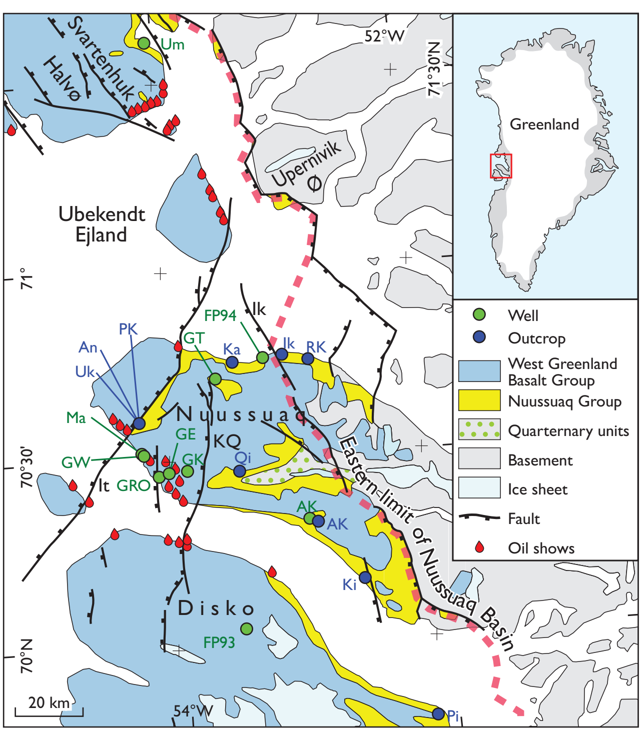
Potential hydrocarbon reservoirs of Albian–Paleocene age in the Nuussuaq Basin, West Greenland

Morten L. Hjuler, Niels H. Schovsbo, Gunver K. Pedersen and John R. Hopper

The onshore Nuussuaq Basin in West Greenland is important for hydrocarbon exploration since many of the key petroleum systems components are well exposed and accessible for study. The basin has thus long served as an analogue for offshore exploration. The discovery of oil seeps on Disko, Nuussuaq, Ubekendt Ejland, and Svartenhuk Halvø (Fig. 1) in the early 1990s resulted in exploration onshore as well. In several wells, oil stains were observed in both the siliciclastic sandstone and in the volcanic series. An important aspect of any petroleum system is a high quality reservoir rock. The aim of this paper is to review petrophysical aspects of the reservoir potential of key stratigraphic intervals within the Nuussuaq and West Greenland Basalt groups. Reservoir parameters and porosity–permeability trends for potential siliciclastic and volcanic reservoirs within the relevant formations of the Nuussuaq Basin are discussed below.

Geological setting

The Nuussuaq Basin formed in the Cretaceous–Palaeogene as part of a complex system of linked rift basins that developed along West Greenland during the opening of the Labrador Sea and Baffin Bay (Oakey & Chalmers 2012). As a result of Neogene uplift, the sediments and overlying Palaeogene volcanic rocks are exposed on Disko, Nuussuaq, Upernivik Ø and Svartenhuk Halvø (Fig. 1, Dam *et al.* 2009). The sedimentary succession is interpreted as deposited in fluvial, delta, shelf and deep marine environments, and is divided into ten formations forming the Nuussuaq Group (Fig. 2). The overlying West Greenland Basalt Group (WGBG) includes subaerial lava flows and hyaloclastite breccias (Larsen *et al.* 2016). A companion paper to this contribution (Sørensen *et al.* 2017, this volume) provides additional information regarding the structural development and potential source rock distribution of the Nuussuaq Basin.



