Geology and seepage in the NE Atlantic region

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Abstract: Exploration for hydrocarbons in the NE Atlantic mainly focuses on the central eastern margin. The western margin has remained virtually unexplored, with no exploration wells drilled so far. A cost-efficient way to infer the presence of natural hydrocarbons in the poorly explored regions of the NE Atlantic is the application of synthetic aperture radar (SAR). This study presents four areas, the Western Barents Sea Margin, the Irish Atlantic Margin, East Greenland and Jan Mayen, where clustered oil-slick data indicate possible active oil seepage. The eastern margin of the NE Atlantic contains numerous oil-slick observations, but along the western margin the number of observations is limited, partly due to a persistent sea-ice coverage. Based on the tectonostratigraphic setting, it is suggested that Triassic and Jurassic source rocks are the most likely candidates for the generation of seeps in the areas studied. Near Jan Mayen and East Greenland, Cenozoic source rocks could also be present. SAR data are a useful tool in an early stage of exploration, but further work is needed to improve the understanding of the subsurface below the observed oil slicks in the NE Atlantic to determine the origin of the seepage.

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The North Atlantic has a long history of major basin-forming events. Therefore, it is an area ideally suited for hydrocarbon exploration. By the 1950s, significant oil and gas production had started in many places, including in the enormous Groningen gas field in The Netherlands. This field triggered exploration for stratigraphic equivalents offshore in the North Sea towards England (Breunese & Rispens 1996). By the early 1960s, these were confirmed and the era of major exploration in the North Sea was underway. Coincidently, the theory of plate tectonics was developed, providing a new paradigm that would prove to be fundamental for unravelling the geological history and development of these economically important areas.

Today, the North Sea is considered a mature area for exploration and for the last decade production has been in decline. In response, exploration has turned towards frontier areas along the eastern margin of the NE Atlantic – less explored and, possibly, higher risk areas such as the mid-Norway margin, further offshore around Rockall, the Faroes and the Barents Sea (see Brennand et al. 1998).

Approximately 260 oil and gas fields have been discovered within the NE Atlantic area. Most of them are concentrated along the eastern margin of the NE Atlantic Ocean in the Tromsø-Hammerfest Basin, Trondelag Platform, Viking Graben and Shetland Basin (Fig. 1). Along the western margin in East Greenland, five exploration and exploitation licences are currently active, despite tough circumstances such as the challenging (sub-)Arctic environmental conditions (Fig. 1). To date, 14 wells have been drilled offshore Greenland, all of them scientific wells, of which the deepest reached 1310 m below seabed (Ocean Drilling Program (ODP), Leg 152, Site 918). No hydrocarbon exploration wells have been drilled and no 3D seismic surveys have been shot.

Both margins of the NE Atlantic share a similar pre-break-up geological history due to their conjugate nature. The collision of Baltica and Laurentia during the Late Silurian caused the Caledonian Orogeny. Subsequent collapse of the Caledonian belt was followed by a long history of extension linked to the Mesozoic break-up of Pangaea and, ultimately, to the early Cenozoic opening of the NE Atlantic Ocean at approximately 56 Ma. A detailed overview of the Upper Palaeozoic–Mesozoic stratigraphy of this region is provided by Stoker et al. (2016).

