Inversion structures as potential petroleum exploration targets on Nuussuaq and northern Disko, onshore West Greenland

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The onshore Cretaceous–Paleocene Nuussuaq Basin in West Greenland (Fig. 1) has long served as an analogue for offshore petroleum exploration. With the discovery of oil seeps on Disko, Nuussuaq, Ubekendt Ejland and Svartenhuk Halvø in the early 1990s, onshore exploration was also carried out. This eventually resulted in the GRO#3 wildcat exploration well on western Nuussuaq in 1996, which showed several intervals with hydrocarbons (Christiansen *et al.* 1997). Recent photogrammetric mapping of conspicuous marker horizons within the volcanic sequences of the basin shows that significant compressional structures may have developed in the latest Paleocene on central Nuussuaq and northern Disko that could be promising potential exploration targets.

Regional geological setting of the Nuussuaq Basin

The Nuussuaq Basin, central West Greenland, is a rift basin that developed during the Cretaceous–Paleocene in response to regional extension between Greenland and Canada. It is situated at the north-eastern edge of a complex system of rift basins and transfer systems that linked extension and sea-floor spreading in the Labrador Sea to the Baffin Bay (Fig. 1). The basin was formed by two major phases of extension in the Early Cretaceous and Late Cretaceous, with an intervening quiescent period of thermal subsidence, when thick successions of source-prone mudstone were deposited regionally (see Dam *et al.* 2009 for a detailed summary of the lithostratigraphy of the basin). Significant volcanism beginning in the Paleocene resulted in the deposition of a thick volcanic succession (Fig. 2, electronic supplementary (ES) figure: Fig. ES1; Larsen *et al.* 2016). The supplementary material includes a summary of the complete volcanic and sedimentary stratigraphy.

Oakey & Chalmers (2012) document significant changes in the kinematic evolution of the Baffin Bay and Labrador Sea during the latest Paleocene–Eocene (magnetic Chrons C25N–C24N) that are related to the opening of the North Atlantic Ocean. Based on seismic-stratigraphic interpretation constrained by wells, this time also marks the apparent onset of inversion in the offshore basins (Gregersen & Bidstrup 2008).

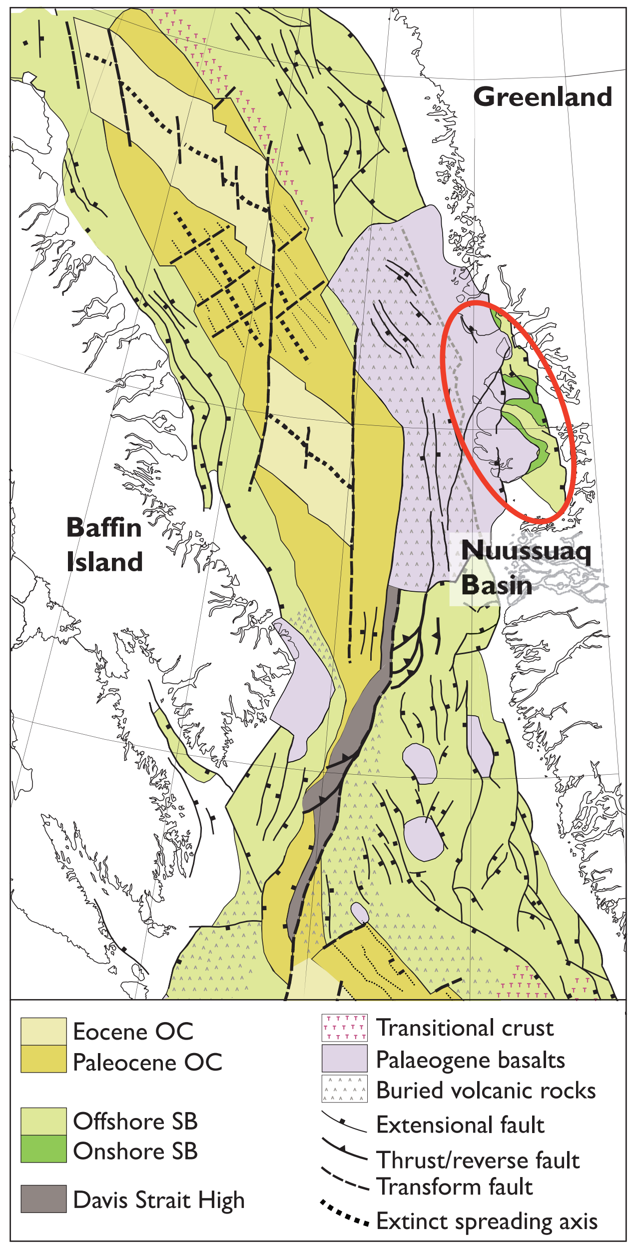

Fig. 1. Regional setting of the Nuussuaq Basin, simplified from Oakey & Chalmers (2012). **OC**: oceanic crust. **SB**: sedimentary basin.

