GEOLOGY OF DENMARK SURVEY BULLETIN 36 • 1998

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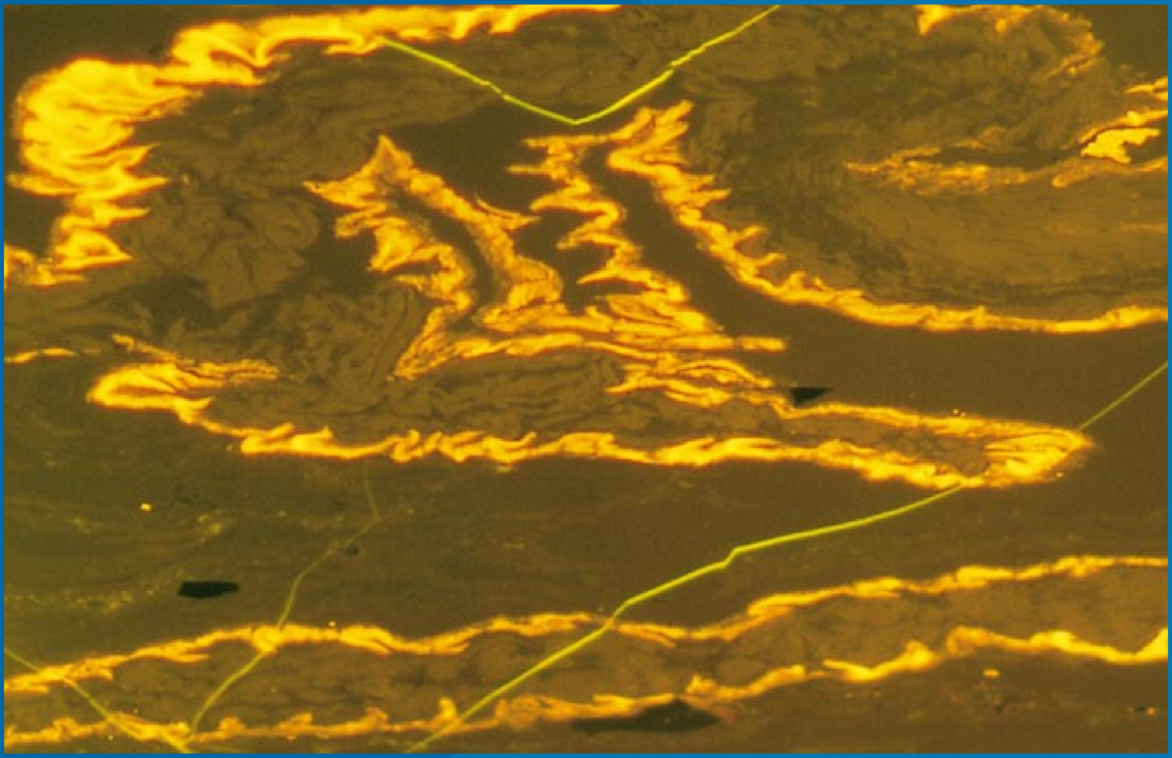

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

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Keywords
Organic petrography and geochemistry, facies, non-marine deposits, mire environments, organic maturity, source rock, petroleum, coal, kerogen, Danish Central Graben, Søgne Basin, Middle Jurassic.

Cover
Photomicrograph of yellowish-orange fluorescing folded cutinites derived from the outer layer of leaves (cuticle) in a groundmass of vitrinite. Sample 4473A, West Lulu-1 well, Middle Jurassic Bryne Formation, seam T3, 17.78–25.40 cm; reflected blue-light, water immersion. The section is *c.* 300 µm across.

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Contents

Abstract

Petersen, H.I., Andsbjerg, J., Bojesen-Koefoed, J.A., Nytoft, H.P. & Rosenberg, P. 1998: Petroleum potential and depositional environments of Middle Jurassic coals and non-marine deposits, Danish Central Graben, with special reference to the Søgne Basin. *Geology of Denmark Survey Bulletin* 36, 78 pp.

New data from five wells in the Søgne Basin, Danish Central Graben of the North Sea – West Lulu-1, West Lulu-3, Lulu-1, Amalie-1 and Cleo-1 – together with previously released data from the West Lulu-2 well, show that the cumulative thickness of the Bryne Formation coal seams decreases towards the palaeo-shoreline from 5.05 m to 0.60 m, and that the seams have varying extents. Their overall organic petrographic and geochemical composition reflects the palaeoenvironmental conditions in the precursor mires, in particular the rate of rise in the watertable, principally related to the relative rise in sea level, and the degree of marine influence. Laterally towards the palaeo-shoreline, all coal seams have increased proportions of C_{27} steranes and higher C_{35}-homohopane indices suggesting stronger marine influence on the coastal reaches of the ancient mires. In each well it is also observed that coal seams formed during accelerated relative sea-level rise (T-seams) are characterised by higher contents of sterane C_{27} and higher C_{35}-homohopane indices than seams formed during slower rates of base-level rise (R-seams). The most landward and freshwater-influenced parts of the seams have higher proportions of sterane C_{29} and the highest Pr/Ph ratios.