One cost-efficient way to infer the presence of natural hydrocarbons in the poorly explored regions of the NE Atlantic is the application of remote-sensing images. Synthetic aperture radar (SAR) is a tool which has proven to be reliable for the detection of oil slicks at the ocean surface (e.g. MacDonald et al. 2002; Williams & Lawrence 2002; Garcia-Pineda et al. 2010; Crooke et al. 2015). The advantages of SAR images are their large areal coverage and the repeatability of observations during multiple consecutive time intervals. Combining
Fig. 1. The NAG-TEC Atlas study area. Yellow boxes mark the locations of the study areas: (a) Western Barents Sea Margin; (b) Irish Atlantic Margin; and (c) East Greenland and Jan Mayen. Slick clusters represent areas of enhanced slick density and may include natural oil seeps. See the text for data explanation (oil-slick data provided by CGG: GOSD 2014). The absence of slick clusters NE of Greenland is mainly due to the year-round sea-ice cover in that area, hampering satellite observations (sea-ice extent from Fetterer et al. 2002). Hydrocarbon field polygons were kindly provided by IHS Energy in 2014 (http://www.ihs.com) and Greenland licences come from the Government of Greenland (Minerals and Petroleum Licence Map, http://licence-map.bmp.gl). Bathymetry and elevation data were compiled in the NAG-TEC project.
oil-slick observations with publically available knowledge of the geology of the underexplored regions in the NE Atlantic provides insight into their hydrocarbon potential. The aim of this work is to identify areas of active oil seepage and thus the existence of possible active petroleum systems using clustered oil-slick data from the Global Offshore Seepage Database of CGG’s NPA Satellite Mapping Group (GOSD 2014).

The study focuses on four underexplored regions: (1) the Western Barents Sea Margin; (2) the Irish Atlantic Margin; (3) East Greenland; and (4) Jan Mayen (Fig. 1).

Methods

Oil-slick data

Oil slicks on the ocean may be the surface expression of oil seeps rising from the seafloor and can therefore be used for source de-risking in new ventures exploration. Seepage data in this study derive from the Global Offshore Seepage Database (GOSD 2014), which contains over 20 000 records of satellite-sourced SAR images. Conventional SAR satellites are single-wavelength, side-looking radars with polar orbits and return visit times of about 1 month, although newer SAR platforms have both higher spatial resolution and shorter revisit times. The ocean surface is therefore imaged multiple times, which, under optimal weather conditions, allows repeat slicks to be located. In the vast majority of cases, these slicks derive from leaking hydrocarbon traps. Important exceptions include leaking wrecks or pipelines on the seabed. NPA’s seep-detection methodology identifies three types of slicks: pollution, natural film (e.g. from plankton, algal blooms) and natural oil seeps. The data presented here show only generalized clusters of natural oil seeps with multiple repeats within the NAG-TEC Atlas study area (Fig. 1). For proprietary reasons, individual seep locations are not shown. Details on this methodology are given in Williams & Lawrence (2002).

The SAR methodology is much less effective in regions with temporal or permanent sea-ice cover or in areas with strong currents. The absence of slicks along the NE Greenland Margin (e.g. in the region of the Danmarkshavn Basin) is probably due to the nearly year-round sea-ice cover (Fig. 1). The onshore geology, nonetheless, has important similarities to the mid-Norway margins and the Barents Sea, suggesting that highly prospective areas may be present offshore NE Greenland.

It should be emphasized that SAR oil-seep detection has certain limitations, and geochemical sampling of either the surface slicks or of the seabed vents generating the slicks (by shallow coring) will be required to prove a hydrocarbon source. Repeating slicks only imply the presence of a working petroleum system of some kind; further validation will be required to confidently de-risk the presence of a mature source rock and oil-filled reservoirs in the unexplored basins of the study area.

Geological data

An up-to-date assessment of the present understanding of the Devonian and younger stratigraphy of the NE Atlantic conjugate continental margins was made for the NAG-TEC Atlas using published and publically available material (Hopper et al. 2014). In addition, knowledge and expertise of contributors, unpublished information from contributing geological surveys, and released commercial wells were used for the atlas. Lithological columns summarizing key lithologies of the three areas were produced using the more detailed stratigraphic columns presented in Stoker et al. (2016). In addition, country-specific petroleum-geology-related data were taken from the Norwegian Petroleum Directorate (NPD; http://factpages.npd.no/factpages/), the Irish Petroleum Affairs Division (Department of Communications, Climate Action and Environment, Petroleum Affairs Division (PAD); DCCAE; http://www.dccae.gov.ie/natural-resources/en-ie/Oil-Gas-Exploration-Production/Pages/home.aspx#) and the Government of Greenland (Minerals and Petroleum Licence Map, http://licence-map.bmp.gl).