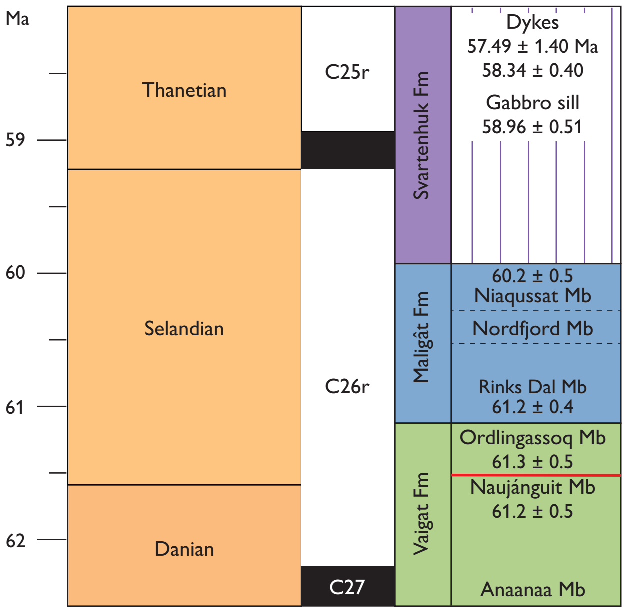

Fig. 2. Summary of the Paleocene volcanic stratigraphy of the Nuussuaq Basin from Larsen *et al.* (2016). The red line marks the stratigraphic position of the Tunoqqu surface. More complete sedimentary and volcanic stratigraphy from published material is available as an electronic supplement (Fig. ES1).

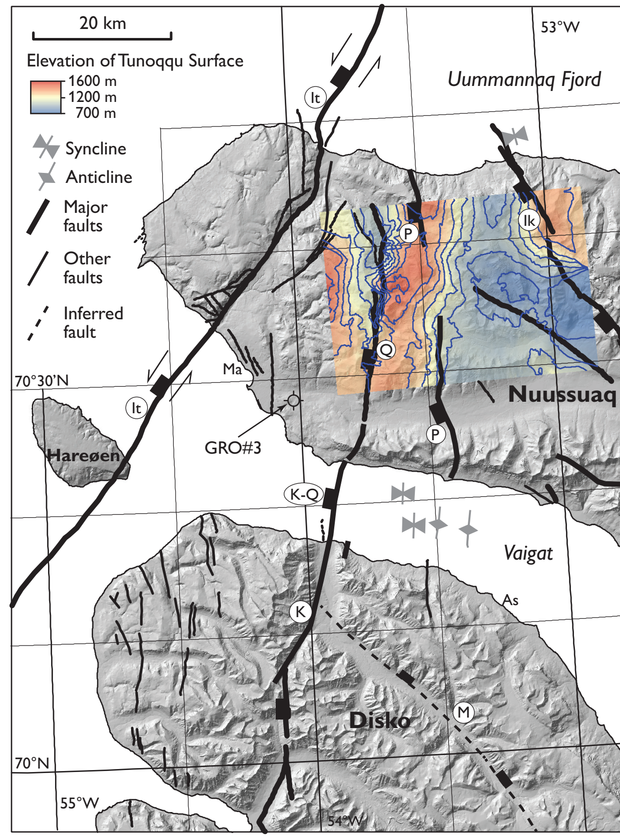

Fig. 3. Tunoqqu surface mapped by photogrammetry. **As**: Asuk locality. **Ma**: Marraat locality. **Ik**: Ikorfat Fault. **It**: Itilli Fault. **K–Q**: Kuugannguaq–Qunnilik Fault. Faults 'P' and 'M' follow the nomenclature of Chalmers *et al.* (1999). Note that fault 'M' is inferred from gravity modelling, not surface geology. Location of the GRO#3 well is also shown. Note that in the Vaigat, folding with an overall N–S trend is indicated on seismic reflection data.

