian and Tertiary Ekofisk Formation as a substantial secondary reservoir. The reservoir is characterized by high porosities of 20 to 40%, and low permeabilities of 0.5-2Md. The effective permeability is however increased by a factor of 2 or 3 above core measured rock permeability by stylolite associated extension fractures. Tectonic fractures are rarely observed except in the immediate vicinity of the main fault. Consequently, induced fractures are required for production. A flinty hardground at the base of the Danian unit acts as a possible barrier both to fluid flow and vertical fracture growth *(Ovens et al., 1998).*

The reservoir contains oil beneath a sizable gas cap; the oil- and gas zones in discovery well M-1X in 1971 were 122m and 80m, respectively. The gas cap exists in both structural blocks of the Dan Central Field; there is however no pore fluid connectivity across the major fault, i.e. the fault is sealing *(Megson, 1992).* Moreover, the gas cap is not present in the West Flank. The water saturation in Dan, as in Kraka, is approximately 50% in the oil bearing zone and the oil-water transition zone is thick (several tens of meters) due to capillary forces in the low permeable chalk. The oil water contact in the Dan reservoir is also tilted, dipping in a SSW direction. The OWC height differential across the field is 60m (by 1992). There is a general pressure gradient in the aquifer with hydrodynamic flow towards a low pressure area to the SE. Dan and Kraka both have local evidence for a tilted free water level dipping in directions consistent with the regional pressure trend.

The original volumes in place are estimated to 1922MMstb of oil and 42.7bn.Nm^3 of gas. Cum. oil and gas production as of January 1^{st} 2014 was 683MMstb and 23.8 bn. Nm^3, respectively. Hydrocarbons are produced through 61 oil- and 48 gas wells, as of 2013, 44 water injectors were installed. On the west flank, oil producers and water injectors are set up in a line-drive of long, parallel horizontal wells *(ENS, 2014)*.

1.3 Halfdan

Discovery:
1958 (Igor/Sif)
1998 (Nana)

Year on stream:
1999 (Nana)
2004 (Sif), 2007 (Igor)

Block:
5505/13

Field delineation:
100km^2 (Halfdan main), 40km^2 (Sif), 109km^2 (Igor)

Water depth: 43m

Trap:
Dynamic

Primary reservoir:
Tor Fm

Secondary reservoir:
Ekofisk Fm

Reservoir depth: 2030-2100m

The Halfdan Field, which comprises the Halfdan, Sif, and Igor areas, is located in the Southern Central Graben, downflank of the Dan- and Skjold Fields (figure 5). The Halfdan accumulation is a stratigraphic or dynamic trap without a present-day structural component. The non-structural trapping is provided by a combination of up-dip thinning of the hydrocarbon bearing section, late structural tilting, and the slow re-adjustment caused by the low permeability reservoir. The field is however thought to have constituted an earlier closure that disappeared, with later tilting causing oil-flow towards the Dan Field to the southeast. Inferred oil migration from Halfdan to Dan corresponds to 25% of the Dan STOIIP per million years *(Albrechtsen et al., 2001).* Reconstruction of a Miocene four-way dip closure from seismic isochore maps suggests that the structural trap of the Halfdan Field was largest in the Tortonian (10-8m.a) *(Rasmussen et al., 2005).*

The Halfdan reservoir is unfractured, low permeability chalk of Maastrichtian and Danian ages, similar to that found in the western flank of the Dan Field *(ENS, 2014).* Like in the Dan Field, the Danian and Maastrichtian formations are separated by a hard ground with extremely poor permeability *(Hansen & Nederveen, 2005).* At reservoir levels, the porosity ranges between 25- and 30%, with permeabilities on the range of 0.5 to 2.0mD. Oil permeability is generally some 5 to 15 times lower in the Danian compared to Maastrichtian for the same porosity chalk *(Albrecthsen at el., 2001).*

The southwestern part of the field primarily contains oil in Maastrichtian layers, while the eastern and northern areas mainly contain gas in Danian layers. Modelling of exploration well Nana-1XP and discovery well MFF-19C showed a 75m thick oil column within the Maastrichtian, including a significant transition zone. Both the gas-oil and oil-water contacts exhibit an apparent tilt from east to west, indicating non-equilibrium conditions and lateral pressure variations *(Albrecthsen at el., 2001)*. The FWL is inferred to have a dip of 40m km^{-1}, suggesting that the water- and oil zones are both dynamic *(Vejbæk et al., 2005).*

The original volumes in place are estimated to 1500MMstb of oil and a small gas cap of 500 Bscf. Cum. oil and gas production as of January 1st 2014 was 409MMstb and 27.12bn.Nm^3, respectively *(ENS, 2014).* In the main field, oil is produced through a line-driver of alternating injectors and producers, like in the Dan West Flank. Gas production from Danian layers in the northeast is based on primary recovery from multilateral horizontal wells, using reservoir pressure. Due to the thinness of the reservoir and the presence of mobile water directly below it, waterflooding is not viable *(Albrecthsen et al., 2001).*

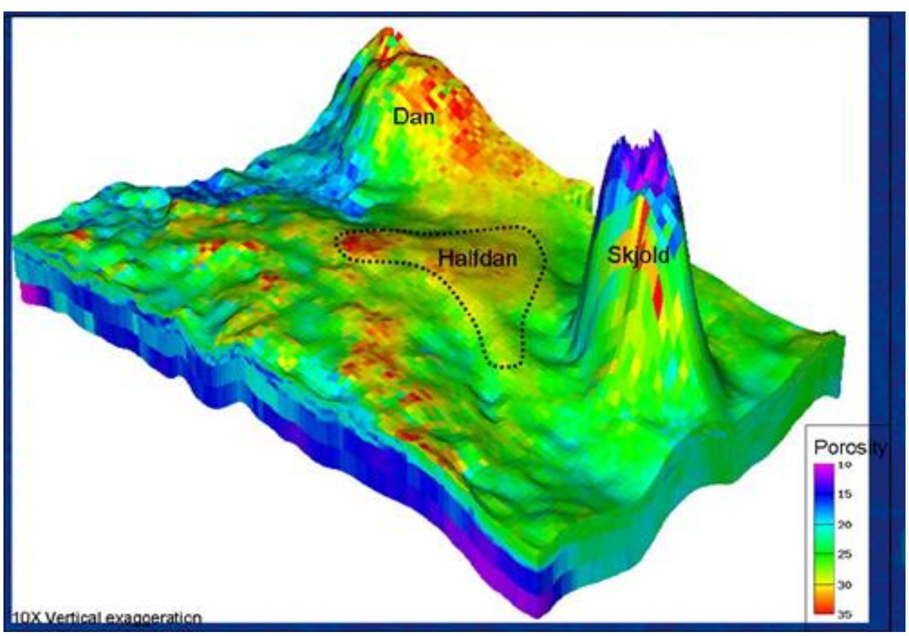

Figure 5. 3D view from Northwest of Halfdan area displaying porosity cube (Albrechtsen et al., 2001)

2. Regional Tectonics

2.1 Introduction and Structural Elements

Much of the tectonic framework in the North Sea region developed in two convergent episodes (figure 6): the Caledonian Orogeny, comprising the Grampian and Acadian episodes at 460-450m.a and ~400m.a, respectively and the Variscan/Appalachian Orogeny at 400-300m.a *(Evans et al., 2003).* The NW-SE Variscan trend dominates in the Central Graben area, while the NE-SW Caledonian trend dominates in the Northern North Sea and Moray Firth Basin. A third suite of E-W trending basement lineaments originate from pre-Variscan Carboniferous extension *(Bartholomew et al., 1993).* Since Permian times, the North Sea has mainly been located in an intraplate setting; however, several younger regional structural events can be recognized. The present-day North Sea geological province is the product of a Mesozoic failed rift system, which developed during two main rifting phases commonly referred to as the Permo-Triassic- and the Late Jurassic phases *(Fossen and Hesthammer, 1998).* In broad terms, the North Sea can be considered as a series of linked, elongated grabens developed in response to the predominantly E-W extensional intra-plate stresses *(Bartholomew, et al., 1993).*

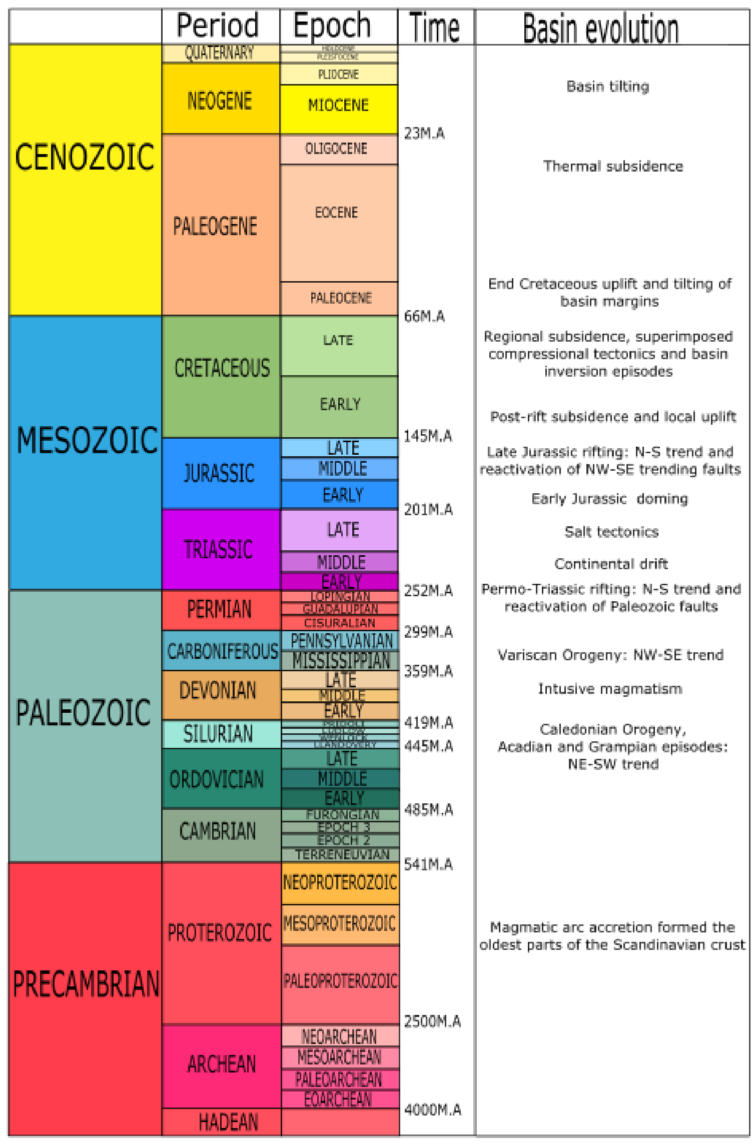

Figure 6. Geological time scale and main basin evolution events in the Central North Sea (complied from multiple publications sited below).

The Central Graben is however not a simple rift graben: the faulting, folding and subsidence patterns in the region are complex and not yet fully understood *(Gowers & Sæbøe, 1985).* This complex architecture is due to a combination of fault re-activation, salt movements and inversion tectonics.

The main structural elements of of the Danish Central Graben are shown in figure 7. The most outstanding element is the Coffee Soil Fault, which runs along the entire eastern margin of the Central Graben in the Danish sector. This major fault separates the Danish Central Graben from a segment of the Ringkøbing-Fyn High termed the East North Sea High. The eastern part of the graben is subdivided into the Søgne Basin towards the north, the Tail End Graben in the central part, and the Salt Dome Province (comprising the Kraka, Dan and Halfdan areas) and the Rosa Basin in the south. Minor elements such as the Poul Plateau constitute the transition between the main boundary fault and the graben itself. Towards the west, the Tail End Graben passes into the Heno Plateau. In the northern part of the graben, a more complex development occurred involving the evolution of a series of grabens, the Arne–Elin, Gertrud and Feda Grabens. The Søgne Basin is separated from the Gertrud Graben by the Mandal High and the Piggvar Terrace. The Mid North Sea High forms the eastern limit of the Danish Central Graben; at the transition this is segmented into the Mads and Inge Highs *(Møller & Rasmussen, 2003).*

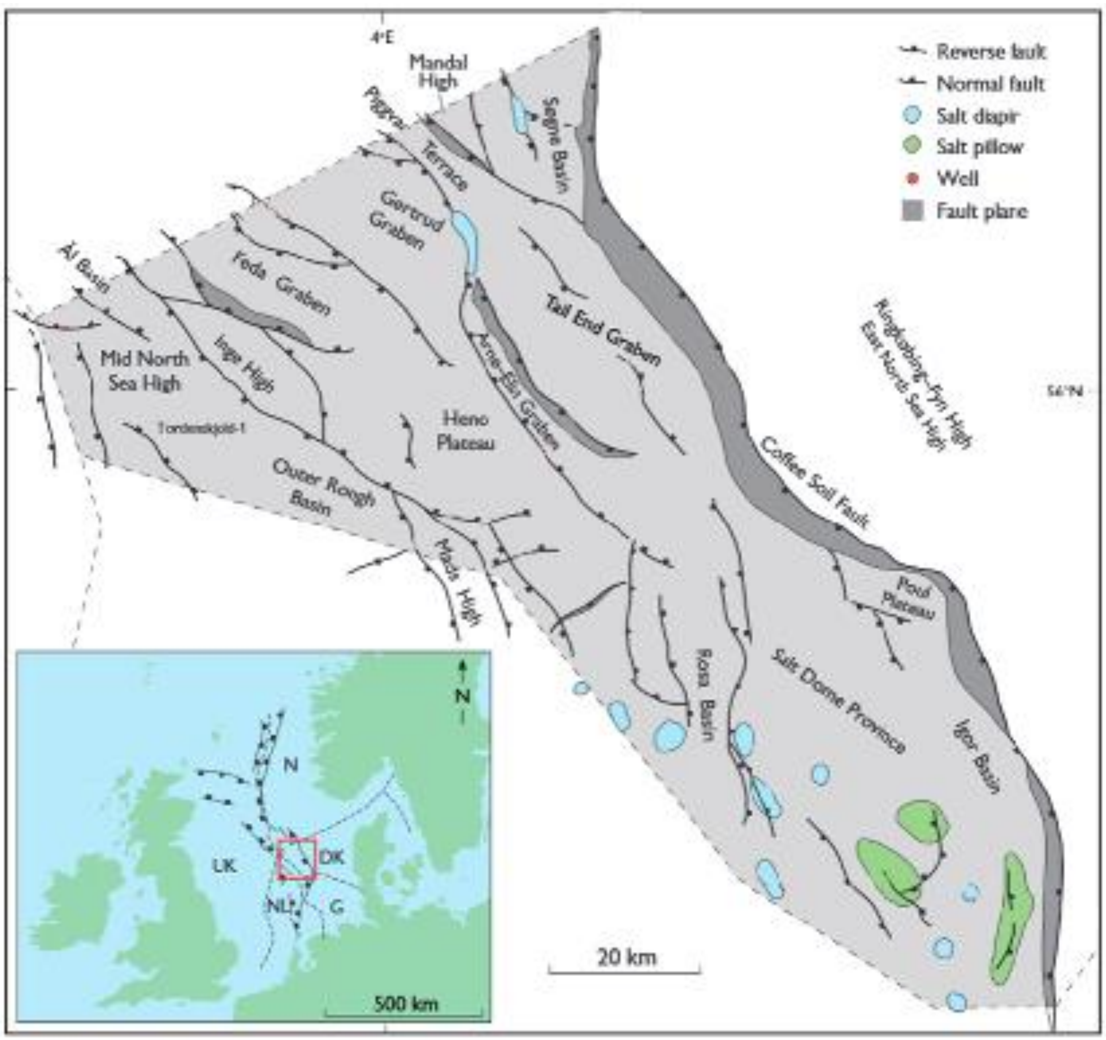

Figure 7. Structural elements of the Danish Central Graben (Møller & Rasmussen, 2003).

2.2 Pre-Carboniferous

The oldest parts of the Scandinavian crust were formed by magmatic arc accretion during the Mid-Proterozoic (Svecofennian Terrane) followed by Late Proterozoic reworking and possibly plate accretion in southern Scandinavia (Sveconorwegian Terrane). These basement rocks remained essentially undeformed by any major compressional events until the Caledonian Orogeny, during which the younger, more widespread basement rocks in the region were formed *(Evans et al., 2003).*

The N-S trending basement fabrics in the Central Graben have been modified by a wide, diffuse, NW-SE trending, steeply dipping shear zone, that acted as a large-scale tear fault or transfer zone during the phases of crustal thickening and subsequent extension (figure 8). Oblique extension along this wide basement zone resulted in an area comprising anastomosing shear zones separated by relatively unfaulted lens-shaped areas, characterized by sigmoidal or rhomboid shapes. An individual shear zone can reach 5km width at Base Cretaceous level, while the relatively unfaulted areas between the shear zones are typically 5-10km wide and 25-30km in length *(Evans et al., 2003; Bartholomew et al., 1993).*

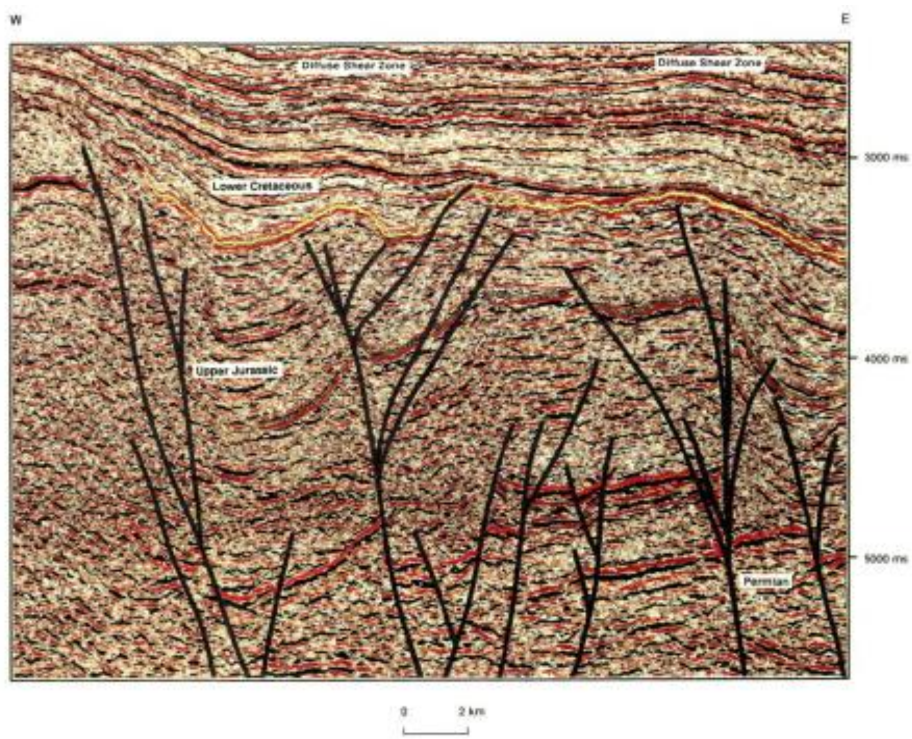

Figure 8. Structural framework map demonstrating the shear-zone geometry in the Central North Sea area and illustrating the position and anastomosing nature of the shear zones, the scale of the intershear areas and the present-day heights. Example from the UK 22/21 area (Bartholomew et al., 1993).

Caledonian collision, which comprised the Grampian and Acadian episodes at 460-450m.a and ~400m.a, respectively, involved three-way convergence between Baltica (Scandinavia), Laurentia (North Atlantic) and Avalonia (originally a magmatic arc on the fringe of the southern continent of Gondwana), which were initially separated by the Northern- and Southern Iapetus oceans. The Tornquist Sea between Avalonia and Baltica formed the third arm of the triple convergence zone. Across the Tornquist Sea, the subduction zone dipped to the south-west away from Scandinavia (figure 9). Caledonian basement rocks, embracing ages of about 480 to 430m.a identifies Early Ordovician to Early Silurian phases of Caledonian tectonism (Grampian/Scandian phase) linking medium to high grade metamorphic rocks across the whole of the North Sea *(Evans et al., 2003).*

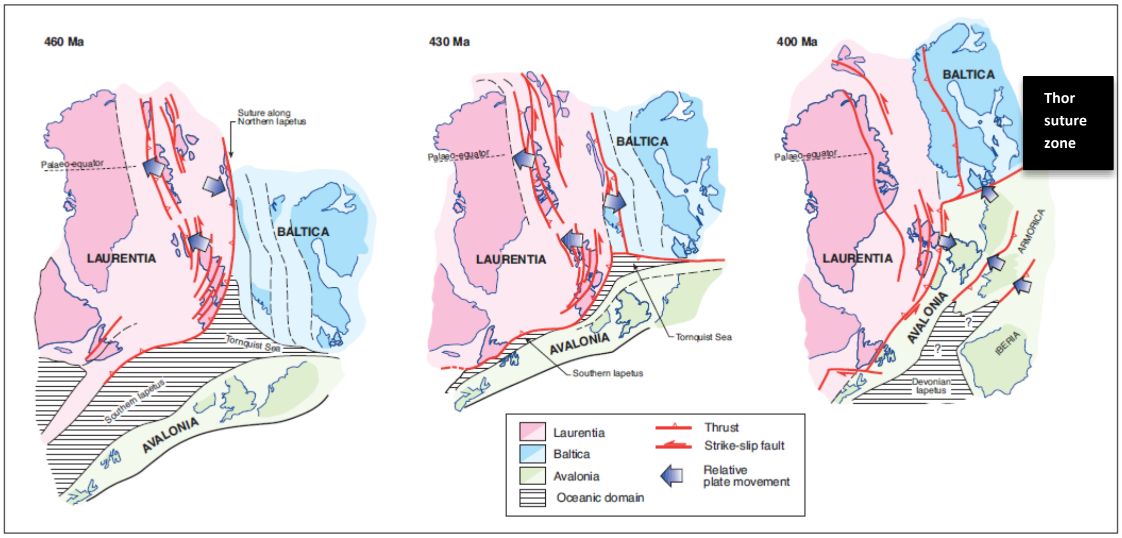

Figure 9. The Caledonian Orogeny. The Scandinavian crust extends for about 100km beneath the North Sea to the south west of the Thor/Tornquist suture zone (Evans et al., 2003).