The underexplored status of the study areas implies that there is an inherent large degree of uncertainty with respect to stratigraphy and geology. Many locations have few or no wells. In such cases, the understanding of the subsurface is mostly based on interpretation of seismic lines or outcrops.

Distribution of oil slicks

In general, oil-slick observations are most numerous along the eastern margin of the NE Atlantic and limited along the western margin. Below, the locations of clustered oil slicks in four underexplored regions of the NE Atlantic are presented.

The Western Barents Sea Margin contains many observations of oil slicks. The cluster region covers an area of roughly 25 000 km². The density of 2D seismic reflection surveys in the region is relatively high, reaching up to 7.5–10 line km km⁻² (fig. 6.1 in Funck et al. 2014), and there are about 100 wells. The cluster of oil slicks measures roughly 340 km in length and up to 90 km in width (Fig. 2). Because the oil-slick dataset used only covers the NAG-TEC study area, no oil slicks are shown in waters above the Hammerfest Basin, where, for example, the Goliat oil field is situated. Within the
oil-slick cluster, two oil fields are present: Gohta and 7120/01-02, both on the Loppa High. The slicks occur in waters above the Tromsø and Harstad basins, especially above the Ringvassøy–Loppa Fault Complex (Fig. 2).

The oil slicks identified offshore Ireland occur in four clusters (Fig. 3). A cluster offshore NW Ireland measures 170 km in diameter, and is located above the Erris Basin and the Eastern Rockall Basin. Further south, a cluster is located close to the coastline and is centred around Achill Island. It measures roughly 100 km in diameter and lies east of the Slyne Basin, relatively close to the shoreline. Southeast of that lies the smallest cluster, which measures roughly 100 km in length and 70 km in width. It is located along the eastern margin of the Porcupine Basin and the bordering basins. Finally, the largest cluster is present above the Porcupine High, and measures 200 km in length and up to 160 km in width. Three oil fields have been discovered in this region: Bandon, Connemara and Burren. They are all located outside of the four oil-slick clusters.

Along the western margin of the NE Atlantic no oil fields have been discovered yet (Fig. 4). In this region, the detection of oil slicks is hampered by sea-ice (Fig. 4). This has its largest extent in March and its minimum extent in September (Fetterer et al. 2002). Repeated satellite radar observations of this region are limited to the ice-free summer period between minimum and maximum ice-extent. Three oil-slick clusters have been observed offshore East Greenland. Two of these occur nearly completely seawards of the continent–ocean boundary (COB) as defined by Funck et al. (2016). The smallest East Greenland cluster is located in the approximately 20 km-wide King

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**Fig. 2.** Detailed map of the Western Barents Sea Margin, showing regional structural basins and highs (Funck et al. 2014), and the area within which oil slicks have been observed (oil-slick data provided by CGG: GOSD 2014). The presence of oil and gas fields demonstrates that an active petroleum system is in place, mainly in the Hammerfest Basin.
Oscar Fjord. This area lies to the north of the Jameson Land Basin in which two exploration and exploitation licences were granted by the Greenland Government in June 2015 (Fig. 4). The next oil-slick cluster lies approximately 100 km off Scoresby Sund and measures roughly 90 km in diameter. It is not located above a known basin, but lies 65 km seawards from the COB. The southernmost cluster lies south of the onshore Kangerlussuaq Basin (Fig. 4). The L-shaped cluster is located around...
the COB and measures 275 km in length along its longest axis.

In the area of the Jan Mayen microcontinent, two small oil-slick clusters were identified. The northernmost cluster is located NE of the Jan Mayen Ridge, and lies seawards of the COB (Fig. 4). The cluster in the south is located above the structural elements of the Hléssund Trough and the Hakarenna Channel. Within the Jan Mayen microcontinent, only five wells have been drilled, which are all scientific Deep Sea Drilling Project (DSDP) wells.

