Miocene oil-bearing diatom ooze from the North Sea

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In recent years there has been an increased interest in Neogene hydrocarbon accumulations in the North Sea. The production of gas from Pliocene–Quaternary deposits in the Dutch sector, the discovery of oil-bearing Miocene sands in the Lille John area and oil accumulation in middle Miocene deposits in the T-1 well in the northern part of the Danish Central Graben area, have documented Neogene hydrocarbon accumulations. Some of these deposits are of economic interest. This study presents an oil-bearing, middle Miocene diatom ooze in the Valhall Field (well 2/8-G-2), within the Norwegian sector (Fig. 1). The Valhall Field is located just north of the Danish–Norwegian sector boundary.

Geological setting

During the Miocene, the North Sea formed a silled-bounded basin with connection to the Atlantic Ocean via a strait between Norway and Shetland (Rasmussen *et al.* 2008; Fig. 1). The main sediment source areas were the Shetland Platform, which supplied sediments to the northern North Sea and the southern Scandes from which sediments were routed southwards into the south-eastern North Sea (Fig. 1). During the early Miocene relatively large delta complexes formed from these areas and resulted in eastward progradation off the Shetland Platform (Skade Formation; Eidvin *et al.* 2014) and south-westward progradation south of the southern Scandes (Ribe Group; Rasmussen *et al.* 2010). During the

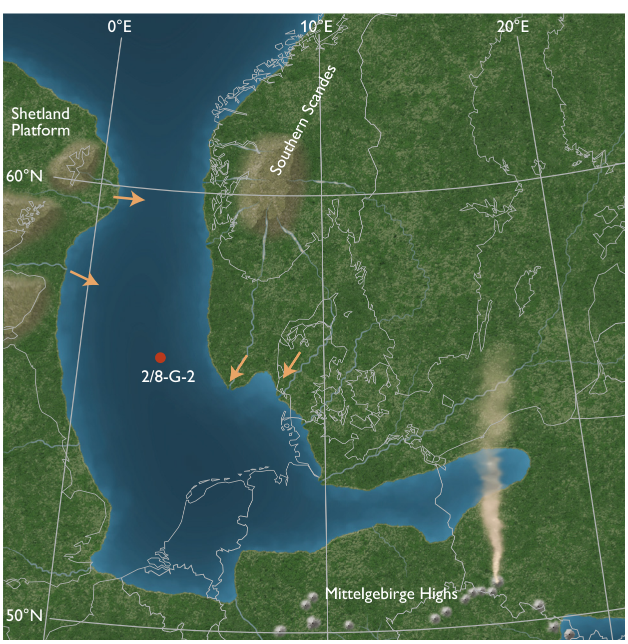

Fig. 1. Palaeogeographical reconstruction of the early Miocene North Sea. Note that the main sediment influx from the Shetland Platform (yellow arrows) filled the northern North Sea and that sediment supply to the eastern North Sea had its source in southern Scandes. Based on Rasmussen *et al.* (2008).

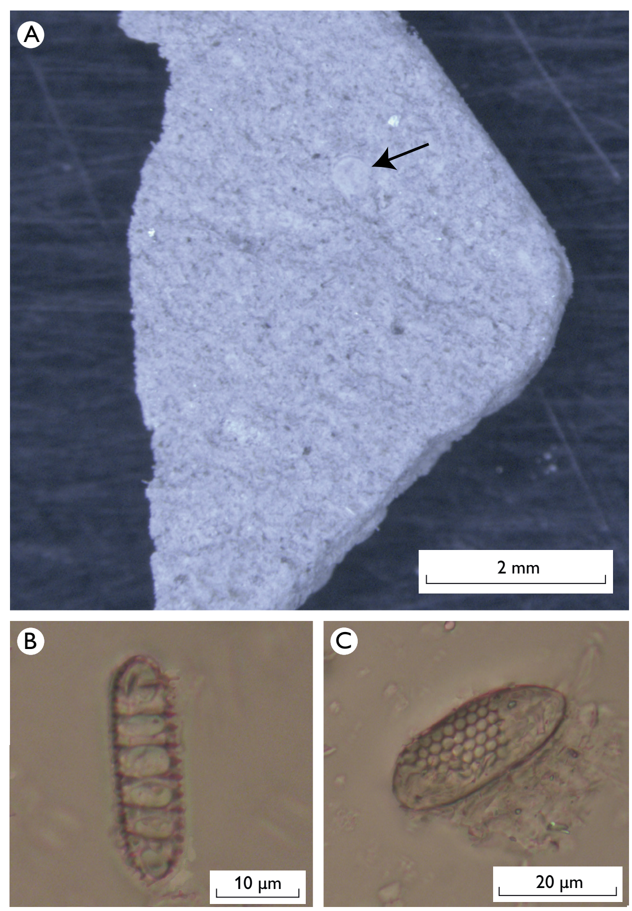

Fig. 2. Cored diatom ooze from the Valhall Field, Norwegian sector of the North Sea. **A**: Optical microscope image of chip of diatom ooze, note the diatom in the upper part (black arrow). **B**: ?*Denticulopsis kanayae.* **C**: ?*Denticulopsis nicobarica*.