In Europe, Caledonian continental collision ceased during the Late Silurian to Early Devonian, but continued in the Appalachians until the Mid- to Late Devonian. Closure and shortening across the Appalachians caused the development of pull-apart basins and associated inversion tectonics in the North Sea, which ultimately led to termination of Caledonian tectonics *(Evans et al., 2003).*

Closure of the Tornquist Sea and the Iapetus Ocean during Devonian times involved soft docking with some thrust tectonics and basin inversion on the subducting plates, and late strike-slip movements along the sutures. The closure of the Iapetus Ocean created a new craton configuration known as the ‘Old Red Sandstone Continent’ on which large continental Devonian redbeds were deposited. The north-westerly trending Thor or Tornquist suture located along the line of the closure of the Tornquist Sea was fundamental to the subsequent tectonic development of north-west Europe as it formed the south-western margin of the thick lithosphere of Archean-Proterozoic Baltica *(Evans et al., 2003).* Reactivation of basement trends parallel to this suture ultimately led to the development of the Dan Transverse Zone, which has affected much of the halokinetic movement in the Southern Salt Dome Province *(Sundsbø & Gowers, 1993).* During Late Proterozoic to Early Paleozoic times this lineament may have acted as an extensional plate margin *(Evans et al., 2003).*

2.3 Carboniferous

Separation between Laurentia and Baltica was initiated in Early Carboniferous, and continued throughout the Mesozoic Era. During the Early Carboniferous, the stable Old Red Sandstone Continent established in the Caledonian orogeny, was broken up by widespread crustal extension and rapidly subsiding grabens and half-grabens separated by horsts and half-horsts . Devonian pull-apart tectonics was followed by Variscan tectonic movements, which involved the development of syn-rift post-rift and inversion related stratigraphic megasequences that were controlled primarily by episodic rifting, periodic fault reactivation and eustatic sea level changes *(Evans et al., 2003).*

Evolution of the Variscan orogen included the step-wise accretion of Gondwana-derived terranes to the southern margin of Laurussia, ultimately leading to the formation of the Paleozoic mega-continent Pangea. These movements resulted in tightening of Caledonian collisional structures, remobilization of older continental crust, and forming of new structures such as the Variscan Belt, which forms the southern margin of the present day North Sea *(Evans et al., 2003).* During Late Visean to Westphalian main phase of the Variscan orogeny, the collision front between Gondwana and Laurussia propagated eastward and southwestward in conjunction with progressive closure of the Paleo-Tethys and Proto-Atlantic oceans *(Wilson et al., 2004).* Subduction of large volumes of oceanic and continental crust and sediments along a subduction system associated with the Paleo-Tethys arc-trench system, the boundaries between the different Gondwana-derived terranes, and Devonian-Early Carboniferous back arc basins, caused calc alkaline I- and S-type intrusive magmatism *(Ziegler & Stampfli, 2001)*.

At the end of the Carboniferous, the Variscan Orogeny was approaching the end of its phase of mountain building *(Evans et al., 2003):* the Paleo-Tethys spreading axis was obliquely subducted beneath the eastern parts of the orogen during the latest Carboniferous and Early Permian *(Ziegler & Stampfli, 2001).* The plate movements responsible for the newly formed, approximately easterly trending Variscan Mountains were subjecting these mountains to transtensional stresses that were active right across the North Sea area to the Caledonian shields of Scandinavia and Scotland. Major structural units converged in the west, while in the east the Tornquist–Teysseyre Line provided a north-westerly trending zone of weakness and potential strike-slip movement. Differential movements of the bounding masses led to transtensional crustal extension and Early Rotliegend volcanism *(Evans et al., 2003).* ^{40}Ar-^{39}Ar dating on basalt samples taken from an exploration core in well 29/2-4 in the UK sector of the Central North Sea suggests that the basaltic volcanism was active in the Late Carboniferous at ~299m.a. The presence of volcanics below the dated horizon however suggests that the onset of Permo-Carboniferous volcanism in the Central North Sea commenced earlier, probably at around 310m.a *(Wilson et al.,2004).*

The termination of Variscan tectonics marked a major change in the tectonic pattern in north-west Europe; a long period of basically compressive forces was replaced by an extensional stress regime *(Deegan & Scull, 1977).*

2.4 Permian

By Early Permian times, the North Sea area was entering a semi-desert climatic zone similar to that of modern Arabia or the southern Sahara. Early Permian, largely basaltic volcanism pre-dated much of the Permian extension, suggesting that the North Sea region was underlain by hot asthenosphere, possibly the edge of a north-west European hot spot. Volcanism and intrusions beneath the North Sea were accompanied by uplift, tilting, and erosion of the Variscan foreland *(Deegan & Scull, 1977; Evans et al., 2003).* In the Central Graben, subsequent Permian extension resulted in considerable topographic relief (in excess of 1000m); forming the post-orogenic Southern- and Northern Rotliegend basins and a narrow set of rifts and grabens. The Southern Rotliegend basin comprising the Kraka, Dan and Halfdan areas was separated from the northern basin by Ringkøbing-Fyn High (figure 10).

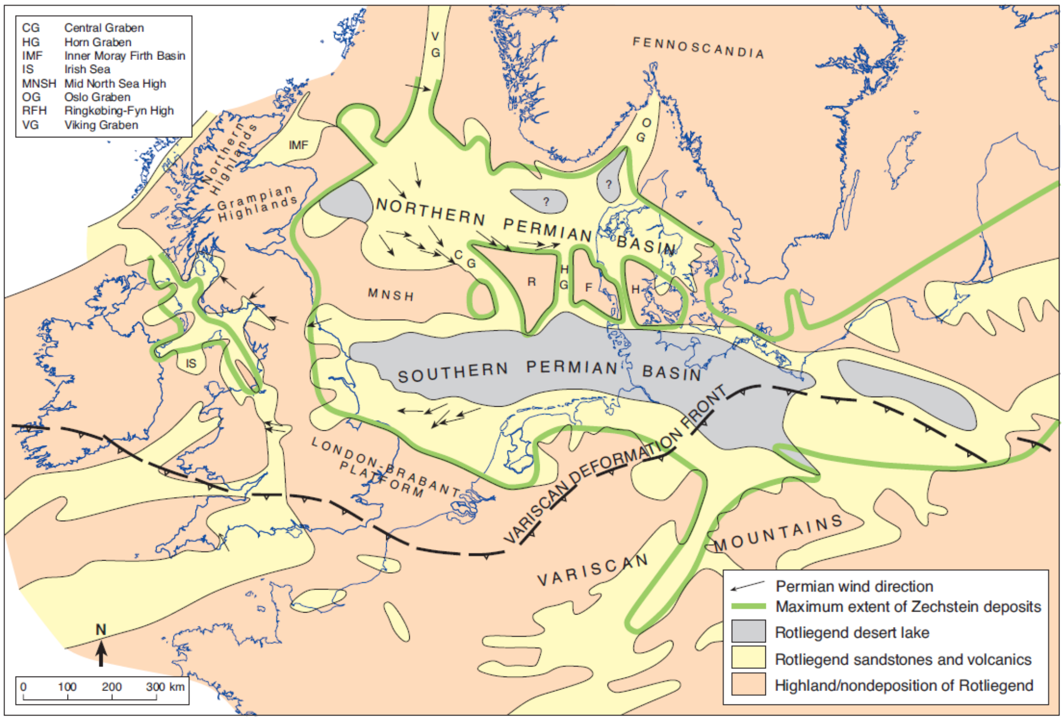

Figure 10. Permian sedimentary basins in northwest Europe. Note that the Central Graben was mostly located in the Northern Permian Basin, but the Southern Salt Dome Province comprising Kraka, Dan and Halfdan was located in the Southern Permian Basin (Evans et al., 2003).

Rotliegend sandstone deposits accumulated in the basinal areas; however, as the syn-rift subsidence rate was far greater than the slow sedimentation rate of these deposits, the deepest parts of the basin were occupied by desert by Mid Permian. Glacio-eustatic rise in sea level related to melting of the Permo-Carboniferous ice of Gondwana led to the Mid-Late Permian Zechstein transgression *(Evans et al., 2003).*

After the initial flooding, large Zechstein deposits accumulated in the Southern Salt Dome Province. High rates of evaporation were combined with limited access to marine sea water either from the Boreal Ocean to the north through the narrows of the Viking Graben, or from the Eastern Tethyan Ocean in the south. The periodic flooding and evaporation cycles of hypersaline water resulted in evaporite thicknesses (mainly halite) of up to 3000m *(Hodgson et al., 1992)*. Deeply buried Zechstein evaporites present in the Tail End- and Horn grabens, indicate a connection between the Southern and Northern Permian basins through the Søgne Basin-Tail End Graben Salt Dome Province trend *(Michelsen et al., 1992; Rank-Friend & Elders, 2004).* However, the marginal carbonate facies on the Heno Plateau and the thin evaporites and/or carbonates in the middle of the Tail End Graben point towards an intra-basinal barrier in the Central Graben *(Michelsen et al., 1992).*

Rifting is thought to have ceased by the Late Permian and the basin underwent a period of thermal subsidence. By the end of the period, Zechstein evaporites had infilled the previous rift topography so that the Central Graben represented an extensive low-relief basin with little or no topographic expression *(Hodgson et al., 1992).*

2.5 Triassic

Between Late Permian and Early Triassic times, the North Sea migrated from 20–30° N to 40–50° N.As a result, the region experienced a gradual cooling of the climate, and a trend of overall increasing humidity. The Triassic development of the North Sea was characterized by extensional tectonics, halekonesis, and global sea-level fluctuations, which, by modifying base levels, may have had a contributory effect in controlling sedimentation. Ormaasen et al. (1980) and Haq et al. (1981) suggest a gradual rise of global sea level during the period, with regressions in the Lower Triassic, the Middle Triassic and the early and late Upper Triassic *(Evans et al., 2003).*

2.5.1 Triassic Rifting

The breakup of Pangaea had begun with Permian rifting along the incipient Atlantic and the westward extension of Tethys *(Fisher & Mudge, 1998).*Crustal thinning following the Late Permian subsidence phase resumed in the Triassic, with accelerated rifting phases in the Early- and Late Triassic, forming relatively narrow rifts with varied extension directions *(Deegan & Scull, 1977).* Triassic extension was accommodated by reactivation of many Paleozoic fault zones, whilst the Upper Permian salt accommodated the extension by shear and gravity flow *(Hodgson et al., 1992).* Localized pull-apart basins formed in relation to the reactivation of the Trans-European Fault Zone may have led to the formation of the proto-Central Graben during the Triassic rifting event *(Fisher & Mudge, 1998)*. The Central Graben area however only experienced minor extension, as it was offset from the axis of the rift *(Hodgson et al., 1992).*

Although the Triassic fault pattern in the Central North Sea has a dominantly N-S orientation, the interaction with Paleozoic structural trends, overprinting from concurrent and later salt diapirism and subsequent deep burial of Triassic basinal sequences, complicates any dating and quantifying efforts. Roberts et al. (1990, 1993) calculate Triassic extension to be the equivalent of up to 70% of the total Mesozoic extension in the Central Graben. In contrast, White (1990) and White & Latin (1993) maintain that the Triassic stretching episode is poorly constrained and is of minor importance in the evolution of the Central Graben *(Fisher & Mudge, 1998).*

2.5.2 Triassic Salt Tectonics

The framework of salt tectonics in the Central North Sea was set early in the Triassic *(Evans et al., 2003).*The difficulties in analyzing the structural evolution in areas strongly affected by halokinesis of the Zechstein evaporates are considerable. However, regional mapping of the Central North Sea have clearly established that salt pillows and diapirs are aligned along the rhomboid structural pattern defined by the dominant NW-SE trending basement lineaments *(Bartholomew et al., 1993).*

In the Southern Salt Dome Province, halokinetic movements led to the development of relatively isolated sediment pods or mini-basins with divergent and onlapping sequence geometries throughout the Triassic (figure 11) *(Evans et al., 2003).* Reactivation of a Tornquist-parallel basement trend now termed the Dan Transverse Zone affected much of the salt movement in the Southern Salt Dome Province: the Dan, Skjold and Gorm fields are all aligned along the NW-SE trending zone *(Sundsbø & Gowers, 1993).*

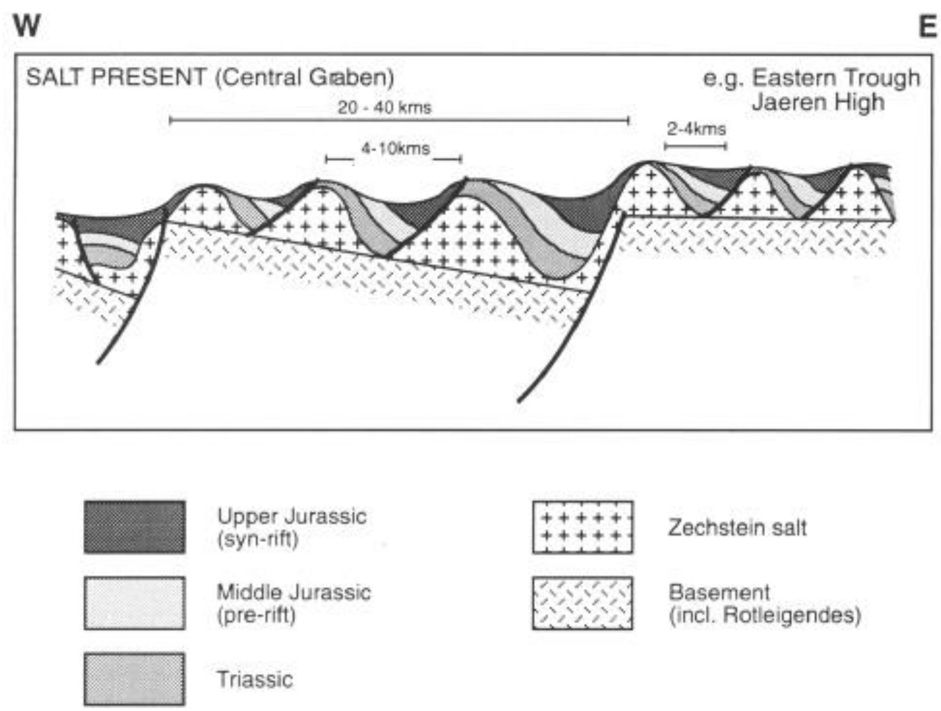

Figure 11. Example of Triassic Zechstein pods (Hodgson et al., 1992).

There is no consensus about the evolution of pod-interpod structure. Current understanding of the pod formation is based on two main alternating models; the first model is based on the concept of syn-sedimentary salt movement that began during the onset of Early Triassic deposition, subsequently influencing later depositional styles. The alternative model argues for rift-raft tectonics occurring in the Late Triassic, creating conduits for salt movement, post deposition of Triassic strata *(Young et al., 2012).* Two general mechanisms for lateral displacement would have been active during the period. The most fundamental of these was the extensional tectonics. One effect of the Zechstein salt was to decouple tectonism in the sedimentary section from the basement structure. The second mechanism was gravity sliding controlled by structural dip.

The original pod-interpod descriptions by Hodgson et al. (1992) and Smith et al. (1993) suggests that salt movement was controlled by extensional tectonics coupled with gravitational instability. In these models, salt was progressively displaced from under the sediment pod to form salt walls or ridges, while the intervening topographic lows were infilled with Triassic sediments. Only a small amount of low initial porosity (and thus high bulk density) continental sediments needed to be deposited before salt-sediment density inversion at the base of the pod began to control, and subsequently drive, this process to its conclusion. Subsidence is assumed to have continued until all the salt was displaced from beneath the sediment pod and the pod 'grounded' on the Top Rotliegendes surface. Pod subsidence then ceased, so that the pods no longer provided synforms at the surface (figure 12). Similarly, Stewart (2007) in a regional view of North Sea salt concluded that the causative mechanism was Triassic thin-skinned extension followed by exhumation and differential erosion creating a Jurassic paleotopography of pod “hill summits” and “salt valley floors.” More recently Jackson et al. (2010, 2012), concluded that salt movements and growth was triggered by passive diapirism, related to variable sedimentation patterns and loading (figure 13).

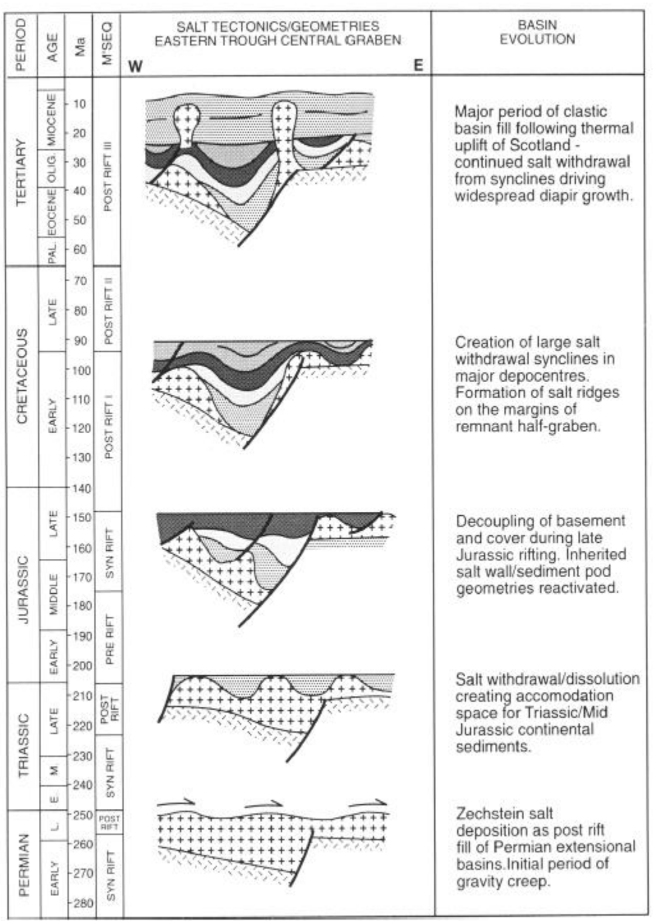

Figure 12. Schematic evolution of pod development (Hodgson et al., 1992).

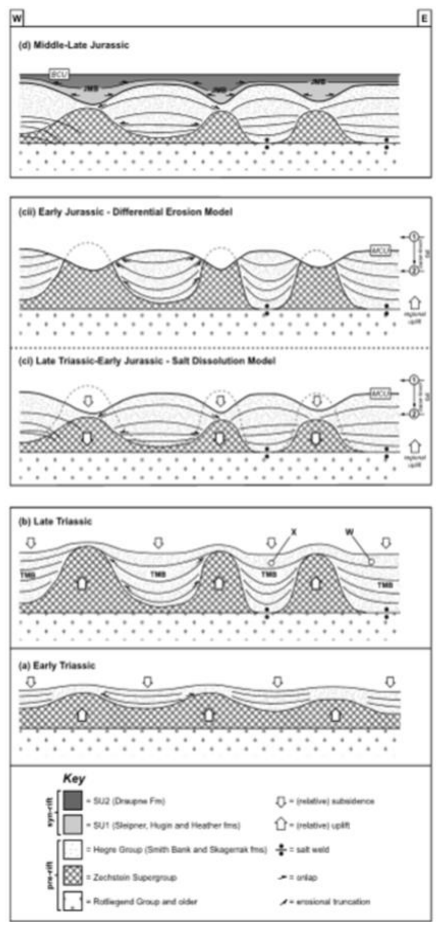

Figure 13. Schematic evolution of pod development Jackson et al. (2010, 2012).