The coals, with respect to thermal maturity, are well within the oil window, except in the Amalie-1 well where they are more mature. The largest average hydrogen indices and thermally extracted and generated bitumen yields are obtained from the T-seams. However, generally an increase in the hydrogen index is recorded in a seaward direction for all seams. Multivariate regression analysis demonstrates that collotelinite, telinite, the vitrinite maceral group, vitrinite-rich microlithotypes and the TOC content have a significant positive influence on the remaining generative potential represented by S_2. Pyrolysis-gas chromatography reveals that during maturation the coals will generate from 72.4 to 82.0% oil-like components and only 18.0 to 27.6% gas. However, this does not necessarily imply that all of these oil-like components can be expelled to form a crude oil accumulation. Distribution of $C_{27–29}$ regular steranes shows good correlation between extracts of Bryne Formation coals and oils/condensates present in Bryne Formation sandstones.

The sum of evidence indicates that the coals in the Søgne Basin have generated and are still capable of generating liquid and gaseous petroleum, but with respect to petroleum generation potential, they are not as good as the documented oil-prone Middle Jurassic coals from North-East Greenland and Tertiary coals from Asia. Mudstones intercalated with the Bryne Formation coals have a similar or lower generative potential as the coals.

In areas outside the Søgne Basin, the coastal plain deposits of the Central Graben Group contain predominantly terrestrial-derived kerogen type III or IIb. The thermal maturity of the organic matter ranges from close to or within the peak oil generation range in the oil window (Alma-1x, Anne-3a and M-8 well) to the late oil window (Elly-3 and Falk-1 wells) or close to the end of the oil window (Skjold Flank-1 well). Only a limited generative potential remains in Elly-3, but the kerogen may initially have possessed a good petroleum potential. In the Falk-1 well, a good generative capacity still remains. The kerogen in Skjold Flank-1 may possess the capability to generate condensate and gas, whereas the organic matter in the Alma-1x, Anne-3a and M-8 wells generally exhibits a poor petroleum generative potential.

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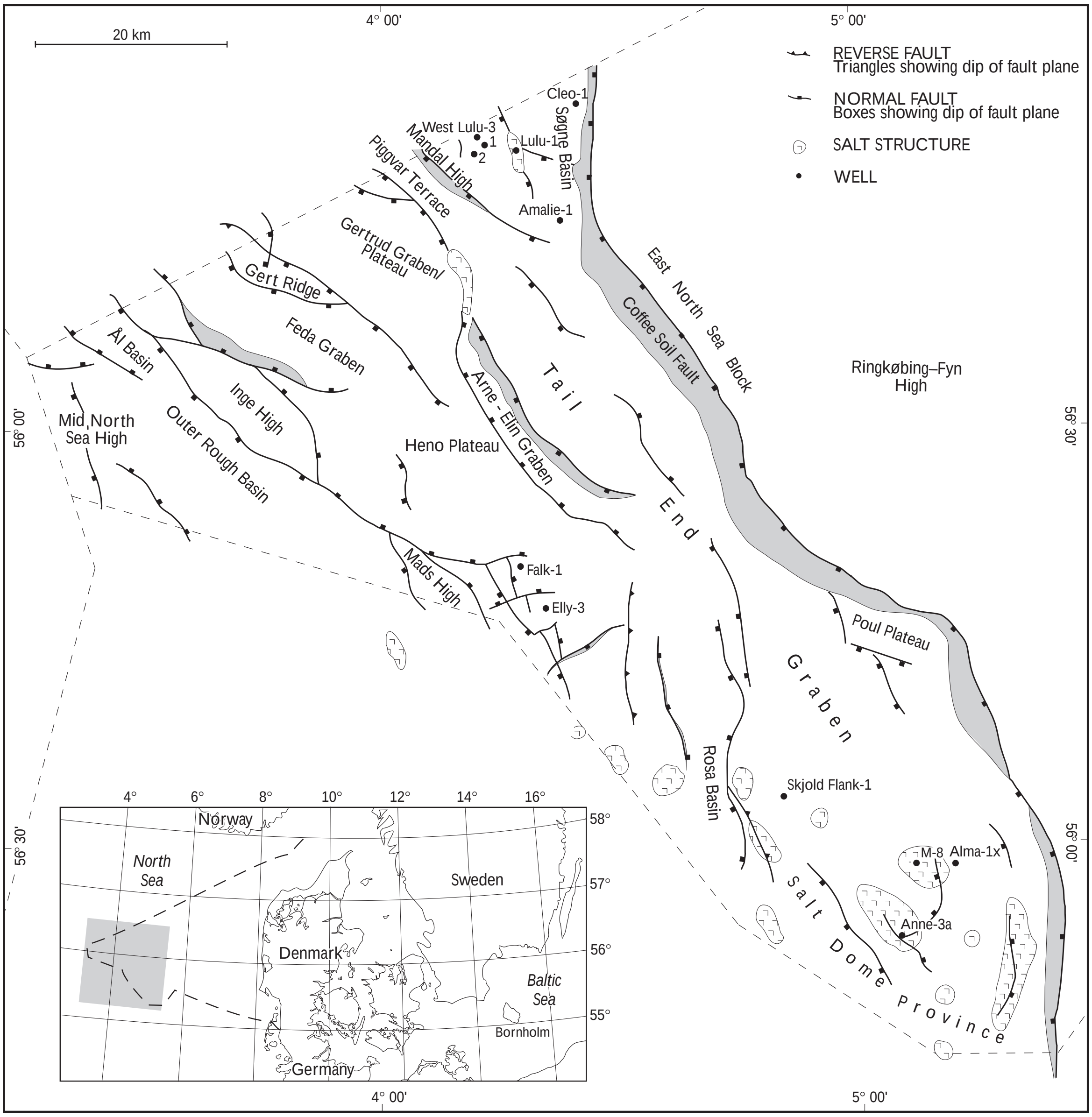

