A REVIEW OF THE COALY SOURCE ROCKS AND GENERATED PETROLEUMS IN THE DANISH NORTH SEA: AN UNDEREXPLORED MIDDLE JURASSIC PETROLEUM SYSTEM?

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This paper reviews the Middle Jurassic petroleum system in the Danish Central Graben with a focus on source rock quality, fluid compositions and distributions, and the maturation and generation history. The North Sea including the Danish Central Graben is a mature oil province where the primary source rock is composed of Upper Jurassic – lowermost Cretaceous marine shales. Most of the shale-sourced structures have been drilled and, to accommodate continued value creation, additional exploration opportunities are increasingly considered in E&P strategies. Triassic and Jurassic sandstone plays charged from coaly Middle Jurassic source rocks have proven to be economically viable in the North Sea. In the Danish-Norwegian Søgne Basin, coal-derived gas/condensate is produced from the Harald and Trym fields and oil from the Lulita field; the giant Culzean gas-condensate field is under development in the UK Central North Sea; and in the Norwegian South Viking Graben, coal-derived gas and gas-condensate occur in several fields. The coaly source rock of the Middle Jurassic petroleum system in the greater North Sea is included in the Bryne/Lulu Formations (in Denmark), the Pentland Formation (in the UK), and the Sleipner and Hugin Formations in Norway. In the Danish Central Graben, the coal-bearing unit is composed of coals, coaly shales and carbonaceous shales, has a regional distribution and can be mapped seismically as the 'Coal Marker'. The coaly source rocks are primarily gas-prone but the coals have an average Hydrogen Index value of c. 280 mg HC/g TOC and values above 300 mg HC/g TOC are not uncommon, which underpins the coals' capacity to generate liquid hydrocarbons (condensate and oil). The coal-sourced liquids are differentiated from the common marine-sourced oils by characteristic biomarker and isotope compositions, and in the Danish Central Graben are grouped into specific oil families composed of coal-sourced oil and mixed oils with a significant coaly contribution. Similarly, the coal-sourced gases are recognized by a normally heavier isotope signature and a relatively high dryness coefficient compared to oil-associated gas derived from marine shales. The coal-derived and mixed coaly gases are likewise assigned to well-defined gas families. Coal-derived liquids and gas discoveries and shows in Middle Jurassic strata suggest that the coaly Middle Jurassic petroleum system has

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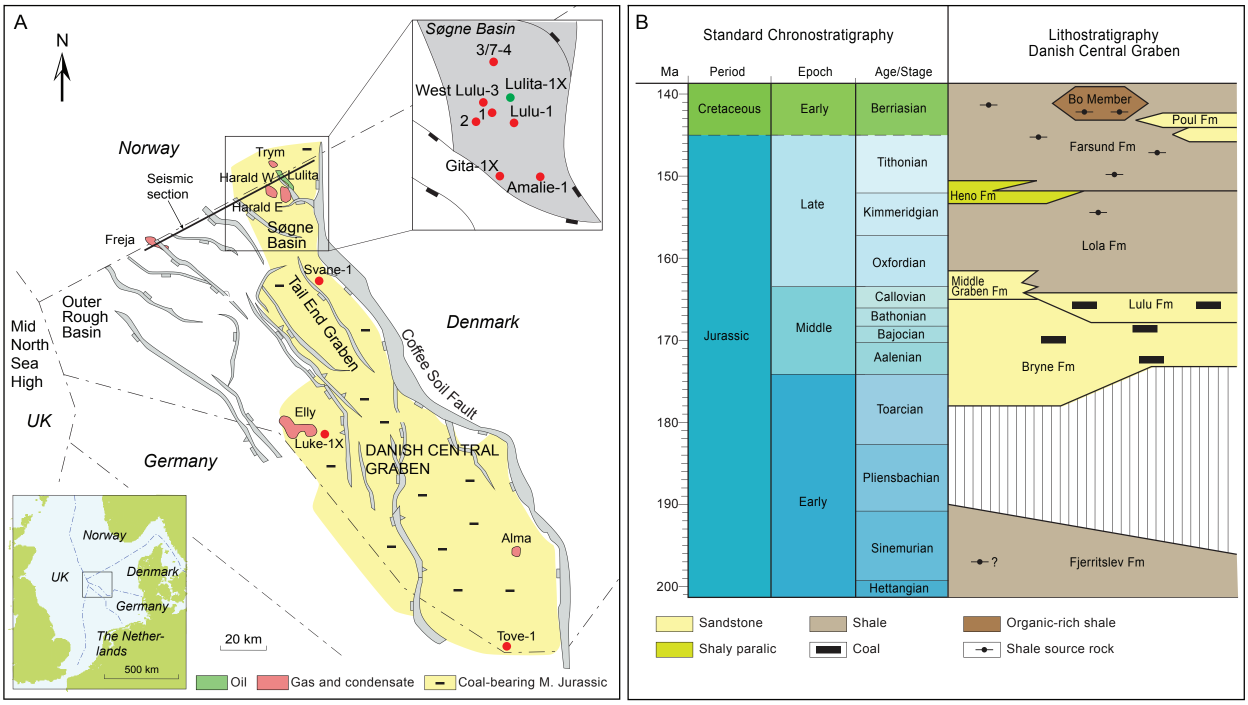

Fig. 1. (A) Map of the Danish Central Graben with fields and discoveries containing hydrocarbons generated by Middle Jurassic coaly source rocks. The regional extent of the Middle Jurassic coal-bearing strata is also displayed. The seismic section located close to the Danish-Norwegian North Sea border is shown in Fig. 7. (B) Stratigraphy of the Jurassic section in the Danish Central Graben. Middle Jurassic units are assigned to the Bryne, Lulu and Middle Graben Formations.

a regional distribution. A 3D petroleum systems model was constructed covering the Danish Central Graben. The model shows that present-day temperatures for the Middle Jurassic coal source rock ('Coal Marker') are relatively high (>150 °C) throughout most of the Danish Central Graben, and expulsion of hydrocarbons from the 'Coal Marker' was initiated in Late Jurassic time in the deep Tail End Graben. In the Cretaceous, the area of mature coaly source rocks expanded, and at present day nearly the whole area is mature. Hydrocarbon expulsion rates were low in the Paleocene to Late Oligocene, followed by significant expulsion in the Miocene up to the present day. High Middle Jurassic reservoir temperatures prevent biodegradation.

INTRODUCTION

The primary source rocks in the North Sea are the Upper Jurassic – lowermost Cretaceous marine shales of the Farsund, Mandal and Kimmeridge Clay Formations and equivalents (Damtoft *et al.*, 1992; Cornford, 1998; Ineson *et al.*, 2003; Justwan *et al.*, 2005; Petersen *et al.*, 2010, 2016, 2017). In the Danish Central Graben, these world-class source rocks have charged the major chalk fields which account for the vast majority of the daily production of approximately 150,000 brl of oil and 3.9 billion Sm^3 (c. 71,000 brl oil-equivalent) of gas (Danish Energy Agency, 2016).

However, in addition to the prolific marine-shale charged chalk play, the Danish Central Graben also contains a commercial Middle Jurassic coaly-sourced sandstone play in the southernmost part of the Danish-Norwegian Søgne Basin (Fig. 1a). In a mature oil province such as the North Sea, the recognition of another efficient petroleum system is intriguing as it may suggest additional or even overlooked exploration potential. The play relies on Middle Jurassic coaly source rocks charging Middle Jurassic fluvial and shoreface sandstone reservoirs associated with coal beds and coaly shales. In the Danish Søgne Basin, production of gas and condensate occur from the Harald field whereas the Lulita field produces waxy crude oil and gas. In addition, gas and condensate is produced from the Norwegian Trym field located immediately north of Lulita (Fig. 1a).

Biomarker and stable carbon isotope data have correlated the oils/condensates to the coaly strata of the Middle Jurassic Bryne and Lulu Formations (Lulu/Bryne-Lulu(!) Petroleum System) (Fig. 1b) (Petersen *et al.*, 1996, 1998, 2000, 2011, 2016; Petersen and Brekke, 2001; Odden, 1999; Carr and Petersen, 2004). In contrast to the oils generated from the marine shales, these coaly sourced hydrocarbons are recognised by a typical terrigenous geochemical composition such as Pr/Ph ratios generally >3, sterane C_{27} /C_{29} ratios around unity or less, waxy *n*-alkane distributions, and relatively heavy stable carbon isotopes. Compared to the widespread gas accumulations sourced from coaly Upper Carboniferous units in the Southern North Sea (Gautier, 2003), the coaly-sourced Middle Jurassic

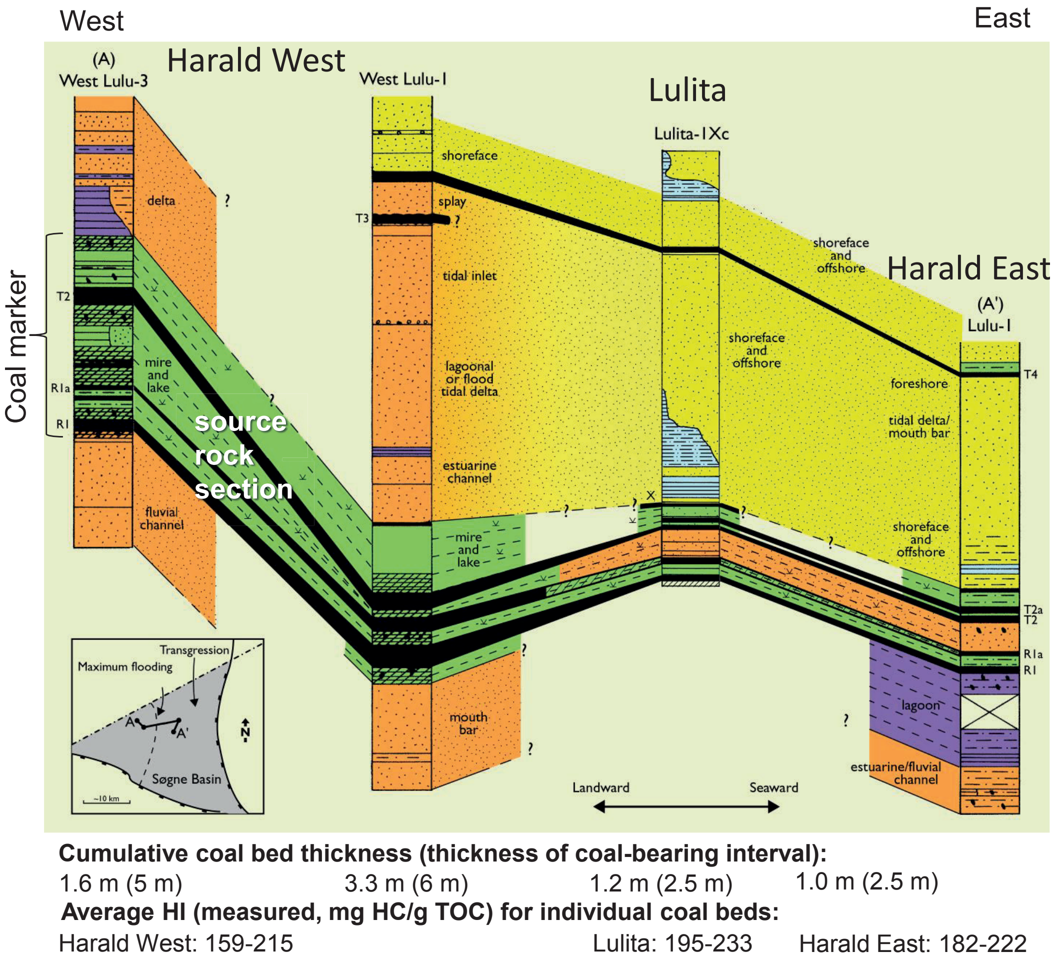

Fig. 2. Correlation (not to scale) of coal beds in the 'Coal Marker' horizon from west to east in the Søgne Basin (modified from Petersen *et al.*, 2000). Individual coal bed and cumulative coal bed thicknesses decrease towards the palaeo-shoreline to the east due to more frequent flooding/drowning of the precursor mires.

petroleum system in the Danish Central Graben has so far only been proven to be commercial in the Søgne Basin. However, recent evaluation of oil, gas and shows data indicate the regional presence of the petroleum system in the Danish Central Graben. This includes several discoveries in Middle and Upper Jurassic sandstone reservoirs: Alma, Amalie, Elly and Svane (Fig. 1a).