The concept of rift-raft tectonics was suggested by Penge et al. (1993, 1999). In this model, Triassic sedimentary blocks or ‘rafts’ floating on Zechstein salt were separated by rifts where the Triassic interval thins over an elevated salt wall. The rifts were zones of intense faulting, the focus of deformation, erosion, and end-Triassic to Early Cretaceous sedimentation. Pods were formed by eastward east-ward basin tilt wherein the rafts are displaced slide blocks of Triassic and the intervening Jurassic depocenters are collapse grabens into reactive diapirs between the rafted blocks (figure 14). Structural variations are attributed to the inter-relationships of strain as defined by regional dip, salt thickness, and lithology of the overburden.

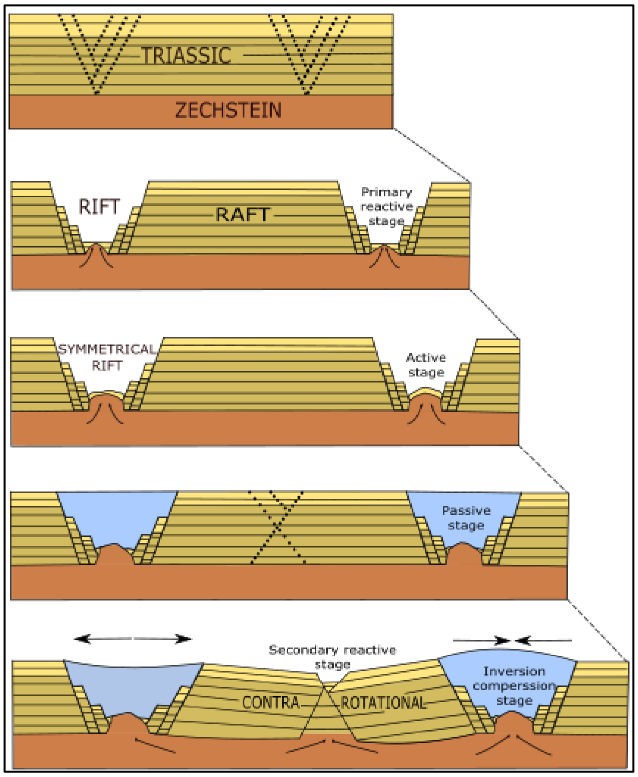

Figure 14. Rift-raft tectonic pod formation (after, Penge et al., 1993).

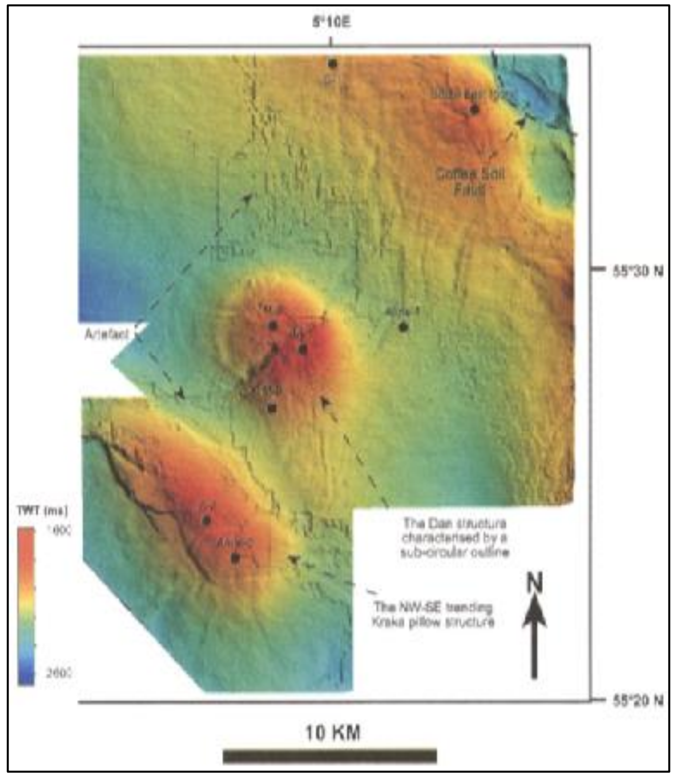

Figure 15. Present day location of the Kraka and Dan pods on a shaded relief time structure map (ms TWT) of the Base Chalk Group (Rank-Friend & Elders 2004).

Triassic salt structures provide trapping mechanisms in the Dan and Kraka fields (figure 15).The present day Dan structure is associated with a relatively simple sub-circular outline at Base Chalk level, despite this; it is characterized by a more complex geometry. Dan can be defined as consisting of an upper and lower part, separated by a NNW-SSE trending fault, which detaches along its western flank (figure 16). Based on 2D seismic data, Jørgensen (1992) interpreted the upper part of the structure as consisting of entirely Triassic salt of the Dudgeon Saliferous Formation. On the other hand, Sundsbø & Megson (1993) interpreted the intra-Triassic structure to be composed of intruded Zechstein salt. The latter suggestion was based on interpretation of 3D seismic data. Adopting the strike-slip model of Cartwright (1987) for the Danish Central Graben, Sundsbø & Megson (1993) argue that episodic dextral and sinistral strike-slip motion and associated extension within the Dan Transverse Zone would have permitted Zechstein salt to escape and intrude overlying Triassic strata. Graversen (1994) also suggested that the location of piercements was governed by intersections between graben-parallel faults and crosscutting, transverse faults at basement level. Rank-Friend and Elders (2004) suggested that the asymmetric salt core is a roller type salt structure, and argues that the lower asymmetric part of the structure represents a Zechstein core whilst the upper part is composed of intra-Triassic salt bodies. It is suggested that while Triassic salt is indeed present, it has primarily provided weak zones or surfaces along which Zechstein salt has intruded. This model was based on the same 3D dataset used in Sundsbø & Megson (1993).

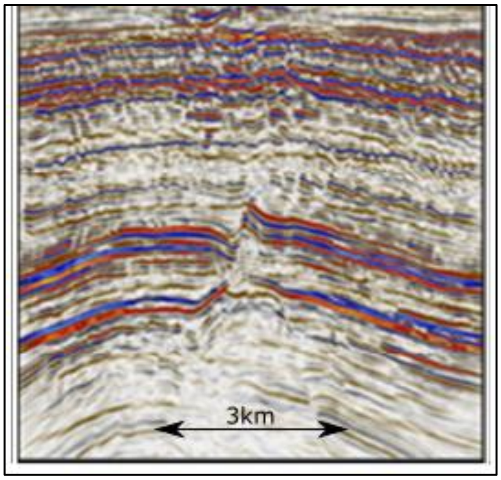

Figure 16. OBN seismics of the Dan Structure (Zaske et al., 2014).

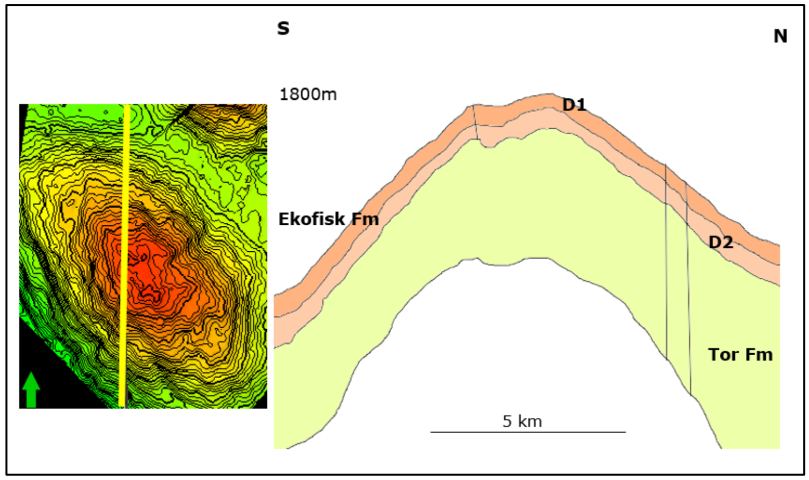

Figure 17. Cross section of the Kraka Dome.

The present-day Kraka structure is an elongated, slightly asymmetrical pillow (figure 17). Initiation of a domal structure in the Kraka area started in the early Late Cretaceous. The main chalk reservoir was deposited during Late Cretaceous to Danian times, during which the area was tectonically quiet. The present day structure was established during renewed salt movements in Eocene *(Albrechtsen et al., 2001).*

2.6 Jurassic

The Early Jurassic was characterized by a slow relative sea-level rise, which was initiated in the Late Triassic (Norian) *(Michelsen et al., 2003).*

Permo-Triassic rifting was abruptly terminated by a phase of upper Early Jurassic to Middle Jurassic doming accompanied by the development of a volcanic complex at the proto- triple junction between the Viking Graben, the Central Graben and the Moray Firth Basin (figure 18). The dome extended 700 km in a north–south direction and 1000 km east–west across the Central North Sea *(Andsbjerg & Dybkjær, 2003),* and is commonly assumed to be the result of a transient mantle plume head *(Underhill, 2003).* According to Michelsen et al. (2003), the central North Sea area, including the Ringkøbing–Fyn High, became uplifted as a broad arch rather than a dome. The uplift led to widespread erosion across the region, although the Sorgenfrei–Tornquist Zone seems to have been mainly unaffected. The regional uplift of the central North Sea Basin resulted in radical palaeogeographic changes, including closure of the seaway linking the Arctic Sea with the Tethys Ocean *(Michelsen et al., 2003).*

The Mid Jurassic (Callovian) collapse of the up-domed area combined with eustatic sea-level rise led to the first marine transgression in the Danish Central Graben during the Callovian–Oxfordian (Andsbjerg & Dybkjær, 2003). Marine influence on the area increased through Mid Jurassic times, culminating in the major Late Jurassic marine transgression (Michelsen et al., 2003). The domal collapse initiated the Jurassic extensional phase, which led to the development of the trilite-rift system consisting of the Central Graben, the Viking Graben, and the Moray Firth Basin *(Deegan & Scull, 1977),* and led to rapid subsidence of the Central Graben area *(Michelsen et al., 2003).* In the Central Graben, Callovian to Early Oxfordian fault-controlled subsidence was concentrated along N–S-striking faults (figure 19). This subsidence pattern was however modified by salt movements in the Southern Salt Dome Province *(Møller & Rasmussen, 2003).*

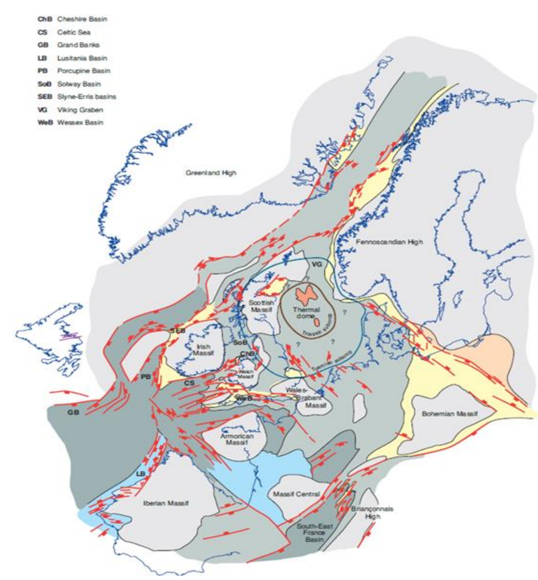

Figure 18. Early Jurassic configuration of North West Europe (Evans et al., 2003).

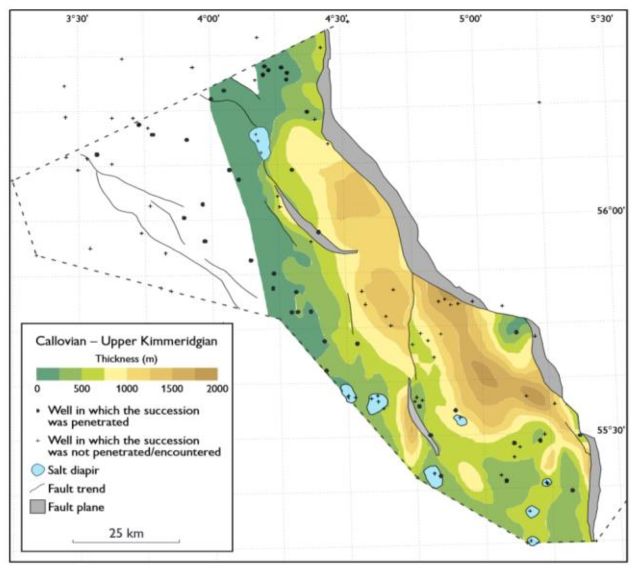

Figure 19. Isochore map of the Callovian – Upper Kimmeridgian succession in the Central Graben showing the main faults that were active in this period (Møller & Rasmussen, 2003).

As a result of Jurassic rifting, the Central Graben became compartmentalized into a number of minor grabens and highs *(Michelsen et al., 2003).* Pronounced differential subsidence and sedimentation of these successive half-grabens was focused in the eastern and southern regions, namely in the Salt Dome Province, the Søgne Basin, and the Tail End Graben during the latter part of the Middle. The Feda Graben was probably initiated in the early Late Jurassic (?Oxfordian) and formed the dominant sediment depocenter in the area during the Kimmeridgian *(Ineson et al., 2003).*

During the Late Kimmeridgian to Early Tithonian rifting stage, the Danish Central Graben developed as NNW-SSE-trending graben, resulting in NNW-SSE subsidence along the Coffee Soil Fault from the Salt Dome Province in the south and further northwards *(Møller & Rasmussen, 2003).* The Tail End Graben, bounded by the Coffee Soil Fault, was the dominant Late Jurassic structural element in the Danish Central Graben, with accumulation of up to 3600 m of sediments. The depocenter of the Tail End Graben shifted westwards during the Late Jurassic while faulting shifted from north–south to NNW–SSE trends (figure 20) *(Japsen et al., 2003).* This was due to the over-all sea-level rise and the development of secondary depocentres in successive half-grabens. The Gertrud Graben developed as a discrete depocenter during the Late Kimmeridgian whereas onlap onto the Mid North Sea High to the west began in the Tithonian. Consequently, the Danish Central Graben was segmented into a number of NW–SE-trending depocentres, separated by elongate highs or broad plateaus by the latest Jurassic *(Ineson et al., 2003)*.

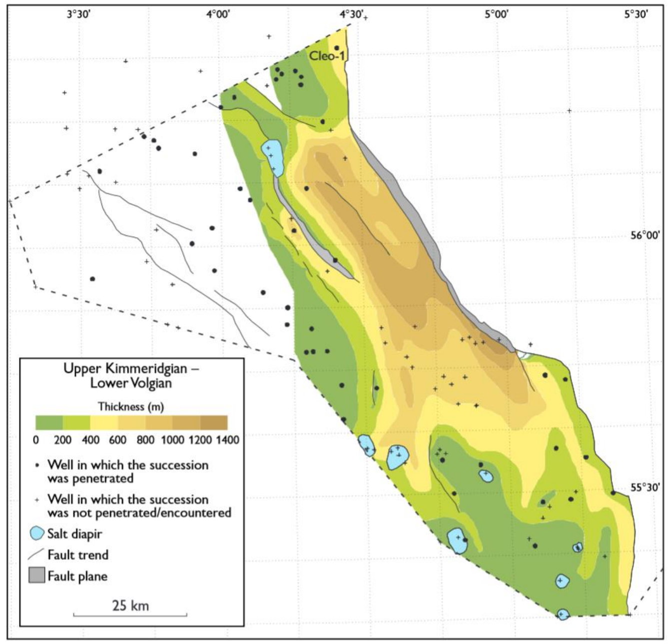

Figure 20. Isochore map of the Upper Kimmeridgian – Lower Volgian succession in the Central Graben. Note that the depocentres have shifted to occur along NW–SE-trending faults in the Tail End Graben and Gertrud Graben, while the depocentres still lie close to the faults (Møller & Rasmussen, 2003).

According to Bartholomew (1993), the NNW-SSE trend was caused by basement lineaments that placed geometric and kinematic constraints upon primary basin formation: the basin developed along the inherited structural grains rather than a N-S trending basin orthogonal to the principal extension direction.

Middle-Late Jurassic extension was interrupted in the latest Jurassic –earliest Cretaceous by a complex tectonic phase that was essentially NNW-SSE extensional in character but involved block rotation associated with localized compression, reverse faulting and uplift *(Ineson et al., 2003).* Rotation of fault blocks and deep erosion on footwall crests resulted in the formation of a distinct angular unconformity which is best seen in the northern part of the graben where the influence of salt movements was insignificant *(Møller & Rasmussen, 2003)*.

The age of this event is poorly constrained, but Upper Volgian – Lower Ryazanian organic-rich sediments of the organic-rich Bo Member of the Farsund Formation are rotated on the Heno Plateau (Ravn-2) and in the Gertrud Graben (Gwen-2 and Jeppe-1 wells) suggesting that the tectonic pulse post-dates these Lower Ryazanian deposits *(Møller & Rasmussen, 2003).* The topography formed during this tectonic pulse was filled by an onlapping Lower Cretaceous succession (Cromer Knoll Group). The lowermost sediments of this group were deposited in latest Ryazanian – Early Valanginian times, thus suggesting that this third tectonic pulse occurred in the mid-Ryazanian.

Latest Jurassic – Early Cretaceous tectonics in the Central Graben involved salt tectonics, particularly in the Feda Graben where movements began in the Volgian. Basinwards shift of depocentres in the Tail End Graben also reflects involvement of salt in this part of the graben. The extensional tectonic pattern during this phase, however, resulted in local compression between different blocks; this effect was most marked between the two opposite-dipping Feda and Gertrud Grabens where the Gert Ridge was formed. It is uncertain whether this local thrusting was the result of strike-slip movements or local compensation between two subsiding blocks *(Møller & Rasmussen, 2003)*. According to Vejbæk & Andersen (1987), the Arne- Elin Graben, which separates the Gertrud Graben and the Heno Plateau, developed as a transtensional flower structure in response to NNW-SSE left lateral strike-slip movements. The existence of local thrusting in the Late Jurassic has also been suggested by Gowers et al. (1993) for the Norwegian Central Graben *(Møller & Rasmussen, 2003)*.

2.7 Lower Cretaceous

The Early Cretaceous was a time of transition during which the principal locus of rifting in north-west Europe shifted westwards from the North Sea into the proto-North Atlantic. The western parts of the European plate were largely surrounded by active plate margins, which induced intra-plate stress fields through changing relative motions *(Evans et al., 2003).* Thermal subsidence in the Central Graben area was still governed by crustal extension associated with left-lateral transtensional strike- slip movements along the NNW-SSE trending fault system, although it became more passive during the Early Cretaceous. In addition to rift tectonics and thermal subsidence, basin development in the Central Graben was strongly influenced by the presence of mobile Zechstein salt, which may have had a profound influence on the development of depocentres in the Søgne Basin, the Tail End Graben and the Salt Dome Province *(Andsbjerg & Dybkjær, 2003).*

During the main part of the Early Cretaceous, normal faulting and transtensional wrenching resulted in the development of several normal fault bounded depocentres. In many cases these depocentres coincide with areas of a thinly developed Late Cretaceous series and thus indicate the effects of the main phases of basin inversion. In the Salt Dome Province, inversion-induced erosion of the upper part of the Early Cretaceous Valhall Formation (Ryazanian- Valanginian) is seen along the northeastern bounding fault of the Gertrud Graben and as thinning over the Arne-Elin Graben *(Vejbæk & Andersen 1987)*. The widespread onlap of truncated Upper Jurassic fault scarps by Lower Cretaceous marine shales implies that active basement faulting had effectively ceased by the end of the Jurassic. Minor fault displacement at Lower Cretaceous structural levels are more likely to have resulted from local differential compaction or Zechstein salt withdrawal than from any basement response to the regional rifting *(Cartwright, 1989).* Faulting and rotation of fault blocks associated with active latest Jurassic- Early Cretaceous rifting ceased in the Valanginian with the reestablishment of the lithospheric thermal equilibrium causing regional post-rift subsidence but with local uplift and development of unconformities *(Bartholomew, 1993).*

2.8 Upper Cretaceous

During Upper Cretaceous, much of North-West Europe was covered by an extensive epeiric sea, characterized by low terrigenous input and chalk deposition *(Anderskouv & Surlyk, 2011).* The Mid- to Late Jurassic rifting and Early Cretaceous transtension created a pronounced tilt-block topographic relief that became gradually draped by Upper Cretaceous to Danian deposits *(Evans et al., 2003).*

The central North Sea area constituted a relatively deep part of the Chalk Sea, flanked to the east by the wide pelagic carbonate ramp and basin of the Danish Basin, the siliciclastic-dominated seas towards the north, the shallower seas around the present British Isles to the west, and the Paris Basin to the south (figure 21) *(Anderskouv & Surlyk, 2011).*

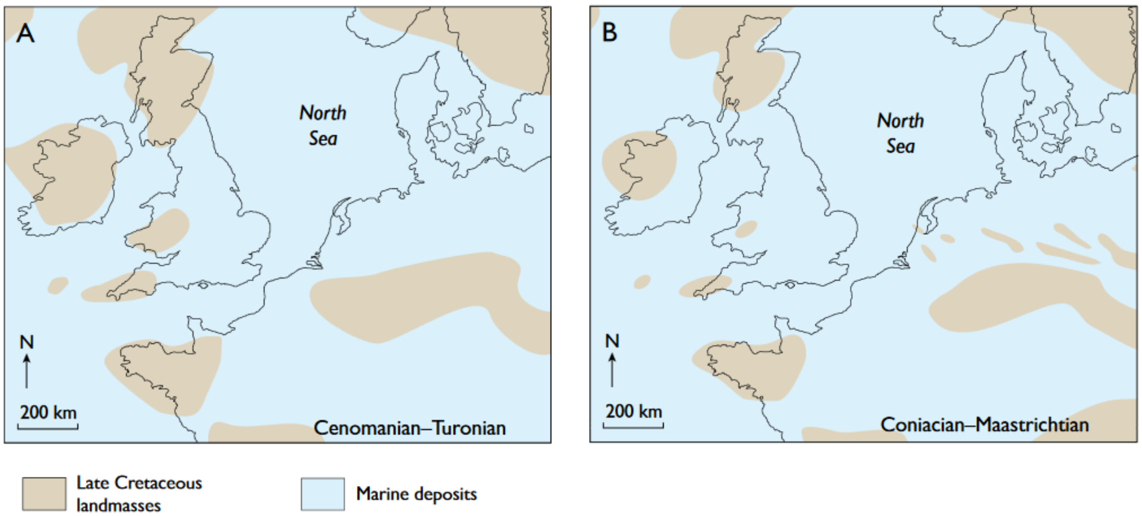

Figure 21. Palaeogeography of North West Europe during the Cenomanian-Turonian (A) and the Coniacian-Maastrichtian (B) (Anderskouv & Surlyk,2011).

