Are Carboniferous coals from the Danish North Sea oil-prone?

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The Central Graben in the North Sea is a mature petroleum province with Upper Jurassic – lowermost Cretaceous marine shale of the Kimmeridge Clay Formation and equivalents as the principal source rock, and Upper Cretaceous chalk as the main reservoirs. However, increasing oil prices and developments in drilling technologies have made deeper plays depending on older source rocks increasingly attractive. In recent years exploration activities have therefore also been directed towards deeper clastic plays where Palaeozoic deposits may act as petroleum source rocks. Carboniferous coaly sections are the most obvious source rock candidates. The gasfields of the major gas province in the southern North Sea and North-West Europe are sourced from the thick Upper Carboniferous Coal Measures, which contain hundreds of coal seams (Drozdzewski 1993; Lokhorst 1998; Gautier 2003). North of the gas province Upper Carboni-ferous coal-bearing strata occur onshore in northern England and in Scotland, but offshore in the North Sea area they have been removed by

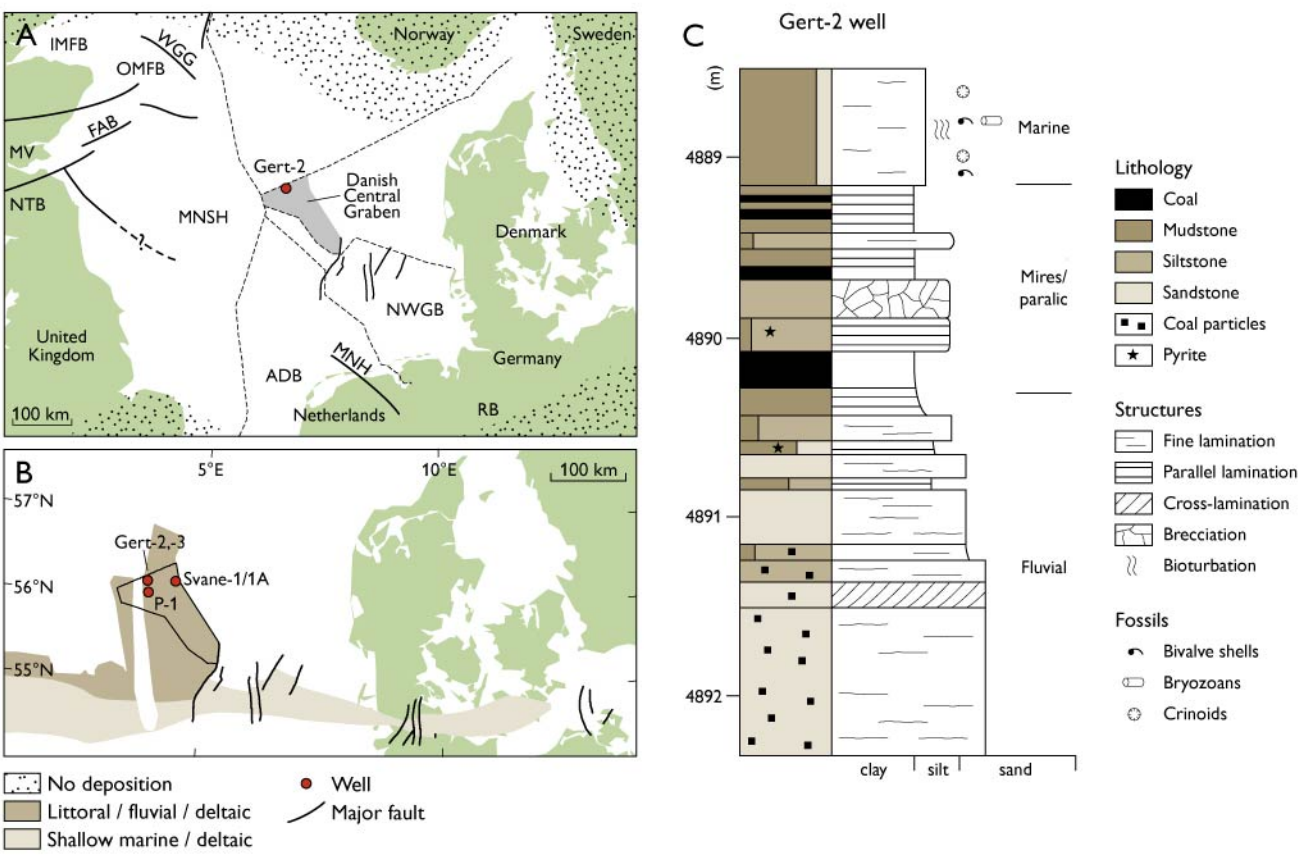

Fig. 1. **A**: Simplified map showing Carboniferous basins in the North Sea area. The Danish Central Graben is also shown (grey area). **ADB**, Anglo-Dutch Basin; **FAB**, Forth Approaches Basin; **IMFB**, Inner Moray Firth Basin; **MNH**, Mid Netherlands High; **MNSH**, Mid North Sea High; **MV**, Midland Vally; **NTB**, Northumberland/Tweed Basin; **NWGB**, North-west German Basin; **OMFB**, Outer Moray Firth Basin; **RB**, Ruhr Basin; **WGG**, Witch Ground Graben. Based on Ziegler (1990), Besly (1998) and Bruce & Stemmerik (2003). **B**: Present-day distribution of Lower Carboniferous littoral/fluvial/deltaic and shallow marine/deltaic deposits in the southern North Sea area. The positions of the Gert-2, Gert-3, P-1 and Svane-1 wells are shown. Modified from Lokhorst (1998). **C**: Sedimentological log of the coal-bearing interval of the Gert-2 well. The coaly interval is underlain by fluvial sediments and overlain by fossiliferous marine mudstones of the so-called Marine Unit. Slightly modified from Petersen & Nytoft (2007).

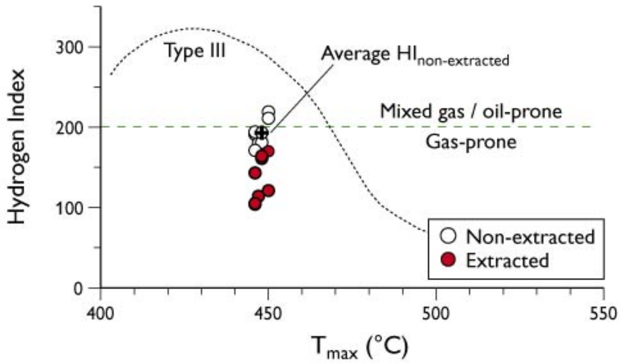

Fig. 2. Hydrogen Index versus T_{max} plot of non-extracted and solvent extracted coal samples from the Gert-2 well. The average Hydrogen Index of the non-extracted coals is also shown.