Fig. 1. Structural and location map of the Danish Central Graben showing the distribution of the wells investigated in this study and the West Lulu-2 well reported on by Pedersen & Andsbjerg (1996) and Petersen *et al.* (1996). The Harald Field is located in the north-western part of the Søgne Basin and includes the wells West Lulu-1, -2, -3 and Lulu-1. The dashed line on both main and inset maps outlines the Danish North Sea sector; for other national sectors of the North Sea, see Fig. 3. Modified from Andsbjerg (1997).

Introduction

Hydrocarbons in the Danish Central Graben of the North Sea mainly have their source in the Upper Jurassic marine shales and are primarily produced from Upper Cretaceous – Paleogene chalk reservoirs, but exploration efforts are increasingly directed towards Middle Jurassic sandstone reservoirs (Damtoft *et al.* 1992). One of the Middle Jurassic target areas has been the Søgne Basin in the northern part of the Danish Central Graben where the commercial Harald Field consists of two gas accumulations and minor reserves of oil and condensate (Fig. 1). Oil tests from the field show typical terrestrial geochemical signatures very similar to extracts from the coals in the Middle Jurassic Bryne Formation (Petersen *et al.* 1995, 1996). This could imply that the gas also had a terrestrial source. In addition, a test from the Elly-2 well, close to the Elly-3 well on the Heno Plateau (Fig. 1), revealed typical terrestrial signatures (Geological Survey of Denmark and Greenland – GEUS, unpublished data). These observations and the increasing evidence for petroleum generation from coals and non-marine strata (see p. 8) make the search for terrestrial source rocks in the Danish Central Graben an intriguing question. Terrestrial Middle Jurassic strata, in particular the coal-bearing Bryne Formation, are obvious possibilities.

The general objective of this study is to provide organic petrographic and geochemical data on the petroleum generative potential of Middle Jurassic terrestrial deposits in the Danish Central Graben. Emphasis is placed on the coals in the Bryne Formation in the Søgne Basin since these constitute a highly interesting source rock candidate, strongly supported by the evidence for terrestrially sourced petroleum in the Harald Field and the evidence for petroleum potential of the time-equivalent Brent Formation coals in the Norwegian part of the North Sea (Bertrand 1989; for the national sectors, see Fig. 3). A detailed interpretation of the depositional environments of the coal-bearing strata and the coal seams, including the areal extent and spatial distribution of the coals, are integrated into the present study. This is done in order to relate organic petrographic and geochemical variations in the coals to the precursor mire environments and to assess the influence of relative sea-level changes on coal composition, which may have direct impact on the petroleum generative potential. Outside the Søgne Basin, emphasis is likewise placed on non-marine Middle Jurassic strata dominated by terrestrially dominated kerogen.

To obtain a well-defined control on the depositional environment and the composition of the associated organic matter deposited in that environment, and accordingly the petroleum generative potential, sampling was preferentially confined to the Middle Jurassic well-cores. However, cuttings and sidewall cores from the Middle Jurassic interval have occasionally been included, in particular outside the Søgne Basin where limited coring of the Middle Jurassic interval may be a problem. From the wells M-8 and Anne-3a in the Salt Dome Province (Fig. 1) only cuttings have been investigated in this study.

The distribution of the investigated wells is shown on the main map in Figure 1. The Søgne Basin is represented by the West Lulu-1 and West Lulu-3 wells and the Lulu-1, Amalie-1 and Cleo-1 wells. Outside the Søgne Basin, the Heno Plateau is represented by the Falk-1 and Elly-3 wells, whereas the Salt Dome Province in the southern part of the Danish Central Graben is represented by the Skjold Flank-1, Alma-1x, M-8 and Anne-3a wells.