The Late Cretaceous evolution of the Central Graben was predominantly influenced by regional subsidence, due to thermal relaxation, interrupted by several important inversion phases *(Rasmussen et al., 2005).* Cretaceous inversion phases, which were important for trapping both oil and gas in pre-Tertiary reservoirs *(Glennie & Underhill, 1998),* are considered to be the result of the interaction of regional stresses induced by the opening of the North Atlantic, Alpine collision, and movements along the Trans-European Fault Zone *(Bartholomew, 1993).* The resultant compressional tectonics reactivated elements of the Mesozoic rift system, leading to the development of reverse faults and broad, low amplitude anticlines along the rift margins *(Evans et al., 2003)*. Positive inversion in Denmark is confined to former depocentres and seems to be laterally controlled by reverse fault movement along the former normal faults defining the pre-existing depocentres. However, Triassic depocentres, which constitute a prominent portion of the sedimentary succession in the subsurface onshore Denmark, have remained virtually unaffected by inversion tectonics. The Triassic basin consists of an amalgamation of many fault-bounded Triassic depocentres that coalesce into one major basin, the Norwegian Danish Basin. For instance, the prominent Triassic depocenter of the Horn Graben is virtually unaffected by inversion as resolvable in seismic sections *(Vejbæk & Andersen, 2002).* The inversion structures in the Danish sector occur along the Roar-Tyra-Igor ridge in the western hanging wall of the Coffee Soil Fault; these form the Roar, Adda, Tyra, Sif, Halfdan, and Igor fields *(Vejbæk et al., 2005).* The Late Cretaceous inverted zones are expressed as generally asymmetric anticlines with predominantly NW–SE and N–S trending axes, often arranged in en-echelon like patterns on the Base Chalk depth structure map (figure 22).

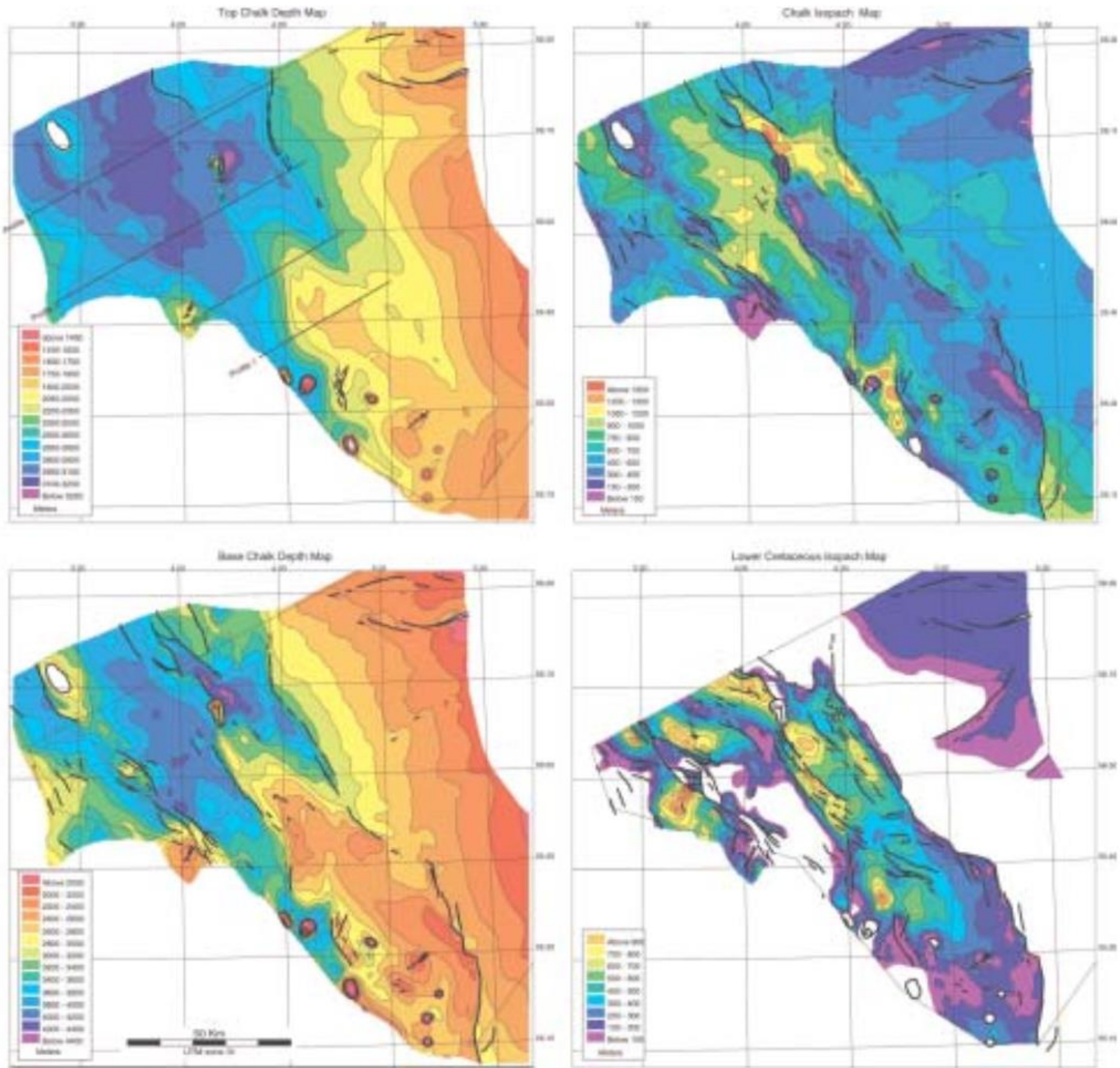

Figure 22. Lower Cretaceous and Chalk Group isopach maps and Top Chalk and Base Chalk depth structure maps (Vejbæk & Andersen, 2002).

The steeper limbs of the folds are often associated with minor thrust faults that propagate from the tips of former extensional basement attached faults in the substrate. As most reverse faults are reactivations of older normal faults, and fold axes generally are parallel to these faults, orientations rather reflect older fabric than the stress field, which governed the inversions. It is clear though, that the structures indicate shortening perpendicular to the graben axis; i.e. suggesting NE–SW compression (*Vejbæk & Andersen, 2002).*

The total shortening across the Central Graben was however limited, with the maximum structural relief on inversion related structures only amounting to 500 m. The moderate degree of compressional deformation and uplift and the prevalent regional basin subsidence centered on the Central Graben ensured that the Upper Cretaceous Chalk stratigraphic record was relatively complete *(Cartwright, 1989).* In the southern part of the

Danish Central Graben, structural inversion resulted in many slumped units within the Chalk Group. These features diminish northwards through the central North Sea, and the inversion influence becomes very weak in the northern North Sea *(Evans et al., 2003).*

Chalk deposition was also greatly influenced by halokinetic movements, which continued throughout the Late Cretaceous, resulting in the formation of salt pillows, domes, ridges and diapirs. Some of the resulting structures had sea-floor expression as shown by the presence of hardgrounds and thinned, condensed and winnowed chalk successions over the structures. Chalk deposition was finally extinguished at the end of the Danian when Paleocene siliciclastic sediments were introduced to the basin as a result of uplift of landmasses adjacent to the North Sea, in particular the Scottish Highlands and the Norwegian landmass *(Evans et al., 2003).*

At the end of the Cretaceous period, the development of the Iceland Plume led to rejuvenation of source areas and the deposition of submarine clastics into the Central North Sea *(Evans et al., 2003).* Oil generation in the deepest part of the Danish Central graben started during the Maastrichtian and peaked in early Miocene to Pliocene times, with significant amounts of oil also being generated during the Paleocene *(Vejbæk et al., 2005).* Further stresses along the line of the future north-east Atlantic Ocean led to major volcanic activity in that region, which is represented by tuffs in the Central North Sea. The end-Cretaceous tectonic episode also resulted in rapid subsidence of the North Sea Basin, which was centered above the main Mesozoic rift system and was accompanied by tilting of the flanks of the Central Graben *(Evans et al., 2003).*

2.9 Paleogene

Thermal subsidence, centered on the rift system, continued into Paleogene times. The nature of Early Palaeogene tectonics is however difficult to determine: except for in areas with preserved coals, there are no horizons which may be used to indicate relative subsidence and fault movement, or to derive any causal link between sedimentary pulses and increases and decreases in tectonic subsidence rates. There seems to be a common consensus on the end-Cretaceous uplift episode, which is clearly demonstrated by the onlap of Late Palaeogene coals onto pelagic Cretaceous chalk, and can be indirectly inferred from the sudden influx of clastics. Many authors also infer a simultaneous rejuvenation of the Mesozoic fault trends *(Milton et al., 1990)*. According to Milton et al. (1990), the evidence for rejuvenation of faults is however subjective; most major faults in the Central North Sea show seismic geometries in the Palaeogene which can be explained entirely by differential compaction of a pre-Palaeogene sequence around a basement high, both during and after Palaeogene deposition.

According to Korstgård & Clausen (1996), post Danian inversion in the Danish Central Graben can be subdivided into a Late Paleocene phase and an Early Oligocene phase (figure 23). Both of which are associated with dextral transpression along a NNW–SSE direction similar to the earlier inversion phases. Vejbæk & Andersen (2002) suggest that the early inversion movements were mainly confined to narrow zones and controlled by pre-existing faults, whereas the late phase was less directly fault controlled and more expressed as gentle folding and upwarping of the basin.

The opening of the North Atlantic Ocean and Norwegian–Greenland Sea was initiated in the Early Eocene. The water masses were separated by a structural high between Greenland and Scotland, now represented by the Iceland–Faeroe Ridge. Volcanism related to incipient North-east Atlantic spreading, terminated at around 52m.a, and sea-floor spreading during the early Eocene placed the North Sea in compression between the spreading sea-floor ridge and the Alpine mountain belt. Towards the end of the Eocene, the regional stress regime in the North Sea changed to one of east–west extension *(Evans et al., 2003).*

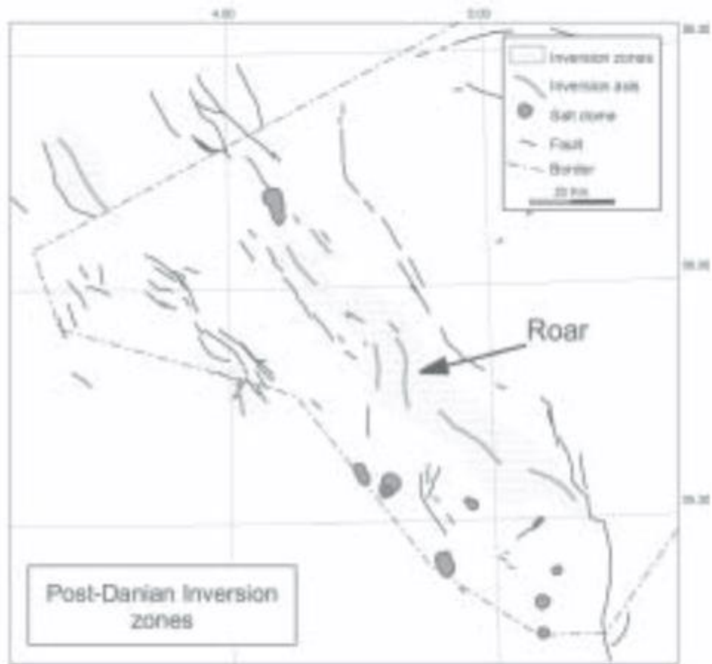

Figure 23. Post-Danian inversion zones in the Danish Central Graben (Vejbæk & Andersen, 2002).

Oligocene basin development was influenced by the dual controls of the closing of the Tethys Ocean to the south-east and the opening of the North Atlantic Ocean to the north and west. The evolving North Sea Basin was connected to the contracting Tethys Ocean through a seaway termed either the Moravian Gateway or the North Polish Strait. Tectonic influences in central Europe meant that from Oligocene times onward, the degree of connection with deep water to the south and east fluctuated and eventually closed. In contrast, the opening of the North Atlantic Ocean led to improved connection with oceanic waters to the north-west.

The combination of steady subsidence in the North Sea Basin and an abundant sediment supply in Oligocene led to the massive accumulation of upper Cenozoic deposits. At the same time, central Europe to the south-east was undergoing significant rifting and volcanism, and a marine connection between the Alpine Foredeep and the North Sea opened through the Rhine and Leine grabens. North of the Rhenish Massif, the Danish landmass was slowly beginning to emerge. Improved connection between the North Sea Basin and the Norwegian–Greenland Sea in the north, complex developments to the east, and inversion of the Western Approaches Basin and southern England meant that cold-water boreal microfauna began to replace the warmer Tethyan forms *(Evans et al., 2003).*

2.10 Neogene – Quaternary

The Oligocene–Miocene unconformity (~24m.a) represents a major phase of exhumation of the parts of the eastern North Sea Basin adjacent to the presently exposed basement areas in Norway and Sweden, which began between 30 and 20m.a. Early- to Middle Miocene tectonic movements in the North Sea may be related to the Alpine Orogeny and/or the opening of the North Atlantic. The Burdigalian phase (~17Ma) and the intra-

Langhian phase (~15Ma), correlates with the Betic Tectonic Event in Southern Spain. The latter also correlates with the first major shift of the northern rift zone in Iceland *(Rasmussen et al., 2005).*Early Middle Miocene salt movements also occurred north of the Ringkøbing–Fyn High.

The Early- to Middle Miocene tectonic pulse was followed by increased subsidence of the North Sea Basin, which continued throughout most of the Late Miocene and into the Lower Pliocene. The combination of increased subsidence and aeustatic sea-level rise in the early Middle Miocene resulted in a transgression in the North Sea. Breaching of the high between Greenland and Scotland in the Atlantic in Mid Miocene led to influx of warm-water Atlantic faunas into the Northwest European Basin through the North Sea Basin. During the Mid- to Late Miocene, uplift on the margins of the North Sea Basin together with climatic cooling and possible subaerial exposure, restricted the connection between the Norwegian–Greenland Sea and the North Sea. The marine connection between the Alpine Foredeep and the North Sea was closed during the Miocene by updoming of the Rhenish Massif in Germany and associated volcanic activity *(Evans et al., 2003).*

Tilting of the North Sea Basin occurred at the Miocene- Pliocene boundary. This major tilting event can be recognized by the progressive truncation of the Cenozoic succession towards the east and northeast of the Danish Central Graben. Its timing is indicated by the development of a Pliocene– Quaternary delta complex that is located in the westernmost part of the Danish sector *(Rasmussen et al., 2005).*

Major uplift of the Baltic Shield took place at the Neogene- Quaternary boundary, accompanied by increased subsidence of the central part of the North Sea basin. Uplift of the Baltic/ Fennoscandian area during the Neogene caused an increase in sediment supply and a consequent overall westward progradation of the deltaic systems in Denmark *(Evans et al., 2003).* The Middle Eocene – Quaternary sedimentary package was very important for the maturation and migration of hydrocarbons. In the Danish area, mature source rocks capable of generating hydrocarbons have so far only been found in the Central Graben. The major oil and gas source rock is the Upper Jurassic Farsund Formation, Middle Jurassic and Carboniferous coal beds may however also have been source rocks for gas. The generation of hydrocarbons from the most prolific source rock occurred during the Miocene– Quaternary. Hydrocarbon migration occurred within regionally distributed sandbeds of both the Middle Jurassic and the Paleocene. Minor migration may have occurred in Upper Cretaceous –Lower Paleocene chalks. However, the most likely migration route within the Jurassic is primarily vertical, through fractures, driven by buoyancy and depth-dependent differences in overpressure *(Rasmussen et al., 2005).*

3. Depositional history

3.1 Pre-Carboniferous

Pre-Devonian basement rocks below the central North Sea include diverse suits of low- to high grade metamorphic phases, igneous rocks and metasedimentary rocks. These rocks are highly fractured, reflecting a history of polyphase deformation from at least Late Proterozoic times onward. Later Silurian to Early or Mid-Devonian basement rocks of ~418-350m.a are probably indicative of Early Acadian, terminal Caledonian tectonic coupling and age resetting. These rocks are unconformably overlain by younger Devonian strata *(Evans et al., 2003).*

3.2 Carboniferous

Over much of north-west Europe, the onset of Carboniferous time was marked by a change from the dominantly continental redbed deposition of the Devonian Period to more-diversified marine, fluvial, deltaic and continental sedimentation. This change was a direct result of a major, southerly derived, marine transgression over the Old Red Sandstone Continent at the beginning of the Carboniferous, and the continued northward continental drift of Laurussia from an arid to a more humid, tropical latitude. Despite this, the boundary between the Devonian and the Carboniferous is not clearly defined, as arid to semi-arid continental deposition continued well into the Early Carboniferous, and marine sedimentation did not significantly affect the area until the late Viséan.

The Carboniferous of the North Sea is poorly understood as very few wells have penetrated Carboniferous rocks. In the southern Central Graben area, the nomenclature of the southern North Sea has been adopted: the succession is subdivided into the Scremerston, Yoredale and Millstone Grit formations. Sediments of similar age are also known from a few wells in Norwegian Quadrant 2 and in the north-western part of the Danish Central Graben, but no formal nomenclature has been developed in these areas (figure 24). In the Southern Central Graben, the lack of exploration data is due to the apparent lack of widespread coal-bearing strata *(Evans et al., 2003).* Local Carboniferous coals may however have been source rocks for gas in the Southern Salt dome Province *(Rasmussen et al., 2005).*

Onshore, the oldest Carboniferous strata comprise lagoonal or estuarine shales and impure limestones of the Cementstone Group. These are in turn overlain by massive, medium-grained sandstones interbedded with reddish purple to greenish grey silty mudstones of the Fell Sandstone Group that are interpreted to have been deposited by a braided-river complex draining westward into a shallow, low-energy, tideless sea. The overlying Scremerston Coal Group is interpreted as the product of a delta-flat environment. The succeeding Lower and Middle Limestone groups mark the onset of fully marine sedimentation and the development of the Yoredale facies with cyclic deposition of marine limestones, shales, sandstones, seatearths and coals. The Yoredale facies continues in the Upper Limestone Group, but with an increase in clastic content, indicating that fluvial and deltaic processes become more dominant as it grades laterally and upwards into the Millstone Grit Series. The

Coal Measures represent the formation of an extensive deltaic system across the area in Late Carboniferous time *(Evans et al., 2003)*.