**Discussion**

**Western Barents Sea Margin**

The oil slicks along the western edge of the Hammerfest Basin – outside of the NAG-TEC study area – coincide with several oil fields in this active petroleum system (Fig. 2). The source rocks of the Goliat Field are considered to be located in the Lower–Middle Triassic Sassendalen Group and in the Upper Jurassic Hekkingen Formation (Fig. 5).
(Bjorøy et al. 2009). Marine shales of the Sassendalen Group were deposited under anoxic conditions and have a high organic content, making them a potentially important hydrocarbon source rock (Worsley 2008; Bjorøy et al. 2009). The Upper Triassic Fruholmen Formation has been identified in various wells in the Hammerfest Basin (Fig. 5). A potential Triassic oil source rock is present in the Kapp Toscana Group. The Hekkingen Formation also has a marine origin with organic shales deposited under anoxic conditions (Bjorøy et al. 2009). Analyses of the source rocks from the Hekkingen Formation in the central Barents Sea (well 7430/10-U-01: 74° 12′ 47.79″ N, 30° 14′ 44.22″ E) show total organic carbon (TOC) values ranging between 3 and 36 wt% (Langrock et al. 2003). This unit is up to 350 m thick in the Hammerfest Basin, but thins into the centre of the basin: a consequence of active doming along the axis of the basin (Dallmann 1999). The deposits from the Hekkingen Formation are oil mature. The overlying Lower Cretaceous Kolje Formation also shows an initial oil potential (Pedersen 2014).

Oil slicks have been observed in waters above the Tromsø Basin. However, their origin is difficult to assess due to the poorly explored status of the basin, where no well penetrates its centre (Fig. 2). Seismic data show a series of tilted fault blocks, of which the faults do not appear to reach the surface (fig. 13a in Stoker et al. 2016). East of the basin centre, well 7119/7-1 (total depth (TD) = 3134 m total vertical depth (TVD) in Permian deposits) did not encounter Lower Cretaceous or Upper Jurassic oil-source prone sediments (NPD: factpages.npd.no/factpages/). Along the western edge of the Tromsø Basin, the Cretaceous succession is very thick but no hydrocarbons were found (3625 m in vertical well 7117/9-2). Jurassic sediments are inferred in the Tromsø Basin but are not proven. Because the Hammerfest Basin and the intermediate Ringvassøy–Loppa Fault Complex contain both Jurassic and Cretaceous rocks, they are also expected to be present in the Tromsø Basin, where they probably generate the hydrocarbons related to the observed seepage.

Wells further away from the Tromsø Basin show various Mesozoic deposits. In exploration well 7219/9-1 (TD = 4286 m TVD in Late Triassic deposits) in the Bjørnøyrenna Fault Complex (Fig. 2), a relatively complete succession of at least 2050 m of the Upper Triassic Fruholmen Formation was found. It consists of interbedded mudstone, shale, sandstone and thin coal (Hjelstuen 2014). In particular, the basal grey to dark grey shales may be candidates for oil generation. Black shale samples from this well have TOC values of 1.3–3.6% (Hoare & Bathurst 2010). The well also contains the Lower Cretaceous Kolje Formation containing residual hydrocarbons (NPD: factpages.npd.no/factpages/). To the east, well 7219/8-S1 (TD = 4404 m TVD in Early Jurassic deposits) found Upper Jurassic and Lower Cretaceous sandstones and mudstones (Fig. 2). The Hekkingen Formation (Fig. 5) only contained mudstones without potential oil-source rocks, while the silty parts of the overlying source-rock-barren Knurr Formation contained some hydrocarbon shows (NPD: factpages.npd.no/factpages/).

East of the Tromsø Basin in the Hammerfest Basin, sediments belonging to the Lower–Middle Triassic Sassendalen Group were found in well 7120/12-2 (TD = 4667 m TVD in pre-Devonian rocks). They consist of sand and siltstones but not shales with organic-rich intervals. This well also contains oil-prone source rocks belonging to the Hekkingen and Kolje formations (Fig. 5). However, all sediments in this well down to 2500–3000 m are immature and unlikely to generate hydrocarbons (NPD: factpages.npd.no/factpages/).