In addition, some data from the West Lulu-2 well taken from Petersen *et al.* (1996) are included in this presentation; this well is also shown in Figure 1.

Petroleum generation from coal and terrestrial kerogen

The role of coal and terrestrial kerogen as a source for commercial petroleum other than gas has been extensively discussed over the last few decades. The dismissal of coal and terrestrial organic matter as a good source rock has mainly been related to the supposed incapability of coal to generate oil and, if generated, to expel the oil. However, the well-documented demonstration of crude oil derived from non-marine coal-bearing strata strongly suggests that coals and non-marine successions are capable of producing commercial amounts of liquid petroleum (Table 1). In addition, other investigations have revealed Middle Jurassic highly oil-prone coals in Hochstetter Forland, North-East Greenland (Bojesen-Koefoed *et al.* 1996), the petroleum potential of Middle Jurassic coals in the Danish Central Graben, North Sea (Petersen *et al.* 1996), Upper Cretaceous oil-generating coals of the San Juan Basin, USA (Clayton *et al.* 1991), while oil shows on Nuussuaq, West Greenland, have several terrestrial organic geochemical characteristics pointing to a non-marine source rock (Christiansen *et al.* 1996). Thus, any objection against the capability of coals and non-marine strata dominated by terrestrial organic matter should be reconsidered on the basis of the available evidence. In the following some of the more important objections against coal and terrestrial kerogen as an important contributor to significant oil generation will be discussed in detail.

The classical grouping of terrestrial organic matter into kerogen types I, II, III and IV is based on H/C and O/C ratios ('van Kevelen diagram'; van Krevelen 1961). The petroleum generation capability is related to the hydrogen content of the organic matter, and kerogen type I is initially hydrogen-rich (H/C > 1.5) while type IV has the lowest H/C ratios (H/C < 0.6). In the 'van Krevelen diagram' the kerogen types I–IV generally plot in the fields of lacustrine alginite, higher land plant liptinite/marine organic matter, humic organic matter and inertinitic organic matter respectively. The entities of kerogen are thus similar to the macerals of coals (e.g. Mukhopadhyay *et al.* 1985; Hutton *et al.* 1994). Most kerogen and coals are heterogeneous and contain mixtures of the different types of organic matter and the bulk chemical analysis reflects the relative abundance of the constituents. Due to the typical dominance of humic organic material (vitrinite) in most coals these will commonly plot as kerogen type III (H/C = 0.6–0.9), although the coals may contain significant proportions of oil-prone hydrogen-rich components like alginite, resinite, cutinite and per-hydrous vitrinite. A similar problem arises during chemical kerogen-typing, where a mixture of two quite different kerogen types may mimic a third type

Table 1. Areas with petroleum generated from terrestrial rocks

Country Area/Basin	Age of source rock	References
China Turpan Basin	Early–Middle Jurassic	Huang *et al.* 1991
Australia Surat/Bowen Basin	Permian–Jurassic	Khorasani 1987; Murchison 1987
Australia Eromanga Basin	Jurassic–Cretaceous	Thomas 1982; Murchison 1987
USA Greater Green River Basin	Late Cretaceous	García-González *et al.* 1997
Australia Gippsland Basin	Late Cretaceous–Tertiary	Shibaoka *et al.* 1978; Shanmugam 1985
New Zealand Taranaki Basin	Tertiary	Johnston *et al.* 1991
Canada Beaufort–Mackenzie Basin	Tertiary	Snowdon 1980; Snowdon & Powell 1982; Issler & Snowdon 1990
Indonesia Ardjuna sub-basin & Mahakam Delta	Tertiary	Durand & Oudin 1979; Noble *et al.* 1991
Nigeria Niger Delta	Tertiary	Bustin 1988

(Murchison 1987; Hutton *et al.* 1994). Thus, although kerogen and coal may be composed of similar complex mixtures of precursor material, common opinion has regarded humic coals in general as gas-prone kerogen type III. This concensus and the presumed ability of coal to absorb generated liquid petroleum due to the small pore diameters and large pore volumes within coal are often considered to be the critical factors which prevent migration out of a coal bed (e.g. Hunt 1991). This may imply that hydrocarbons are only released when increased thermal maturation lead to cracking of liquid petroleum to gas (Radke *et al.* 1980a).