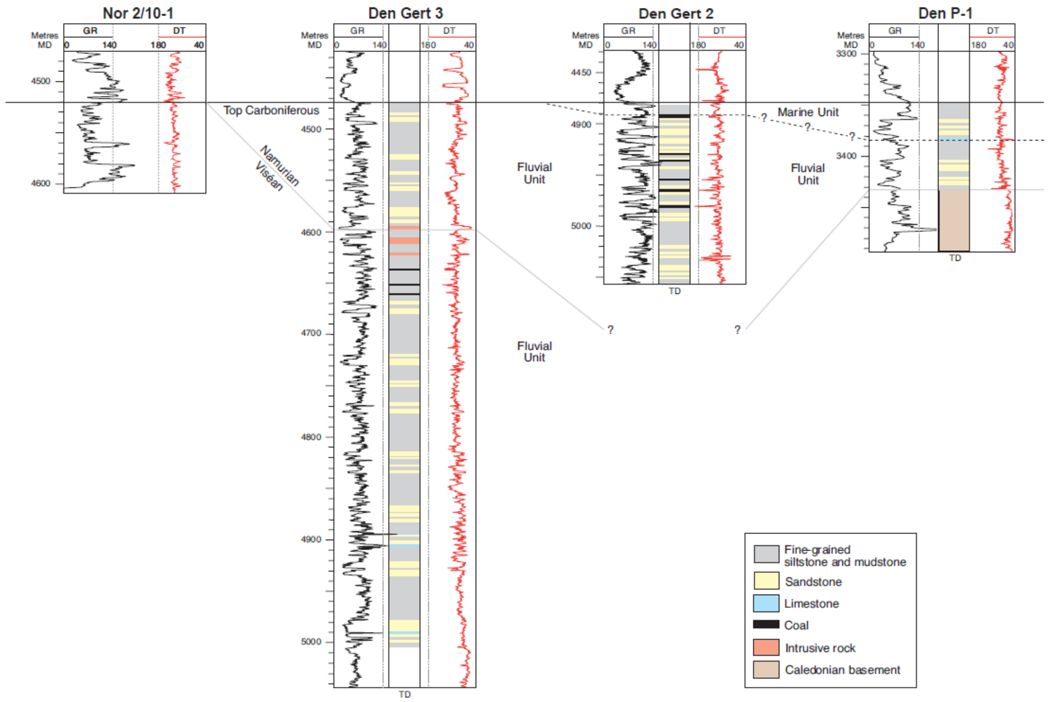

Figure 24. Carboniferous sequences in selected Danish and Norwegian wells (Evans et al., 2003).

3.3 Permian

By Early Permian times, the North Sea area was entering a semi-desert climatic zone at 20-30°N, similar to that of modern Arabia or the southern Sahara (figure 25). Much of the Permian sequence in north-west Europe, was deposited as unfossiliferous desert sandstones or as carbonates and evaporites that were the products of extreme climatic conditions; this has resulted in few fossils and thus in limited age control.

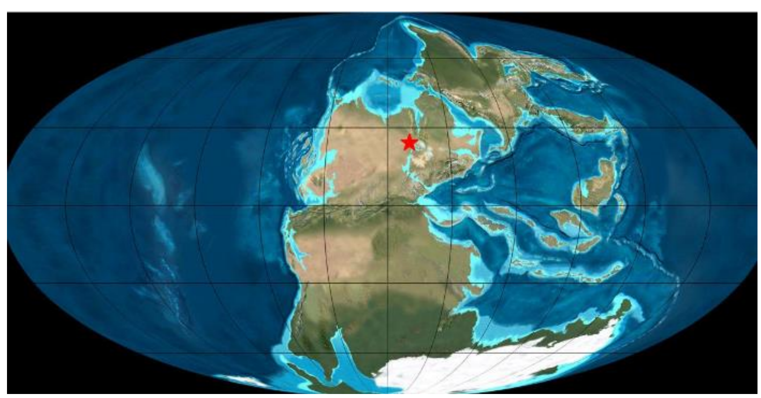

Figure 25. Late Permian (260m.a) location of the North Sea marked by a red star (Blakely, 2016).

Over an east–west-trending zone between central Germany and the Oslo Graben, much of the history of Late Carboniferous and Early Permian events is represented by a major hiatus, the combined Saalian–Altmark Unconformity; this was the outcome of crustal uplift following the late Variscan (Hercynian) Orogeny and associated Early Permian volcanic activity. The dune systems of the resulting Rotliegend deserts seem to have been deposited mostly under conditions of relatively stable air-pressure that were controlled by the repeated presence or absence of a large high-pressure cell over the south polar Gondwana ice cap. The classical Rotliegend sedimentary succession was mainly deposited in the Southern Permian Basin, and thus, the Kraka, Dan and Halfdan areas of the Southern Salt Dome Province. The Rotliegend Group is underlain by sedimentary sequences of Carboniferous, Devonian or Silurian age, or by crystalline rocks of the Caledonian basement *(Evans et al., 2003).*

In the Danish Central Graben, volcanics and interbedded lacustrine siltstones of the Karl Formation were deposited in small half grabens. Michelsen & Nielsen (1993) documented up to 650m of syn-rift Rotliegend volcanoclastic sediments in a narrow half-graben, less than 2km wide, within the Sorgenfrei-Tornquist Zone. At the time of Rotliegend deposition, axial subsidence in both the Southern and Northern Permian basins seems, at least locally, to have continually outstripped sedimentation, bringing the basinal centers to-, or below, the water table. By the end of Rotliegend deposition, the central parts of the desert basins are thought to have been some 200 to 300 m below global sea level. In the Southern Permian Basin, this led to the creation of a desert lake with marginal sabkhas covering an area about half that of the modern Caspian Sea *(Evans et al., 2003).* The post-rift succession of the Danish sector is confined to areas east of the Coffee Soil Fault where a thick sandstone-dominated succession, corresponding to the UK Auk Fm, occurs north of the Ringkøbing-Fyn high. The post-rift sedimentary succession is not present in wells from the western Danish Central Graben *(Stemmerik et al., 2000).*

Continued sea level rise, probably the result of melting of the Gondwanan ice caps, caused flooding of both the Northern and Southern Permian basins. When flooding began, probably mostly through the Viking Graben, the basins could have been completely filled with marine water to create the Zechstein Sea within a few years or even several months *(Evans et al., 2003).* In the North Sea, four main evaporite cycles and a clastic cycle termed Z1-Z5 can be distinguished. The 'ideal' cycle reflects the influence of increasing salinity caused by evaporation due to restriction of sea-water inflow some time after the initial marine incursion. It commences with the thin clastic member, passing upwards in turn through limestone, dolomite and anhydrite to halite, and finally to highly soluble salts of magnesium and potassium *(Taylor, 1998).* The Zechstein salt is mechanically weak and soluble in water. It has high thermal conductivity and expansivity but low compressibility and is easily mobilized by solid-state flow. Although the salt has a very low density, clastic sediments have lower densities until buried and lithified. Thus, salt will flow at very low temperatures and low differential stresses, and is susceptible to both gravity and tectonic forces *(Penge et al., 1993).*

The top of Permian (Zechstein) strata occurs at depths in excess of 4000 m below sea level over wide areas of the Central Graben *(Evans et al., 2003).* In the Kraka, Dan and Halfdan fields, this section has not been penetrated. Kraka well A2 drilled to a TD of 3092m may however have encountered Permian strata mixed in with the Triassic section.

3.4 Triassic

Triassic strata in the North Sea area were deposited an arid to semi-climate, 40-50°N. The Triassic is notable for its lithologically monotonous redbed intervals, which accumulated in mainly linear, northerly orientated synforms or intra-pods formed by Triassic halokinetic movement (figure 26) *(Evans et al., 2003).* In the basins in the Danish Central Trough, Triassic sediments are generally conformable on the Zechstein but there is pronounced angular discordance between the Rotliegend and the Zechstein *(Fisher & Mudge, 1998).*

Baselevel changes, induced by fluctuating sea levels, together with long-term climate changes due to continental drift also had an overall effect on sedimentation. This sequence is poorly constrained due to a lack of high quality, widely distributed biostratigraphic control and correlatable log and seismic markers. The extent of the Triassic deposits can nevertheless be mapped through the top-Zechstein surface, as the Triassic commonly conformably overlies Zechstein sequences *(Evans et al., 2003).*

Figure 26. Exposed analogues for the Triassic redbed rocks of the North Sea (Evans et al., 2003).

Triassic sediments in the North Sea are generally subdivided into two parts, a northern compartment dominated by continental deposits and a southern compartment characterized by continental and marine inter-beds. The Danish Central Graben is believed to be located in the transition zone between these two regions. Triassic strata of the Southern Central Graben have been penetrated by Kraka well A-2, Dan well M-8 and wells O-1 and U-1 (figure 27).

In the Southern Salt Dome Province, the Zechstein Group is overlain by supratidal- and alluvial sediments of the Bacton Group (figure 28). Following the Bacton Group is the Dowsing Dolomitic Formation which represents the first transgression from the south. The overlying Dudgeon Saliferous and Triton Anhydritic formations represent a regressive phase with deposition of interbedded marlstones and anhydrite-bearing claystones. These are believed to belong to a continental sabkha environment interrupted by distal flood plain settings. The evaporite series was probably precipitated during periodic flooding of the area. Triassic strata have a general thickness of 1500 to 2000 m in the Southern Salt-dome Province. However, rather considerable variations in thickness caused by Early Kimmerian erosion occur *(Michelsen & Andersen, 1983).*

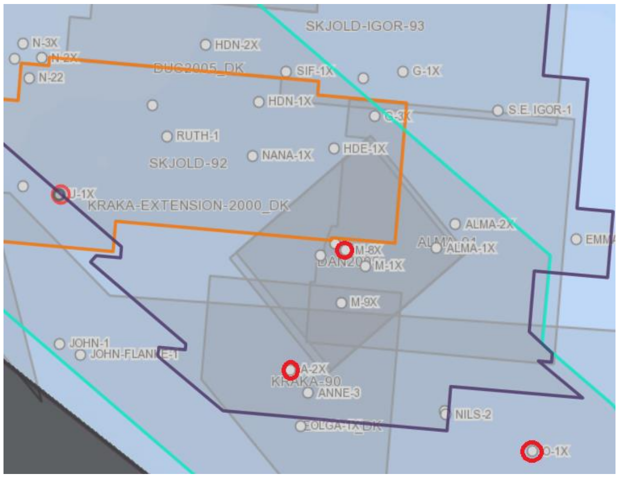

Figure 27. Southern Salt Dome Province wells penetrating the Triassic (red) (Frisbee, 2016).

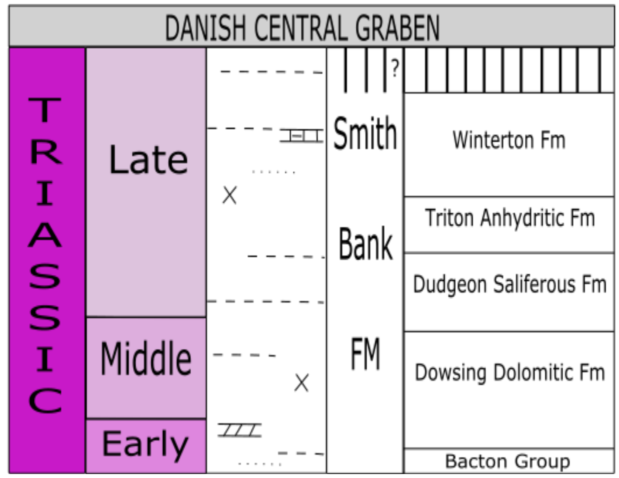

Figure 28. Triassic stratigraphy of the Danish Central Graben (after Michelsen & Andersen, 1983)

3.5 Jurassic

Jurassic sedimentation in the Central North Sea was largely controlled by the Mesozoic rift system. The fault-block activity is reflected in a series of unconformities or transgressive and regressive cycles throughout the Jurassic *(Deegan & Scull, 1977)*.

The Early Jurassic was characterized by a slow relative sea-level rise, which was initiated in the Late Triassic (Norian) *(Michelsen et al., 2003).* The transgression resulted in the establishment of a well-oxygenated marine environment in the Central North Sea Basin, and the deposition of marine muds of the Fjerritslev Formation in the Southern Salt Dome Province *(Andsbjerg & Dybkjær, 2003).* These sands constitute a minor source locally in the Danish Central Graben *(Rasmussen et al., 2005).*

The Central North Sea region was uplifted as a broad arch during the latest Early Jurassic – earliest Middle Jurassic *(Michelsen et al., 2003).* This uplift-phase caused large-scale erosion across most of the North Sea, and removed much of the presumed pre-existing Lower Jurassic marine cover (figures 29 and 30) *(Deegan & Scull, 1977),* ultimately leading to the development of the Mid-Cimmerian Unconformity *(Dahl & Solli, 1993).* The Lower–Middle Jurassic boundary is difficult to identify in the Danish Basin due to relatively poor biostratigraphic data and is conventionally placed between the Fjerritslev and Haldager Sand Formations. Later studies indicate that the Lower–Middle Jurassic transition is situated within the uppermost part of the Fjerritslev Formation in the Sorgenfrei–Tornquist Zone; elsewhere, it coincides with the marked erosion surface between the Fjerritslev and Haldager Sand Formations *(Michelsen et al., 2003).*

The first Jurassic marine transgression in the Danish Central Graben occurred during the Callovian–Oxfordian, probably reflecting the Callovian domal collapse/onset of Middle Jurassic rifting combined with eustatic sea-level rise *(Andsbjerg & Dybkjær, 2003)*. In the Danish Central Graben, Middle Jurassic deposition took place in the down-faulted area west of the Coffee Soil Fault zone, leading to preservation of Lower Jurassic deposits in the south-eastern part of the Danish Central Graben *(Michelsen et al., 2003).*

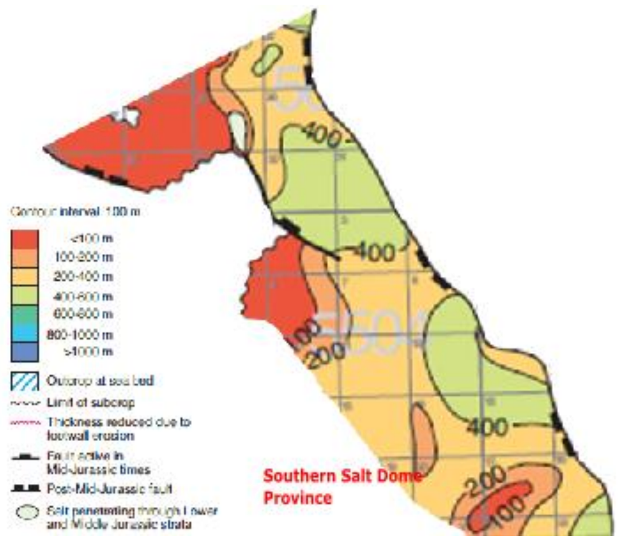

Figure 29. Thickness distribution of Lower- and Middle Jurassic strata (Evans et al., 2003)

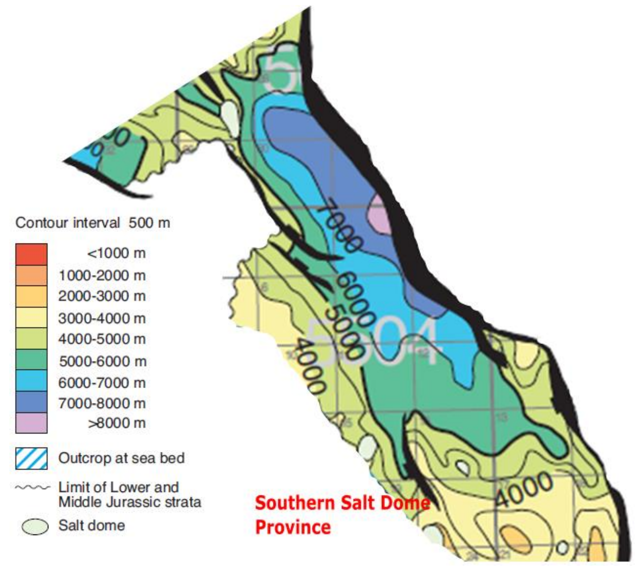

Figure 30. Depth to present day top Middle Jurassic *(Evans et al., 2003)*

In the Southern Salt Dome Province, the lower part of the Middle Jurassic succession is characterized by thick sandy deposits interbedded with silt- and claystones and occasional thin coal beds (Bryne- and Lulu formations). The upper part contains claystones, siltstones and common coal beds of the Middle Graben Formation (figure 31) *(Andsbjerg & Dybkjær, 2003; Michelsen et al., 2003).* The depositional environment evolved from a coastal plain environment with strong fluvial influence to a low-energy paralic environment dominated by lagoons or interdistributary bays. The environmental evolution through Middle Jurassic time shows an increasing marine influence culminating in the major Late Jurassic marine transgression *(Michelsen et al., 2003).*

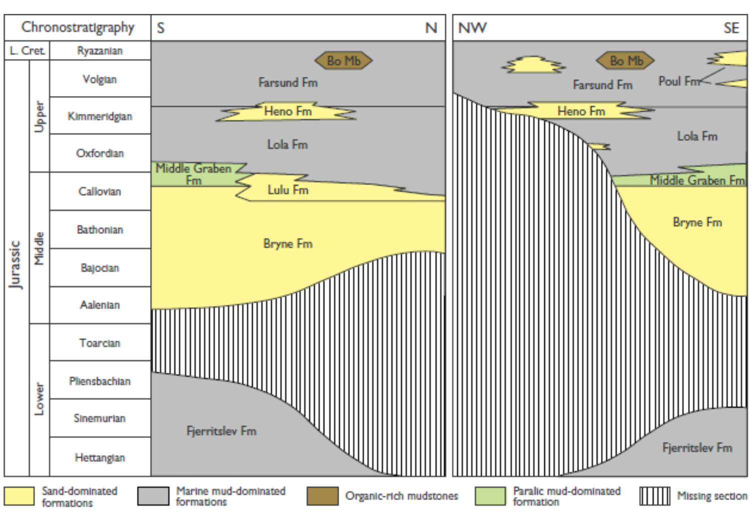

Figure 31. Jurassic lithostratigraphy of the Danish Central Graben (Andsbjerg & Dybkjær, 2003).

Deep-water conditions during the Oxfordian–Kimmeridgian led to the deposition of up to 3600-4000m of clay-dominated sediments in the Tail End Graben, which was the dominant structural element in the Danish Central Graben during the Late Jurassic *(Michelsen et al., 2003; Japsen et al., 2003).* The marine middle–outer shelf conditions which were established in latest Callovian time in the Danish Central Graben continued during the Late Jurassic over all sea-level-rise *(Michelsen et al., 2003).* Marine mudstones of the Lola Formation were deposited in basinal areas of the Southern Salt Dome Province, while the shallow marine sandstones of the Heno Formation were deposited on plateau areas during the Late Kimmeridgian *(Andsbjerg & Dybkjær, 2003)*. This indicates that the sea transgressed westwards and up-dip from the eastern part of the Danish Central Graben. The Central Graben region was probably connected with the Danish Basin during most of the Late Jurassic through the north-western part of the Norwegian–Danish Basin, north of the Ringkøbing–Fyn High. The sedimentary facies of the Central Graben differ markedly from those of the Norwegian–Danish Basin, and none of the formations known from the Danish Basin can be traced to the Central Graben. These differences probably resulted from varying distances to the source areas and from differences in structural evolution *(Michelsen et al., 2003).*

The Late Jurassic transgression culminated during the Volgian with deposition of the deep marine mudstones of the Kimmeridge Clay time equivalent Farsund Formation *(Andsbjerg & Dybkjær, 2003).* The Farsund Formation, with the 'hot shales' of the Bo member being the most prolific, is the primary source rock in the Southern Salt Dome Province *(Rasmussen et al., 2005).* The formation, which reaches maximum thicknesses of more than 3000m in the Tail End Graben, extends from the Norwegian North Sea area, through the Danish Central Graben. It correlates with the upper part of the Kimmeridge Clay Formation in the Dutch North Sea area and the Børglum Formation of the Norwegian–Danish Basin, although the transition zone has not yet been located. The Farsund Formation consists of medium to dark grey claystones that are carbonaceous and variably calcareous, interbedded with numerous thin beds of brownish dolomite. Thin units of turbidite sandstones occur locally in the deeper parts of the basins. Towards the eastern part of the Danish Central Graben, close to the Coffee Soil Fault, the proportion of sandstones increases and there appears to be a transition locally to the sandy Poul Formation (Michelsen et al., 2003).

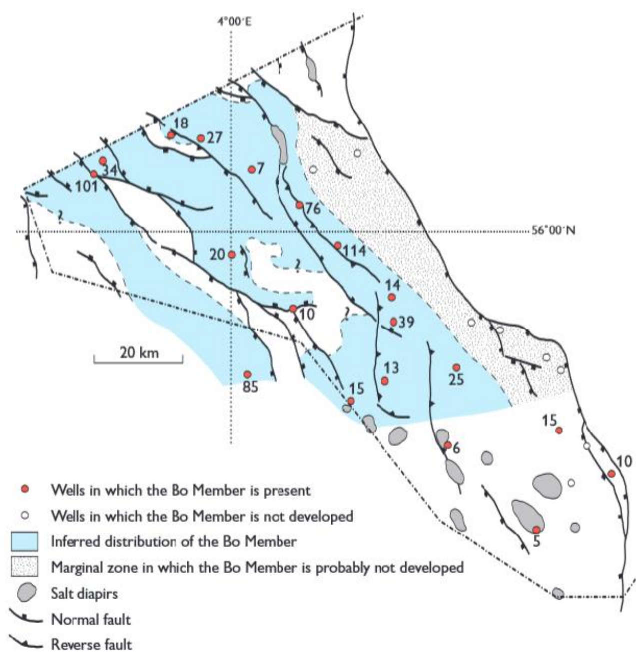

Figure 32. Distribution of the Bo Member in the Danish Central Graben (Ineson et al., 2003).

