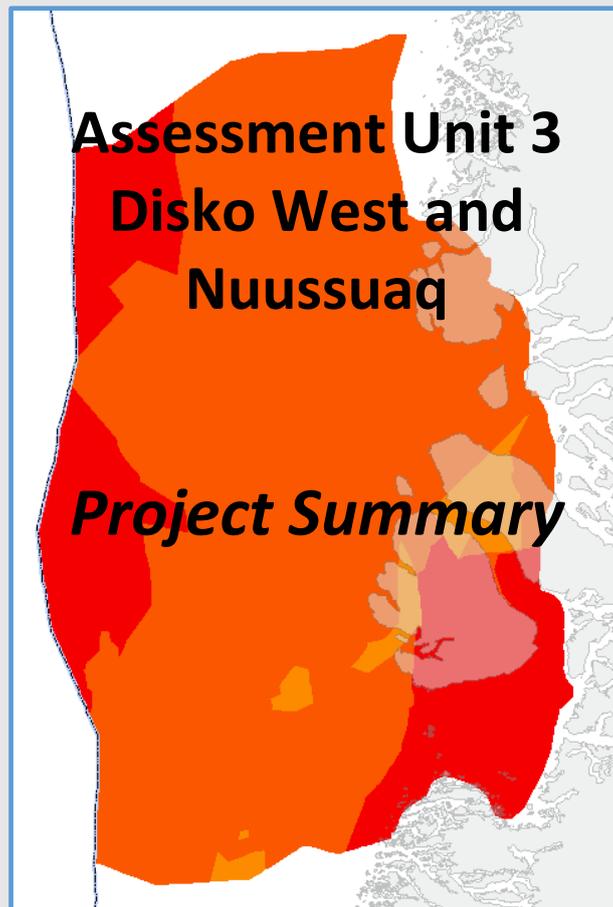


Greenland Resource Assessment



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Greenland Resource Assessment, Disko West and Nuussuaq (Assessment Unit 3)

Executive Summary

A play-based resource assessment of conventional hydrocarbons has been performed for the offshore areas of central West Greenland and the onshore Nuussuaq Basin (Assessment Unit 3, AU3). Four play levels have been assessed, with an estimated mean for the undiscovered resources of ~3,650 MMBOE risked recoverable hydrocarbons. The known prospectivity includes 24 leads with Mean Case Risked Recoverable volumes of ~100 MMBOE. The unidentified prospectivity has Mean Case Risked Recoverable volumes of ~3,550 MMBOE resulting in an average area yield of ~27 MB/1000 km² (risked). The unrisked Pmean volumes for the leads of the four evaluated play levels range from 10 to 5000 MMBOE.

The geologic probabilities for AU3 were determined based on careful play mapping constructing a series of numeric CRS (Common Risk Segment) maps and CCRS (Composite Common Risk Segment) maps of the assessment area. In this manner, the probabilities are consistently applied throughout the area for both the known and unknown prospectivity.

Due the thick cover of Tertiary volcanic rocks, a high exploration risk is encountered everywhere in the region at all deeper play levels. Therefore, a portfolio analysis to highlight the most prospective areas has not been carried out for Assessment Unit 3, since de-risking initiatives are not possible to carry out in the offshore areas with present-day seismic imaging technologies.

It should, however, be noted, that the leads onshore Nuussuaq can be de-risked significantly at relatively low cost and that these therefore may provide viable exploration targets.

The assessment results presented are based on all available data collected and interpreted by the industry, GEUS, NUNAOIL and the Government of Greenland and reflect the state of geologic knowledge of the offshore and onshore areas at the time of central West Greenland. Any future drilling and evaluation of the petroleum systems and plays based on new data within this area will add to the geologic knowledge and will therefore lead to a refinement of these assessment results.

The assessment was carried out using the Player[®] GIS software provided by GIS-pax. The methodology and results of the assessment have been quality controlled by the Norwegian Petroleum Directorate and GIS-pax.

