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Upper Jurassic–lowermost Cretaceous marine shale source rocks (Farsund Formation), North Sea: Kerogen composition and quality and the adverse effect of oil-based mud contamination on organic geochemical analyses

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ABSTRACT

The Jude-1 well is located in the central part of the Danish Central Graben, North Sea, and was drilled into immature black shales of the Upper Jurassic–lowermost Farsund Formation, a world-class marine source rock. The well was drilled with oil-based drilling mud (OBM). The lithofacies consists of argillaceous shale, calcareous shale and dolomite stringers as confirmed by cuttings and core. A core was taken in the upper part of the formation at the beginning of a 'hot' argillaceous shale interval characterized by elevated TOC and HI values. Cuttings and core samples were investigated to unravel kerogen composition, source rock quality and the contamination effect of OBM on organic geochemical analyses. The organic facies of the source rocks corresponds to Type II kerogen or Organofacies B (*sensu* Pepper and Corvi, 1995). Considerable fluctuations in HI values through the Farsund Formation reflect pronounced variations in source rock quality, although a faint lamination of the shales and overall high TOC contents testify to prevailing oxygen-deficient depositional conditions preventing significant bioturbation and reworking of the sediment and organic matter. Petrography of core samples reveals a relatively homogenous sapropelic kerogen composition dominated by a groundmass of yellowish fluorescing amorphous organic matter and liptodetrinite intimately associated with the mineral matrix. Telalginite is less abundant, but *Tasmanites*- and in particular *Leiosphaerida*-type telalginites were observed. Minor but varying amounts of detrital terrigenous macerals suggest a considerable distance to land areas and thus limited supply of land plant-derived organic matter. The argillaceous shale lithofacies generally is more oil-prone and organic-rich than the more gas-prone calcareous shale facies. The uppermost section includes the 'hot' argillaceous shales, which together with two deeper argillaceous shale intervals are highly organic-rich and oil-prone. Average TOC of the 'hot' argillaceous shales is ~7 wt% and HI reaches >500 mg HC/g TOC. The total Ultimate Expulsion Potential (UEP) of the over 853 m (2799 ft) thick Farsund Formation is ~142 mmboe/km^2. Results from non-contaminated samples are thus consistent with the Farsund Formation being a world-class highly oil-prone marine source rock. The predicted oil composition corresponds to 'paraffinic low wax oils'. The adverse effect of OBM contamination on geochemical analyses is demonstrated by Rock-Eval data and measured bulk kinetics of contaminated core samples. The measured kinetics has a considerable proportion of low activation energies related to OBM contamination which is also supported by high Production Indices. Further, gas chromatograms of the saturated fraction of extracts from contaminated cores clearly show evidence of OBM in the nC_{11}–nC_{14} range. Rock-Eval S_2 peaks have a 'shoulder' showing that the low E_a-peaks result from carry over from the S_1 peak, caused by the OBM contamination. As a consequence Hydrogen Index values are increased.

1. Introduction

The principal source rocks in the North Sea area are Upper Jurassic–lowermost Cretaceous marine shales which *inter alia* are referred to as the Kimmeridge Clay Formation, Mandal Formation and - in the Danish North Sea sector - the Farsund Formation (Thomsen et al., 1983; Damtoft et al., 1992; Cornford, 1994, 1998; Ineson et al., 2003; Petersen et al., 2013) (Fig. 1). The shales constitute world-class source rocks and have charged most fields in the North Sea, including all major chalk fields (*e.g.* Dan, South Arne, Valdemar; Fig. 1) in the Danish Central Graben. In the Danish Central Graben the vast majority of the produced oils have been typed by Petersen et al. (2016) to different organofacies of the Farsund Formation and in the South Viking Graben