From a wider-scale North Sea perspective, the coaly-sourced Middle Jurassic petroleum system is not limited to the Danish Central Graben. For example, the Middle Jurassic Pentland coals are the primary source for the Culzean high pressure – high temperature (HPHT) lean gas condensate field in the UK Central North Sea; Culzean has estimated recoverable reserves of around 250 million barrels of oil-equivalent (MMboe) in the Triassic Joanne and the Middle Jurassic Pentland sandstone reservoirs (Mouritzen *et al.*, 2017). The field will have an expected plateau production of 60,000–90,000 MMboe/day. In the Norwegian North Sea the Middle Jurassic Sleipner and Hugin coals have generated the gas and gas condensate in the Loke, Sleipner Øst and Gungne fields in the South Viking Graben (Isaksen *et al.*, 2002). The Middle Jurassic coaly source rock can thus be linked to Triassic, Middle Jurassic and Upper Jurassic plays in the greater North Sea area. The Triassic play requires juxtaposition of the sandstone reservoirs with the Middle Jurassic coaly source rocks, or downward expulsion when the Middle Jurassic rests directly on the Triassic to allow hydrocarbon charging.

The present paper reviews the current knowledge of the Lulu/Bryne-Lulu(!) Petroleum System in the Danish Central Graben in light of the most recent understanding of source rock quality, fluid composition and occurrence, and maturation and generation modelling.

GEOLOGICAL SETTING AND MIDDLE JURASSIC COAL-BEARING DEPOSITS

The Danish Central Graben forms part of the ~500 km long Central Graben that constitutes the southern part of the Jurassic North Sea rift complex, and consists of a system of NW–SE trending half-grabens (Fig. 1a). The Danish Central Graben is bounded by the Coffee

Soil Fault to the east and by the Mid North Sea High to the west. Jurassic rifting was initiated in the east in Bajocian time where the Søgne Basin and Tail End Graben started to subside as separate ENE-dipping half-grabens due to activity along the Coffee Soil Fault (Møller, 1986; Andsbjerg and Dybkjær, 2003; Japsen *et al*., 2003; Møller and Rasmussen, 2003). Deposition gradually shifted westwards when grabens to the west began to subside in Late Callovian and latest Oxfordian times. An unconformity separates the Middle Jurassic succession from underlying Triassic and Permian sediments, whereas the immediate overburden consists of Upper Jurassic marine mudstones or Cretaceous deposits. The original half-graben structure with a thickened Jurassic sediment fill in the central to eastern parts of the basin was later partially disturbed by salt movements and a pronounced Cenozoic sag phase.

The Middle Jurassic succession is best described in the Søgne Basin. Here, fluvial sandstones dominate the lower part, while the upper part consists of a paralic interval of sandstones, shales and coal beds overlain by shoreface and back-barrier deposits (Petersen and Andsbjerg, 1996; Petersen *et al*., 1998; Andsbjerg, 2003). The sediment package is 130–300 m thick in the Søgne Basin. The fluvial-dominated lower part is assigned to the Bryne Formation and the paralic and marginally marine upper part to the Lulu Formation (Michelsen *et al*., 2003). The Lulu Formation contains up to at least nine separate coal beds that have been correlated in the Harald-Lulita-Trym area (Fig. 2) (Petersen *et al*., 2000). Coal thickness and lateral variations are common in coal-bearing strata due to coal bed amalgamations and splits, and in the Harald-Lulita-Trym fields the coal beds vary in thickness from <0.1 m to >1 m (Petersen and Brekke, 2001). A cumulative coal bed thickness of up to ~5 m occurs in the Harald field, which was located landward of the palaeo-shoreline. In the central to southern part of the Danish Central Graben, the coal-bearing Middle Jurassic strata are referred to as the Middle Graben Formation (Michelsen *et al*., 2003) (Fig. 1b). In the Danish Central Graben, the coal-bearing unit is seismically mapped as the 'Coal Marker' horizon and the regional distribution is further underpinned by well penetrations. The composite log of the Gita-1X well (location in Fig. 1a) shows that the Bryne and Lulu Formations contain c. 12 coal beds, and the 'Coal Marker' interval is an approximately 12 m thick coal-bearing unit composed of coaly shale and 4–5 coal beds with a maximum coal bed thickness of ~3 m. The Middle Graben Formation contains carbonaceous shales and a thin coaly bed in the Elly-3 well (Elly discovery), and in the Falk-1 well immediately to the north of Elly it includes two >1 m thick intervals of dark coaly shales each with a thin coal bed (Petersen *et al*., 1998). Both wells are located in the western central part of the Danish Central Graben (Fig. 1a). In the SE part, c. 4 coal beds and coaly shales were penetrated in the Alma-1X and Alma-2X wells of the Alma field (Fig. 1a).

The precursor peats in the Søgne Basin accumulated in coastal plain mires and were largely controlled by rises in water table caused by rises in relative sea-level (Petersen and Andsbjerg, 1996). Variations in the rate of rise in relative sea-level affected the stability of a high-standing water table and the marine influence during peat formation. In general, coastal parts of the peat mires were subjected to prolonged and continuous waterlogging, while more landward areas were prone to more subtle water-table fluctuations, occasionally associated with slight doming of the peat surface resulting in prolonged peat accumulation and thus thicker coal beds. The more frequent exposure of the coastal reaches of the mires to marine influence/flooding is recorded by the biomarker composition of coal extracts showing increased proportions of C_{27} steranes and even the presence of C_{30} steranes (Petersen *et al*., 1998). The coal beds belong to transgressive system tracts, and in accordance with this depositional setting, interbedded shoreface and offshore deposits are more common towards the palaeo-coastline. The entire Middle Jurassic succession records a backward-stepping sedimentary package, with an overall upward increase in marine influence ending with marine transgression during the early Late Jurassic and deposition of marine mudstones (Petersen *et al*., 2011).

SOURCE ROCK QUALITY

The source rock quality of the coals and coaly shales of the Bryne and Lulu Formations is relatively well understood from the Harald-Lulita-Trym area, where the coal-bearing units have been cored and the coal beds sampled and analysed in detail both geochemically and petrographically (Petersen *et al*., 1996, 1998, 2000, 2011; Petersen and Brekke, 2001).

In general, the coal macerals are dominated by vitrinite, varying amounts of inertinite and minor amounts of liptinite, but the peat-forming conditions had an impact on the organic geochemical and petrographic coal composition and thus to some extent the source rock potential (Petersen *et al*., 1996; Petersen and Brekke, 2001). Coastal parts of coal beds may have a higher generation potential than the more landward parts, in particular where coals grade into more sapropelic cannel and boghead coals and shaly lacustrine facies. In the Lulu Formation, the marine-influenced coal beds (T-seams *sensu* Petersen and Andsbjerg, 1996) comprise slightly better source rocks compared to coal beds less influenced by marine waters (R-seams) (Fig. 2). This is partly explained by the formation of so-called per-hydrous vitrinite

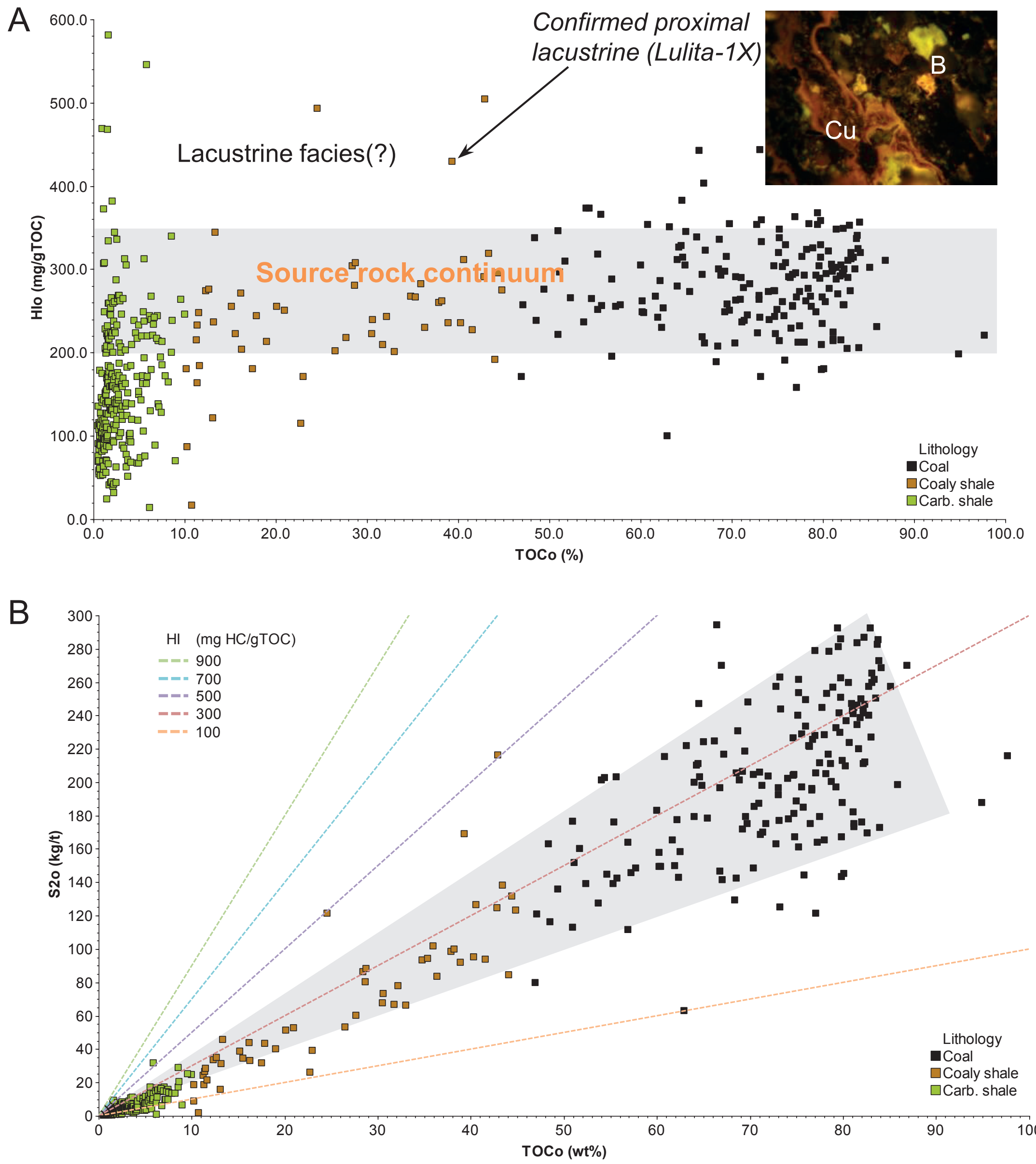

Fig. 3. Plots of original (back-calculated) source rock values. (A) HIo versus TOCo and (B) S2o versus TOCo. The samples are lithologically grouped into coal, coaly shale and carbonaceous shale. The coals and coaly shales and a considerable part of the carbonaceous shales form a "source rock continuum", showing that the rocks contain the same coaly organic matter and have similar source rock quality. The source rock potential varies from gas- to condensate/oil-prone. Photomicrograph (oil immersion, fluorescing-inducing blue light) in (A) shows orange- and yellow-fluorescing cutinite (Cu) and *Botryococcus*-type alginite (B) in proximal lacustrine mudstone from the Lulita-1X well.

which is hydrogen-enriched and has a higher content of aliphatic compounds (Petersen and Rosenberg, 1998; Sykes, 2001). However, this difference in coal bed quality is probably compensated for by variations in the source rock quality of the entire coal-bearing succession (see below: Ultimate Expulsion Potential). The most significant impact on source rock quality is caused by the presence of sapropelic lacustrine facies. Cannel and boghead coals have yet not been identified in the coal-bearing Bryne and Lulu Formations, but lacustrine facies have (*see below*). The complex vitrinite-dominated maceral composition of humic coals and coaly mudstones results in a complex three-phase generation and expulsion process consisting of onset of petroleum generation, petroleum build-up in the coal matrix, and finally initial oil expulsion followed by efficient expulsion within the "effective oil window" (Petersen, 2006). For a global set of Jurassic humic coals, the "effective oil window" ranges from ~0.85–0.95%R_o to ~1.7–1.9%R_o, the onset, range and hydrocarbon phase depending on the source rock quality of the coals (Petersen, 2002, 2006).