The deposition of the Early Ryazanian Bo Member phase coincided broadly with the end-Jurassic tectonic phase. The mudstone-dominated member, representing the peak of organic carbon enrichment, has a total organic carbon (TOC) content of 3–8%, though locally exceeding 15%. It reaches of 15-30m and is a persistent feature of the Danish Central Graben (in the Danish sector, mature source rocks capable of generating hydrocarbons have so far only been found here *(Rasmussen et al., 2005)*, although it is not present in the Southern Salt Dome Province (figure 32).

Lateral variation in both thickness and organic richness is attributed to intrabasinal structural topography and to the location of sediment input centers. Biostratigraphy indicates that the onset of enhanced organic carbon burial began in the middle–late Middle Volgian. Core data from the Jeppe-1 and E-1 wells in the Northern Central Graben indicate that the organic-rich shales of the Bo Member are not wholly of hemipelagic origin, as commonly assumed, but may locally be dominated by fine-grained turbidites. Absence of bioturbation, well-preserved lamination and high TOC values suggest that bottom waters were predominantly anoxic although the presence of in-situ benthic bivalves at discrete horizons in the E-1 well suggests that suboxic conditions prevailed on occasion *(Ineson et al., 2003).*

Depth to Base Upper Jurassic ranges from 2100 m in the John Flank-1 well (southwest of the Kraka Field) to 7500 m in the deepest parts of the Tail End Graben, where the Upper Jurassic attains a maximum thickness of 3600-4000m of which a maximum of 1400 m has been drilled (the G-1 well). Depth to Top Jurassic ranges from 1700 m in the John Flank-1 well to 4800 m at the base of several Early Cretaceous depocentres in the northern parts of the Central Graben *(Japsen et al., 2003).*

3.6 Lower Cretaceous

Early Cretaceous stratigraphy of the North Sea reflects intra-plate stress variations in the European plate, regional thermal subsidence, and halokinetic movements. Their relative importance in controlling sedimentation patterns in the North Sea basins is however currently a matter of debate *(Evans et al., 2003).*

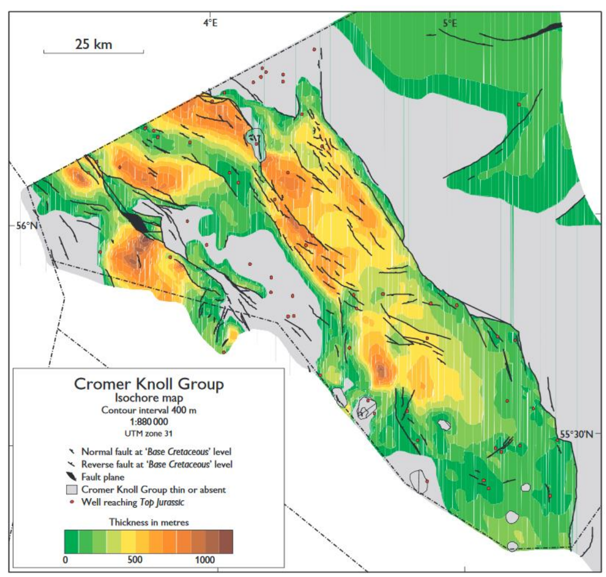

Figure 33. Cromer Knoll Group isochore. Note that the Cromer Knoll Group is only recognized within the Central Graben. (Japsen et al., 2003).

Gowers and Sæbøe (1985), Oakman and Partington (1998), and Stewart and Clark (1999) suggested that active extensional faulting and local inversion was the primary control on basin geometries throughout the Early Cretaceous. In contrast, other regional studies (e.g. Erratt et al., 1999) have interpreted Lower Cretaceous strata primarily as post-rift sequences filling inherited basin-floor topography *(Evans et al., 2003).* According to Andsbjerg & Dybkjær (2003), salt movements had a profound influence on the development of depocentres in the Søgne Basin, the Tail End Graben and the Salt Dome Province *(Andsbjerg & Dybkjær, 2003)*.

The base of the Cretaceous unit (figure 33) is marked by an upward change in facies from dark, organic-rich claystones of the Farsund Formation to claystones and carbonates of the Cromer Knoll Group, deposited under oxic bottom-water conditions. This facies change is believed to have been essentially synchronous across the North Sea basin, reflecting a rapid turnover of the water mass within an epicontinental seaway, the cause of which is unknown *(Evans et al., 2003).* In the Danish Central Graben, the maximum thicknesses (1100m) of the Cromer Knoll Group are found in the Outer Rough Basin, while thicknesses of more than 800m are estimated in the Ål, Iris and Roar Basins and in the Feda, Gertrud and Arne–Elin Grabens *(Japsen et al., 2003).*

Transgressive/regressive cycles, resulting from relative sea-level changes, played a part in controlling facies and sediment thickness distributions during the Early Cretaceous. It is however difficult to resolve any causal relationships between these relative sea-level changes and tectonic events, whether local or regional *(Evans et al., 2003).*

3.7 Upper Cretaceous – Danian

3.7.1 Introduction to Chalk

During Upper Cretaceous, much of North-West Europe was covered by an extensive epeiric sea, characterized by low terrigenous input and chalk deposition, the central North Sea area constituted a relatively deep part of the Chalk Sea *(Anderskouv & Surlyk, 2011).* The chalk and its correlative mudstone-dominated succession in the northern part of the North Sea were deposited over a period of 35 million year. The landmasses transgressed by the Late Cretaceous Sea were low lying and peneplaned, so that large areas of northern Europe were flooded and only a few massifs formed land. The exact position of the coastlines during that time is known only at a few locations due to the scarcity of preserved shoreline and marginal deposits. Since the Late Cretaceous, the North Sea region has drifted northwards by about 7° of latitude *(Evans et al., 2003).*

Deposition of the Late Cretaceous–Danian Chalk Group in the southern part of the Danish Central Graben took place during a phase of regional subsidence following Late Jurassic rifting. This period was marked by high sea-level, high sea-surface temperature and a peak in production of organic matter. The Late Cretaceous regional subsidence pattern was modified by halokinesis of the Zechstein salt and was punctuated by widespread structural inversion in the form of compression along old extensional fault trends, flexuring and folding of basin infill. This resulted in the development of areas with bathymetric elevations and the formation of local depocentres in the intervening lows. The structural movements gave rise to a number of unconformities that are easily recognized as truncation and onlap surfaces on seismic profiles and to stratigraphic hiatuses recorded in wells *(Abramovitz et al., 2010).* Thickness variations of the Chalk Group are mainly related to the two dominating depositional mechanisms: suspension deposition and redeposition caused by tectonically induced slope instability *(Vejbæk & Andersen, 2002).*

The Upper Cretaceous-Danian Chalk Group forms a coherent body across most of the North Sea region, with an average thickness of about 500 m. The North Sea chalk is a mono-mineralic carbonate rock that consists of 96–99% calcite (CaCO3), non- carbonate biogenic particles (radiolarian, diatoms and sponge spicules) and small amounts of clay minerals due to influx of erosional detritus. After pelagic deposition, the chalk deposits were subjected to redistribution by various processes. These include downslope mass flow movements from slope instability caused by syn-depositional tectonics as well as along-slope bottom currents that caused seafloor geometry modifications in the form of incised valleys, channels, drifts, ridges and mounds. The thickness distribution of the Chalk Group varies from less than 100 ms on top of salt diapirs such as Kraka and Dan, and up to 650 ms (c. 1300 m) in the rim-syncline east of the Dagmar Field.

The Kraka, Dan, and Halfdan fields produce from the Maastrichtian Tor Formation and the Danian Ekofisk Formation. These units are separated by a zone with extremely poor permeability, the so-called Danian-Maastrichtian hardground *(Hansen & Nederveen, 2005).* This hardground is the result of a major sea level fall in the latest Maastrichtian and earliest Danian. Pore-water degassing and sediment expansion, as a response to the lower pore-water pressure caused by the sea level fall may have caused sediment instability and mass movements, possibly explaining the regional increase in mass movements during the latest Maastrichtian *(Evans et al., 2003).*Oil permeability is generally some 5 to 15 times lower in the Danian compared to Maastrichtian for the same porosity chalk. This primarily reflects the differences in coccolith size distributions; the coccoliths constituting the rock framework are significantly larger in the Maastrichtian than in the Danian *(Albrecthsen at el., 2001)*.

3.7.2 Reservoir Characteristics

The southern North Sea chalk is characterized by high porosities of 25-35%. Preservation of porosity at depth is believed to be the result of:

1. Early hydrocarbon migration into pore space, inhibiting diagenesis and enhancing porosity

2. Overpressure, preventing coccolith plates from undergoing extensive pressure solution

The chalk in the Southern Salt Dome Province was deposited in Milankovitch-type cyclic units of 1-8ft thickness *(Larsen et al., 1997)* ranging from a primary laminated porous section to more tight sections with signs of bioturbation and lack of lamination. The latter is believed to have formed by decreased sedimentation rates and increased bioturbation under relatively oxic conditions *(Damholt & Surluk 2004).* The more porous layers represent redeposited chalks deposited under more anoxic conditions that tend to have better reservoir qualities, presumably due to destruction of the early diagenetic fabric. The reservoir porosity generally decreases with depth, although there is no simple relationship between burial depth and porosity on a regional scale. Detailed porosity profiles for the chalk can be converted from acoustic impedance derived by seismic inversion, as porosity is the main cause for changes in the acoustic impedance *(Vejbæk et al., 2005).*

This cyclicity is also recognized in magnetic susceptibility of the chalk as 0.5 and 2 cycles/m variations which are ascribed to Milankovitch cycles *(Stage, 1999).*

Due to very small pore throat sizes, the chalks have low permeabilities in the range of 0.5-2.0mD. Danish chalk reservoirs typically have significant capillary entry heights, long transition zones, and very high HC saturations (up to 97%) due to high capillary entry pressures and wettability characteristics *(Vejbæk et al., 2005).*

Oil generation in the deepest part of the central graben started during the Maastrichtian and peaked in early Miocene to Pliocene times, with significant amounts of oil also being generated during the Paleocene. Hundreds of meters of Lower Cretaceous mudstones may separate the source rocks of the Kimmeridge Clay time equivalent Farsund Formation from the hydrocarbon accumulations in the chalk. The exact mechanisms of secondary migration through this barrier remain unclear, although vertical migration along faults and/or fractures seems most likely. Little is known about the lateral movements of fluids within the chalk. The range of permeability of producing fields suggests that lateral migration is possible, but is likely to be slow. Very low vertical and lateral permeability may explain the complex trapping mechanisms and the fact that most discoveries are confined to areas of early source maturation. Oil that entered the chalk prior to Miocene inversion and later tilting may remain trapped by the low relative permeabilities, leading to tilted OWCs combined with an actively flowing aquifer, as in the Dan field. In the Danish sector, the oil has an average density of 30-38°API. Although dominantly oil prone, gas accumulations occur in Upper Cretaceous reservoirs, both as gas caps and as gas fields (e.g. Halfdan North East).

Due to very slow flow rates, oil distribution of Danish oil fields is rarely in equilibrium. Dan, Kraka and Halfdan all have local evidence for tilted free water levels, which can largely be attributed to lateral pressure gradients in the water zone. The pressure gradients result in sloping free water levels for oil/water systems exceeding 10m km 1- for the Kraka case. FWL slopes are of great significance for trap definitions. Maintained lateral pressure gradients reflect disequilibrium compaction caused by rapid Neogene deposition. Since this, only insignificant pressure dissipation has occurred. This is consistent with the very low regional permeability *(Vejbæk et al., 2005).*

3.7.2.1 Kraka

The Kraka oil zone is characterized by high water content (>50%) and limited thickness (70 m), and the gas cap is thin, less than 8 m. The free water level in the Kraka Field dips to the south-east *(Abramovitz, 2008).*

Kraka has an OWC dipping at roughly 10 m/km in a SE direction, owing to a lateral water zone pressure gradient in the order of 5psi/km (34.5kPa/km). This pressure gradient fits into a regional pattern of overpressure caused by rapid Neogene burial and reflects the low permeability of Palaeogene and Cretaceous deposits. The field structure remained stable through most of the Cenozoic and hydrocarbon charging is likely to have occurred within the last 10 Ma, possibly sourced from the Upper Jurassic Farsund Formation. However, porosity anomalies mapped farther down the southeast flank on the basis of seismic inversion analysis may suggest porosity preservation by early hydrocarbon invasion *(Rasmussen et al., 2005).*

3.7.2.2 Dan

The OWC in the Dan reservoir has a height differential of 61m across the field and dips to the SSW. The tilt was caused by a combination of hydrodynamic effects and possible Neogene tilting of the basin *(Jørgensen 1992; Thomasen & Jacobsen, 1994).* There is a general pressure gradient in the aquifer with hydrodynamic flow towards the low pressure area to the SE. The tilted FWL in Dan is situated~50m below the 100% Sw depth, which varies across the field (Vejbæk & Kristensen, 2000). The Sw in Dan, as in Kraka, is approximately 50% in the oil bearing zone and the oil-water transition zone is thick (›60 m) due to strong capillary forces in the low permeable chalk *(Jørgensen 1992; Vejbæk & Kristensen, 2000).*

3.7.2.3 Halfdan

Oil saturations in the Halfdan Field are up to 85% with water saturations ranging from 0.15% in the best reservoir layers to 1.00 in the aquifer layers below and in the lowermost Danian unit, immediately above *(Jørgensen, 2002).* The field is also estimated to be overpressured and influenced by a SE-dropping aquifer pressure as in the Kraka Field. However, there is good evidence that lateral pressure gradients also exist in the oil-zone. Migration of hydrocarbons into the field may have occurred as early as Eocene, but probably mainly after 22Ma BP from the presumed Upper Jurassic source rock when the area was a structural trap *(Rasmussen et al., 2005).*Both the gas-oil and oil-water contacts exhibit an apparent tilt from east to west, indicating non-equilibrium conditions. Despite this, no evidence for separate gas caps are present. The lateral pressure variations are assumed to indicate fluid migration and a local GOC/GWC position controlled by the local fluid pressures *(Albrechtsen et al., 2001).* The oil zone pressure gradient is quoted to result in a flow of 500BBL oil a-1 up the NW flank of the Dan Field. Inferred oil migration from Halfdan to Dan corresponds to 25% of the Dan STOIIP per million years, however, no residual oil zone has been found in the Nana-1XP area. This absence indicates that oil migrates into Halfdan at a rate, which compensates for the loss to the Dan Field *(Albrecthsen at el., 2001).*

3.7.3 Maastrichtian

3.7.3.1 Kraka

The Maastrichtian chalk forms the secondary reservoir in the Kraka Field. The thickness of the Tor Formation (Maastrichtian porous) of the Kraka Field varies from less than 25 m to more than 100 m. The Tor Formation has been divided into units M1 to M4 by Klinkby et al. (2005) and into units M1-M5 by Abramovitz (2008). According to Abramovitz, Klinkby et al. (2005) interpreted an intra-Maastrichtian seismic horizon (base of unit M4; figure 34) as the base of the reservoir interval in the Kraka–Dan area, separating porous chalk from tighter chalk below. They on the other hand suggest that the porous M5 unit represents the base of the reservoir interval. The base of the M5 unit is seen as a distinct, relatively high- amplitude continuous reflection in the seismic data, and can be correlated from the Kraka wells to Olga- 1X and the Dan Field wells (M-1X, M-2X, M-8X, M-9X and M-10X), where it corresponds to a consistent regional reflection between two intra-Maastrichtian intervals *(Abramovitz, 2008).*

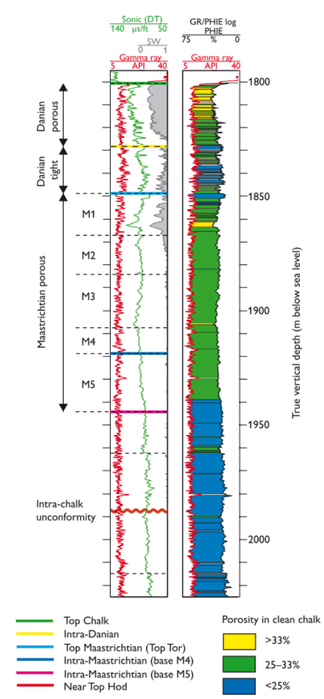

Figure 34. Maastrichtian subdivision of the Kraka Field in the Anne-3 well (Abramovitz, 2008).

Individual units are 10–20 m thick and show some lateral variation in thickness both across the Kraka Field and regionally. Typically, the reservoir units have porosities (PHIE) in the range of 25–35% and matrix permeabilities of about 2–3 mD *(Klinkby et al., 2005).*

3.7.3.2 Dan

The Tor Formation forms the primary oil reservoir in the Dan Field, where the oil column is estimated to 15m and 91m in Dan West Flank and Dan Main, respectively *(Zaske et al. 2014).*

The Dan Maastrichtian is subdivided in to 9 reservoir units based on a combination of biostratigraphy, seismic and wireline log data *(Kristensen et al., 1995),* where the upper units contain most of the producible hydrocarbons. 3 overall units (6 biostrat/wireline units) occur in the Late Maastrichitan and 2 (3 biostrat/wireline units) in the Early Maastrichtian. The uppermost Maastrichtian above the last occurrence of *P. Grallator* is missing within the Dan area (figure 35).

Chronostratigraphic age	Biostratigraphic events	Main seismic units	Reservoir units
	P. grallator LOD		
Late Maastrichtian		I	1
			2
	H. borisii FAD		
		II	3
	I. cooksoniae LOD		
		III	4
			5
			6
Early Maastrichtian	*A. acutulum* LOD	IV	7
			8
		V	9
	E. hapala LOD		

Figure 35. Intra-Maastrichtian units in the Dan Field (Kristensen et al., 1995).

In the Dan Field, the Tor Formation, which has an average thickness of 105m, thickens from the NE to SW with a local minimum just NE of the present day Dan structure top *(Kristensen et al., 1995).* Some Lower Maastrichtian intra-chalk units pinch out to the NE and are also less porous and permeable in this direction *(Scholle et al., 1998).*

This combined with large thickness variations within the area and a relatively thin Maastrichtian unit compared to adjacent fields indicates that some tectonic movement probably occurred during chalk deposition in the Dan structure. A simple hypothesis involves sediment transport from high-standing areas to ones of greater water depth during a limited number of large-scale mass movement events. Debris flows and proximal turbidity currents could have transported large sediment volumes, as has been observed farther to the north in the North Sea. However, no significant turbidite deposits have been identified within areas of thickened sediment accumulation in the Dan Field *(Scholle et al., 1998)*. According to Damholt & Surlyk (2004), the chalk group in the Dan area was deposited on a gentle paleotopographic high as a combination of pelagic fallout and small scale low density turbidity currents. A second hypothesis involves a single, or a very small number of erosional events, which could explain the large scale truncation of Tor units *(Scholle et al., 1998).*

3.7.3.3 Halfdan

The Tor Formation forms the primary oil reservoir in the Halfdan field, where the Maastrichtian oil column is about 50m thick *(Jørgensen, 2002).*

The chalk was deposited in an elongated basin oriented approximately Northwest-Southeast. The axis of this late Maastrichtian basin was located southwest of the Nana- 1XP well. Increasing condensation (due to deterioration of the reservoir properties) and ultimately pinch out of this unit is found towards the basin slopes. The basinal Maastrichtian chalk in the Halfdan area exhibits a characteristic cyclic pattern of high and low porosity intervals similar to the Dan Field Maastrichtian chalk with individual cycles being regionally correlatable (figure 36).