Snowdon (1991) suggested that generated hydrocarbons (HC/g TOC) should exceed a saturation threshold value before expulsion occurs, and further stated that type III organic matter within the oil window generally contains less than the critical 30–50 mg HC/g TOC. Based on a two-phase migration theory, Huc *et al.* (1986) suggested the contrary that hydrocarbon migration is favoured in coals when compared to adjacent shales. For instance, the Talang Akar delta plain coals, offshore north-west Java, Indonesia, were shown to effectively expel crude oil (Noble *et al.* 1991). These coals contain mainly oil-prone macerals, of which *c.* 70% react to form hydrocarbons in the temperature range of oil stability. Also, Stout (1994) reported that the migration of petroleum in coals is strongly dependent on maceral associations (microlithotypes), and the transmission of lithostatic pressure to the liquid petroleum in the coal may increase the release of oil (Bertrand 1989). In particular the alternation between relatively incompressible inertinite-rich microlithotypes and compressible microlithotypes may favour expulsion (Durand & Paratte 1983), and the natural fracture system of coals may be of importance for hydrocarbon flow (Close 1993). Most important is indication of a continuous evolution and destruction of the micropore system during organic matter maturation which eliminates the absorption capacity of the coal (Durand & Paratte 1983; Katz *et al.* 1991). For example, it is suggested from pyrolysis data from Middle Jurassic coals of North-East Greenland that part of the coals will be able to generate up to 50% liquid petroleum by weight during maturation (Bojesen-Koefoed *et al.* 1996), which will dramatically change the micropore system. Cook & Struckmeyer (1986) note that if coal seams absorb liquid petroleum, generated oil pool occurrences in coal-bearing strata should have a negative correlation with coal seam thickness; however, this does not appear to be the case. These authors further suggest that at low ranks (< 0.65 $\%R_{max}$) migration of liquid petroleum out of coal is an efficient process. This is important in relation to the different maturity levels during which different macerals, due to a wide range of activation energies, are effective petroleum generators (Fig. 2; e.g. Boreham & Powell 1993). Early, incipient petroleum generation from vitrinitic substances has been suggested by Cook & Struckmeyer (1986) and Liu & Taylor (1991), and Khorasani (1987) observed petroleum generation from suberinite and terpene resinite in the reflectance range $\%R_{max}$ = 0.34–0.45 and $\%R_{max}$ = 0.45–0.60 of the associated vitrinite, respectively. Similar low maturity levels for petroleum generation

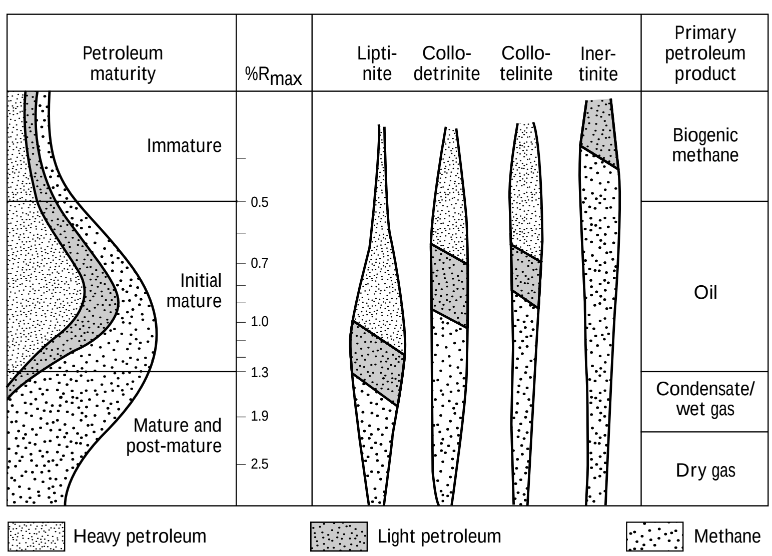

Fig. 2. The primary petroleum products derived from the liptinite and inertinite maceral groups and the macerals collodetrinite and collotelinite during maturation. Modified from Murchison (1987).

from resinite has been observed in the Beaufort–Mackenzie Basin (0.40–0.60 %R_o vitrinite), Canada (Snowdon & Powell 1982) and in the Gippsland Basin (0.50 %R_o vitrinite), Australia (Shanmugam 1985).

According to Hunt (1991) a potential coal source rock must exhibit Hydrogen Index (HI) values of 200 and H/C ratios greater than *c.* 0.9, and the coal should contain more than 15% liptinite. Both the HI and the H/C ratio are averages of a commonly heterogeneous maceral composition of the coal, and may mask the presence of a significant proportion of oil-prone components. This justifies detailed petrographic investigations of coals and kerogen. According to Bertrand (1989) the influence of the liptinite content on HI is only evident when it is over 10%, and the vitrinite macerals are regarded as an important source for petroleum. Likewise, a complex relationship between coal petrography and hydrocarbon generative potential, expressed as pyrolysis derived S_1+S_2, was found in a study on Middle Jurassic coals in the West Lulu-2 well in the Søgne Basin, Danish Central Graben (Petersen *et al.* 1996). The microlithotypes vitrite and clarite, the macerals telinite and collotelinite, the maceral group liptinite in general, and the TOC appeared to be favourable for high S_1+S_2 contents. Fluorescent vitrinite suggests that this may be partly related to liptinitic material incorporated into the vitrinite or the presence of per-hydrous vitrinite, i.e. the vitrinitic precursor material had an initial higher hydrogen content owing to deposition under anoxic conditions (e.g. Hunt 1991). A similar explanation was suggested by Bagge & Keeley (1994) in a study on the oil generating potential of Middle Jurassic coals in northern Egypt. They were not able to demonstrate a correlation between liptinite content and source rock potential, and suggested that hydrogen-rich vitrinites were partly responsible for the petroleum generative capacity. In a transmission electron microscope (TEM) study Liu & Taylor (1991) also concluded that type III kerogen associated with minor amounts of submicroscopic lipid-rich material may provide an excellent source rock independent of whether organic material occurs as coal or as dispersed coaly matter in sedimentary rocks.