The measured source rock properties of the coals and coaly shales (Hydrogen Index, HI, mg HC/g TOC; Total Organic Carbon, TOC, wt%) represent present-day values. These values may be reduced as a result of thermal maturation and hydrocarbon generation. Although most wells in the study area that penetrate

Middle Jurassic strata were drilled on structural highs outside the deeper parts of the basins, the coaly source rocks are still affected by maturation to a varying degree. Significantly matured coals, for instance, occur in the Luke-1X and Amalie-1 wells where the coal beds are buried to depths of c. 4400 m and 5070 m, respectively. Thus, in order to determine the intial petroleum generation potential, back-calculation of the measured values to original values (HIo, TOCo, S2o) is required.

An in-house study established the relationship between the transformation ratio, *f*, and maturity using Rock-Eval T_{max} for Type III kerogen based on the transformation algorithms in Banerjee *et al*. (1998). Measured present-day T_{max} values were paired with an *f* value based on calculated (T_{max}, *f*) pairs and T_{max} *versus f* curves. The *f* value is used for back-calculation to original source rock properties (TOCo, S2o, HIo). This is a pragmatic solution, and we acknowledge that the method may be a simplification that does not capture all the complexity in source rock properties and maturation of coals, in particular the recognized initial increase in generation potential (HI) to a maximum HI (HI_{max}) during the early maturation stage (Sykes and Snowdon, 2002; Petersen, 2006). A total of 497 samples from the Bryne and Lulu Formations were subdivided into coals (>45wt% TOC), coaly shales (10–45wt% TOC) and carbonaceous shales (<10wt% TOC) and back-calculated to original values (Fig. 3). The samples constitute a so-called 'source rock continuum' and plot approximately around the 300 HI-line in the S2o *versus* TOCo diagram. The source rock continuum indicates the presence of the same kerogen type in the source rocks, which is concentrated in the coals and diluted by clay in the shales. It should be noted that of the carbonaceous shale samples, 25% have very poor to no generation potential (Fig. 3). This is likely because these shales were deposited in settings including those which are more prone to dilution and oxidation of organic matter, such as flood plains. However, the vast majority of the coal samples (83%) and the coaly shale samples (75%) have HIo values from 200 to 350 mg HC/g TOC (Fig. 3). About 47% of the coals have HIo >300 mg HC/g TOC, and 11% are mainly oil-prone with HIo >350 mg HC/g TOC (Fig. 3). The HIo range demonstrates that, in contrast to the Carboniferous coals that act as a gas source rock in the southern North Sea, NW Germany and the Netherlands, the Middle Jurassic coals are gas-prone but in addition possess the capacity to generate liquids (condensate and oil).

The organofacies (*sensu* Pepper and Corvi, 1995a) of the coals is therefore more type D/E than the gassy type F which corresponds more closely to gas-prone Palaeozoic coals. It is also evident that several samples have HIo values greater than 350 mg HC/g TOC, which is probably associated with more lacustrine facies containing oil-prone fresh-water alginite (*Botryococcus*-type) such as the thin proximal coaly lacustrine facies documented in the Lulita-1X well (Petersen *et al*., 2000) (Fig. 3). The presence of similar shaly lacustrine facies is indicated by high HI values in wells in the Norwegian part of the Søgne Basin, including the 3/7-4 well (Trym field; Fig. 1a) (Petersen *et al*., 2011). This suggests that the Middle Jurassic coal facies may grade into lacustrine facies, significantly improving the generation potential. This is further substantiated by wells in the northernmost part of the Søgne Basin in the Norwegian North Sea sector which have penetrated highly oil-prone lacustrine shale units 11 m and 20 m thick, with HI values (not back-calculated) ranging from 470–770 mg HC/g TOC and 302–664 mg HC/g TOC (Petersen *et al*., 2011).

Despite its ability to generate liquids, the coaly organic matter is primarily gas prone. This can be shown in a more quantitative way by estimating the sourced fluid phases (oil and gas) of the coaly source rock successions by calculating the Ultimate Expulsion Potential (UEP; MMboe/km^2). The UEP estimates the ultimate expellable volume of hydrocarbons in million barrels of oil-equivalents (MMboe) per km^2 if the source rock section passed through the petroleum generation window. The Pepper and Corvi (1995b) expulsion scheme was used for UEP calculation. The UEPs for the West Lulu-2 (Harald West field; section split into 87 intervals with back-calculated TOC/Rock-Eval data) and Lulita-1X (Lulita field; section split into 75 sub-intervals with back-calculated TOC/Rock-Eval data) wells calculated by applying the kinetics of Organofacies D/E (terrigenous; c.f. Pepper and Corvi, 1995a) and the back-calculated TOCo and HIo values are shown in Fig. 4. Organofacies F (coal) is not used, as these kinetics will only yield gas and are therefore not representative for the Middle Jurassic coals.

The total UEP of the ~147 m thick section in West Lulu-2 is ~35 MM boe/km^2, and that for the ~242 m thick section in Lulita-1X is ~69 MM boe/km^2. This is the whole Middle Jurassic section, including the 'Coal Marker', which is the best source rock interval with liquid source potential. The remainder of the Middle Jurassic section primarily contributes with gas. For modelling, only the 'Coal Marker' interval is considered as source rock (see below). The average HIo of the coal beds only is almost the same for the two wells (309 and 313 mg HC/g TOC), but the Lulita-1X well seems to contain more oil-prone kerogen in the upper part (Fig. 4). The overall higher UEP for the Lulita-1X well is caused by the greater thickness of the section. The Ultimate Expellable Oil (UEO) is ~16 MM boe/km^2 and ~10 MM boe/km^2 for the Lulita-1X and West Lulu-2 wells, respectively, and the Ultimate Expellable Gas (UEG) is ~53 MMboe/km^2 and ~26

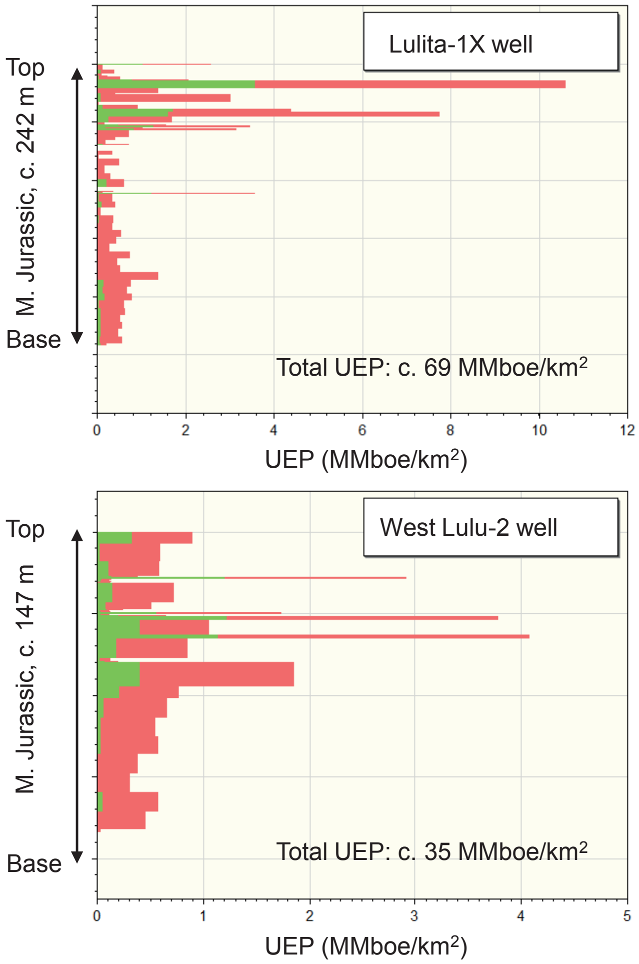

Fig. 4. Ultimate Expulsion Potential (UEP) strip logs of the Lulita-1X and West Lulu-2 wells from the Søgne Basin (red: gas; green: oil) based on original source-rock properties. The higher UEP for Lulita-1X is partly caused by the greater thickness of the unit by almost 100 m, but the section also contains intervals in the upper section that are more oil-prone (note the different scales on the UEP axes).

MM boe/km^2 (Fig. 4). Both wells demonstrate the capacity to generate liquids although the primary phase is gas. The liquid potential is much less than the world-class marine shales of the Upper Jurassic – lowermost Cretaceous Farsund Formation, but identifies the coal-bearing Bryne/Lulu strata as the most important secondary source rock in the Danish Central Graben. As an example, the total UEP of the about 850 m thick shale section of the Farsund Formation in the Jude-1 well located in the central part of the Danish Central Graben is ~142 MM boe/km^2, and the UEO and UEG are ~78 MM boe/km^2 and ~63 MM boe/km^2 respectively (Petersen *et al*., 2017).

COMPOSITION AND OCCURRENCE OF COALY HYDROCARBONS

Oil

A comprehensive and detailed classification of oil types (oil family typing) in the Danish Central Graben based on evaluation of organofacies-specific biomarkers, stable carbon isotopes and principal component analysis (PCA) was recently published by Petersen *et al*. (2016). In summary, the Danish Central Graben contains several oil families of which the majority can be typed to different facies of the marine shales of the Farsund Formation. However, the purely coaly-sourced oils (oil family 6D/E-F) typed to the Middle Jurassic coaly source rocks can easily be differentiated from the marine oils by a number of diagnostic geochemical characteristics (Fig. 5; Table 1):

(i) The Pr/Ph ratio is generally high with an average of 3.5, which is consistent with the values for coals which are typically >3 (Philp, 1994);

(ii) regular steranes show a strong predominance of the vascular land-plant derived C_{29} over the algae-derived C_{27} steranes, and typically the isoSt27/isoSt29 ratio (isosteranes) is <0.8. The content of C_{30} steranes (C_{30} 4-desmethylsteranes), which indicate an input of marine organic matter in source rocks and in oils charged from them (Moldowan *et al*.,1985; Peters *et al*., 1986), is likewise low and is less than 4% of the steranes;

(iii) The homohopane index, H35/H34, is low and averages 0.5;

(iv) carbon isotope ratios are the heaviest of the oils in the Danish Central Graben, with an average $\delta^{13}C$ for whole oil of -26.21‰ and an average $\delta^{13}C$ of the saturated fraction of -27.00‰;

(v) the sulphur content is on average 0.07 wt%.