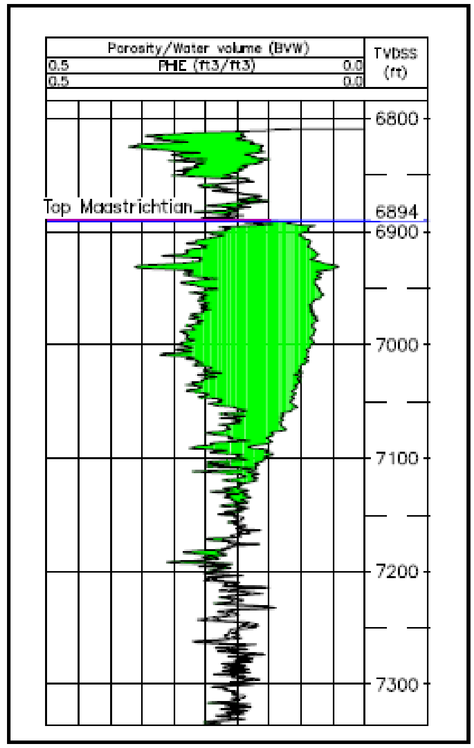

Figure 36. Halfdan type log, Maastrichtian (Albrecthsen et al., 2001)

In the condensed parts, the cyclic patterns are distorted, making well to well correlations less obvious. Properties of the chalk vary on a 3-7 ft. scale, reflecting depositional cycles. Each cycle consist of a high and low porosity interval, causing the significant vertical porosity variations. The Maastrichtian is relatively pure, composed of primarily of coccolithic material and minor fractions of foraminiferal and other skeletal material. The non-calcareous component of the chalk (up to 5%) constitutes mainly silica found as disseminated or nodular chert and minor amounts of argillaceous material in the form of disseminated clay- chalk deposition occurred in a low energy environment dominated by pelagic settling and winnowing on local highs. Large scale re-working is generally absent in the area. Average porosities in the upper Maastrichtian lies between 25- and 30%.

A sharp porosity change is observed in the lower Maastrichtian to Campanian (top Hod Fm equivalent), below which the average porosity is reduced to 10-15%. Within the central and western part of the Halfdan Field the hardground is located deep in the section, several hundred feet below the OWC. This transition is however much shallower in Halfdan Northeast gas field, as a consequence of the condensation of Maastrichtian in this area *(Albrecthsen at el., 2001).*

3.7.4 Danian

3.7.4.1 Kraka

The Danian of the Kraka Field is divided into the Danian Tight and the Danian Porous units, which are in turn subdivided into two and three units, respectively (figure 37).

The Danian Tight unit is thin in an area northeast of the Kraka structure and thickens away from it. Towards the south the unit is more than 50 m thick, the basal part pinching out towards the north. Seismic and biostratigraphic data indicate that the lowermost part of the Danian Tight unit is missing in the crestal area of the Kraka Field. Local thickness minima are elongated in NW–SE and SW–NE directions, and are believed to represent erosional features, possibly initiated by minor movements along faults trending in these directions. The two elongated thickness maxima in the south are thought to result from low-angle listric sliding towards the south. The fault planes are interpreted as soling out near the Top Maastrichtian. As in the Maastrichtian Porous unit, deposition was seemingly unaffected by growth of the Kraka structure.

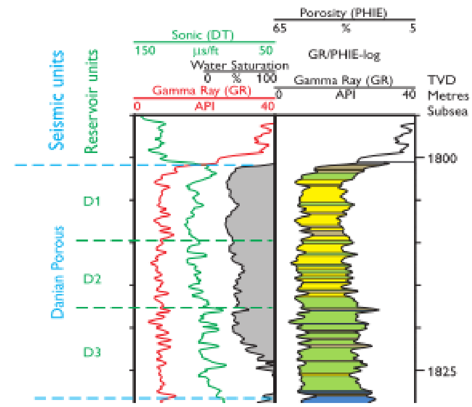

Figure 37. Danian subdivision of the Kraka Field in the Anne-3 well (Klinkby et al., 2005).

The Danian Tight unit is subdivided into two reservoir units, typically with porosities in the range of 20–30%. The presence of tight and clayey chalk beds, as well as chert, reduces the transmissibility, resulting in poor reservoir quality. This interval may, therefore, act as a baffle to vertical fluid flow, as proposed by Jørgensen (1992).

The Danian Porous unit is thin over the crest of the present- day structure and over wide areas to the north and northwest. It thickens in an irregular pattern away from the crest of the Kraka structure, and the thickest chalk deposits occur to the southwest and southeast, where they exceed 50m. This pattern seems to indicate that salt movements were initiated in the late Danian before the onset of the more pronounced movements in post-Danian time. Local thickness maxima and minima along the flanks of the structure follow those of the Danian Tight unit in a NW–SE direction. The thickness variations of the Danian Porous unit may thus be attributed accordingly to late Danian to early post-Danian sliding of poorly consolidated chalk sediments.

The Danian Porous unit is subdivided into three reservoir units that typically have porosities in the range of 25–35%. The porosity of each unit varies only slightly across the Kraka Field, although larger variations are seen regionally *(Klinkby et al., 2005).*

3.7.4.2 Dan

In the Dan field, the Danian chalk of the Ekofisk formation has an average thickness of 45m. It is subdivided into three units: a tight lower unit, a succession of cherty bioturbated chalks, and a unit comprising marly chalks with rare marlstone beds. In general, the Ekofisk formation is variable in porosity and permeability properties. The porosity in the high-porous units of the chalk range from 20-40% *(Megson 1992; Ovens et al., 1998; Arbramowitz 2007),* but the matrix permeability of the fine-grained chalk is very low, typically at 0.5-2mD *(Ovens et al., 1998).*

3.7.4.3 Halfdan

Within Halfdan, the Danian secondary reservoir produces primarily gas in the northeastern part of the field. However, one oil producer is installed directly above the main Halfdan Tor oil field. Oil production from this well started in mid-February 2012 *(Calvert et al., 2014).*

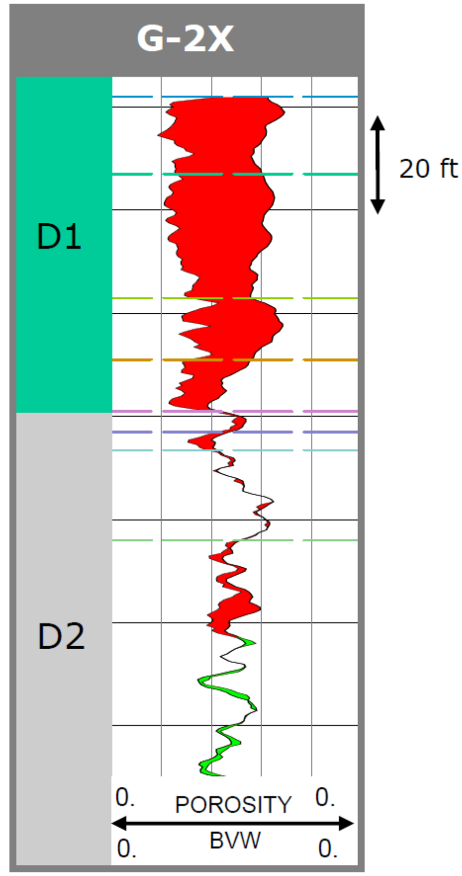

Figure 38. Halfdan type log – Danian (Henriksen et al.,2009)

The Danian Ekofisk Formation is a widespread, thin accumulation with high porosity and low permeability, capped by marl and shale of Tertiary age *(Albrecthsen et al., 2001).* Within Halfdan, the Danian is divided into an upper reservoir-unit and a lower non-reservoir-unit (figure 38) *(Albrecthsen et al., 2001).* Within the D1 and D2 reservoir units, and in particularly in the D2 unit, diagenesis of the chalk gives rise to extreme reduction of the permeability. The permeability reduction is most pronounced across laminated smectite rich beds formed by alteration of volcanic ash *(Christiansen et al., 2009).* D1 is characterized by extremely small grain sizes (average around 1 micrometer), high porosities (30-35% in reservoir zones) with a cyclical development and very low permeabilities of 0.1-1 mD *(Henriksen et al., 2009).* D2 is characterized by impure argillaceous and siliceous, slowly deposited pelagic chalk, which is interpreted to form a baffle between the Maastrichtian oil development target and the upper Danian gas *(Albrecthsen et al., 2001).* The gas bearing chalk is generally less than 21m in thickness and the target zones for reservoir drilling are typically less than 6m thick. The chalk reservoir is difficult to distinguish from the overlying shale on conventional seismics as the effects of porosity and gas/fluid mixture cause the reservoir chalk to exhibit similar acoustic impedance as the shale above *(Henriksen et al., 2009).*

3.7.5 Onshore Analogues

Onshore chalks have only been used as reservoir analogues to a limited extent because they are commonly considered to be of a shallower-water nature than the North Sea chalks. However, this is not necessarily the case, for deep basinal chalks of the Danish Basin exposed in northern Jutland were deposited in similar water depths to those for much of the North Sea, and are very useful field analogues. Also, some North Sea chalks are of a shallower water nature as they were deposited on structural highs. Good analogues are exposed on Møns Klint, Denmark, on the island of Rügen in eastern Germany and around Hamburg in northern Germany *(Evans et al., 2003).*

3.8 Paleogene

Jurassic structural highs had a major influence on early Paleocene basin topography. On these highs, the Ekofisk Formation, and locally the Tor Formation, were eroded and redeposited in basinal areas by gravity flows. This reworking is commonly observed along graben margins and intrabasinal highs, as well as close to rising salt diapirs *(Evans et al., 2003).*

In most wells in the Danish sector, the chalk group is overlain by marlstones of the Selandian Våle Formation: this boundary is gradational and can be difficult to position (figure 39). The Våle Formation comprises hemi-pelagic deposits and deposits from dilute turbidity currents, and is overlain by mid- to upper Paleocene shales of the Lista and Sele formations. The boundary between the latter formations is placed at the contact between "non-laminated, non-tuffaceous shales" (Lista Formation) and "laminated tuffaceous shales" (Sele Formation) *(Schiøler et al., 2007).*

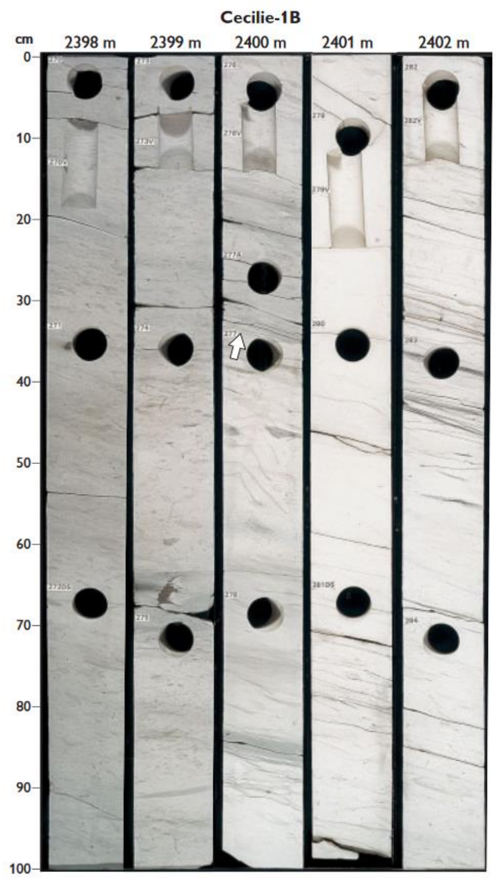

Figure 39. Core photographs of the Ekofisk–Våle formation boundary in the Cecilie-1B well. The shift from chalk to marlstones is gradational and placing the boundary can be difficult; it is positioned in the middle part of the core interval 2400.00–2401 m, at 2400.35 m (arrow), where light grey marls become dominant. Depths are core depths (Schiøler et al., 2007).

The top of the Paleocene interval, as described in the Millennium Atlas (Evans et al., 2003), is marked by the ash-fall deposits of the Balder Formation, which form an excellent seismic reflector and a reliable time-marker horizon. There is however no global consensus as to the placement of the Paleocene-Eocene boundary *(Evans et al., 2003).*

Eocene compression related to the Alpine Orogeny, provided a mechanism for basin margin uplift, resulting in several hundreds of meters of deep submarine-fan and hemipelagic sediments being deposited in the basinal depocentres of the Central Graben *(Evans et al., 2003).* In the Southern Salt Dome Province, these deposits belong to the Sele and Balder formations *(Schiøler et al., 2007)*. Towards the end of the Eocene, the regional stress regime in the North Sea changed to one of east–west extension. This, combined with other regional adjustments associated with the culmination of the Pyrenean orogeny, terminated the Eocene pattern of deposition. The influence of the Pyrenean orogeny resulted in the widespread unconformity seen at the top of the Eocene throughout the North Sea *(Evans et al., 2003).*

Tectonic movements influenced oceanic circulation and may have been the cause of a local hiatus in parts of the central North Sea region during the Early to Mid-Oligocene. This hiatus has also been attributed to a fall in eustatic sea level. In the Danish offshore area, this hiatus is represented by a regional unconformity which is overlain by a thin, glauconitic bed that represents the slow, clastic deposition that accompanied the initial early Oligocene transgression *(Evans et al., 2003).* In the Oligocene major fine-grained clastic wedges prograded into the basin from the north and thick deltaic sands were deposited locally. The massive infill from the north continued into the Miocene.

3.9 Neogene – Quaternary

Three major pulses of delta and coastal-plain progradation occurred during the Early Miocene, represented by the Ribe Formation, the Bastrup sand and the Odderup Formation. The major deltas prograded from the north and northeast towards the south and southwest and dominated the eastern part of the Danish North Sea Basin. The deposition of terrestrial-dominated sediments gave way in the Middle Miocene to dominantly open marine sedimentation of the Hodde and Gram formations. These fully marine deposits dominated the Danish Central Graben throughout the Middle and most of the Late Miocene. The water depth exceeded 100mduring the deposition of the Hodde and Gram formations. The transgression was partly due to aeustatic sea-level rise in the early Middle Miocene, the so-called Mid-Miocene climatic optimum, and partly due to increased subsidence. Sediment transport routes shifted to the northeast and east in the Middle Miocene. At the end of the Miocene sediment supply was from the east, especially from the Baltic area, the so-called Eridanos Delta. Sediment influx from the northeast was also high during the Late Miocene and Pliocene.

A deep-water environment dominated the eastern North Sea Basin, possibly the result of continued subsidence during the Pliocene: this permitted westward progradation of a major Upper Pliocene delta system. Marked tilting of the North Sea Basin at the Pliocene– Miocene boundary can be recognized by the progressive truncation of the Cenozoic succession towards the east and northeast. The timing of this major tilting is indicated by the development of a Pliocene– Quaternary delta complex that is located in the westernmost part of Danish waters and continues into British waters.

4. Selected Groups and Formations

4.1 Lola Formation

Age: upper Middle Jurassic to Late Jurassic (Late Callovian/Early Oxfordian – Late Kimmeridgian)

Reference well: DK well U1, 10668-9555 ft. below KB / 3223-2884m below MSL

Lithology: Dark olive-grey to grey claystones with primarily terrestrial organic material

Environment: Low energy, offshore open marine environment

Log characteristics: fairly constant high GR and relatively low sonic velocities. A few high velocity peaks corresponding to dolomite or limestone beds may occur.

Lower boundary: the formation overlies the Middle Graben Formation in the Southern Salt Dome Province. The boundary with the Middle Graben Formation shows a sudden and relatively large drop in sonic velocity. On structural highs along the western margin of the Central Graben and on local highs the formation lies unconformably on Triassic or older strata.

Distribution and thickness: the formation is present in the eastern and southern parts of the Danish Central Graben. It thins west of the Tail End Graben and probably continues southwards and grades into the lower part of the Kimmeridge Clay Formation in the Dutch North Sea area. Maximum thicknesses of~1000 m occur in the Tail End Graben.

Reference: http://www.geus.dk/DK/publications/geol-survey-dk-gl-bull/Documents/nr1_p145-216.pdf

4.2 Farsund Formation

Age: Late Jurassic to Early Cretaceous (Late Kimmeridgian – Ryzanian)

Reference well: NO well 2/7-3, 3623-3414m below KB

Danish sector reference section: DK well G-1, 12036-7863 ft. below KB 3631-2359m below MSL

Lithology: medium to dark grey claystones that are carbonaceous and variably calcareous interbedded with numerous thin, brownish dolomite. The organic matter is mainly liptinitic.

Environment: relatively deep marine. Local units of turbidite sandstone occur in the deeper parts of the basin. Close to the Coffee Soil Fault, the sandstone component increases, and there appears to be a local transition to the sandy Poul Formation.

Log characteristics: relatively high GR and relatively low sonic velocities. High velocity peaks and corresponding low GR readings reflect dolomite or limestone beds or carbonate cemented sandstone and siltstone beds.

Lower boundary: the formation overlies the Lola formation in most of the Central Graben. The boundary with the Lola Formation is defined above a velocity minimum and a corresponding gamma-ray maximum. Above the boundary, there is commonly a general increase in velocity, a decrease in GR values and a much higher frequency of sonic velocity peaks. On plateau areas in the western and north-western part of the Danish Central Graben, the Farsund Formation overlies the Heno Formation. This boundary is characterized by an abrupt or gradual increase in GR readings and a corresponding decrease in velocity.

Upper boundary: the upper boundary with the Åsgard Formation (Cromer Knoll Group) is placed at the first significant change from high gamma-ray and low sonic velocity readings of the Farsund Formation to the low GR values and higher sonic velocities of the Åsgard Formation.

Distribution and thickness: The formation extends from the Norwegian North Sea area, through the Danish Central Graben. Southwards it correlates with the upper part of the Kimmeridge Clay Formation in the Dutch North Sea area. Eastwards, the formation correlates with the Børglum Formation of the Norwegian–Danish Basin, although the transition zone has not yet been located. Maximum thicknesses of more than 3000 m occur in the Tail End Graben.

Reference: http://www.geus.dk/DK/publications/geol-survey-dk-gl-bull/Documents/nr1_p145-216.pdf

Norwegian Fact Page*: http://factpages.npd.no/factpages/Default.aspx?culture=nb-no&nav1=strat&nav2=PageView|Litho|Formations&nav3=39

*Scroll to the bottom to see wells with available core photos

4.2.1 Bo Member

Age: latest Jurassic to Early Cretaceous (Late Volgian to Late Ryazanian, mainly occurring within the Lower Ryazanian)

Reference well: DK well BO-1, 8561-8434 ft. b. KB, 2576-2537m b. MSL

Reference section: DK well E-1, 9853-9771 ft. b. KB, 2966-2910m b. MSL

Lithology: black to dark grey-brown, laminated claystones, which are carbonaceous and slightly calcareous to non-calcareous. The total organic carbon content ranges from 3–8%, locally attaining values of more than 15%. The organic matter is mainly liptinitic. The Bo Member is a good to very good source rock, showing very high pyrolysis yields (10–100 kg HC/ton rock) and Hydrogen Index (HI) values in the range 200–600. In particular, the Bo Member is characterized by an abundance of 28,30 bisnorhopane (H28), a compound that is indicative of anoxic environments. Thin beds of dolomite may occur. In the Jeppe-1 core, the unit also includes thin sandstone–mudstone couplets up to 5 cm thick; log data suggest that thicker sandstone-rich intervals are also present in the member.

Deposition: low-energy, oxygen-deficient deep marine environment. The sandstone–mudstone couplets were deposited from dilute turbidity currents.

Log characteristics: high GR values, which are significantly higher than those of the underlying and overlying claystones of the Farsund Formation. The sonic velocity is low. The GR values may show significant variation within the member with decreasing-upwards trends, 3–5 m thick, separated by intervals with more consistently high values (e.g. Bo-1).

Boundaries: the lower and upper boundaries are placed at shifts to the significantly GR values of the Farsund Formation.

Distribution and thickness: The member is recognized widely in the Danish Central Graben, where this portion of the Farsund Formation is preserved. On structural highs, the upper part of the Farsund Formation is commonly truncated and the member may be absent or reduced in thickness. The thickness varies greatly from less than 10 m in the southern Salt Dome Province to more than 100 m in the western part of the Danish Central Graben, probably controlled by local factors such as structural position and sediment supply.

Reference: http://www.geus.dk/DK/publications/geol-survey-dk-gl-bull/Documents/nr1_p403-436.pdf

4.3 Hod Formation

Age: Late Cretaceous (Turonian to Campanian)

Reference well: UK well 29/25-1, 2225-2012m.

Danish sector reference sections: N/A

Lithology: hard, white to light grey, crypto- to microcrystalline limestones which may become argillaceous or chalky in places. White, light grey to light brown, soft to hard chalk facies may dominate the formation or alternate with limestones. The limestones may be pink or pale orange. Thin, silty, white, light grey to green or brown, and soft, grey to black, calcareous clay/shale laminae are occasionally present. Pyrite and glauconite may occur throughout the formation and the latter may be common in the lower part.

In the Danish and Norwegian sectors, the Hod Formation is subdivided into Lower, Middle and Upper units. The *Lower Hod* (Turonian) consists of laminated, burrowed chalk with a low clay content, and commonly includes laminated grainstone turbidites. Bioturbation increases upward where marl/limestone cycles become common. The *Middle Unit* (Turonian – Santonian) has a higher clay content and is cyclically bedded. The *Upper Unit* (Santonian – Campanian) is also cyclic bedded, but generally has a higher clay content.

Deposition: Open marine with deposition of cyclic pelagic carbonates (periodites) and distal turbidites.

Log characteristics: N/A

Boundaries: the lower boundary is usually marked by a distinct log break to a lower GR response and higher velocity from the Plenus Marl to the Hod Formation. The boundary may be less distinct when the Plenus Marl is more calcareous. The upper boundary towards the Tor Formation is generally marked by a change in GR readings to a more constant and slightly lower level, and also by higher velocity.