Obviously high contents of microscopic visible liptinite macerals favour the petroleum generative potential, but the importance of the vitrinitic components, particularly the nature of the vitrinite, and submicroscopic lipid-rich material should not be underestimated. The oil generative potential of coal and dispersed organic matter in non-marine sediments thus depends on the depositional environment and the composition of the parent vegetation (e.g. Collinson *et al.* 1994).

Structural setting

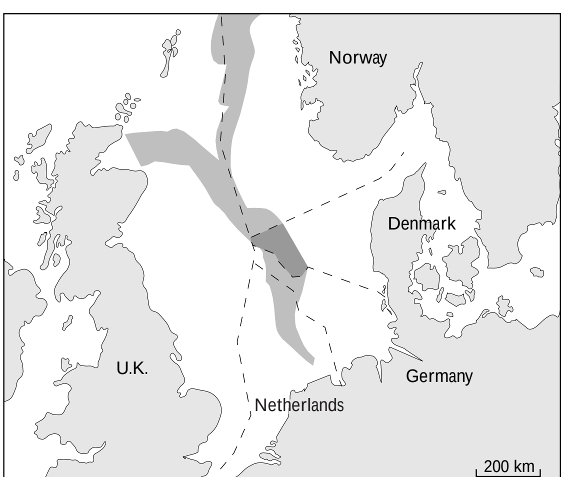

Fig. 3. Map showing the location of the Central Graben in the North Sea with, in darker shading, the Danish part. For details and structural elements see Fig. 1. The dashed lines outline the national sectors of the North Sea.

The Danish Central Graben is part of the Central Graben (Fig. 3), a complex N–S trending Mesozoic intracratonic rift basin. It was initiated in the Triassic and was most active during the Middle and Late Jurassic (Møller 1986). The Central Graben separates the Mid North Sea High to the west from the East North Sea Block of the Ringkøbing–Fyn High to the east in the Danish Sector (Fig. 1). The development of the Danish Central Graben was determined by differential subsidence of grabens and basins along N–S and NW–SE trending faults.

Subsidence of the Danish Central Graben started in the north-eastern part of the area, where the Søgne Basin and Tail End Graben (Fig. 1) began to subside as separate half-grabens during the Middle Jurassic (Gowers & Sæbøe 1985; Møller 1986). Initiation of rift-associated subsidence was probably related to domal uplift and subsequent dome collapse in the North Sea area (Ziegler 1982, 1990; Underhill & Partington 1993). Most authors (e.g. Gowers & Sæbøe 1985; Møller 1986; Cartwright 1991; Korstgård *et al*. 1993) agree that asymmetric subsidence was initiated in the Søgne Basin in connection with boundary fault activity during the Middle Jurassic. Middle Jurassic subsidence occurred mainly along N–S trending faults inherited from the pre-Jurassic, especially along segments of the Coffee Soil Fault (Fig. 1).

According to Mogensen *et al*. (1992) salt structures were generated in the Søgne Basin in the Triassic. Subsidence and faulting in Middle Jurassic times initiated the development of boundary fault salt pillows and up-dip salt structures in the southern Søgne Basin.

Middle Jurassic lithostratigraphy

A formal lithostratigraphy for the Middle Jurassic of the North Sea was published by Jensen *et al*. (1986). All Middle Jurassic deposits of the Søgne Basin in the north-eastern part of the Danish Central Graben are referred to as the Bryne Formation, which has previously been established in the Norwegian Central Graben by Vollset & Doré (1984). In the southern part of the Danish Central Graben, the Middle Jurassic deposits are referred to as the Central Graben Group of NAM & RGD (1980) (see Fig. 4).