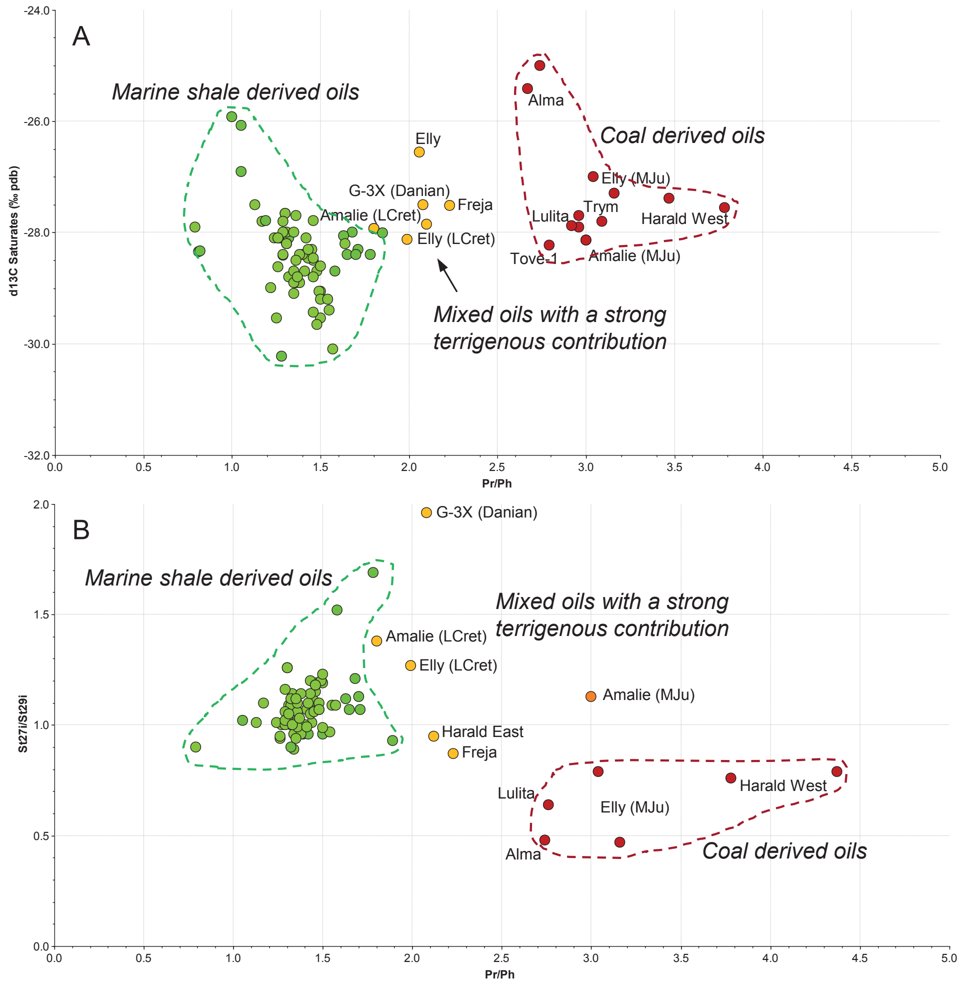

Fig. 5. Discrimination of major oil families by (A) $\delta^{13}C_{sat}$ *versus* Pr/Ph and (B) isosterane C_{27}/C_{29} *versus* Pr/Ph. The coal-derived oils and oils with a significant terrigenous contribution can be distinguished from the marine shale-sourced oils by their significantly higher Pr/Ph ratios, commonly heavier $\delta^{13}C_{sat}$ values and considerably lower isosterane C_{27}/C_{29} ratios. Modified after Petersen *et al.* (2016).

The mixed oils/condensates with a clear coaly contribution (oil families 5D/E-B and 4B-D/E; Petersen *et al.*, 2016) can likewise be identified by these geochemical parameters, although the characteristics are slightly less pronounced than in oils belonging to family 6D/E-F) (Fig. 5; Table 1). The producing fields in the Søgne Basin (Harald, Lulita, Trym) have well-established oil/condensate-source rock correlations by biomarkers and isotopes (Petersen *et al.*, 2000; Petersen and Brekke, 2001).

Liquids charged from the Middle Jurassic Bryne/Lulu Formations are not only restricted to the fields in the Søgne Basin but are more widespread in the Danish Central Graben. Coaly liquids were encountered in Middle Jurassic sandstones in the Alma, Elly and Amalie discoveries, but also in the Maastrichtian in the Tove-1 well in the southernmost part of the Danish Central Graben (Fig. 6). The light hydrocarbons (C_4–C_{13}) in fluids from the Middle Jurassic Bryne reservoir in Amalie-1 were investigated by Odden (1999), who concluded the fluids had a terrigenous origin. In addition, mixed liquids with a strong terrigenous contribution have been recovered from strata overlying the Middle Jurassic, probably indicating vertical migration and mixing with marine-sourced oils. Vertical migration (leakage) is commonly substantiated by mud-gas logs which show a thermogenic gas migration front of nC_{3+} gases in strata younger than the Middle Jurassic. Mixed oils in post-Middle Jurassic strata occur in Upper Jurassic barrier island sandstones in the Freja discovery on the Gert Ridge at the boundary between the Danish and Norwegian Central Graben (Johannessen *et al.*, 2010); in the Lower Cretaceous ‘Kira Sandstones’ in the Amalie-1 well; and in Upper Cretaceous chalk in the Harald East field and Elly discovery (Figs 6 and 7). The mixed nature of the ‘Kira Sandstones’ hydrocarbons has also been demonstrated by the composition of the light hydrocarbons which, according to Odden (1999), point to a dominant contribution from the Farsund source rocks. The Freja discovery also contains mixed fluids in Middle Jurassic sandstones (Fig. 7).

The mainly gas/condensate potential of the coaly source rocks is thus consistent with the majority of the

Table 1. Coal-derived oil and gas families in the Danish Central Graben.

HC families (Danish Central Graben)	Source rock type	Geochemical characteristics	Likely source rock unit
Oil family 6(D/E-F)	Coaly source rocks	High Pr/Ph, on average 3.5; strong predominance of C_{29} over C_{27} regular steranes, typically isoSt27/isoSt29 is <0.8; C_{30} steranes <4%; low H35/H34, on average 0.5; heaviest isotopic composition, $\delta^{13}C_{oil}$ on average -26.21‰, $\delta^{13}C_{sat}$ on average -27.00‰	Middle Jurassic coaly Bryne and Lulu Fms
Oil family 5(D/E-B)*	Mixture of terrigenous and marine sources	High Pr/Ph, slight dominance of C_{27} over C_{29} regular steranes; isotopically relatively heavy	Middle Jurassic coaly Bryne/Lulu Fms + minor Upper Jurassic Farsund Fm contribution
Oil family 4(B-D/E)	Mixture of marine and terrigenous source rocks	Relatively high Pr/Ph, on average about 2; dominance of C_{27} over C_{29} regular steranes; C_{30} steranes 5-6%; relatively low H35/H34, on average 0.65; isotopically slightly heavier than marine shale derived oils	Middle Jurassic coaly Bryne/Lulu Fms + some Upper Jurassic contribution, likely lower Farsund Fm and/or Lola Fm
Gas family GasF(Non-A)	Coaly source rocks	Heavier $\delta^{13}C$ methane (> -43‰), ethane, propane and butane isotope values than the oil-associated gas derived from the Upper Jurassic marine shales	Middle Jurassic coaly Bryne and Lulu Fms
Gas family GasF(Non-A/Oil-A)	Mixture of terrigenous and marine sources	Heavier $\delta^{13}C$ methane isotope values than the marine shale-derived gas, but slightly lighter than pure coal-derived gas [GasF(Non-A)]	Middle Jurassic coaly Bryne/Lulu Fms + minor Upper Jurassic Farsund Fm contribution
Gas family GasF(Non-A/?cracked)*	Most likely coaly source rocks	Very heavy $\delta^{13}C$ propane isotope value (-20‰), heavy δD methane (-155‰), high i-butane/n-butane ratio (i/nC4)	Likely high mature Middle Jurassic coaly Bryne and Lulu Fms; potentially cracked gas

*Only one sample, limited data

Oil families after Petersen et al. (2016)

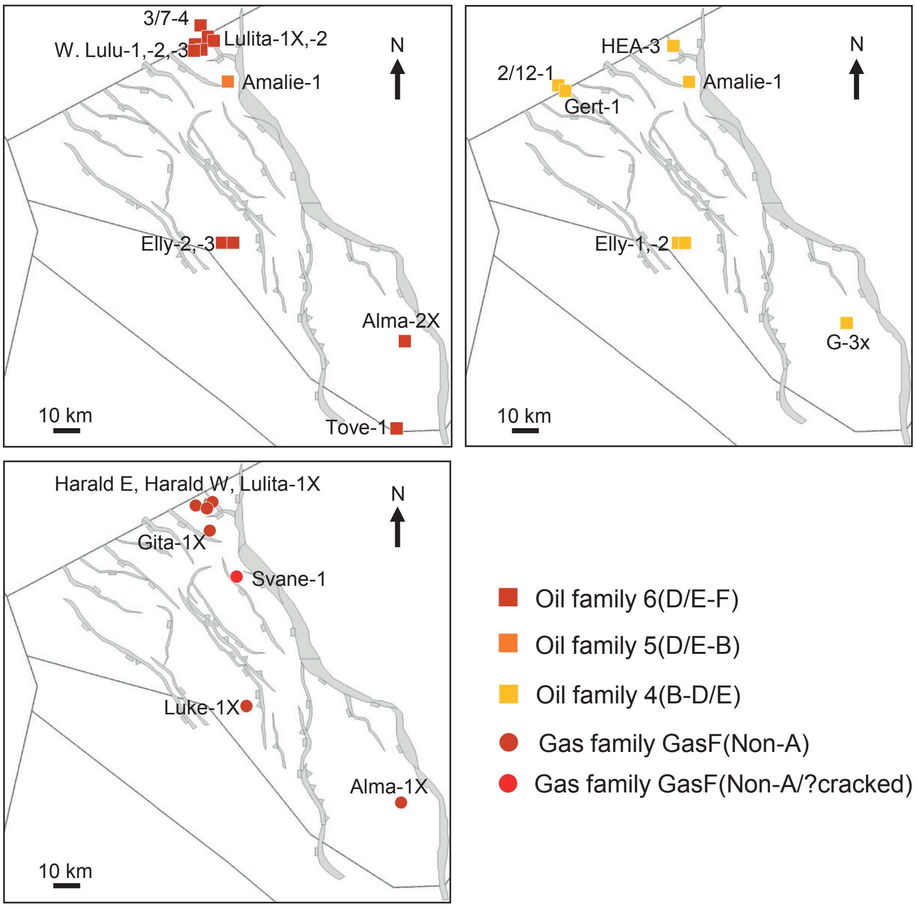

Fig. 6. Distribution of coal-related oil and gas families in the Danish Central Graben. Oil families after Petersen *et al.* (2016). Oil family 6(D/E-F) is coal-derived whereas oil families 5(D/E-B) and 4(B-D/E) are mixed with a contribution from the Upper Jurassic marine shales (Farsund Formation).