The results of this study are reported in an extensive ArcGIS project supported by a comprehensive slide package which includes 12 presentations, reflecting the workflow of the project, including:

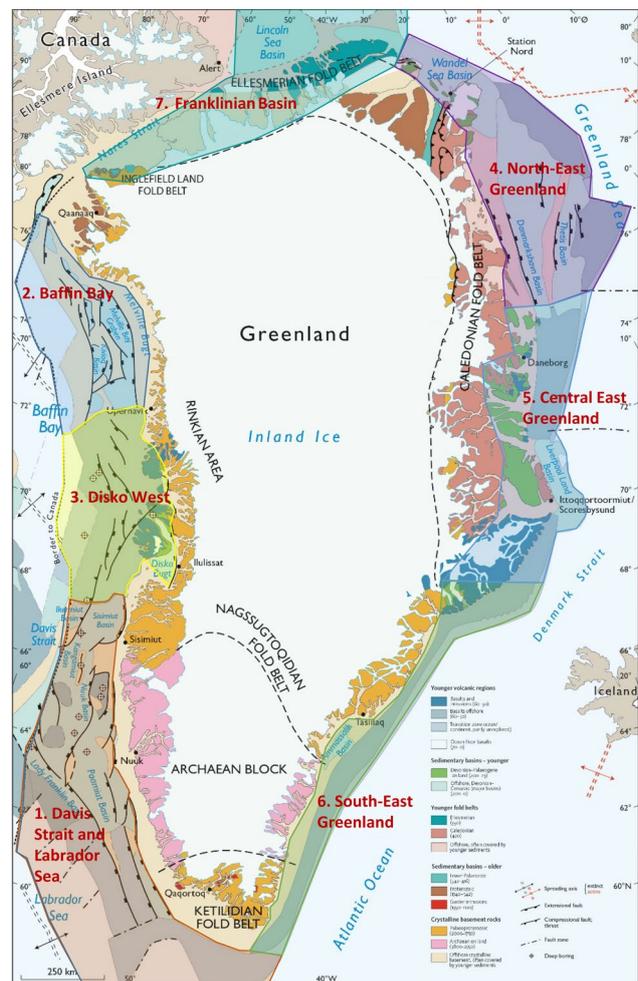
- Introduction
- Database
- Structural Framework
- Seismic-Stratigraphic Framework
- Stratigraphic Evolution
- Petroleum Systems
- Post-Well Analysis
- Plays Analysis
- Lead Overview
- Input Parameters
- Yet-to-Find Analysis
- Appendix – Seismic examples and estimation of volcanic thickness

The Player and ArcGIS projects together with the slide pack are available for the petroleum exploration industry at no cost and can be downloaded from the project website, www.greenland-resource-assessment.gl.

Introduction

The AU3 Resource Assessment (Disko West and Nuussuaq Basin, West Greenland) is the third of seven assessments of the “Whole-of-Greenland Petroleum Resource Assessment Project” covering the entire Greenland continental shelf (Fig. 1). The aim of the project is to provide an estimate of a quantitative, play-based Yet-to-Find potential of conventional hydrocarbons on the Greenland continental shelf. The project is carried out to facilitate business decisions and guide the industry towards the most prospective areas, as well as helping the Greenland Authorities and politicians in strategic decision making and in planning for future licensing rounds. In addition, it will support the definition of new G&G de-risking initiatives.

Figure 1 - Geological map of Greenland with the seven assessment units indicated.



The project is mainly sponsored by NUNAOIL and is carried out as a collaboration between GEUS, NUNAOIL and the Government of Greenland hosted by GEUS. The work is based on all available existing data provided by the industry, GEUS, NUNAOIL and the Greenland Government. Furthermore, it includes a regional basin modelling study, carried out in-house at GEUS. The results will be reported as the work on the individual assessment units are finalized.