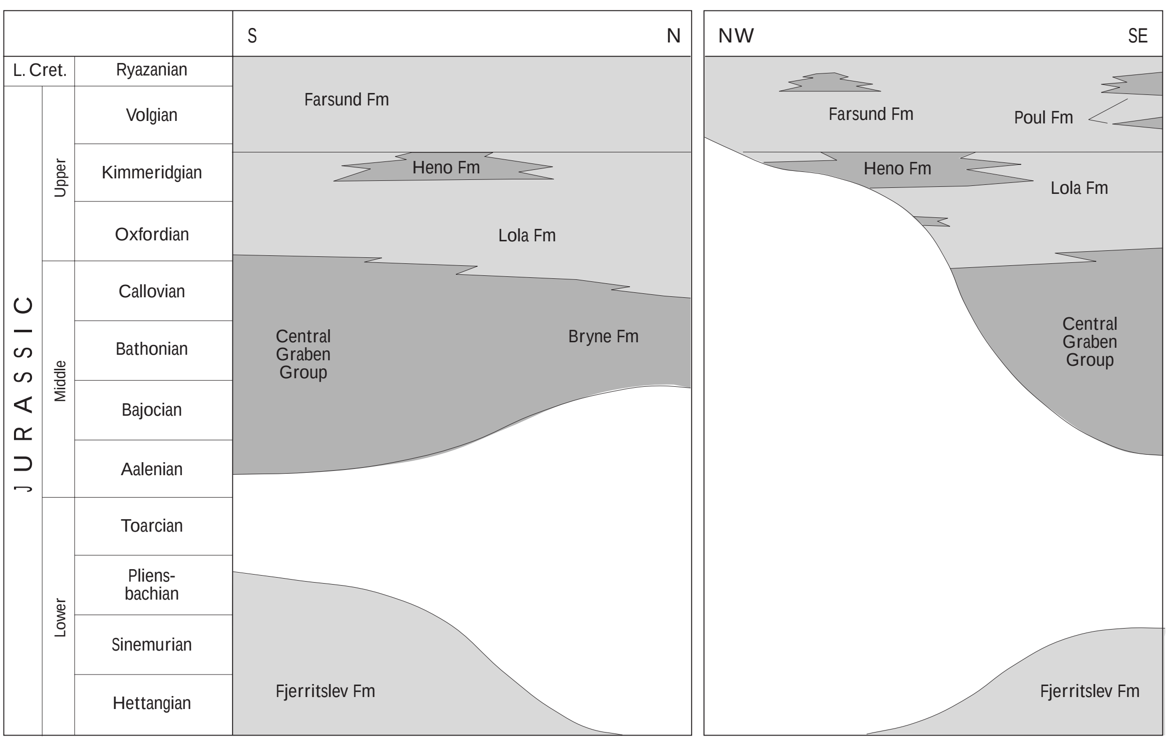

Fig. 4. The Jurassic lithostratigraphy of the Danish Central Graben showing the Middle Jurassic Central Graben Group and the Bryne Formation. From Andsbjerg (1997).

The Bryne Formation

Middle Jurassic sandstones with interbedded mudstones and coals were encountered by the first exploration well, Lulu-1, in the Danish part of the Søgne Basin (Fig. 1). Similar deposits encountered in the Norwegian part of the Central Graben were included in the Bryne Formation, and Jensen *et al*. (1986) extended the Bryne Formation to include the Middle Jurassic deposits of the northern part of the Danish Central Graben (Fig. 4).

In the Søgne Basin the Bryne Formation is separated from Triassic and Permian deposits by a major unconformity. The Bryne Formation is conformably overlain by marine mudstones of the Upper Jurassic Lola Formation (Jensen *et al*. 1986) and unconformably by Cretaceous deposits on structural highs. The Bryne Formation shows thicknesses from 130 to 300 metres in wells in the Danish part of the Søgne Basin. It wedges out on structural highs, but may possibly attain larger thicknesses in the deepest parts of the basin.

A detailed sedimentological analysis of cores from the Lulu-1 well was published by Frandsen (1986) who interpreted the sediments as deposits of a deltaic interdistributary bay overlain by coastal sediments. Middle Jurassic deposits further south in the Danish Central Graben had previously been interpreted as alluvial plain and delta plain deposits by Koch (1983). Damtoft *et al*. (1992) suggested a fluvial channel and floodplain environment for the Bryne Formation, whereas Johannessen & Andsbjerg (1993) interpreted the sediments as alluvial plain deposits overlain by tidal and shallow marine deposits.

The Central Graben Group

The Central Graben Goup was named by NAM & RGD (1980) with the Dutch Central Graben as the type area, and was extended to include the Salt Dome Province in the southern part of the Danish Central Graben by Jensen *et al*. (1986). In the Danish part of the Central Graben the Central Graben Group consists of the sand prone Lower Graben Sand Formation overlain by the mudstone dominated Middle Graben Shale Formation (Jensen *et al*. 1986; Fig. 4). The maximum drilled thickness of the Central Graben Group is 237 m (O-1 well), but more commonly the thickness ranges between 50 and 150 m.

The deposits of the Central Graben Group have been interpreted as alluvial plain sediments overlain by deposits of a delta plain dominated by swamps and interdistributary bays (Koch 1983; Jensen *et al*. 1986).

Biostratigraphic datings

The Middle Jurassic of the central and southern North Sea generally has a poor biostratigraphy. This is due to the predominance of non-marine facies, and to the large depth at which Middle Jurassic deposits are encountered in the Central Graben.