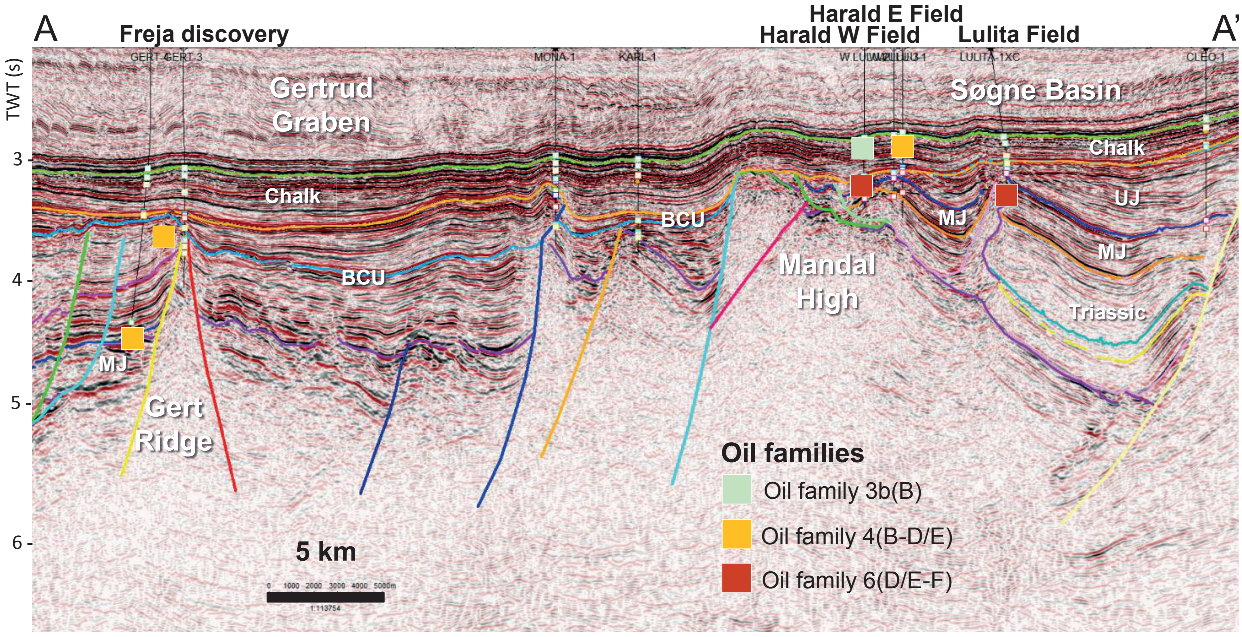

Fig. 7. SW-NE (A-A’) oriented seismic section from the northernmost part of the Danish Central Graben (for location, see Fig. 1) extending from the Freja discovery to the Harald and Lulita fields in the Søgne Basin. The oils in the Middle Jurassic belong to the coal-derived oil families 6(D/E-F) and 4(B-D/E), the latter with a contribution from the Upper Jurassic Farsund Formation marine shales. Oil family 3b(B) in the overlying chalk in the Harald West field is marine, whereas the oil in Harald East is mixed, probably due to vertical leakage from the Middle Jurassic. BCU: Base Cretaceous Unconformity; MJ / UJ: Middle/ Upper Jurassic.

Table 2. Observed and modelled condensate–gas ratio (CGR).

Field/Discovery	Observed CGR (brl/MMscf)	Modelled CGR (brl/MMscf)
Harald	80-110	60-180
Alma	90-102	85
Elly/Luke	5-30	30-70

coaly-sourced fluids encountered in the Danish Central Graben, but the Lulita oilfield stands out. As shown above, the source rock potential of the coal-bearing successions in the West Lulu-2 and Lulita-1X wells are of almost similar quality, although the upper part in Lulita-1X contains more oil-prone intervals, and the source rocks would basically generate the same fluid phases (same Condensate-Gas Ratio, CGR) under the same thermal conditions. However, the similarity in source rock quality at the two well locations is probably not representative for the source rock facies present in the kitchen areas. The Lulita field contains waxy oil with APIs of 31°–33° and a Gas-Oil Ratio (GOR) of 1395–2145 scf/brl, which is very different from the condensates in the Harald West field which have APIs from 46° to 48° and a CGR of 80 stb/MMscf (Fig. 8). The CGR of the Harald West field is comparable to the CGR of the Alma discovery in the southeast Danish Central Graben which is about 100 stb/MMscf (Table 2). The significant phase difference between the Lulita and Harald West fields is related to the different kitchen areas. The Lulita kitchen is located in the deeper half-graben to the ESE of the Lulita field, and although well information from this part of the basin is not available, a contribution from a lacustrine facies is likely (proximal lacustrine facies drilled by Lulita-1X; Carr and Petersen, 2001). Furthermore, the Lulita kitchen is less mature than the kitchen charging Harald West. The coaly-sourced Lulita oilfield with a potential lacustrine contribution is currently unique in the greater North Sea. Ohm *et al.* (2006) considered charging from the marine Farsund Formation as a possibility, but the Farsund shales have overall poor source rock quality in the Søgne Basin and a marine source rock would not account for the waxiness and terrigenous character of the oil (Petersen *et al.*, 2011). Therefore this is not thought to be likely.

Gas

The occurrence of coal-derived (= non-associated [Non-A]) gas in the Danish Central Graben shows a strong overlap with that of coaly-sourced liquids, sourced from the same Middle Jurassic Organofacies D/E coaly units (Bryne and Lulu Formations) (Fig.

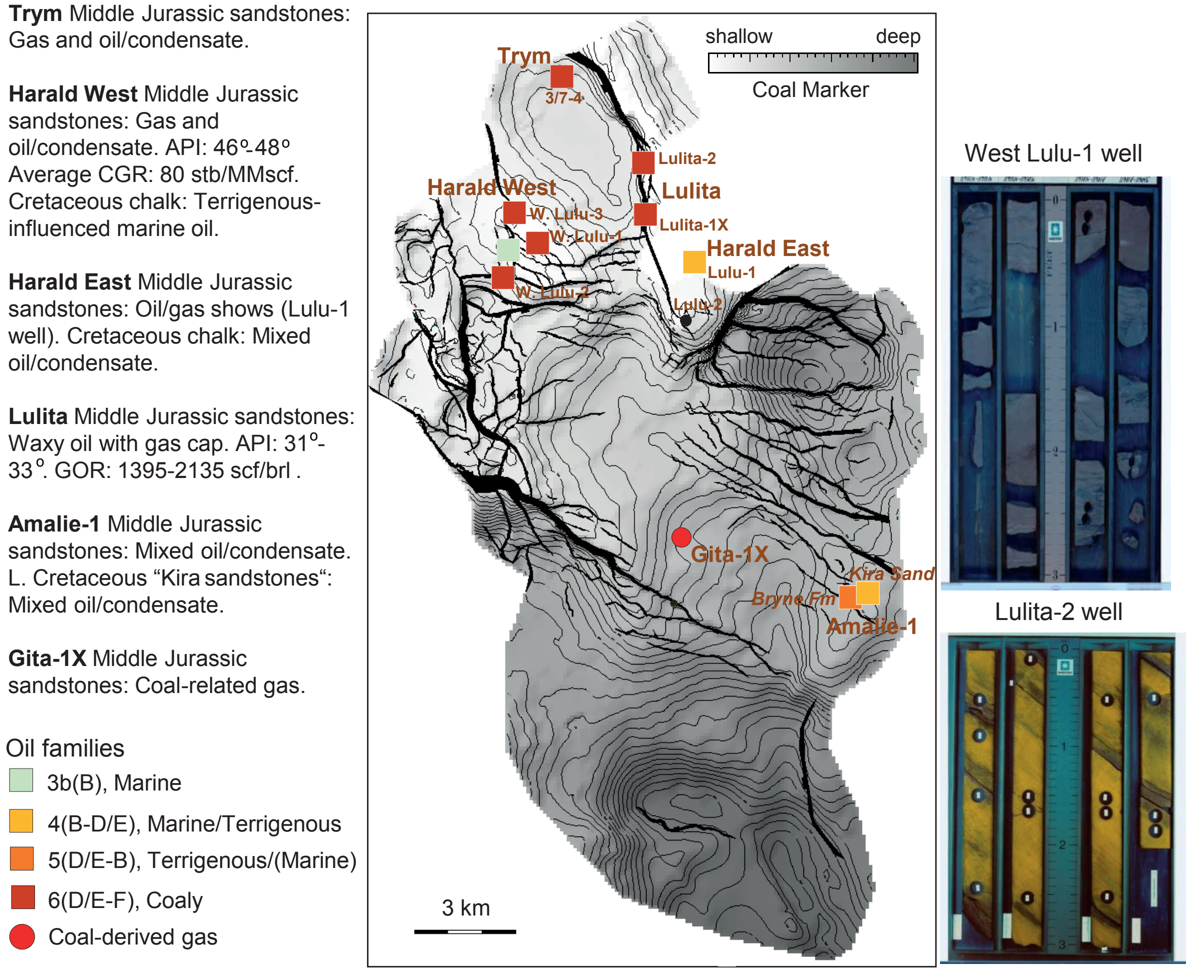

Fig. 8. Fields and discoveries in the Søgne Basin containing coal-derived hydrocarbons shown on the 'Coal Marker' horizon (see also seismic section in Fig. 7). The Lulita field contains waxy oil, and the Harald West and Trym fields gas and condensate in Middle Jurassic sandstone reservoirs. The fluid phase difference is emphasized by the strong yellow fluorescence of cores from the Lulita reservoir and the weak bluish fluorescence of cores from the Harald West reservoir.

6). In a regional study, the coal-derived gases have been assigned to the gas families GasF(Non-A) and GasF(Non-A/Oil-A) (*unpublished*, Maersk Oil), the latter composed of mixed coal-derived and oil-associated [Oil-A] gas (Table 1). The coal-derived gas is characterized by heavier stable carbon isotope values of methane, ethane, propane and butane, as shown by the isotopes of the gases from the Harald West and Lulita fields, the Alma discovery and the Gita-1X and Luke-1X wells (Fig. 9a; Table 1). As mentioned above, the Middle Jurassic coals are more oil-prone and wet gas-prone compared to "typical" Palaeozoic coals, and commonly these coaly gases plot outside the pre-defined "coal-related dry gas" field in classic gas plots (Fig. 9b). Isotope data derived from isotube and headspace gas samples from the Gita-1X well drilled in the Søgne Basin show the presence of *in-situ* generated coal-derived gas in the Middle Jurassic Bryne Formation and oil-associated gas in the marine Farsund Formation (Fig. 10). The isotope compositions show a clear shift to lighter values for the gas generated by the marine shales of the Farsund Formation. It should be noted that the Middle Jurassic gas data are from headspace samples and the Upper Jurassic Farsund gas data from isotubes which may not provide exactly the same results; however, a difference in isotopic values of about 20‰ for methane is considered significant and real. The Bryne Formation gases in Gita-1X display the expected linear trend in a 'Chung diagram' (Chung *et al.*, 1988) but do not have the lighter methane isotope values observed for some of the other gases (Fig. 9a). It is likely that this is due to a combination of the gas being charged from a more mature coaly source and the absence of mixing with oil-associated gas. The lighter methane isotopes, particularly observed in the Harald East and Lulita fields and the Alma discovery, may be related to the Middle Jurassic coaly D/E organofacies, but may also indicate mixing of the coal-derived gas with lighter methane from oil-associated gas or biogenic gas. The latter would not affect the higher molecular weight gases (ethane, propane, butane). However, at