Photogrammetric mapping of inversion structures

During the Danian and earliest Selandian, large volumes of picritic lava were erupted in the southern part of the Nuussuaq Basin, forming the Vaigat Formation (e.g. Larsen & Pedersen 2009). The formation is divided into three main members (Fig. 2) that primarily consist of greyish weathering, Mg-rich, picritic rocks. However, intervals of brown to light-coloured, crustally contaminated siliceous basalts to magnesian andesites that make good marker horizons also occur throughout the succession. Two marker horizons in the uppermost Nujanáguit Member (Fig. 2) are regional in extent, easily mappable, and originally formed a sub-horizontal surface, referred to as the Tunoqqu surface.

Photogrammetric mapping shows that the Tunoqqu surface is now segmented into areas of different elevation and structural trends as a result of later tectonic deformation (Sørensen 2011). This is most notable on Nuussuaq where the western part is elevated and in part highly faulted. Around the Qunnilik valley, the surface has been uplifted and faulted into many small blocks by numerous faults, so that it now forms an asymmetric anticline with a steeper dipping western limb and a gently dipping eastern limb (Fig. 3). Measured vertical displacement on faults varies from a few metres to around 100 m, whereas the amplitude of the folding, measured as the elevation difference between the axial parts of the syncline and anticline amounts to around 900 m. The limbs of the anticline are coincident with two extensional faults that pre-date the Tunoqqu surface, the Kuugannguaq–Qunnilik (K–Q) and P faults of Chalmers *et al.* (1999). The main fold axis appears to have an overall N–S trend (Fig. 4), although in detail there may be local variations. The details, however, are difficult to resolve with the mapping technique, so some caution should be used when interpreting details. Seismic data from the Vaigat show evidence that underlying strata are also folded (Marcussen *et al.* 2002). These too indicate a N–S axial trend in the folds.

The exact timing of the inversion is difficult to resolve, but must post-date the deposition of the Naujánguit Mb. It is most likely a very late Paleocene structure and thus formed at the same time as the onset of offshore inversion (Gregersen & Bidstrup 2008). Guarnieri (2015) suggests an E–W-directed, compressional, palaeostress regime along West Greenland during the latest Paleocene that is consistent with the orientation of the structure. Whether the inversion was a short-lived event or took place during a longer period of time is less clear from the present data. In any case the NE–SW-trending Itilli Fault, an important strike-slip fault active during the Eocene, shows a left-lateral movement that seems to be incompatible with N–S-trending compressional folds on central Nuussuaq and northern Disko. For this reason the activity of the Itilli Fault likely post-dates the tectonic inversion, suggesting a short-lived period for the compressive event.

Distribution of potential source rocks

Hydrocarbon seeps have been mapped in the region and five distinct oil types have been identified (Fig. 4; Bojesen-Koefoed *et al.* 1999). Two oil types are particularly important for exploration: the Marraat oil and the Itilli oil. The source rock for the Marraat oil was sampled in the GRO#3 well within the marine, syn-volcanic Eqalulik Formation. The source rock for the Itilli oil has not been sampled, but is interpreted to be of Cenomanian–Turonian age or older and have a wide distribution (Bojesen-Koefoed *et al.* 1999). Although currently unproven, this interval is expected to be present in the lower Itilli Formation in the region (Bojesen-Koefoed *et al.* 1999).

Figure 4 shows inferred distribution of the two most important source-prone formations. The distribution of the Itilli Formation is regarded to be of regional extent, extending west and north-west into the Davis Strait and Baffin Bay. Based on sediment thicknesses modelled by Chalmers *et al.* (1999), it is suggested here that the lower Itilli Formation was probably sufficiently buried to have generated oil in large areas west and north-west of the Ikorfat Fault, although the timing of hydrocarbon generation is highly uncertain. The map is thus consistent with the broad distribution of the Itilli oil type observed throughout the region. In contrast, the region where the Eqalulik Formation may have been sufficiently buried to generate oil is likely more limited. Here it is suggested that the oil potential of the formation is restricted to the west of the Kuugannguaq–Qunnilik Fault and thus is not likely to migrate to areas east of the fault, consistent with the lack of Marraat oil observed in areas other than south-west Nuussuaq.