erosion. However, Lower Carboniferous strata are present offshore and have been drilled in the Witch Ground Graben and in the north-eastern part of the Forth Approaches Basin (Fig. 1A), where most of the Lower Carboniferous sediments are assigned to the sandstone/shale-dominated Tayport Formation and to the coal-bearing Firth Coal Formation (Bruce & Stemmerik 2003). Highly oil-prone Lower Carboniferous lacustrine oil shales occur onshore in the Midland Valley, Scotland, but they have only been drilled by a single well offshore and seem not to be regionally distributed (Parnell 1988).

In the southern part of the Norwegian and UK Central Graben and in the Danish Central Graben a total of only nine wells have encountered Lower Carboniferous strata, and while they may have a widespread occurrence (Fig. 1B; Bruce & Stemmerik 2003) their distribution is poorly constrained in this area. The nearly 6000 m deep Svane-1/1A well (Fig. 1B) in the Tail End Graben encountered gas and condensate at depths of 5400–5900 m, which based on carbon isotope values may have a Carboniferous source (Ohm *et al.* 2006). In the light of this the source rock potential of the Lower Carboniferous coals in the Gert-2 well (Fig. 1C) has recently been assessed (Petersen & Nytoft 2007).

Lower Carboniferous strata in the Danish Central Graben

In the Danish Central Graben, Lower Carboniferous strata were drilled by the Gert-2, Gert-3 and P-1 wells (Fig. 1B). The depth to the Lower Carboniferous ranges from 3289 m in the P-1 well to 4840 m in the Gert-2 well. Whereas the P-1 well reached Caledonian basement after penetrating about 67 m of Carboniferous sediments, the Gert-2 well drilled 192 m of Carboniferous strata before drilling terminated at about 5000 m depth within the Carboniferous. The drilled Carboniferous section in the Gert-2 well is principally non-marine (Fluvial Unit) and contains a coaly interval at about 4890 m (Fig. 1C) that constitutes a transition to marine shales and shoreface and tidally influenced sandstones of the Marine Unit (Petersen & Nytoft 2007). The coals overlie a fluvial fining-upward succession and are overlain by fossiliferous marine shales (Fig. 1C). The coals formed in peat-forming coastal plain mires as shown by high sulphur contents (average 5.3 wt%) and the presence of framboidal pyrite (Petersen & Nytoft 2007). High contents of vitrinite (65–82 vol.%), derived from degradation of higher land plant woody material, indicate waterlogged, oxygen-deficient conditions in the precursor mires. Although the proportion of more oil-prone liptinite constituents is generally small (4–8 vol.%), the paralic peat-forming conditions may be favourable for the oil generation potential of the resulting coals (Petersen 2006). This raises the question: are the coals encountered in the Gert-2 well oil- or gas-prone?