	Outcrop	Formation	Member
AK	Ataata Kuua	Kangilia	Qilakitsoq
An	Anariartorfik	Itilli	Anariartorfik
Ik	Ikorfat	Atane	Ravn Kløft+Kingittoq
Ki	Kingittoq	Atane	Kingittoq
Ka	Kangilia	Kangilia	Annertuneq Congl.
Pi	Pingu	Atane	Skansen
PK	Pingunnguup Kuua	Itilli	Anariartorfik
Qi	Qilakitsoq	Atane	Qilakitsoq
RK	Ravn Kløft	Atane	Ravn Kløft+Kingittoq
Uk	Ukalersalik	Itilli	Anariartorfik

	Well	Cores	Formation	Logs
AK	GGU247801	566 m	Atane	-
FP93	FP93-3-1	139 m	Atane	-
FP94	FP94-11-04	340 m	Itilli	-
GE	GANE-1/1A	631 m	Agatdal+Vaigat	Core logs
GK	GANK-1	364 m	Kangilia+Vaigat	-
GRO	GRO-3	-	Itilli+Kangilia+ Agatdal+Vaigat	Well logs
GT	GANT-1	891 m	Itilli+Kangilia	-
GW	GANW-1	199 m	Vaigat	-
Ma	Marraat-1	448 m	Vaigat	Well logs
Um	Umiivik-1	1200 m	Itilli+Kangilia	-

	Faults
Ik	Ikorfat fault
It	Itilli fault zone
KQ	Kuugannguaq-Qunnilik fault

Fig. 1. Geological map of the study area showing well and outcrop locations. Abbreviations of outcrop, well and fault names are explained to the right, where lithostratigraphic units occurring at outcrops and wells are also listed.

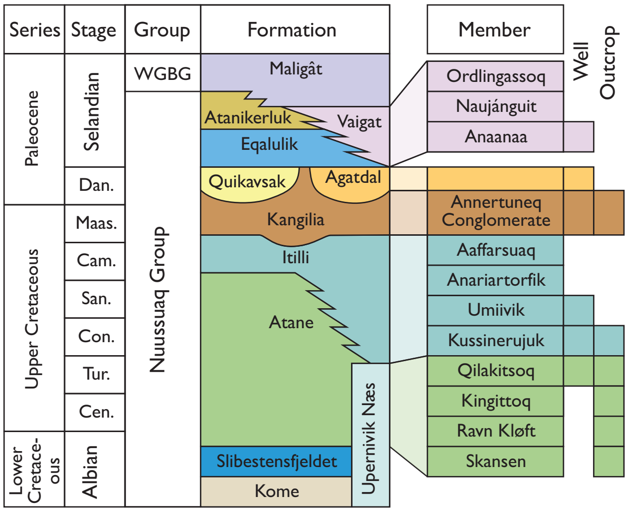


Fig. 2. Lithostratigraphic scheme of the Nuussuaq Group and the lowermost part of the West Greenland Basalt Group (WGBG). Members studied here are indicated to the far right. Modified from Dam *et al.* (2009).

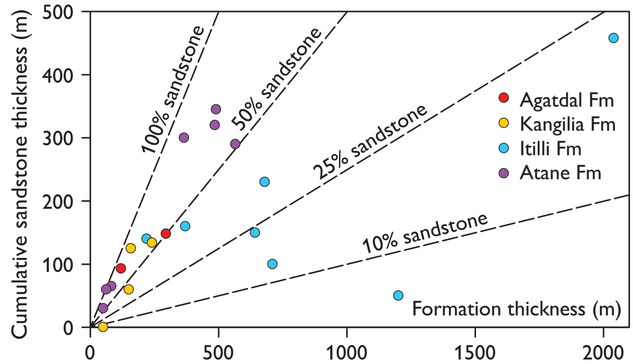


Fig. 3. Formation thickness versus cumulative sandstone thickness, data from the analysed wells and outcrops in the Nuussuaq Basin.

Lithology and distribution of relevant formations

The Atane Formation is known from the eastern part of the Nuussuaq Basin east of the Kuugannguaq–Qunnilik fault, (KQ fault, Figs 1, 2). The formation is up to 800 m thick in individual outcrops and consists of delta deposits, which include laterally extensive sandstone sheets (Dam *et al.* 2009).

The mudstone-dominated, marine Itilli Formation (Fig. 2) is known from northern and western Nuussuaq (west of the Ikorfat fault) and is more than 2.5 km thick (Sønderholm & Dam 1998). The Umiivik Member crops out in northern Nuussuaq between the Ikorfat and the Itilli faults (Fig. 1), whereas the Anariartorfik Member crops out west of the KQ fault.