A major sequence boundary separates the Bryne Formation into a fluvial dominated lower part and an upper part composed of predominantly paralic and marginal marine deposits (Andsbjerg & Dybkjær 1997). In the uppermost part of the fluvial dominated succession the presence of the dinocyst *Adnatosphaeridium caulleryi* suggests an age not older than Bathonian. This evidence, in combination with Late Bathonian ages above the sequence boundary, indicate that sequence boundary incision took place during the Bathonian, probably during the later part of the Bathonian. The occurrence of *Scriniocassis* sp. in the lowermost part of the Bryne Formation indicates an age not younger than the Late Bajocian for that interval.

The upper part of the Bryne Formation is reasonably well dated in a few wells due to dinoflagellate cysts found in marine and estuarine deposits (Andsbjerg & Dybkjær 1997). Above the major sequence boundary the Bryne Formation seems to be of Late Bathonian to Late Callovian age. The occurrence of the dinoflagellate cysts *Cleistosphaeridium varispinosum* and *Nannoceratopsis gracilis* in incised valley-fill deposits right above the sequence boundary suggests that the valley fill ranges from Late Bathonian to earliest Callovian. The presence of *Dissilodinium willei* in the succession above the incised valley-fill deposits suggests a Middle Callovian age for that interval, and the occurrence of

Ctenidodinium continuum, *Liesbergia scarburghensis* and *Meiourogonyaulax* cf. *M. caytonensis* near the top of the Bryne Formation indicates a latest Callovian to earliest Oxfordian age.

In the southern part of the Danish Central Graben wells with deposits of the Central Graben Group are not as closely spaced as the wells with Bryne Formation sediments, and the Central Graben Group deposits exhibit fewer biostratigraphic datings. As is the case for the Bryne Formation, the lower part of the Central Graben Group succession yields poor biostratigraphic datings. A few good datings are supplied by age diagnostic spores. *Krauselisporites hyalina* in the upper part of the Lower Graben Sand Formation suggests a Bathonian age, and *Kekryphalospora distincta* lower in that formation indicates an age not younger than Early Bajocian. A few dinoflagellate cysts have been found in the Lower Graben Sand Formation. In the upper part of the formation the Late Bajocian – Early Callovian *Pareodynia evitii* has been found below an erosive channel base, which may correlate to the major sequence boundary separating the upper and lower parts of the Bryne Formation.

In the uppermost part of the succession, in the coal-bearing Middle Graben Shale Formation, *Chytroeisphaeridia hyalina* and *Ctenidodinium sellwoodii* indicate ages not younger than Mid and Late Callovian respectively; however, the presence of *Energlynia acollaris* and *Wanaea thyssanota* may indicate an age up to Early Oxfordian. *Pareodinia prolongata* and *Rigaudella aemula*, which may range up to the Middle Oxfordian, are also found within this succession.

Samples, analytical methods and data processing

Samples

The material in this study is mainly taken from drill-cores as this procedure enables a precise correlation between sample lithology, depositional environment and organic petrography and geochemistry of the sample. If considered necessary, other sample types (sidewall cores, cuttings, extracted cuttings) were included. All core samples are indicated on the sedimentological logs presented in this bulletin.

The coal seams in the well-cores in the Søgne Basin were sampled from floor to roof (channel samples) such that, if possible, the samples represent the total thickness of the seams and also cover macroscopically visible changes in coal layering (coal facies change). A few samples were likewise collected from coaly mudstones associated with the coal seams. In the Søgne Basin a total of 110 core samples were collected, viz. 44 from West Lulu-1, 29 from West Lulu-3, 18 from Lulu-1, 13 from Amalie-1 and 6 from Cleo-1. The 6 core samples from the Cleo-1 well were supplemented with 13 sidewall core samples, 18 cuttings and 5 extracted cuttings from the Middle Jurassic interval.

Outside the Søgne Basin samples were likewise preferentially taken from drill-cores. However, due to limited coring in the Middle Jurassic interval, cuttings were also used. Core samples were collected from levels in the cores with visible disseminated organic matter or from black mudstones presumed to be rich in organic material. A total of 105 samples have been investigated, viz. 10 core samples and 20 cuttings from Alma-1x, 11 cuttings from Anne-3a, 10 core samples from Elly-3, 12 core samples and 5 cuttings from Falk-1, 12 cuttings from M-8, and 10 core samples, 13 cuttings and 2 extracted cuttings from the Skjold Flank-1 well (Fig. 1).

Organic petrographic analyses

Particulate pellets suitable for optical analyses were prepared by crushing the samples to a grain size between 63 µm and 1 mm. Approximately 20 ml of a dried (24 hrs at 60°C) homogenised sample split was embedded in epoxy. Following hardening the sample was cut vertically into two pieces and the ‘new’ face was ground and polished using 1/4 µm diamond powder for the final polish to obtain a smooth surface. The preparation procedure thus takes into account the grain size and density induced separation during embedding in epoxy resin.