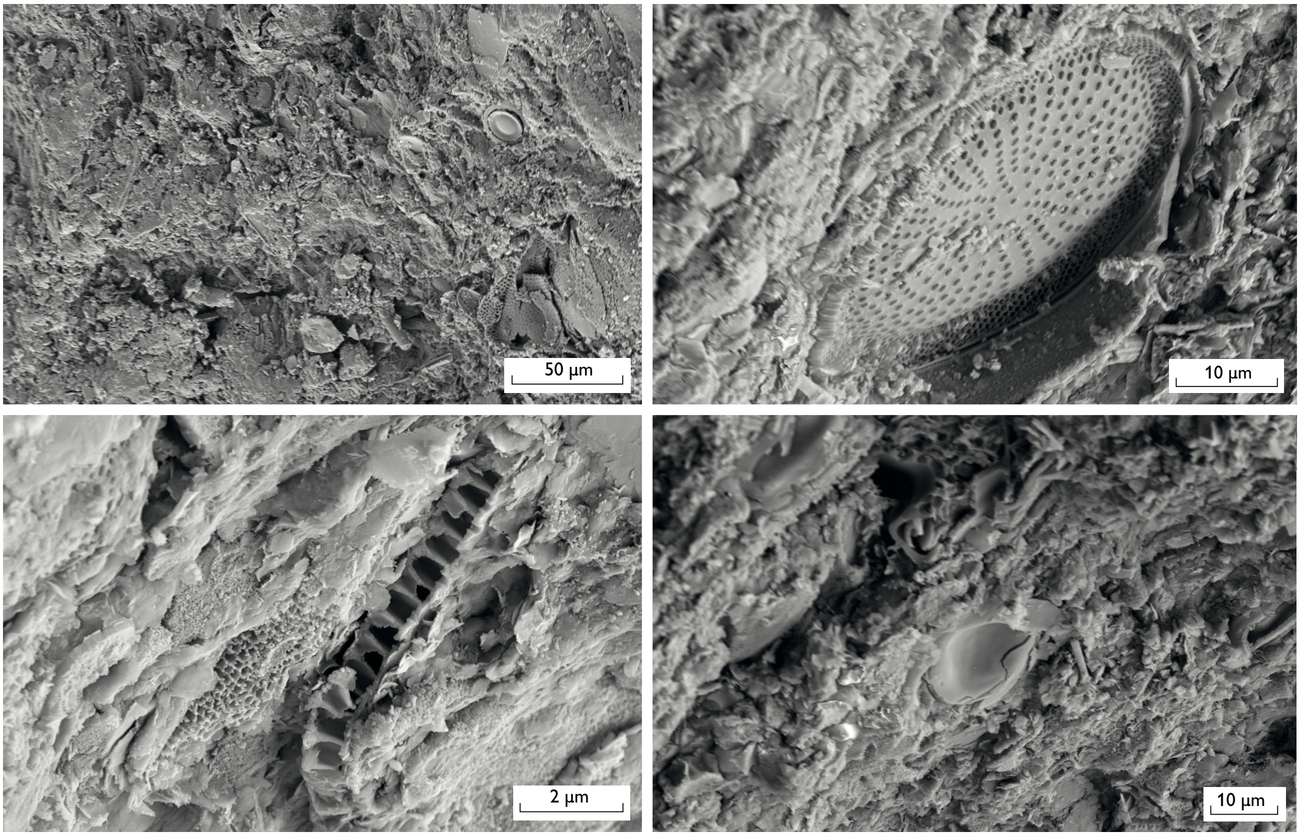

Fig. 3. Four scanning electron microscope images of the diatom ooze. Note the valve of the centric diatom *Thalassiosira* spp. in the upper right image.

middle Miocene these delta complexes where flooded due to reorganisation of the tectonic regime in North-West Europe which resulted in accelerated subsidence of the basin margins. Consequently, much of the North Sea was starved of sediment during the middle and early late Miocene.

The North Sea area was located in the western wind belt with seasonal storms. Therefore, the coast was strongly influenced by wave action. In the deeper basin, which was up to *c.* 1000 m deep, hemipelagic deposition predominated. A counter-clockwise current system redistributed and reshaped muddy sediments along the delta and shelf slopes within the basin (e.g. Hansen *et al.* 2004). During the early Miocene a humid, warm temperate climate predominated, similar to present day western Florida (USA). A change to a cooler climate commenced in the middle Miocene which probably also resulted in the enhanced influence of cold-water current systems from the Atlantic Ocean. Under these cooler climatic conditions diatoms bloomed and resulted in deposition of diatom ooze.