The up to 438 m thick marine Kangilia Formation (Fig. 2) crops out on northern Nuussuaq between the Ikorfat and Itilli faults (Fig. 1) and has been drilled in the GANT-1 and GRO-3 wells. It has also been measured in an outcrop on southern Nuussuaq. Mudstones dominate in the outcrops while sandstones dominate in the wells. The Annertuneq Conglomerate Member mainly comprises conglomerates and sandstones (Dam *et al.* 2009).

The sub-marine to marine Agatdal Formation (Fig. 2) is known from the Agatdal area on central Nuussuaq west of the Ikorfat fault as well as from the GRO-3 well west of the K–Q fault (Fig. 1). The formation is up to 148 m thick and consists of mudstones, sandstones and conglomerates (Dam *et al.* 2009).

The volcanic Vaigat Formation (Fig. 2) is up to 1600 m thick in western Nuussuaq and northern Disko and increases to at least 5 km in thickness on Ubekendt Ejland (Larsen *et al.* 2016). The lower part of the formation is dominated by hyaloclastic breccias that are overlain by lava flows.

Methods

Ten wells and eight sedimentary outcrop successions located in the Nuussuaq Basin and described by Sønderholm & Dam (1998) and Dam *et al.* (2009) were analysed to quantify the sandstone component of the siliciclastic formations of the Nuussuaq Group. All sandstone intervals were defined as potential sandstone reservoirs and expressed as the cumulative sandstone thickness of a formation. Potential reservoir content was defined as the cumulative sandstone thickness divided by formation thickness. The cumulative sandstone thickness in outcrops and wells was estimated from sedimentological logs and core descriptions. Mudstones and heteroliths were classified as non-reservoir lithologies and included in the term 'shale'. In the uncored GRO-3 well, sandstone content was determined from wire-line logs and implies a shale content of 0–15%. Five wells containing volcanic successions of the WGBG were analysed to identify potential reservoir sections within the hyaloclastite successions. These were quantified as the cumulative thickness of hyaloclastite breccias. Lava flows were classified as non-reservoirs. Porosity–permeability trends were established for the GANE-1/1A, GANT-1 and Marraat-1 wells based on core analysis data. The porosity of the clastic formations in GRO-3 was calculated from the density wire-line log. Sandstones with porosities >10% are referred to as porous sandstones. A porosity log of the GANE-1/1A well was generated from gamma-ray and density logs obtained from core scans.

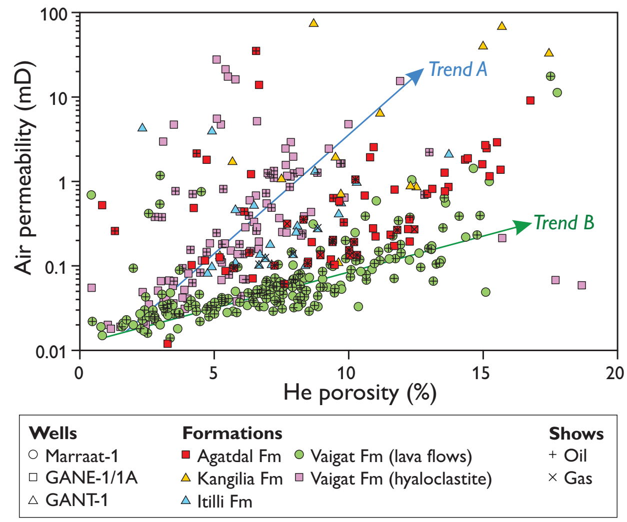


Fig. 4. Helium porosity and air permeability for selected wells. Oil shows are abundant along trend A (hyaloclastite reservoirs). Both oil and gas shows occur in the lava flows (trend B). The siliciclastic samples generally plot between the two trends.

Reservoir properties of formations containing potential hydrocarbon reservoirs

Potential reservoirs were identified within sandstones of the Atane, Itilli, Kangilia, and Agatdal formations and hyaloclastite breccias of the Vaigat Formation (Fig. 2). The main reservoir parameters including cumulative reservoir thickness (CRT), potential reservoir content (PRC) and porosity–permeability data are summarised below, with details in the Electronic Supplement (ES).