Source rock quality and hydrocarbon generation capacity

The average Tmax of the coals is 448°C, which corresponds to a vitrinite reflectance of ~0.95%R_o indicating that the coals are at the threshold of, or slightly within, the so-called 'effective oil window' (in which efficient oil expulsion occurs; Sykes 2001; Petersen 2006). In addition the Hydrogen Index (HI) values of the coals are very close to their HI_{max} values. During initial maturation the HI of coals increases to a maximum value, which is considered to be a better estimate of the generation potential of coal (Sykes & Snowdon 2002; Petersen 2006). Thus, at first glance HI values from 171–219 mg HC/g TOC may suggest some potential for liquid petroleum formation (Fig. 2). The type of generated petroleum is, however, determined by the paraffinicity of the organic matter, i.e. the proportion and length of hydrogen-bearing carbon chains (aliphatic chains) in the kerogen structure. The ability to generate and expel typical waxy terrestrial crude oil requires the presence of long-chain aliphatics with more than ~20–25 carbon atoms (Isaksen *et al.* 1998; Killops *et al.* 1998). Fourier transform infrared spectroscopy (FTIR) of the Gert-2 coals clearly reveals a response in the aliphatic stretching region, but the response can mainly be assigned to isolated CH_2 compounds, which are of no importance to the liquid petroleum generation potential (Petersen & Nytoft 2006). Quantification of the proportion of long-chain aliphatics in the kerogen structure of the Gert-2 coals by comprehensive chemical treatment (so-called ruthenium tetroxide catalysed oxidation; see Petersen & Nytoft 2006, 2007) demonstrates a negligible or extremely low amount of aliphatic chains with more than 18 carbon atoms. The dominance of shorter aliphatic chains strongly indicates that the coals are gas- and condensate-prone.

Carboniferous coals are inherently gas-prone

The above results are in line with the findings of Petersen & Nytoft (2006), who showed that Carboniferous coals in general contain very minor proportions of long-chain aliphatics in the range $C_{19–35}$ and are therefore inherently poorly suited to generate oil. Thus, for Carboniferous coals only an effective gas/condensate window exists.

Of the total amount of aliphatic chains in the range $C_{12–35}$, Carboniferous coals contain on average about 20% in the $C_{19–35}$ range (Fig. 3A). In contrast, Jurassic coals from the Søgne Basin in the North Sea contain about 26%, while Cenozoic coals contain on average as much as 55% (Fig. 3A). The significantly higher proportion of long-chain ali-phatics in the youngest coals seems to be related to the high amount of organic de-trital groundmass (Fig. 3B). The groundmass consists of detrital vitrinitic and liptinitic organic matter that can be positively correlated to the long-chain ali-phatics in the kerogen structure (Petersen & Nytoft 2006). The oil-proneness of the Cenozoic coals thus seems to be related to the evolution of more diversified plant communities, including the appearance of angiosperms in the Late Cretaceous.

Limited expulsion efficiency and implications for enhanced gas-proneness

In agreement with the kerogen structure the generated hydrocarbons from the Lower Carboniferous Gert-2 coals are dominated by shorter-chain aliphatics. These do not facilitate expulsion (Isaksen *et al.* 1998), and the generated hydrocarbons remain trapped in the coals. This is sustained by a pronounced difference in the HI of the non-extracted coals and the HI of the extracted coals: upon extraction the HI is on average reduced by 30% (Fig. 2; Petersen &