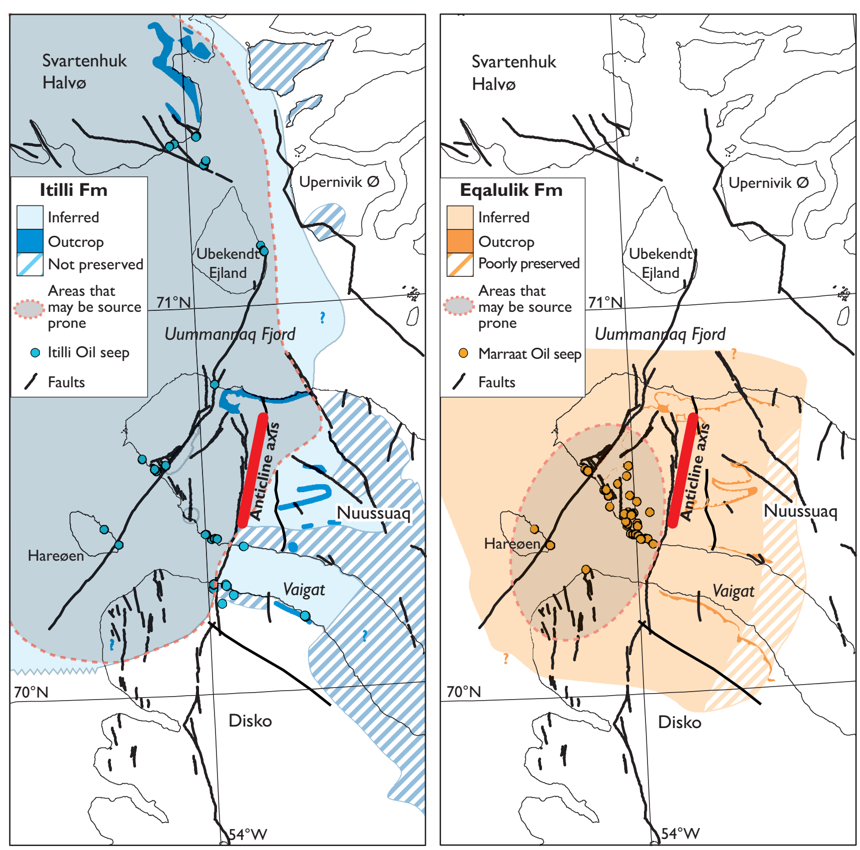

Fig. 4. Inferred distribution maps of the Itilli and Eqalulik formations. Black lines are faults (see Fig. 3). The overall trend of fold axis of the anticline mapped is shown by the red line. The maps are based on the known distributions from onshore outcrops and from offshore seismic data that indicate the presence of significant Cretaceous–Paleocene sedimentary strata (Marcussen *et al.* 2002). Also shown are the locations of Marraat and Itilli oil seeps and stains. It is notable that the Marraat oil is concentrated only on Nuussuaq between the Qunnilik and Itilli Faults whereas the Itilli oil is known regionally. The distribution of areas where there may be oil-prone intervals is shown by the grey shading. This is highly speculative and based on the locations of oil seeps and outcrops. Along southern Nuussuaq and northern Disko, the lower Itilli Formation is absent east of the K–Q Fault, but recent samples collected suggest it is present near the Ikorfat Fault along northern Nuussuaq.

Conclusions

Oil and gas shows in cores, along with numerous oil seeps, attest to the fact there is a working petroleum system in the region. Previous exploration on western Nuussuaq where seeps are most abundant failed to identify viable traps and early exploration was therefore abandoned after drilling of the GRO#3 well. However, the structural anticline defined by the Tunoqqu surface covering an area of ~250 km^2 on central-west Nuussuaq suggests that large structures could well be present in the region and in the underlying sedimentary rocks.

Previous play concepts in the region generally assume that the main source rocks are to the west or south-west of the main oil-seep areas, i.e., in the main deep marine depocentres. The areas farther east have been considered to be less prospective, since any oil would have to migrate longer distances and bypass the faulted area around the K–Q Fault. The presence of oil seeps at Asuk far to the east of this fault is thus enigmatic, raising questions about the source rock. Here, we suggest a new lead concept and propose that the central-west Nuussuaq and Uummannaq Fjord areas also hold potentially mature source rocks. This would imply that the region west of the Ikorfat Fault is prospective on Nuussuaq and possibly also in Vaigat and on northern Disko. The migration path of the oils found at Asuk could very well be from the north, rather than the west.

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