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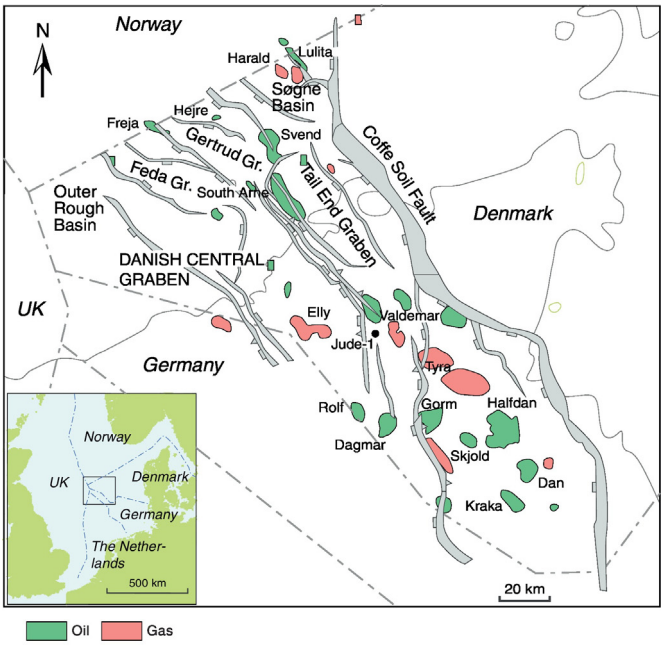

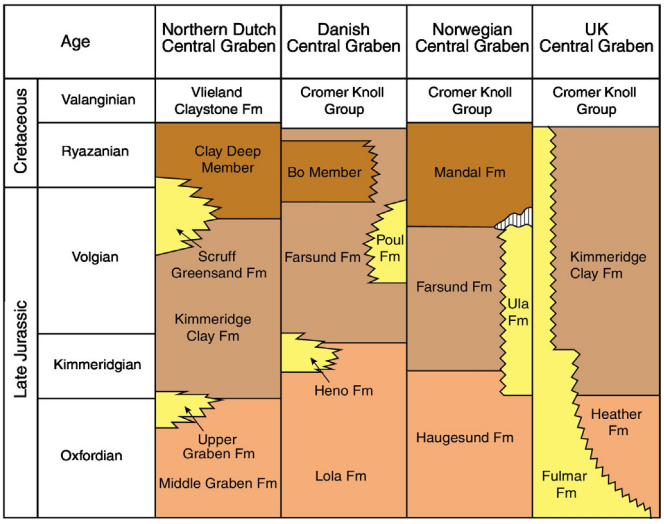

Fig. 1. Top: The Danish Central Graben with major structural elements, oil and gas fields and the location of the Jude-1 well. Bottom: Lithostratigraphy of the Upper Jurassic–lowermost Cretaceous marine shales in the North Sea region. The primary source rock in the Danish Central Graben is the Farsund Formation, including the Bo Member 'hot' shales.

(Norwegian North Sea) Justwan et al. (2006) correlated the dominating oil families to different organofacies of the time-equivalent Mandal Formation.

The organic richness level and source rock quality of the shales show lateral and stratigraphical variations in the petroleum generation potential (Justwan et al., 2005; Keym et al., 2006; Petersen et al., 2010a, 2012). Commonly an argillaceous shale section with high gamma-ray (GR) responses is observed in the upper part of the Farsund Formation. The section is normally preceded by argillaceous shales showing a gradual increase in GR level readings ('warming-up' trend) and is overlain by shales with considerably lower GR responses. This interval of 'hot' argillaceous shales in the Danish Central Graben is referred to as the Volgian–Ryazanian Bo Member (Michelsen et al., 2003; Ineson et al. 2003), and normally (but not always) the 'warming-up' trend and Bo Member argillaceous shales are associated with considerably increased organic richness and improved source rock quality (Petersen et al., 2010a, 2013). This part of the Farsund Formation is partly equivalent to the Clay Deep Member and Mandal Formation from the Dutch and Norwegian North Sea, respectively (Fig. 1). However, in the Danish Central Graben high GR responses do not always correspond to oil-prone shale intervals in the Farsund Formation (Petersen et al., 2010a, 2013). Other factors may affect the GR response, including borehole size and drilling mud weight (Thomas et al., 1985).