The other oil slicks in the region are located in the Harstad Basin, where no public well data are available (Fig. 2). Based on seismic data and 3D modelling studies, the total thickness of the sedimentary succession in the Harstad Basin is expected to reach more than 10 km (Ebbling & Olesen 2010; Funck et al. 2016). According to Halland et al. (2014), the basin is part of a structurally defined deep Cretaceous basin that stretches northwards to the Bjørnøya Basin. This large sediment thickness and the presence of oil slicks suggest that source rocks and leaky seals may be present and that petroleum may be generated from the Harstad Basin.

In general, exploration in the SW Barents Sea region has yielded abundant gas and relatively little oil. This may be explained by Cenozoic exhumation and depressurization of hydrocarbon-bearing reservoirs, which possibly results from glacial erosion during Pleistocene glaciations (Corcoran & Doré 2002; Cavanagh et al. 2006). However, a recent study based on thermochronology challenges this idea by presenting results which suggest that the last important phase of exhumation occurred during the late Miocene–early Pliocene (Zattin et al. 2016).

Summarizing, upwards-migrating hydrocarbons are likely to be found on the flanks of basins in the Barents Sea where partly leaking seals occur (Ohm et al. 2009). The presence of oil slicks, faults which may act as conduits for oil migration from leaky reservoirs or source rocks, and the occurrence of formations with source rocks in the area suggest that in this region petroleum is being generated and migrates towards the surface.

Irish Atlantic Margin

The Irish Atlantic Margin contains two large basins bordered by several smaller basins. The Rockall
In the Slyne Basin:
- type-II oil-prone shales (Toarcian); TOC 6.5% (well 27/9-1)
- predicted to be present in basins along Rockall Basin Margins (PAD, 2006)

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mudstone/shale       conglomerate       dolomite
siltstone            volcanics         evaporite
sandstone            limestone/chalk  source rock (grey = inferred)
Basin is the largest basin in this area (Figs 1 & 3) and is filled with a thick sedimentary succession of Cenozoic age. The smaller Porcupine Basin is located further south (Fig. 3), and contains a thick succession of Cretaceous and Cenozoic deposits (fig. 15 in Stoker et al. 2016). In both basins, Jurassic and Permo-Triassic rocks have been encountered along the basin margins. The two basins experienced rapid subsidence and relatively starved sedimentation since the mid-Cenozoic, following the regional sagging event described by Praeg et al. (2005). According to current knowledge, only the Jurassic sedimentary succession along the Irish Atlantic Margin (Fig. 5) contains oil-prone source rocks (PAD 2006).

Oil and gas fields in Atlantic Ireland are rare, but the presence of an active hydrocarbon system is demonstrated by numerous shows and several discoveries (PAD 2006). Important discoveries include the Dooish gas condensate on the NE Rockall margin, the Corrib gas field in the Slyne Basin, the Connemara oil field and Jurassic discoveries in the Porcupine Basin (Fig. 3). Indications of hydrocarbons are seen based on the presence of gas chimneys and seeps in areas not yet explored (PAD 2006). The source rock of the Dooish gas condensate discovery is thought to be a Jurassic oil-prone mudstone.

The northernmost cluster of oil slicks along this margin is located near the Erris Basin and the Eastern Rockall Basin (Fig. 3). Two wells penetrating the sedimentary succession in this area (19/5-1 and 12/2-1z) encountered Jurassic sediments. In well 19/5-1, a succession of limestones and mudstones of 255 m thickness has been interpreted and dated to the Hettangian–Sinemurian based on biostratigraphic data (Odell & Thomas 1978). Well 12/2-1z encountered 136 m of sandstones and gravels, which are inferred to be of Middle Jurassic age based on regional data (Mecklenburgh 2004; MELLENIA 2004). Although no source rocks were found in the Jurassic succession of this well, it does have a hydrocarbon column with a net thickness of 187 m in Upper Permain and overlying Middle Jurassic sandstones right below the base-Cretaceous unconformity (3951 m along hole). The well was plugged and abandoned as a gas condensate discovery in 2003 (PAD 2006). The seeping hydrocarbons are probably generated from Jurassic source rocks in this region.