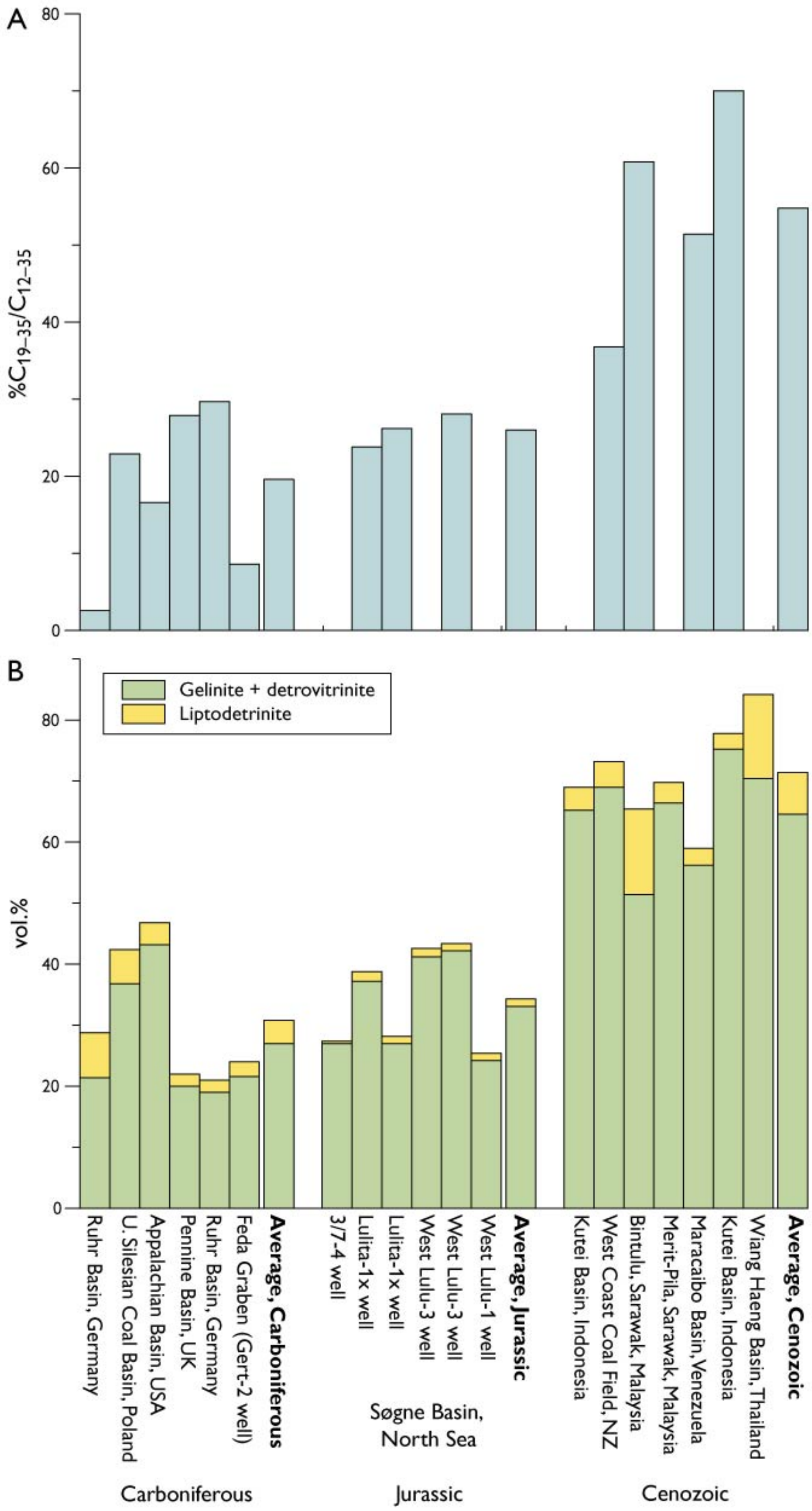

Fig. 3. **A**: The proportion (%) of $C_{19–35}$ long-chain aliphatics of the total amount of $C_{12–35}$ aliphatics in a number of Carboniferous, Jurassic and Cenozoic coals. **B**: The proportion (vol.%) of groundmass composed of detrital vitrinite and liptinite in a number of Carboniferous, Jurassic and Cenozoic coals.

Nytoft 2007). Hence, the measured HI values of the Gert-2 coals are strongly influenced by the trapped petroleum in the coals. The limited (or lack of) expulsion maintains a low saturate/aromatic hydrocarbon ratio of the trapped petroleum, which according to Pepper & Dodd (1995) is less thermally stable than expelled oil that is dominated by saturated (aliphatic) hydrocarbons. For source rocks with HI values below 300 mg HC/g TOC, intra-source rock cracking of hydrocarbons commences from 115–145°C (Pepper & Dodd 1995). The average HI of the Gert-2 coals is 193 mg HC/g TOC, and the vitrinite reflectance values suggest burial temperatures of 124–132°C, implying that intra-source rock oil-to-gas cracking of the trapped hydrocarbons may enhance the gas-proneness of the coals. Observation of pyrolytic carbon in the coals may provide direct evidence for gas generation (Petersen & Nytoft 2007).

Concluding remarks

As is the case with other Carboniferous coals, the drilled Lower Carboniferous coals encountered in the Gert-2 well, located at the northern margin of the Danish Central Graben, are gas-prone. The gas-proneness is inherited from the coaly organic matter, which generally contains a small amount of oil-prone kerogen due to the lack of long-chain aliphatics. Limited expulsion efficiency maintains a low saturate/aromatic ratio of the generated and trapped petroleum. The thermally less stable petroleum mixture promotes intra-source rock oil-to-gas cracking of the trapped hydrocarbons in the coals, which enhances their gas-proneness. The thin coaly section, present in the Gert-2 well, has no economic significance. However, provided that the Lower Carboniferous coaly section is regionally distributed and the section elsewhere is thicker with a larger number of coal seams and/or thick sections of coaly shale, it can potentially be a gas source for deep plays in the Danish Central Graben and adjacent areas. This is supported by the encountered gas in the Svane-1/1A well (Ohm *et al.* 2006).

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