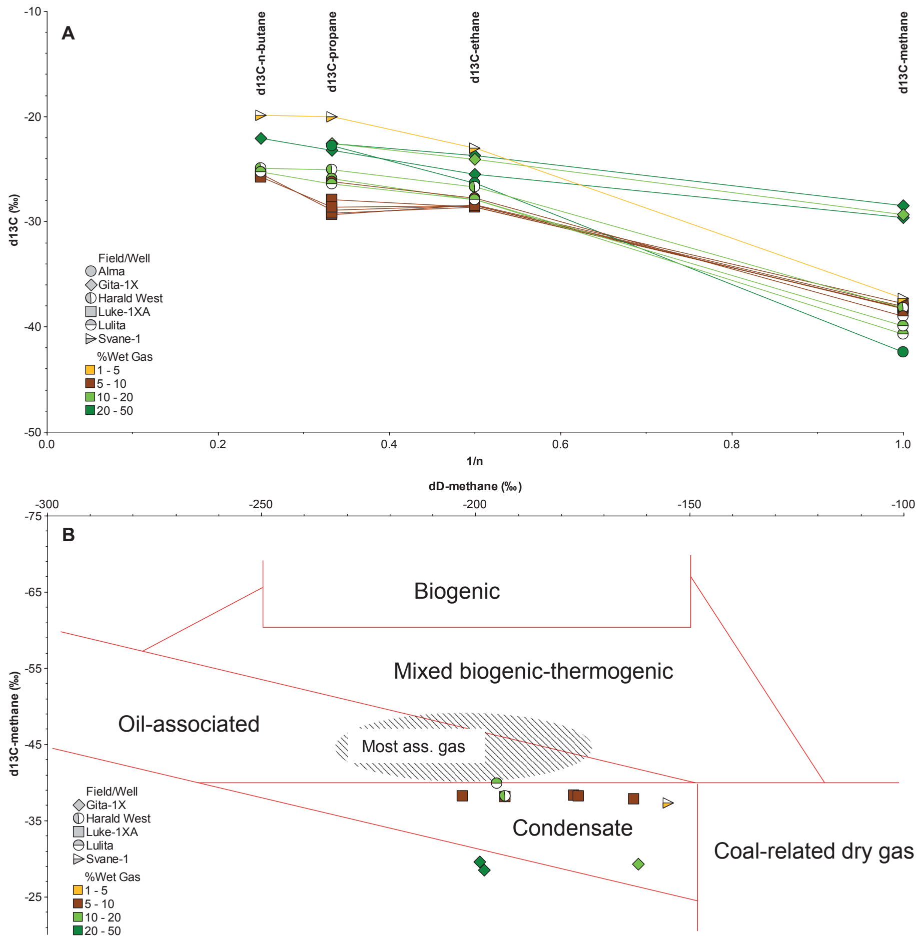

Fig. 9. (A) Isotopic compositions of coal-related gases characterized by heavy ethane, propane and butane values. The gas from the Svane-1 well has significantly depleted δ^{13}C isotopes of C_2–C_4. Relatively lighter methane isotopes for some of the gases may suggest minor mixing with oil-associated gas. Diagram after Chung *et al.* (1988). (B) The coal-related gas from the Middle Jurassic source rocks are wetter and plot outside the pre-designated "coal-related dry gas" field in the gas plot after Schoell (1983). This is linked to the more liquid-prone source-rock quality of the Middle Jurassic coaly units.

the present day, the Middle Jurassic reservoirs are too hot for both biogenic gas formation and biodegradation (Fig. 11); thus if biogenic gas is present, it was trapped earlier in the burial history of the reservoirs. Mixing with oil-associated gas seems most likely and, based on the mixing curves in Clayton (1991), the oil-associated gas may constitute up to 40%.

The Svane-1 well was drilled in the Tail End Graben – the primary kitchen area in the Danish Central Graben – and is the deepest Danish well (TD: 5952 m; Fig. 1a). A gas sample was collected from 5910 m (19389.76 ft) in the Upper Jurassic Heno Formation sandstones. The gas is typed to GasF(Non-A/?cracked), suggesting that the gas is composed of highly mature coal-derived gas and/or cracked gas. The butane, propane, ethane and methane isotopes suggest a primary origin from coaly units, and the coal-derived gas is interpreted to have been sourced from Middle Jurassic coaly units (Table 1). There is no specific indication of a Carboniferous coal source as suggested by Ohm *et al*. (2006). However, the very heavy ethane, propane and butane isotopes may also suggest gas cracking. Secondary cracking of gaseous hydrocarbons result in an increase in dryness, and the carbon isotope compositions of residual C_{2+} gases become heavier (Zou *et al*., 2007). It is notable that even this high mature and/or potentially cracked gas plots outside the "dry coal gas" field (Fig. 9b).

HYDROCARBON GENERATION, EXPULSION AND MIGRATION

A 3D petroleum systems model was constructed covering the Danish Central Graben area. The details of the basin model are outside the scope of this review, but the main objectives were to build a well-calibrated 3D model addressing structural evolution, compaction and pore pressure, temperature and maturity, timing of hydrocarbon generation and hydrocarbon expulsion, and hydrocarbon migration and alteration. The structural model is based on 37 mapped seismic horizons. Salt movement and variations of the

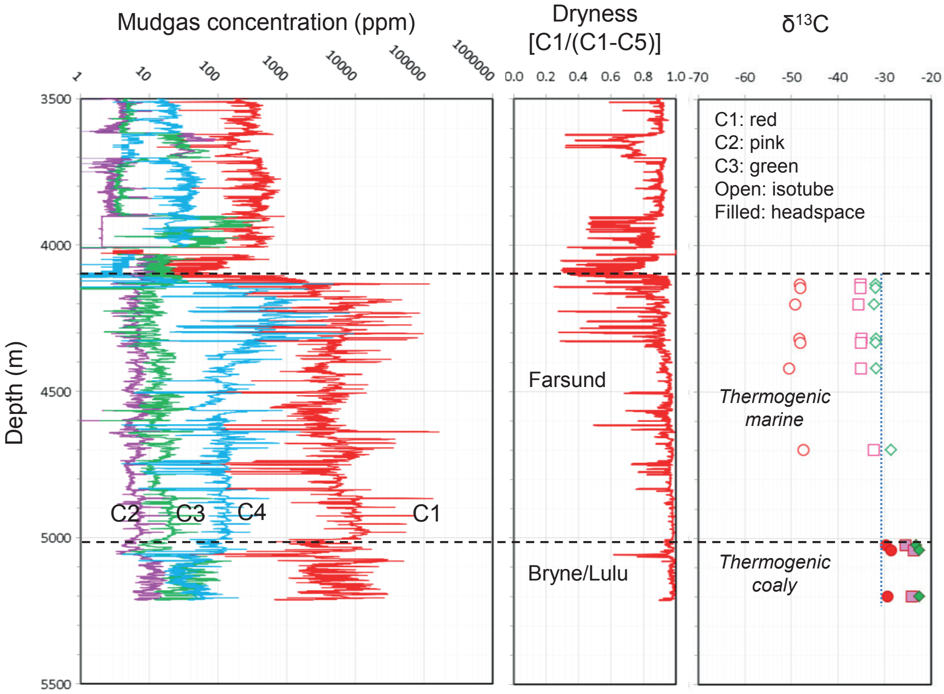

Fig. 10. Mud-gas concentrations (ppm), dryness [$C_1/(C_1–C_5)$] and isotopic composition of isotube and headspace gas samples through the Upper Jurassic Farsund Formation marine shales and into the coaly Middle Jurassic Bryne/Lulu Formations in the Gita-1X well. Note the high dryness in the Middle Jurassic and the significant shift towards lighter isotope values in the marine shales.

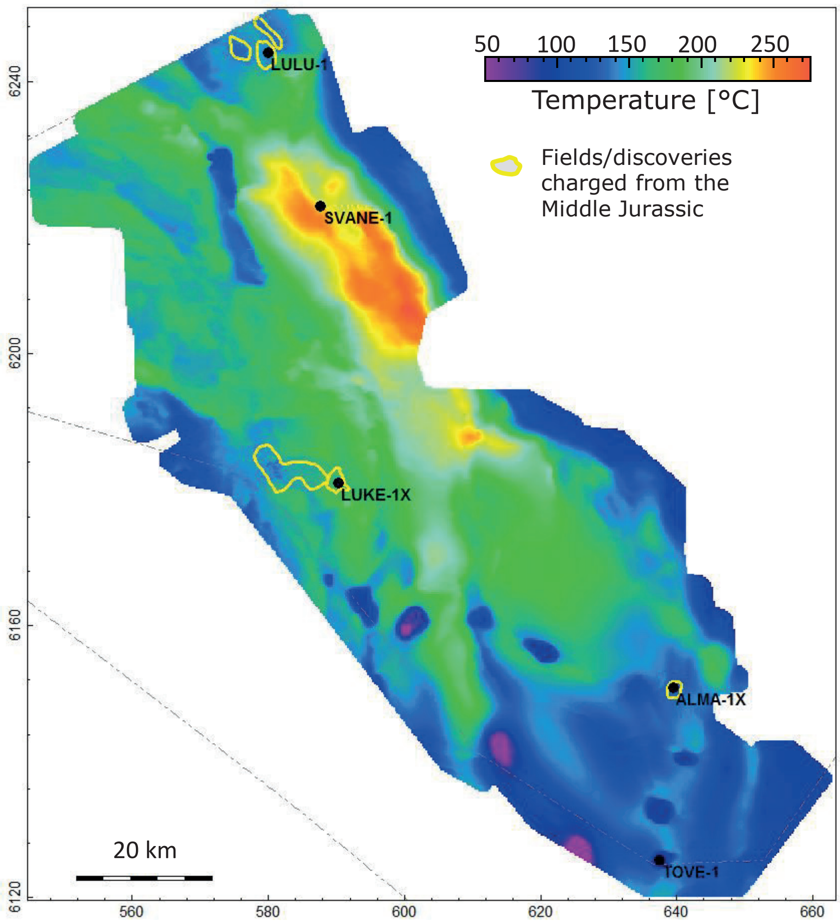

Fig. 11. Modelled present-day temperature (°C) of the Middle Jurassic 'Coal Marker' horizon in the Danish Central Graben. Middle Jurassic fields/discoveries charged from the coaly source rocks are shown together with selected wells for orientation (see Fig. 1).

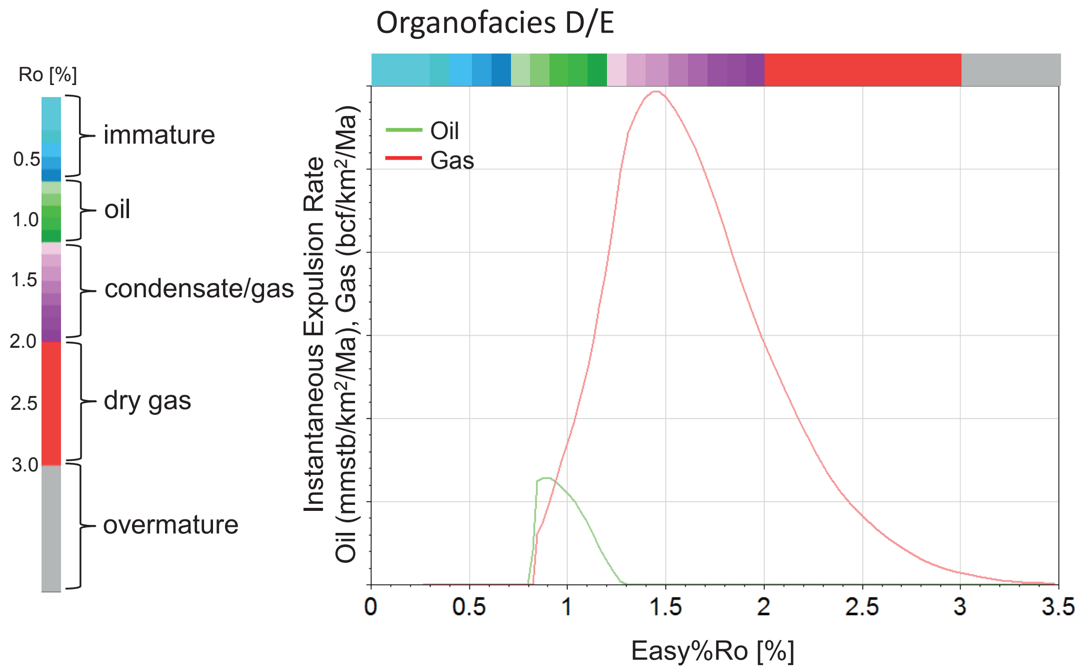

Fig. 12. Modelled instantaneous expulsion of oil (HC_{6+}) and gas ($HC_{1–5}$) using Organofacies D/E *sensu* Pepper and Corvi (1995a). Standard vitrinite reflectance scale for comparison.

water depth through time were integrated in the model. The lithology distribution was addressed by the construction of 36 facies maps representing the lateral and vertical variation of the sediment fill in the graben. Detailed source rock models were used for the Middle Jurassic coal section and the Upper Jurassic marine shales of the Farsund Formation (the latter is not discussed in the current study). A good regional calibration to porosity and pore pressure was achieved, and for the chalk compaction a compaction front model was implemented explaining the rapid loss of porosity within the chalk. The basis for the temperature calculation was a coupled crustal model, which was modified in order to achieve a good fit between measured and calculated temperature, and vitrinite reflectance data from multiple wells in the Danish Central Graben.