The Jude-1 well was drilled with oil-based drilling mud (OBM) as a vertical well in the central part of the Danish Central Graben < 10 km south of the Valdemar Field (Fig. 1). The OBM was of the type SIPDRILL 2/0 that is composed of C_{11}–C_{14} n-alkanes and <2% aromatics. The well reached a total depth (TD) of 3542 m (11,620 ft) into the Farsund Formation and included a 5–1/4 in. (13.34 cm) core taken from 2815 to 2858 m (9237–9377 ft) at the beginning of the 'warming-up' trend. The combined densely sampled core and cuttings from the Farsund Formation in this well provided a unique opportunity to carry out a detailed study of the Farsund Formation shales with the objectives to investigate (1) kerogen composition and source rock quality and (2) the adverse effect of oil-based drilling mud (OBM) on geochemical analyses.

2. Geological setting

The Danish Central Graben forms part of the Jurassic North Sea rift complex, and the graben consists of a system of NNW-SSE trending half-grabens bounded by the Coffee Soil Fault to the east toward the Ringkøbing-Fyn High and by the Mid North Sea High to the west (*e.g.* Japsen et al., 2003; Møller and Rasmussen, 2003). The Tail End Graben in the east (Fig. 1) is the dominant Jurassic structural element and contains >3000 m of Jurassic sediments. Further westward the Gert/Mjølner structure separates the Gertrud Graben from the Feda Graben, the latter forming the main Jurassic depocentre in the Norwegian Central Graben (Fig. 1). In both grabens the thickness of Upper Jurassic strata locally exceeds 1500 m. Rifting started in Middle Jurassic times and persisted into the Early Cretaceous. The syn-rift sedimentary fill is shale-dominated and includes the black shales of the Farsund Formation that were deposited from Kimmeridgian to Ryazanian times. These shales are underlain by the marine shales of the Upper Jurassic Lola Formation, which likely constitutes an additional but less rich source rock (Fig. 1).

The cored section in the Jude-1 well consists of homogenous to finely laminated shale with some silt. The sediments represent a low-energy and low-oxygen depositional environment with limited biodegradation and with more silty laminae deposited by very weak currents. The clay fraction of the shales mainly is illitic. The minor detrital fraction (principally silt-size) consists primarily of quartz but also calcareous grains which increase in proportion below approximately 2833 m (9294 ft). Larger fragments of bivalves and other bioclast fragments occur occasionally. The silt-sized siliciclastics, bioclasts and a minor amount of terrigenous organic matter likely were transported into the deeper basin by episodic dilute turbidites. Dolomitized stringers occur at several levels in the Farsund Formation.

3. Methods

A total of 167 cuttings samples were collected from the Farsund Formation in the depth interval 2697.48–3541.78 m (8850–11,620 ft). Furthermore, the cored section was sampled at ~30 cm (1 ft) intervals from 2816.35–2857.60 m (9240–9375.4 ft), including a densely sampled 30 cm interval at 2826.72–2827.02 m (9274–9275 ft) from which 30 samples were collected. In total, 166 core samples were collected. The screening analyses were carried out by the Geological Survey of Denmark and Greenland (GEUS). The samples were analysed for Total Organic Carbon (TOC, wt%), Total Carbon (TC, wt%) and Total Sulphur (TS, wt%) on a LECO CS-200 induction furnace. TOC was derived by removal of carbonate-bonded carbon by HCl treatment before combustion. Rock-Eval type data were derived from pyrolysis in a Source Rock Analyzer (SRA) instrument that yields similar data as the Rock-Eval instrument (S_1 [mg HC/g rock]: free hydrocarbons in the samples; S_2