Diatom ooze

The diatom ooze is fine-grained and grey to brown, since it contains oil (Fig. 2). Diatom valves and radiolarians could be seen in optical and scanning electron microscopes (Figs 3, 4). The diatom ooze consists of a mixture of abundant diatom valves, radiolarians and clay (Fig. 4). The porosity is 50–60 %.

Porosity is mainly associated with diatom valves and either occurs inside the valves or in pockets next to the valves or other fossils. Reduced porosity is observed in some samples, attributed to clay intruding into the diatom valves. The permeability is assumed to be low, due to the small size of the pores and tortuous connectivity between the largest pores. The measured porosity of the diatom ooze would correspond to a permeability of 0.006–0.02 mD in diatom ooze from various localities in the Pacific Ocean (Gamage *et al.* 2011).

Nannofossils and microfossils

Core sample (1802.7 m from the well 2/8-G-2) was analysed for nannofossil, microfossil and the presence of diatoms. Diatom valves and debris were found to be common. Diatoms include ?*Thalassiosira* spp., ?*Denticulopsis kanayae* and ?*Denticulopsis niobarica*. *D. kanayae* and *D. nicobarica* range from the early to middle Miocene (Barron 1985; Fig. 2). The sample was barren with respect to nannofossils and the mi-

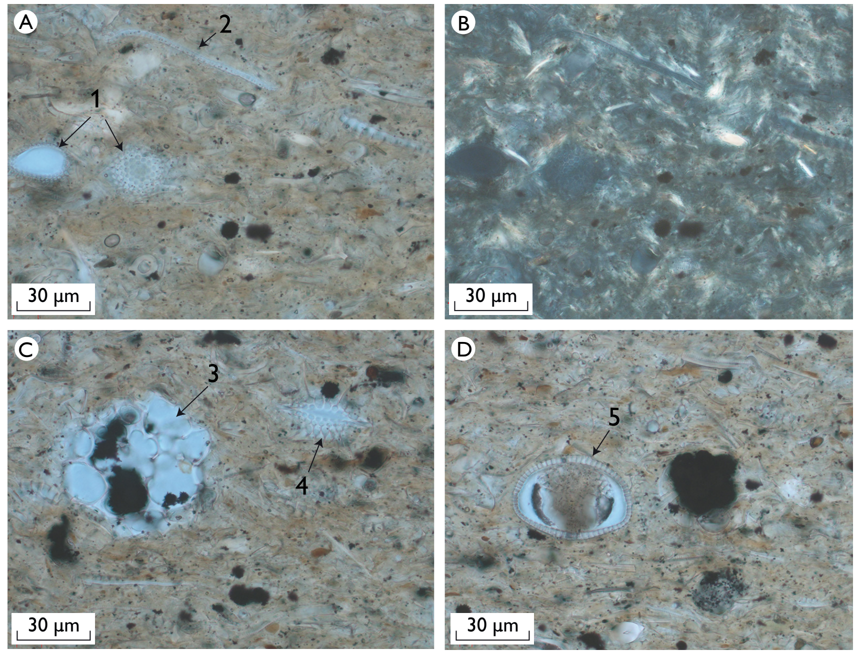

Fig. 4. Optical microscope images of the diatom ooze. The ooze comprises siliceous microfossils (e.g. diatoms and radiolarians) and clay. Porosity inside microfossils is recognised by the blue staining of the epoxy impregnating the ooze. A and B are identical; B with crossed nicols. **1**: *Stephanopyxis turris* (diatom). **2**: cross section of a diatom valve. **3**: ?*Peridinium longispinum* (radiolarian), **4**: ?*Stephanopyxis turris*. **5**: diatom frustule. Alexander Mitlehner, UK, kindly helped with the identification of the diatoms.

crofossil fraction yielded one radiolarian (*Cenodiscus* spp.) and no foraminifera.