Atane Formation. CRT is in the range 26–360 m corresponding to a PRC of 45–80% (Fig. 3 and ES). The reservoir quality is well developed in central Nuussuaq with sandstone porosities of 5–25% (mean 17%) and air permeabilities of 0.5–150 mD (Appel & Joensen 2014).

Itilli Formation. CRT is in the range 21–458 m corresponding to a PRC of 2–51% (Fig. 3 and ES). The relatively low content of potential sandstone reservoirs compared to the Atane, Kangilia and Agatdal formations reflects significant variations within and between the members of the Itilli Formation. In the GRO-3 well, the individual sandstone units are up to 100 m thick and average porosity is 4%.

Kangilia Formation. CRT is in the range 0–134 m corresponding to a PRC of 0–72% indicating significant lateral variation in depositional environments (Fig. 3 and ES). In the mudstone-dominated successions, the Annertuneq Conglomerate Member constitutes a potential reservoir. In the GRO-3 well, porosities range between 5–17% (average 6%).

Agatdal Formation. CRT is in the range 71–148 m corresponding to a PRC of 50–67% (Fig. 3 and ES). Porosities of 6–21% and permeabilities up to 9 mD were measured in the GANE-1 well (Fig. 4), and in the GRO-3 well, an average formation porosity of 9% was assessed.

Vaigat Formation. Several oil shows have been encountered in the hyaloclastites and lava flows. Only the hyaloclastites seem to possess the necessary permeability to constitute a reservoir despite indications of lower average porosities (6%) than the lava flows (8%). For identical porosity values, the permeability is 30 times higher for the hyaloclastites compared to the lava flows (Fig. 4). The CRT of the hyaloclastites is in the range 80–671 m corresponding to a PRC of 84–100% (Fig. 2 and ES).

Porosity–permeability relations of potential reservoirs

The regional distribution of porosity and permeability in the Nuussuaq Basin deposits is poorly known due to the scarcity of core measurements or studies concerned with the effects of diagenesis on reservoir quality (Kierkegaard 1998). One relatively swift way of improving the porosity database is by using core scans to generate a porosity log (Pedersen *et al.* 2013). This is shown for the Agatdal Formation in GANE-1/1A in Fig. 5. The core log-generated

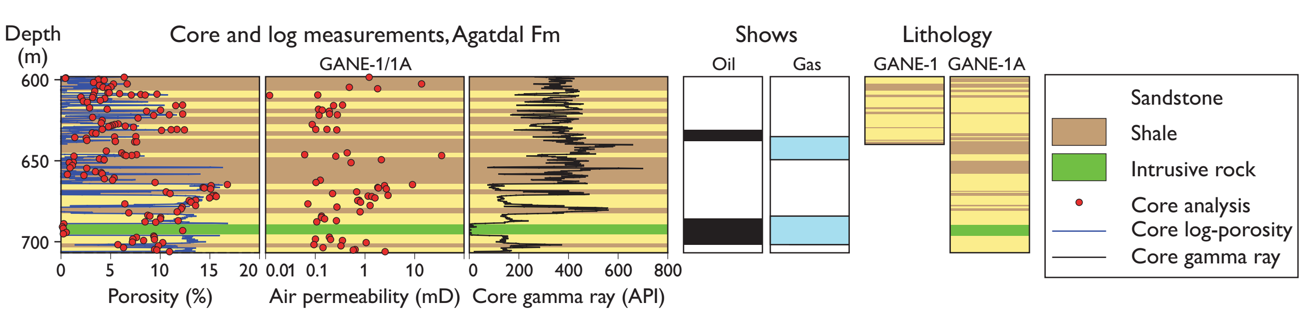


Fig. 5. Stratigraphical variation of lithology, porosity and permeability within the Agatdal Formation in the GANE-1/1A well.

porosity curve fits nicely with the core measurements and the core log-derived lithology corresponds well with the lithological log from Dam *et al*. (2009).

Core analysis data from the Marraat-1, GANE-1/1A, and GANT-1 wells were used to outline porosity–permeability trends within the siliciclastic and volcanic successions (Fig. 4). In the siliciclastic reservoirs, the porosity and permeability data show a high degree of scatter and no consistent trend can be identified. The large range in porosity and permeability values probably reflects variations in grain size and diagenesis. A large part of the porosity in the GANT-1 sandstones is secondary and related to dissolution of detrital feldspar grains (Kierkegaard 1998).