A hydrocarbon resource assessment of the Greenland continental shelf north of the Arctic Circle has previously been performed as part of the U.S. Geological Survey (USGS) Circum-Arctic Resource Program (Schenk 2011; Moore & Gautier 2017). This assessment, however, used a probabilistic approach heavily relying on analogue modelling comparing the Arctic assessment units with similar but geologically better understood and better calibrated petroleum provinces elsewhere in the world. This study therefore only provided a broad overview of the possible resource potential within the assessment units of the study.

Database

The database for AU3 includes an extensive 2D seismic data set of various vintages, one 3D seismic survey, magnetic and gravity surveys, data from one onshore and 6 offshore exploration wells. Data from 26 onshore stratigraphic boreholes and mineral exploration wells have been used where adequate, as well as numerous scientific publications and industry reports. Furthermore, excellent outcrop analogues occur in the onshore Nuussuaq Basin, at Cape Dyer, and on Bylot Island and Ellesmere Island (Fig. 2).

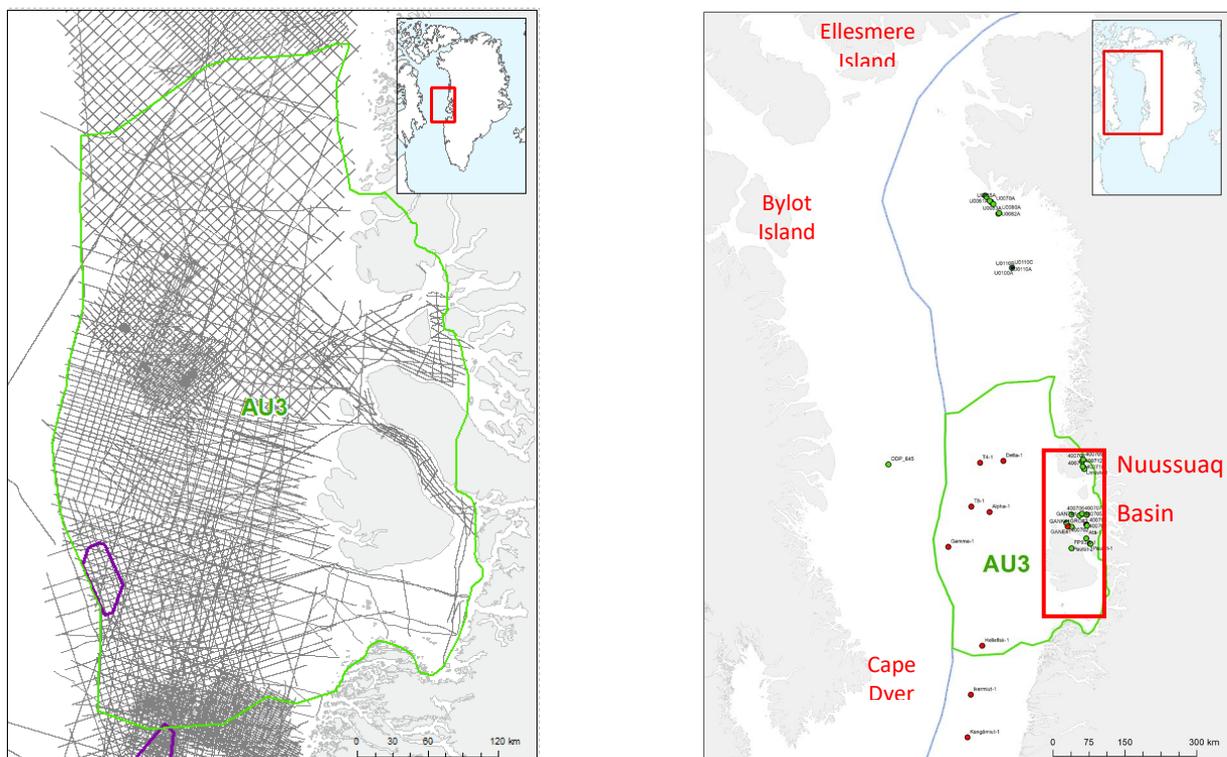


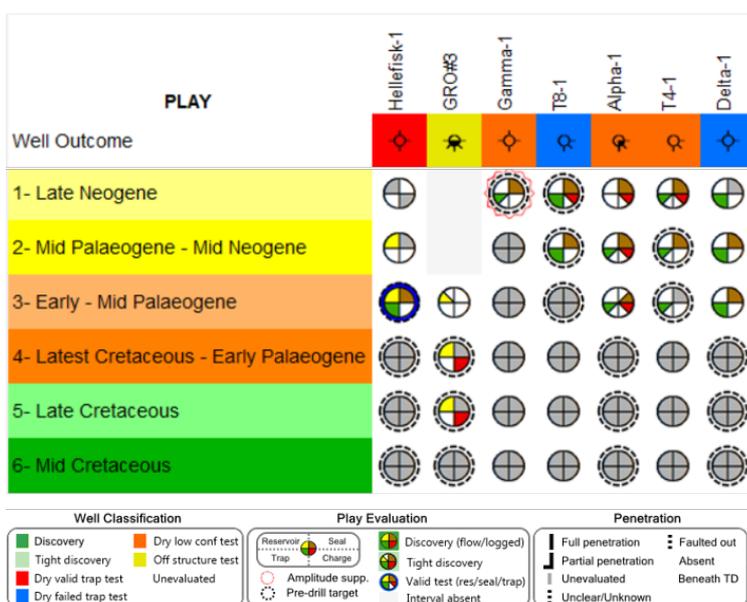
Figure 2 – **Left:** Seismic database of AU3. Purple outline shows extent of 3D surveys. **Right:** Outline of AU3 and Nuussuaq Basin and locations of exploration wells (red) and stratigraphic boreholes (green).

Exploration History

Although six offshore exploration wells have been drilled in Assessment Unit 3, none of these drilled the main Cretaceous plays. Due to severe mobilization problems with the drilling rig, the onshore GRO#3 exploration well had to be drilled off-structure and did therefore not properly test the Cretaceous plays (Fig. 3). The area must therefore still be characterized as a frontier exploration region, with major exploration issues related to very poor seismic imaging below the thick succession of volcanic rocks of the West Greenland Basalt Group.