Palynology

Six core samples were analysed for palynology (1797.0 m, 1802.7 m, 1803.4 m, 1813.0 m, 1819.0 m and 1827.0 m). In all samples, the assemblages of organic particles are characterised by a dominance of marine dinoflagellate cysts (dinocysts). Bisaccate and non-saccate pollen and wood particles occur very sporadically while no freshwater algae were recorded. The dinocyst assemblage is rich and diverse and the consistent presence of *Nematosphaeropsis* spp. and *Impagidinium* spp. indicates an outer neritic to oceanic setting (Brinkhuis 1994). An increase in cold-water tolerant dinocyst taxa (mainly *Habibacysta tectata*) was found (Fig. 5), ranging from no recordings in the lowermost sample, to sporadic occurrences in the next samples and common occurrences in the two uppermost samples. The occurrences of the dinocyst species *Unipontodinium aquaductum* in all six samples (Fig. 5) strongly indicate that the cored interval should be referred to the *Unipontodinium aquaductum* Zone of Dybkjær and Piasecki (2010). The age of this zone is mid-Langhian to early Serravallian (middle Miocene). The

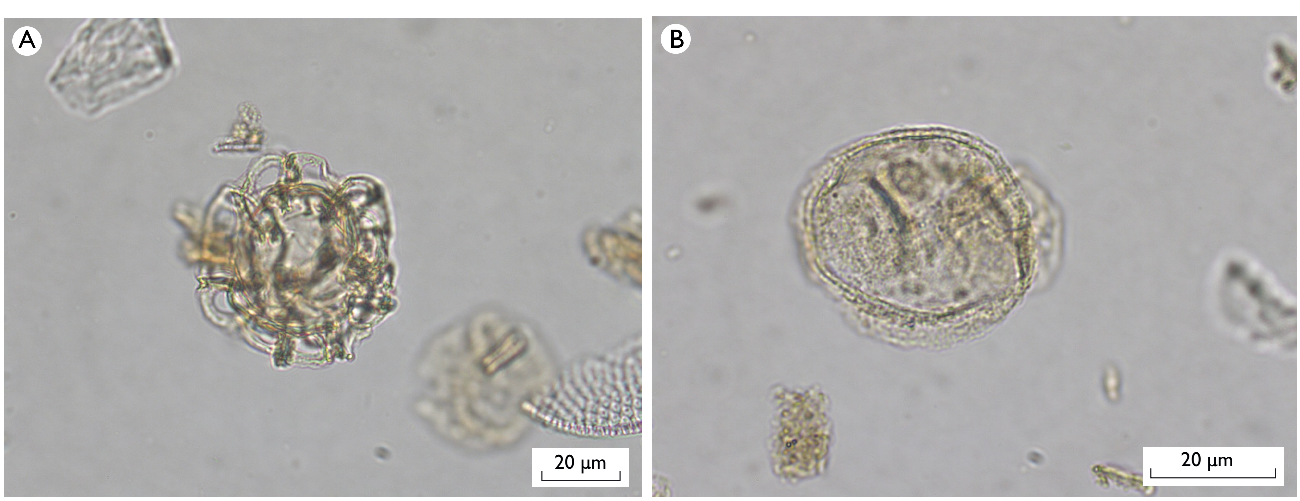

Fig. 5. Dinoflagelate cysts from the oil-bearing cores. **A**: *Unipotodinium aquaductum*. **B**: *Habibacysta tectata*. Increased abundance of *Habibacysta tectata,* a cold-water tolorant species, is probably associated with the climatic deterioration in the middle Miocene (Serravalian).

Unipontodinium aquaductum Zone occurs in the upper part of the Hodde Formation defined onshore Denmark which correlates with the lowermost part of the Nordland Group.

Depositional environment

Based on palynology and seismic stratigraphic studies (e.g. Rasmussen *et al.* 2005), the depositional setting was outer neritic to oceanic, with a water depth just below 1000 m. Late early Miocene biosiliceous, organic-rich sediments of the upper Lark Formation in the Central Graben area have been described by Sulsbrück & Toft (2018). This part of the upper Lark Formation was deposited at the termination of shoreline progradation from the southern Scandes (Ribe Group). The studied section represents slightly younger deposits than those laid down during the transgression of the lower Miocene Ribe Group. Consequently, the depositional environment was sediment starved and fully marine. The occurrence of cold water dinocysts in the studied cores, probably reflects the beginning of the middle Miocene (Serravallian) global climatic deterioration (Zachos *et al.* 2001).

Petroleum system

The oil-bearing Miocene diatom ooze from the Norwegian sector of the North Sea described here documents oil migration into younger deposits, which are normally considered to be non-prospective. In the Danish North Sea area, a number of wells have penetrated hydrocarbon-bearing strata of Miocene and Pliocene ages as described above. The oil-bearing deposits are found in the western and central parts of the Danish and Norwegian Central Graben. The oil probably has a source in the Jurassic shale deep in the Central Graben. Migration into Cenozoic deposits probably occurred along salt structures. Due to early Quaternary tilting of the North Sea Basin (Rasmussen *et al.* 2005), up-dip migration into stratigraphic and structural traps located in the eastern part of the Central Graben area and the Ringkøbing–Fyn High may have occurred. This calls for a total re-evaluation of the petroleum system of the Cenozoic succession in the North Sea area.

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