The cluster of oil slicks east of the Slyne Basin is difficult to assess since no wells penetrate the underlying succession and no seismic data were available to the NAG-TEC project. Modelling studies indicate that the total thickness of the sedimentary succession in this area may be of the order of 1–2 km (fig. 6.22 in Funck et al. 2014). This succession may contain oil-prone source rocks which are as yet unknown. West of this oil-slick cluster in the Slyne Basin, Toarcian Type-II oil-prone shales were encountered in well 27/13-1A (Figs 3 & 5). Analyses showed TOC values of up to 6% and a hydrocarbon index (HI) of 205–539 (PAD 2006). To the south, deposition of these shales occurred in a more open-marine environment and TOC values drop to approximately 1%. In the Rockall Basin, thermogenic oil seeps (from gravity core geochemistry) and gas chimneys on seismic data have been observed, providing evidence for an active petroleum system (PAD 2006). Despite careful screening of the oil-slick observations, it is also possible that the slicks east of the Slyne Basin have been transported there from the Slyne Basin area by strong winds and currents. Alternatively, they may originate from other sources than seepage. However, shipping is of moderate intensity in this region and not many shipwrecks are known according to the Irish programme INFOMAR (2016). Therefore further work is needed to determine the origin of the slicks here.

Oil slicks were identified along the eastern margin of the Porcupine Basin and on both sides of the Porcupine High (Fig. 3). On both sides of that high, deposits of Kimmeridgian age have been encountered: for example, in wells 43/13-1, 34/19-1, 35/19-1 and 35/8-2 (PAD 2006). Seismic and well data suggest the presence of tilted fault blocks on both sides of the Rockall and Porcupine basins that potentially host Jurassic source rocks and stratigraphic traps. Hydrocarbons may use the faults for migration towards the surface to generate seepage slicks. Some of these faults reach up into the Neogene succession, although they do not appear to reach the surface (fig. 15c in Stoker et al. 2016). Regional 3D basin modelling demonstrates the potential for generation and expulsion of substantial volumes of hydrocarbons from these source horizons, with generation still continuing at the present time (PAD 2006). Shows in numerous wells across the Porcupine Basin and throughout the stratigraphic column have been reported. Although well data are lacking in the southern Porcupine Basin, thermogenic oil seeps provide positive evidence for a petroleum system in that area. Gas chimneys

**Fig. 5.** Schematic lithostratigraphic correlation diagram showing the general lithology and (potential) source rocks of the study areas. Vertical black lines indicate the presence of a lithostratigraphic unit containing source rock. The diagram was mainly drawn using regional stratigraphic correlation panels in Stoker et al. (2016) and data from PAD (2006).
are also found in the Porcupine Basin (PAD 2006). Oil and gas fields are present to the north of the Porcupine Basin, but no oil slicks were found in that area. This suggests that the seal there is working. The Connemara oil field, the Spanish Point gas and oil field, and well 35/8-2 (oil) are known to have their source in Upper Jurassic mudstones, which are age-equivalent to the Kimmeridge Clay Formation of the North Sea (Fig. 5) (PAD 2006). In summary, the observed oil slicks add to the available data which imply that petroleum is being generated in these basins.

**East Greenland**

The basins along the eastern, NE and northern margin of Greenland resulted from Palaeozoic to Mesozoic rifting (Fig. 1). Borehole control for the offshore basins is absent in the areas where oil slicks have been identified. For details on the Greenland margin tectonostratigraphy, the reader is referred to Stoker *et al.* (2016).