Distribution and thickness: The formation is 515 m thick in the type well, 213 m in UK well 29/25-1 and 107 m in Norwegian well 2/8-8.

Reference:
http://factpages.npd.no/factpages/default.aspx?culture=en&nav1=strat&nav2=PageView|Litho|Formations&nav3=66

Norwegian Fact Page*: http://factpages.npd.no/factpages/Default.aspx?culture=nb-no&nav1=strat&nav2=PageView|Litho|Formations&nav3=66

*Scroll to the bottom to see wells with available core photos

4.4 Tor Formation

Age: Late Cretaceous (Late Campanian to Maastrichtian)

Reference wells: UK well 22/1-2A, 3245-2982.5m; UK well 29/25-1, 2212-1869m; NO well 1/9-1, 3312-3104m.

Danish sector reference sections: N/A

Lithology: white to light grey, tan to pink, hard, chalky limestones. The formation is generally homogenous, or consists of alternating white, grey or beige, moderately hard to very hard, rarely soft, mudstones or wackestones, rarely packstones, chalks, chalky limestones or limestones. Occasional fine layers of soft grey-green or brown marl occur and also rare stringers of grey to green calcareous shales.

Deposition: Open marine with deposition of calcareous debris flows, turbidites and autochthonous periodites.

Log characteristics: N/A

Boundaries: The lower boundary is generally marked by an upward change to a more constant lower level of GR response, and also by higher velocity. The upper boundary is marked by the end of the more constant low GR response with a return to a higher and more irregular GR and a lower velocity in the overlying Ekofisk Formation. The upper boundary represents an unconformity with a submarine hardground, and a change of deposition to clay-rich chalks or minor shales.

Distribution and thickness:

Reference:
http://factpages.npd.no/factpages/default.aspx?culture=en&nav1=strat&nav2=PageView|Litho|Formations&nav3=171

Norwegian Fact Page*: http://factpages.npd.no/factpages/Default.aspx?culture=nb-no&nav1=strat&nav2=PageView|Litho|Formations&nav3=171

*Scroll to the bottom to see wells with available core photos

4.5 Ekofisk Formation

Age: Early Paleocene (Danian)

Reference wells: NO well 1/3-1, 3354-3258m; UK well 22/1-2A, 2982.5-2935m; NO well 2/5-1, 3132-3041m.

Danish sector reference sections:

Lithology: white, tan or beige, hard, dense, sometimes finely crystalline limestones, although softer chalky textures are also present. The formation usually consists of white to light grey, beige to brownish, mudstones or wackestones with occasional packstones/grainstones and pisolitic horizons, often alternating with argillaceous chalks, chalky limestones or limestones. Thin beds of grey, calcareous, often pyritic shales or clays are most common in the lower part while brownish-grey cherts occur rarely to abundantly throughout the formation.

Deposition: Open marine with deposition of calcareous debris flows, turbidites and autochthonous periodites.

Log characteristics: N/A

Boundaries: The lower boundary is marked by a change in GR readings from a constant low level in the Tor Formation to a slightly lower level. The velocity may or may not show a corresponding increase. The lower boundary separates the Cretaceous and Tertiary chalks and may represent an unconformity. The upper boundary is defined where the gamma-ray response increases and the velocity decreases towards the marly beds of the Våle Formation. Where the marl is not present the change is more abrupt.

Distribution and thickness:

Reference:
http://factpages.npd.no/factpages/default.aspx?culture=en&nav1=strat&nav2=PageView|Litho|Formations&nav3=33

Norwegian Fact Page*: http://factpages.npd.no/factpages/Default.aspx?culture=nb-no&nav1=strat&nav2=PageView|Litho|Formations&nav3=33

*Scroll to the bottom to see wells with available core photos

4.6 Våle Formation

Age: Mid Paleocene (Selandian)

Reference well: NO well 1/3-1, 3258–3209m MDKB.

Danish sector reference sections: DK well E-8, 2060.3–2057.0 m MDKB; Siri-1, 2186.5–2156.3 m MDKB

Lithology: light grey to greenish grey, heavily bioturbated pyrite-bearing marlstones. Thin sandstone intrusions are present locally. The marlstones comprise hemi-pelagic deposits and deposits from dilute turbidity currents. The marlstones are probably largely of turbiditic origin. The foraminifer fauna of the Våle Formation is characterized by common calcareous taxa. Taxa belonging to the neritic 'Midway-type' fauna are especially common. The plankton/benthos

Deposition: open marine, outer neritic environment that periodically reached upper bathyal depths. The bottom conditions were predominantly oxic with periods of dysoxia.

Log characteristics: from base to top, the formation is characterized by an overall steady increase in GR response, combined with an overall steady decrease in sonic readings. When the Bor Member sandstones are present, blocky log signatures with higher GR values and lower sonic readings interrupt this general trend.

Boundaries: in most wells in the Danish sector, the change from the chalks of the Chalk Group to the marlstones of the Våle Formation is gradational and the boundary can be difficult to position (Fig. 16). In the Siri Canyon, however, most wells show an erosional contact between the Chalk Group and the Våle Formation and the formation boundary is sharp. On petrophysical logs, the boundary is placed where the stable, low GR response characteristic of the Ekofisk Formation starts to increase upwards and the high sonic readings (also characteristic of the latter formation) start to decrease upwards. The change in the log pattern may be stepwise with each step represented by a small increase in GR values and an accompanying decrease in sonic readings. The Våle Formation is overlain by the Lista Formation.

Distribution and thickness: The formation and its equivalents are present throughout the North Sea Basin, except in a few areas where their absence is due to non-deposition or erosion. The Våle Formation is absent on intrabasinal highs and in parts of the Siri Canyon where the Rogaland Group overlies the Chalk Group with an erosional unconformity. Its thickness varies from 0 to 48 m in the Danish sector of the North Sea.

Reference: http://www.geus.dk/DK/publications/geol-survey-dk-gl-bull/12/Documents/nr12_p24-46.pdf

Norwegian Fact Page*: http://factpages.npd.no/factpages/Default.aspx?culture=nb-no&nav1=strat&nav2=PageView|Litho|Formations&nav3=190

*Scroll to the bottom to see wells with available core photos

4.7 Lista Formation

Age: Upper Paleocene (Selandian–Thanetian).

Reference well: NO well 2/7–1, 2917.5–2872.5m MDKB.

Danish sector reference sections: E-8, 2057.0–2027.6m MDKB; Cleo-1, 2812.0–2765.5m MDKB.

Lithology: dark colored, predominantly greyish, greenish or brownish, non-laminated to faintly laminated, non-calcareous mudstones. The Lista Formation is predominantly non-tuffaceous but becomes tuffaceous towards its top.

Deposition: the formation was probably deposited from very dilute turbidity currents and from suspension. The composition of the microfaunal assemblage indicates a relatively open marine depositional setting in upper to possibly middle bathyal depths with oxic to dysoxic bottom conditions. This is based on the presence of an impoverished agglutinated foraminifer assemblage dominated by tubular suspension feeders together with epifaunal and infaunal detritivores.

Log characteristics: although fluctuating, both the GR and sonic log readings in the Lista Formation have higher mean values than those of the underlying Våle Formation and lower mean values than those of the overlying Sele Formation. In wells where mudstone facies dominate in the Lista Formation, the GR and sonic log patterns can be subdivided into three. The tripartite log pattern reflects the succession of three different mudstone units, established as new members herein.

Boundaries: in most wells where the transition has been cored, the boundary is sharp between the light-colored marlstones of the Våle Formation and the dark-colored, non-calcareous mudstones of the lower Lista Formation. On the GR log, the boundary is picked at an abrupt upward shift to higher values than in the underlying Våle Formation. This level can typically be identified on the sonic log at a velocity minimum. Above this minimum, the sonic readings increase slightly upwards.

The Lista Formation is overlain by the Sele Formation. The base of the Sele Formation was defined by Deegan & Scull (1977 p. 34) at the contact between "non-laminated, non-tuffaceous shales" (Lista Formation) and "laminated tuffaceous shales" (Sele Formation). This boundary definition was followed by Mudge & Copestake (1992a, b). On the other hand, Knox & Holloway (1992 p. 46) followed O'Connor &Walker (1993) and placed the boundary somewhat lower, at the contact between "grey-green and green-grey, blocky, bioturbated claystones" of the Lista Formation and "dark grey fissile mudstones" of the Sele Formation. The boundary concept of Knox & Holloway implies that the "non-laminated, non-tuffaceous shales" of Deegan & Scull are incorporated in the Sele Formation where these, together with overlying laminated indisputable Sele mudstones, constitute the basal Sele unit S1a (Knox & Holloway 1992).

Distribution and thickness: the formation is present throughout the North Sea Basin, except in a few areas where it has been removed by erosion. In the Danish sector, its thickness varies from 0 to 108 m.

Reference: http://www.geus.dk/DK/publications/geol-survey-dk-gl-bull/12/Documents/nr12_p24-46.pdf

Norwegian Fact Page*: http://factpages.npd.no/factpages/Default.aspx?culture=nb-no&nav1=strat&nav2=PageView|Litho|Formations&nav3=95

*Scroll to the bottom to see wells with available core photos

4.8 Sele Formation

Age: Early Eocene (Sparnacian – early Ypresian)

Reference well: UK well 21/10-1, 2131–2100 m MDKB

Danish sector reference sections: Siri-1, 2072.6–2047.5 m MDKB; Tabita-1, 2958.8–2941.4 m MD- KB.

Lithology: medium to dark grey, brownish or black laminated mudstones. Thin tuff layers occur in the upper part of the formation. It contains three or more well-laminated intervals where dark mudstone beds alternate with lighter colored mudstone beds. The well-laminated intervals are enriched in organic material resulting in a high gamma-ray response. The most organic-rich, and often darkest, most well-laminated interval is found in the basal part of the formation. The mudstones show an overall upward increase in the silt fraction.

Deposition: the mudstones of the formation represent a mixture of pelagic fallout and dilute, low-density mud turbidites. The well-laminated character of the sediment, the high content of organic material and uranium, and the general lack of trace fossils and benthic foraminifers indicate starved sedimentation under dysoxic to anoxic bottom conditions. Common diatoms indicate a high nutrient level in the water mass. The tuffs of the Sele Formation are evidence of extensive volcanism in the region. The significant depauperation of the benthic microfaunas during the deposition of the Sele Formation was most likely caused by isolation of the North Sea Basin. The restriction and isolation of the basin was the result of a sea-level fall, possibly combined with (or caused by) tectonic uplift to the north-west.

Log characteristics: the formation is characterized by high GR readings throughout, with a number of GR peaks. On the GR log, the base of the formation is generally marked by a conspicuous upward shift to consistently higher GR readings than those of the underlying Bue Member of the Lista Formation. In most wells, a pronounced GR peak follows a short distance above the base of the Sele Formation:

Boundaries: the lower boundary is characterized by a change from the light to dark grey and greyish black mudstones with thin sandstone laminae of the Bue Member, to dark grey to black well-laminated mudstones without sandstone laminae of the Sele Formation. The upper boundary is at the base of the Balder Formation

Distribution and thickness: basinwide distribution. In the Danish sector, the thickness varies from 5 to 54 m.

Reference: http://www.geus.dk/DK/publications/geol-survey-dk-gl-bull/12/Documents/nr12_p46-57.pdf

Norwegian Fact Page*: http://factpages.npd.no/factpages/Default.aspx?culture=nb-no&nav1=strat&nav2=PageView|Litho|Formations&nav3=142

*Scroll to the bottom to see wells with available core photos

4.9 Balder Formation

Age: Early Eocene (Early Ypresian)

Reference well: NO well 25/11-1, 1780–1705 m MDKB.

Danish sector reference sections: Mona-1, 2945.0–2930.8 m MDKB; Siri-3, 2016.8–1998.8 m MDRT.

Lithology: laminated, dominantly grey, fissile shales with interbedded dark and light grey, purple, buff and green sandy tuffs. The tuffs are normally graded and less than 5 cm thick. Locally the tuff beds are slumped. The tuff layers may be cut by irregular, vertical, calcite-filled cracks up to 20 cm long (Fig. 45). Similar cracks have been reported from the Balder Formation in the Grane Field, Norwegian sector of the North Sea. Sandstone beds, interpreted as intrusive sandstone bodies, occur locally in the Balder Formation.

Deposition: restricted marine palaeoenvironment at upper bathyal depths with dysoxic to anoxic bottom conditions.

Log characteristics: the formation is characterized by a relatively high GR values in its lower and higher parts, but shows low values in its middle part. The change in GR response is normally gradual, but relatively steep. The GR motif is mirrored by a gradual increase in sonic readings commencing at the formation base, culminating at or slightly below the level of minimum GR values in the middle part of the formation, followed by a gradual decrease towards the top of the formation where the lowest sonic reading is reached. The gamma and sonic motifs together create a characteristic barrel-shaped log pattern.

Boundaries: In general, the boundary with the underlying Sele Formation is gradational, although it can be sharp in some wells. Where gradational, it is placed where the tuff layers become prominent. On petrophysical logs, the lower boundary is identified at a significant upward decrease in GR response accompanied by an increase in sonic readings. The upper boundary is at the base of the Horda Formation.

Distribution and thickness: the Balder formation extends over most of the central and northern North Sea. In the Danish sector, it reaches a thickness of more than 20 m in the Siri-3 and Frida-1 wells on the western part of the Ringkøbing–Fyn High and 20 m in Gwen-2 in the northern part of the Danish sector of the Central Graben. The Balder Formation thins to less than 5 m towards the south-west and to less than 10 m in the eastern part of the Danish sector of the North Sea. The Balder Formation is lacking in the Danish well S-1.

Reference: http://www.geus.dk/DK/publications/geol-survey-dk-gl-bull/12/Documents/nr12_p46-57.pdf

Norwegian Fact Page*: http://factpages.npd.no/factpages/Default.aspx?culture=nb-no&nav1=strat&nav2=PageView|Litho|Formations&nav3=6

*Scroll to the bottom to see wells with available core photos

4.10 Horda Formation

Age: Early Eocene to earliest Oligocene (middle Ypresian to earliest Rupelian)

Reference well: UK well 22/1-1A, 2379.5–1992m MDKB.

Danish sector reference sections: Mona-1, 2930.8–2363.5m MDKB; Siri-1, 2037.9–1916.5 m MDKB.

Lithology: greenish grey to greyish green fissile mudstone. Subordinate limestone benches and thin layers of black mudstones occur at some levels in the formation. In many wells, particularly in the Central Graben, the lowermost 20–50 m of the Horda Formation consists of red-brown mudstones.

Deposition: the lower part of the formation contains a microfauna that is significantly different from that of the underlying Balder Formation. The basal 5–40 m of the Horda Formation is characterized by a diverse fauna of both benthic and planktonic calcareous foraminifers together with agglutinated foraminifers. This indicates that the depositional setting was open marine, bathyal and with oxic bottom conditions. The upper part of the Horda Formation is characterized by an abundant and diverse agglutinated foraminifer fauna. Calcareous foraminifers are very sparse or absent in this interval. The upper part of the Horda Formation was deposited at upper bathyal depths with dysoxic bottom conditions.

Log characteristics: the formation is characterized by an overall stable GR and sonic log motif with a lower gamma-ray response than that displayed by the underlying Balder Formation and the overlying Lark Formation. In a few wells, the base of the Horda Formation shows relatively high GR values, which decrease to lower and more stable values over a short interval. The sonic readings decrease slightly upwards from the base to the top of the Horda Formation.

Boundaries: the base of the Horda Formation is placed at the change from the laminated, predominantly grey mudstones with interbedded sandy tuffs of the Balder Formation to the predominantly non-laminated, fissile, greenish grey or red-brown massive mudstones that form the basal part of the Horda Formation. The Balder–Horda boundary may be conformable or marked by a hiatus. The boundary is often difficult to pick on petrophysical logs. In basinal settings, Knox & Holloway (1992) advocated placing the lower boundary of the Horda Formation at the base of a marked GR peak believed to represent a glaucony-rich condensed layer in the basal part of the Horda Formation. However, in many sections in the Danish sector there are two or more gamma-ray peaks in the Balder–Horda boundary interval. As the glaucony-rich layer has not been identified with certainty in the few cores taken across the boundary in the Danish sector, it is not possible to identify the key GR peak unambiguously. Therefore, it is suggested that the lower boundary of the Horda Formation is placed on the basis of the sonic log where a gradual decrease in values in the upper part of the Balder Formation is succeeded by relatively stable, but somewhat lower readings in the Horda Formation. The upper boundary is at the base of the Lark Formation.

Distribution and thickness: the formation extends over the central and northern North Sea and is present in all wells in the Danish sector of the North Sea. The Horda Formation reaches a thickness of 906 m in the Central

Graben well Tordenskjold-1, but thins towards the east and south-east to less than 100 m, with minimum recorded thicknesses of 9 m in the Ida-1 well and 4 m in the S-1 well.

Reference: http://www.geus.dk/DK/publications/geol-survey-dk-gl-bull/12/Documents/nr12_p57-63.pdf

4.11 Lark Formation

Age: Late Eocene to Middle Miocene (Priabonian to Serravallian)

Reference well: UK well 21/10-4, 1867–1217m MDKB.

Danish sector reference sections: Mona-1, 2363.5–1598.3 m MDKB; Siri-1, 1916.5–819.3m MDKB.

Lithology: the lower Lark Formation (L1–3) is dominated by dark, greenish grey, non-fissile mudstones in most wells; in some wells subordinate intervals of brownish grey mudstones are also present. Thin layers of white or reddish brown carbonate are also recorded in the upper levels of the lower Lark Formation. The upper Lark Formation (L4) is dominated by pale to dark brownish grey mudstones with subordinate intervals of greenish grey mudstones in its lower levels. The uppermost 50–100 m of the formation consists of yellowish grey to light brown mudstones. In eastern and northern parts of the Danish sector, discrete sandstone interbeds and thin sandstone stringers occur throughout the formation.

Deposition: the L1 unit was predominantly deposited in an open marine, dysoxic palaeoenvironment at upper bathyal depths. The foraminifer assemblage in the L2- and most of the L3 units indicates an open marine, neritic to outer neritic setting with well-oxygenated bottom conditions for the lower to middle part of the Lark Formation. The microfossil assemblage in the uppermost part of the L3 unit as well as the L4 unit indicates oxic bottom conditions during this interval. In general, the microfaunal assemblage in this part of the formation suggests that it was deposited in a neritic, probably middle neritic, palaeoenvironment over most of the Danish area. The palynofacies assemblage in the Lark Formation is characterized by a rich dinoflagellate assemblage and abundant dispersed terrestrial matter, indicating an open marine environment with considerable influx from nearby land areas. Stratigraphic variations in the relative abundance of terrestrial palynomorphs suggest successive pulses of progradation and backstepping of the palaeocoastline.

Log characteristics: the lower part of the formation is characterized by an overall stable GR log signature, whereas the upper part of the formation has a more unstable signature. This change in GR log signature coincides approximately with the change from lithologies dominated by greenish grey mudstones to lithologies dominated by dark to light brownish grey mudstones at the base of unit L4.

Boundaries: the base of the formation is marked by a change from fissile, greenish grey mudstones of the Horda Formation to non-fissile, greenish grey mudstones of the Lark Formation. This change in lithology coincides with an abrupt increase in GR values to a consistently higher level than that displayed by the Horda Formation. Wells in the eastern part of the Danish Central Graben and on the Ringkøbing–Fyn High show a conspicuous log break on the GR log at the formation boundary, whereas the log break is less pronounced in wells from the central and western parts of the Danish Central Graben. On the sonic log, the boundary between the Horda Formation and the Lark Formation is characterized by a transition from a stable sonic signature to one characterized by numerous fluctuations. The Lark Formation is overlain by the undifferentiated Nordland Group of Deegan & Scull (1977). Over most of the area, the boundary seems conformable and is represented by a change from yellowish grey and light brown mudstones to medium to dark grey mudstones characterized by intervals with shell-hash and coarse-grained sands. This boundary is marked by a conspicuous GR peak at the base of a 20–40 m thick interval with elevated GR values in the lowermost Nordland Group. This interval is further characterized by a marked double peak on the gamma-ray log.

Distribution and thickness: the formation extends over the central and northern North Sea and is probably present in the entire Danish sector of the North Sea. Its depocentre is in the central and northern part of the Danish sector, along the eastern boundary of the Danish Central Graben, where it reaches a thickness of 1194 m in the Siri-3 well. The Lark Formation thins west to a thickness of 389 m in the Tordenskjold-1 well in the Central Graben, and east to a thickness of 240 m in the S-1 well on the Ringkøbing–Fyn High.

Reference: http://www.geus.dk/DK/publications/geol-survey-dk-gl-bull/12/Documents/nr12_p63-73.pdf

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