The hyaloclastite samples show a relatively high permeability–porosity ratio (trend A in Fig. 4) compared to the lava flows (trend B in Fig. 4). At 10% porosity, the expected permeability is 5 mD for hyaloclastites, but only 0.8 mD for lava flows, a tendency assumed to reflect textural control on permeability. In hyaloclastites, a network of connected pores ensures fluid or gas flow, whereas the isolated pore systems in lava flows strongly impede permeability, even at high porosity.

Conclusions

The onshore Nuussuaq Basin in West Greenland contains potential hydrocarbon reservoirs within the siliciclastic Atane, Itilli, Kangilia and Agatdal formations, and within the hyaloclastite intervals of the Vaigat Formation. The siliciclastic reservoirs occur in a wide range of geological environments from fluvial over deltaic to slope and marine settings. The potential reservoir sandstone content is generally more than 50% for the sections studied from the Atane, Kangilia and Agatdal formations, but significantly lower in the Itilli Formation. The cumulative sandstone thickness is mostly >100 m for all formations, including the Itilli Formation.

Porosity and permeability data suggest that sandstone and hyaloclastite reservoirs may be of good quality with porosities up to 20%. Permeabilities are mostly below 10 mD. However, porosity and permeability data are restricted to the western part of Nuussuaq and the diagenetic control on the reservoir quality is poorly understood regionally.

Acknowledgements

This contribution is partly the result of a project funded by the Ministry of Mineral Resources, Greenland.

References

Appel, A.U. & Joensen, I.Á. 2014: Prograderende deltaaflejringer fra øvre Kridt, Atane Formationen, Nuussuaqbassinet, centrale Vestgrønland. Unpublished Bachelor thesis, Department of Geosciences and Natural Resource Management, University of Copenhagen, 49 pp.

Dam, G., Pedersen, G.K., Sønderholm, M., Midtgaard, H., Larsen, L.M., Nøhr-Hansen, H. & Pedersen, A.K. 2009: Lithostratigraphy of the Cretaceous–Paleocene Nuussuaq Group, Nuussuaq Basin, West Greenland. Geological Survey of Denmark and Greenland Bulletin **19**, 171 pp.

Kierkegaard, T. 1998: Diagenesis and reservoir properties of Campanian – Paleocene sandstones in the GANT#1 well, western Nuussuaq, central West Greenland. Geology of Greenland Survey Bulletin **180**, 31–34.

Larsen, L.M., Pedersen, A.K., Tegner, C., Duncan, R.A., Hald, N. & Larsen, J.G. 2016: Age of Tertiary volcanic rocks on the West Greenland continental margin: volcanic evolution and event correlation to other parts of the North Atlantic Igneous Province. Geological Magazine **153**(3), 487–511.

Oakey, G.N. & Chalmers, J.A. 2012: A new model for the Paleogene motion of Greenland relative to North America: Plate reconstruction of the Davis Strait and Nares Strait regions between Canada and Greenland. Journal of Geophysical Research **117**, 1–28.

Pedersen, G.K., Schovsbo, N.H. & Nøhr-Hansen, H. 2013: Calibration of spectral gamma-ray logs to deltaic sedimentary facies from the Cretaceous Atane Formation, Nuussuaq Basin, West Greenland. Geological Survey of Denmark and Greenland Bulletin **28**, 65–68.

Sønderholm, M. & Dam, G. 1998: Reservoir characterisation of western Nuussuaq, central West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **1998/6**, 36 pp.

Sørensen, E.V., Hopper, J.R., Pedersen, G.K., Nøhr-Hansen, H., Guarnieri, P., Pedersen, A.K. & Christiansen, F.G. 2016: Inversion structures as potential petroleum exploration targets on Nuussuaq and northern Disko, onshore West Greenland. Geological Survey of Denmark and Greenland Bulletin **38**, 45–48.

Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen, K, Denmark. E-mail: *MLH@geus.dk*