The oil-slick cluster in King Oscar Fjord is structurally located in the Jameson Land Basin. The stratigraphy of this basin is relatively well known as a result of outcrop studies and onshore–offshore correlation. Because of a lack of well data, it is unknown which parts of the Jameson Land Basin stratigraphy are present underneath the King Oscar Fjord. A geoseismic section in the basin shows the presence of Palaeozoic and Mesozoic rocks (fig. 12d in Stoker *et al.* 2016). Outcrop studies in onshore Greenland indicate the presence of source-rock shales of the Upper Permian Ravnefjeld Formation belonging to the Foldvik Creek Group (Stemmerik *et al.* 1998). Two of the five units identified in the shales are organic-rich and laminated. They were deposited under anoxic conditions and their hydrocarbon quality is considered good to excellent, with TOC values of between 4 and 5%, and a HI of 300–400 (Christiansen *et al.* 1993).

Besides the Permian source rocks, there are the dark grey to black marine mudstones of the Bernbjerg Formation which are Late Jurassic in age (Fig. 5). They were deposited in a proximal marine setting, based on plant debris and coal fragments in the sediment (Alsgaard *et al.* 2003). Measured TOC values range between 2.8 and 5.4%, and HI varies between 32 and 143 (Alsgaard *et al.* 2003). The slightly younger Hareelv Formation consists of black organic-rich mudstones (Fig. 5). The sediments were deposited in a slope and base-of-slope setting, and form the youngest preserved sediments in much of southern Jameson Land (Surlyk 1987). Besides massive sandstones, the formation contains mudstones that were deposited in poorly oxygenated environments. The TOC varies from 1 to 13% and the HI is <350 due to the dominantly Type-II kerogen (Stemmerik *et al.* 1998). Because the oil-slick cluster in the King Oscar Fjord lies at the northern edge of the Jameson Land Basin, one may speculate that oil possibly leaks to the surface along basin-bounding faults that appear to reach the surface in the geoseismic section (fig. 12d in Stoker *et al.* 2016).

The oil-slick cluster located east of the Scoresby Sund is seawards of the COB where only oceanic crust is present (fig. 6.19 in Funck *et al.* 2014). A Cenozoic sediment package in which the thickness decreases in an offshore direction from 3000 to 200 m is estimated to overlie the oceanic crust here (fig. 6.22 in Funck *et al.* 2014). Owing to a lack of well or seismic data, the uncertainty remains large, as indicated by the estimates by Voss *et al.* (2009) which present sediment-thickness values of up to 5000 m for this area. The oil slicks may originate from a yet unknown source rock in the thick Cenozoic succession that is visible on a geoseismic section just north of this location (fig. 12d in Stoker *et al.* 2016). The thinning of the total sediment thickness may point to a similar Cenozoic fan-type deposit below the observed oil slicks. No oil-source rocks are known from the Cenozoic in this region.

The southernmost oil-slick cluster south of the Kangerlussuaq Basin is also located seawards of the COB (fig. 6.19 in Funck *et al.* 2014). The cluster is underlain by oceanic crust, and modelling studies estimate a total sediment thickness of between 0 and 700 m (fig. 6.22 in Funck *et al.* 2014). However, there is a large range of estimated thickness values, with the highest ones reaching up to approximately 1500 m (Voss *et al.* 2009), implying a great degree of uncertainty due to a lack of well and seismic data. For both East Greenland clusters seawards of the COB, no structurally defined sedimentary basins are expected at those locations (Stoker *et al.* 2016). This implies that either the mapped location of the COB needs revision or the seepage origin for these slicks is debatable. Further work is needed to verify the origin of these slicks.