For modelling purposes, the Middle Jurassic coaly source rock unit was simplified into only a coal source with an average TOC of 70 wt%, an average HI of 280 mg HC/g TOC, and a thickness of 15 m. The HI-value corresponds to the average of the back-calculated coals (see Fig. 3), and 15 m is a pragmatic approximation of the combined cumulative coal bed and coaly shale thickness in the Middle Jurassic section. The present-day temperature for the Middle Jurassic coal source rock ('Coal Marker') indicates relatively high temperatures (>150 °C) throughout most of the Danish Central Graben, with a maximum of ca. 275
A°C in the Tail End Graben and lower temperatures occurring only in the southernmost part and along the graben margins (Fig. 11). The high temperatures are reflected in the maturity of the coals, which is given here as calculated vitrinite reflectance values using the Easy%Ro algorithm of Burnham and Sweeney (1989) and Sweeney and Burnham (1990) (Figs 12 and 13).

The Middle Jurassic 'Coal Marker' horizon was immature at 153 Ma, but between 153 and 140 Ma the Tail End Graben became sufficiently mature to expel hydrocarbons, which for the Bryne/Lulu Formation coals (Organofacies D/E) began at about 0.85–0.9%R_o (e.g. Petersen 2002, 2006) (Fig. 13). The deepest parts of the Tail End Graben reached the dry gas maturity window. In the Cretaceous (140 to 66 Ma), the area of mature coaly source rocks expanded further up the basin flanks; in the Cenozoic and up to the present day (66 to 0 Ma), nearly the entire area became mature. During this period, the Tail End Graben exhausted its gas potential (overmature).

The model of Pepper and Corvi (1995b) was used for the calculation of hydrocarbon generation and expulsion. In this model the retention of hydrocarbons is only adsorption controlled. Hydrocarbons will be expelled when an adsorption threshold is exceeded (adsorption of oil and gas by the organic material). Four temperature-dependent reactions are considered in the model: (i) transformation of kerogen to oil; (ii) transformation of kerogen to gas; (iii) oil-to-gas cracking of adsorbed oil in the source rock; and (iv) oil-to-gas cracking outside the source rock during migration. For the Middle Jurassic coals, the kinetics of Organofacies D/E (terrigenous, non-marine, waxy; corresponding to Type III kerogen) were used. Hydrocarbon expulsion from the coaly source rocks

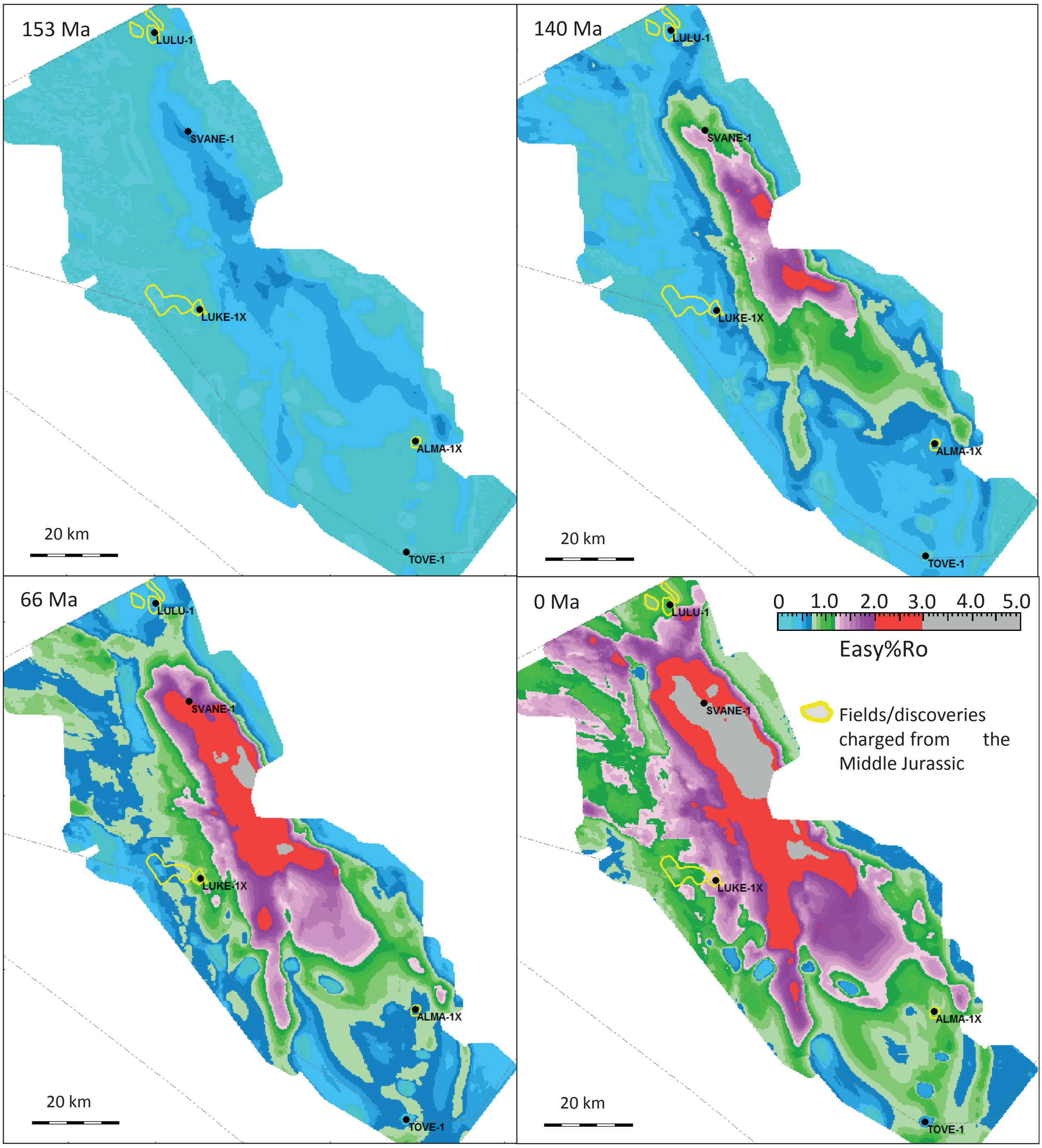

Fig. 13. Time-step maps showing the modelled thermal maturity (Easy%Ro) of the Middle Jurassic 'Coal Marker' horizon in the Danish Central Graben. More rapid maturation occurs in the deep Tail End Graben in the eastern part of the graben complex. Time steps: 153 Ma, base Upper Jurassic Farsund Formation time; 140 Ma, top Upper Jurassic Farsund Formation time (BCU: Base Cretaceous Unconformity); 66 Ma, top Cretaceous time; (D) present day. Middle Jurassic fields charged from the coaly source rocks are shown together with selected wells for orientation (see Fig. 1).

began in Late Jurassic time in the deepest part of the Danish Central Graben (Fig. 14). Continuous expansion of the area with hydrocarbon expulsion in the Cretaceous was followed by low expulsion rates in the Paleocene to late Oligocene. This was caused by a combination of a cooling effect due to the compaction of the Cretaceous chalk resulting in higher thermal conductivity, and a slightly lower sediment-water interface temperature. Significant expulsion resumed in the Miocene and continues at the present day, but only at the flanks of the basin in the south, west and north because of exhaustion of the deep parts of the basin.

The present-day hydrocarbon distribution and properties must be integrated in order to validate a hydrocarbon migration model. In the current study, the oil and gas geochemistry, hydrocarbon shows distribution and field outlines were used (Fig. 15). Hydrocarbon migration was modelled using the

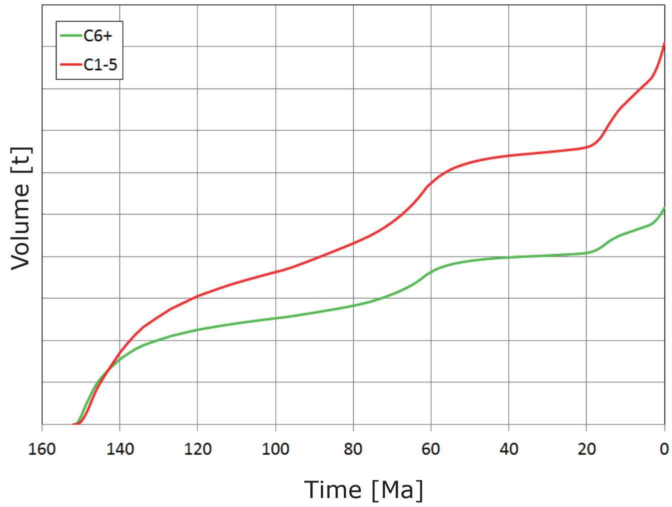

Fig. 14. Cumulative expulsion history for the Middle Jurassic coals in the modelled area.

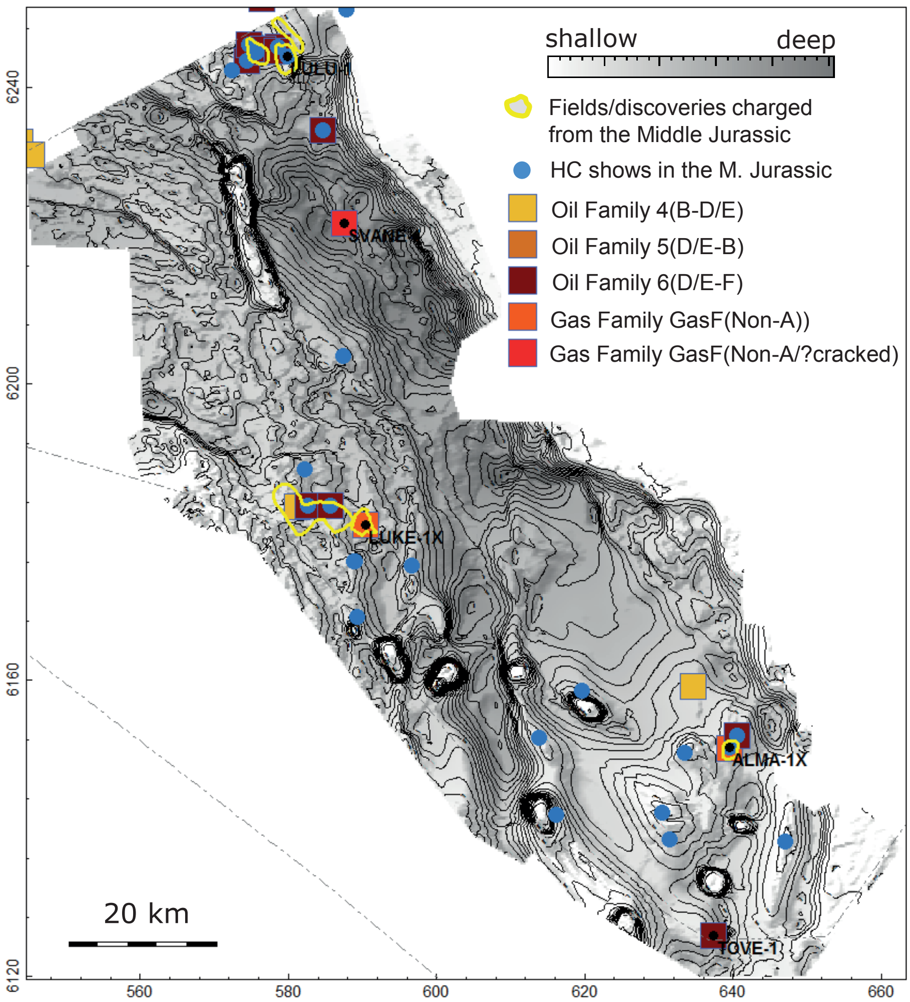

Fig. 15. Observed hydrocarbons (fields, discoveries, shows) in the Middle Jurassic section. Note the regional distribution of shows.

multilayer flow-path methods in the basin modelling tools TrinityT3 and PetroMod3D. Flow path is a map-based migration method. Hydrocarbons migrate to the top of structures, and migration occurs instantaneously. In the multilayer flow path model, several carrier beds can be used together simultaneously. In the model, migration from one layer to the other works via top seal leakage. Flow path layers or carriers have to be pre-defined.