**Jan Mayen**

The Jan Mayen microcontinent (Fig. 4) is a distinct structural entity located between the volcanic complex of Jan Mayen Island in the north and the NE coastal shelf area of Iceland in the south (Svellingen & Pedersen 2003; Blischke *et al.* 2016). The stratigraphic succession of the Cenozoic displays a marked east–west asymmetry (Blischke *et al.* 2014). On the eastern margin of the microcontinent, Palaeogene rocks dip steeply towards the Norway Basin as a result of normal faulting (fig. 16 in Stoker *et al.* 2016). On the western margin, a west-facing listric normal fault system is present, with rotated crustal blocks that are downfaulted...
The oil-slick cluster in the north of the Jan Mayen microcontinent lies seawards of the COB where no basin is thought to be present (Fig. 4). However, the total sediment thickness is modelled to range between 2500 and 5500 m (fig. 6.22 in Funck et al. 2014). This suggests the presence of some kind of basin or accommodating structure that may contain source-rock-bearing deposits. Unfortunately, no well or seismic data can confirm the presence and internal structure of the thick sediment package. Potential oil-source rocks are most likely to be no older than the Eocene, since east of the Jan Mayen Ridge older successions are covered by a thick layer of Palaeogene volcanic rocks (fig. 16 in Stoker et al. 2016), which probably hamper upwards oil migration from underneath. No information on Cenozoic source rocks in this region is currently available.

To the south of the Jan Mayen microcontinent, an oil-slick cluster has been identified above the Hăıssund Trough and Hakarenaa Channel where a sediment package of 300–3000 m is inferred (Funck et al. 2014). The structural setting of the microcontinent suggests that its pre-Palaeogene stratigraphic succession might be comparable to the Jameson Land Basin in East Greenland and the Møre Basin in SW Norway (Blischcke et al. 2014). Consequently, the organic-rich Upper Jurassic Hareelv Formation may be present here and sourcing the seepage (Fig. 5).

A seafloor sampling campaign along the Jan Mayen Ridge in 2011 found indications for active oil seepage (without the observation of oil slicks at the ocean surface) and the presence of petroleum basins (Polteau et al. 2012). Sampling was carried out at a location along a 2D seismic line, JM-17-85, which is located approximately 100 km NE of the area where oil slicks were observed (Fig. 4). This supports the suggestion that petroleum is being generated to the south of the Jan Mayen microcontinent.

Conclusions

This study presents the distribution of oil-slick clusters in the NE Atlantic Ocean. Oil slicks were detected using synthetic aperture radar (SAR), which provides a cost-effective way to infer the presence of natural hydrocarbons in a frontier area, such as the NE Atlantic. Most clusters occur along the eastern margin of the NE Atlantic – the western margin shows fewer oil slicks. This unbalanced distribution can be explained by the presence of sea-ice near Greenland, which hampers satellite radar observations of seepage.

Four areas were studied in more detail. Despite the underexplored status of these areas, some preliminary conclusions may be drawn:

- **Western Barents Sea Margin**: seepage in the Tromsø Basin is most likely to originate from Triassic and/or Jurassic source rocks embedded in tilted fault blocks. The origin of seepage in the Harstad Basin could not be determined due to a lack of subsurface data.
- **Irish Atlantic Margin**: the only known source rocks offshore Ireland are of Jurassic age. The observed oil slicks are probably seeping from them along bounding faults of tilted fault blocks.
- **East Greenland**: seepage in the King Oscar Fjord is inferred to originate from source rocks as found in outcrops, since no wells penetrate the sediments in the Jameson Land Basin. These source rocks are of Late Permian, Late Triassic–Early Jurassic and Late Jurassic age.
- **Jan Mayen**: seepage to the south of the Jan Mayen microcontinent may be from a source rock of Late Jurassic age, equivalent to source rocks in the Møre and Jameson Land basins in Norway and Greenland, respectively;
- **Oil slicks observed seawards of the COB in East Greenland and the north of the Jan Mayen microcontinent** may indicate the presence of yet unknown basins or Cenozoic source rocks.

The current knowledge of the petroleum systems over a large part of the NE Atlantic where seeps are observed is still too limited, so further work is necessary. A first step could be the localization and sampling of the observed oil slicks to come to a first-order ranking of the most promising prospective areas. In addition, the collection of subsurface data from the underexplored regions is crucial for a better understanding of their petroleum geology.

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