In this study, the Middle Jurassic, Base Cretaceous Unconformity (BCU; representing a migration focus for the Farsund Formation), the Lower Cretaceous Top

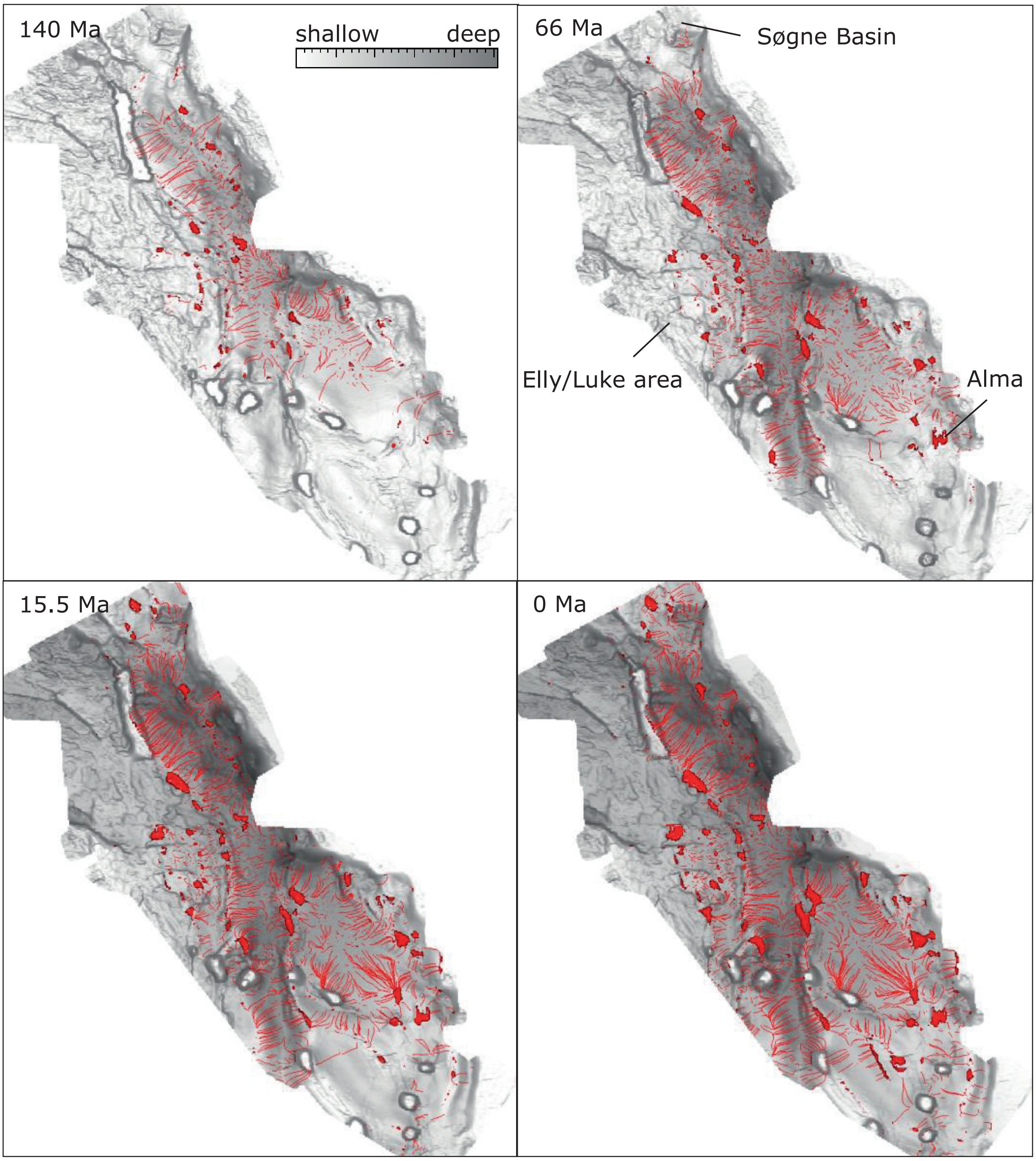

Fig. 16. Modelled flow paths and accumulations of hydrocarbons (charged from the Middle Jurassic coaly source rocks) shown in red on the Middle Jurassic structure map at four time-steps: 140 Ma, top Upper Jurassic Farsund Formation time (BCU: Base Cretaceous Unconformity); 66 Ma, top Cretaceous time; 15.5 Ma, Miocene; and present day.

Tuxen Formation (Chalk) and the Lower Paleocene Top Ekofisk Formation were used as "primary carriers" and also to account for flow into shallower sections, e.g. the Maastrichtian in the Tove-1 well. Although this is a very simplistic approach to migration modelling, it yielded good regional results and explained most of the observed hydrocarbon distribution (Fig. 15). However, in order to confirm the coaly origin of the shows in the Middle Jurassic section, sampling and geochemical analysis is required. The Middle Jurassic depth-structure map and results of the flow migration model through time and up to present day is shown in Fig. 16. Note the relative late filling of the Harald/Lulita area in the northern Søgne Basin compared to the Luke/Elly area in the central-eastern part of the Danish Central Graben. The results of the migration modelling match with the present-day fluid distribution (fields, discoveries, shows) and the oil and gas family analyses (Figs 6 and 15) (Petersen *et al.*, 2016), with hydrocarbons charged from the Middle Jurassic coaly source rocks proven in e.g. the Harald and Lulita fields, Amalie, Elly and Alma discoveries,

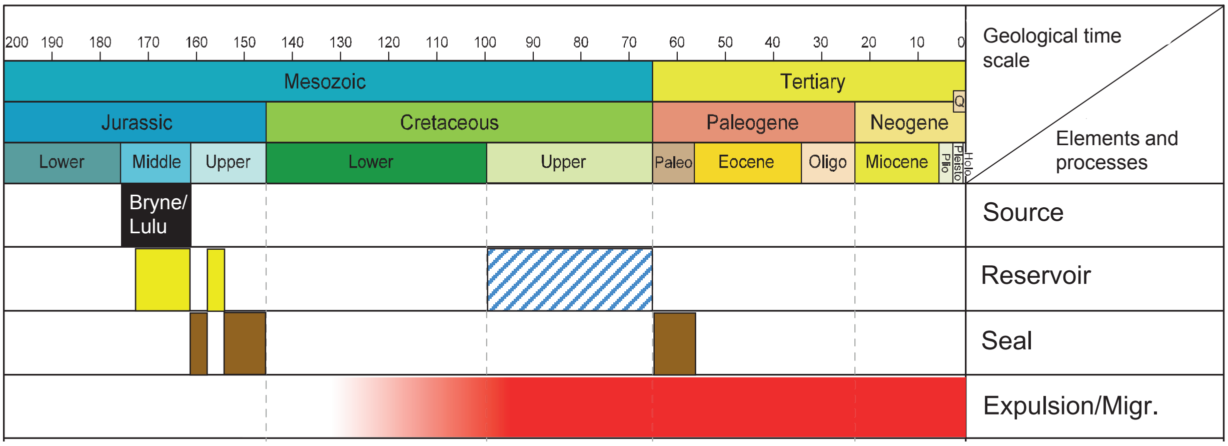

Fig. 17. Simplified event chart summarizing elements and processes of the Middle Jurassic petroleum system in the Danish Central Graben. The chalk reservoir is hatched as it is not charged directly but relies on leakage and vertical migration from deeper-lying reservoirs.

the Luke-1X and Tove-1 wells. The model also mimics the gas-condensate ratios observed in accumulations charged from the coaly Middle Jurassic source rocks (Table 2). This is mainly controlled by source rock maturity and timing because the same source properties were assigned to the Middle Jurassic in the regional model applied. In prospect-scale studies, source rock properties could be adjusted to accommodate coal facies variations, as observed in the Søgne Basin (see above), as well as faults, etc. The areas with the highest CGR (Condensate-Gas Ratio), such as the Harald field and Alma discovery, entered the hydrocarbon generation window relatively late and are less mature compared to the Luke/Elly area which were supplied by a very mature kitchen.

A summary of the elements and processes of the Middle Jurassic petroleum system is shown in the simplified event chart (Fig. 17).

CONCLUSIONS

The Middle Jurassic coaly-sourced petroleum system has proven to be economic in both the Danish, UK and Norwegian North Sea sectors and thus constitutes an additional exploration opportunity to the widespread ‘conventional’ plays which rely on Upper Jurassic marine shales (Kimmeridge Clay Formation and equivalents) as the source rock. In the Danish Central Graben, the Middle Jurassic petroleum system is recognized by: (i) a group of oil families composed of ‘pure’ coal-generated and mixed oils characterized by typical terrigenous geochemical parameters, including high Pr/Ph ratios, a predominance of C_{29} steranes, relatively heavy carbon isotope compositions and very low sulphur contents; (ii) a group of gas families constituted by ‘pure’ coal-derived and mixed gases, characterized by heavier stable carbon isotope values of methane, ethane, propane and butane. The gas can be relatively dry, but is wetter than ‘typical’ Carboniferous-generated dry gas. The Middle Jurassic coaly units vary lithologically from carbonaceous shales to coaly shales and coals, but the source rock potential remains fairly similar for all these lithologies indicating a ‘source rock continuum’ which contains the same type of terrigenous kerogen. The HIo is generally between 200 and 350 mg HC/g TOC. About one-half (47%) of the coal samples have HIo values >300 mg HC/g TOC, and 11% of the coal samples are clearly oil-prone (HIo from 350–500 mg HC/g TOC). This fits with the coal-sourced oil families identified in the Danish Central Graben (Alma, Amalie, Elly, Harald, Lulita, Tove-1).

Expulsion of hydrocarbons from the ‘Coal Marker’ was initiated in Late Jurassic time in the deep Tail End Graben, and the area of mature coaly source rocks expanded in the Cretaceous. In the Cenozoic and up to the present day, almost the entire area became mature with low expulsion rates in the Paleocene to Late Oligocene followed by significant expulsion in the Miocene up to the present day. At the present day, the Middle Jurassic coal source rock (‘Coal Marker’) has reached temperatures of >150 °C throughout most of the Danish Central Graben. High temperatures in the Middle Jurassic reservoirs prevent biodegradation.

Abundant shows in Middle Jurassic units in the Danish Central Graben may suggest that the Middle Jurassic petroleum system is more widespread than anticipated, but sampling and analysis of extracts of the shows is required to confirm the origin of the hydrocarbons. Mud-log gas readings (chromatologs) provide useful information on gas composition, but point sampling of flowline gas by isotubes is required for isotopic analysis and a more robust identification of coal-derived gas and mixed gases. However, a regional-scale distribution extending outside the Danish Central Graben is confirmed by the occurrence of commercial accumulations in the UK and Norwegian North Sea, which is encouraging for future exploration of coaly-sourced Triassic and Jurassic sandstone plays.

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