Exploration efforts in West Greenland have been restricted to five periods (Christiansen 2011):

1. An offshore campaign offshore south-west Greenland in the 1970s with extensive seismic acquisition and drilling of five exploration wells in the shallow-water areas – drilling operators were Total, Mobil, Chevron, and ARCO
2. An onshore programme on Disko–Nuussuaq onshore central West Greenland by a small Canadian company grønArctic in the 1990s including drilling of the GRO#3 exploration well
3. Offshore exploration in the 1990s offshore southwest and central West Greenland by Statoil, Phillips, DONG and NUNAOIL, including drilling of the Qulleq-1 exploration well in 2000
4. New activities in the 2000s offshore West Greenland with a high level of seismic data acquisition by the seismic industry followed by a large number of licence awards and drilling of eight exploration wells by Cairn in 2010-11
5. A major campaign in the Baffin Bay area in the 2010s with drilling of eleven shallow core boreholes (Fig. 2) and extensive seismic acquisition including acquisition of 3D seismic data



Following the collapse of the oil price in 2014, most licences were relinquished, and exploration activities have almost ceased.

Fifteen exploration wells have been drilled in West Greenland, but no commercial discoveries have been made.

Figure 3- Post well analysis of the seven exploration wells drilled in AU3.

Seismic-Stratigraphic Interpretation

The regional seismic stratigraphic interpretation is based on GEUS and NUNAOIL in-house interpretation. Ten super-regional seismic stratigraphic key horizons have been identified in the regions to the south and north of Assessment Unit 3 (Gregersen *et al.* 2019), but only the post-volcanic, Tertiary horizons could be mapped and tied to the offshore exploration wells and assigned to plays since seismic imaging below the thick volcanic pile covering the entire region is not possible with present-day technologies (Fig. 4).

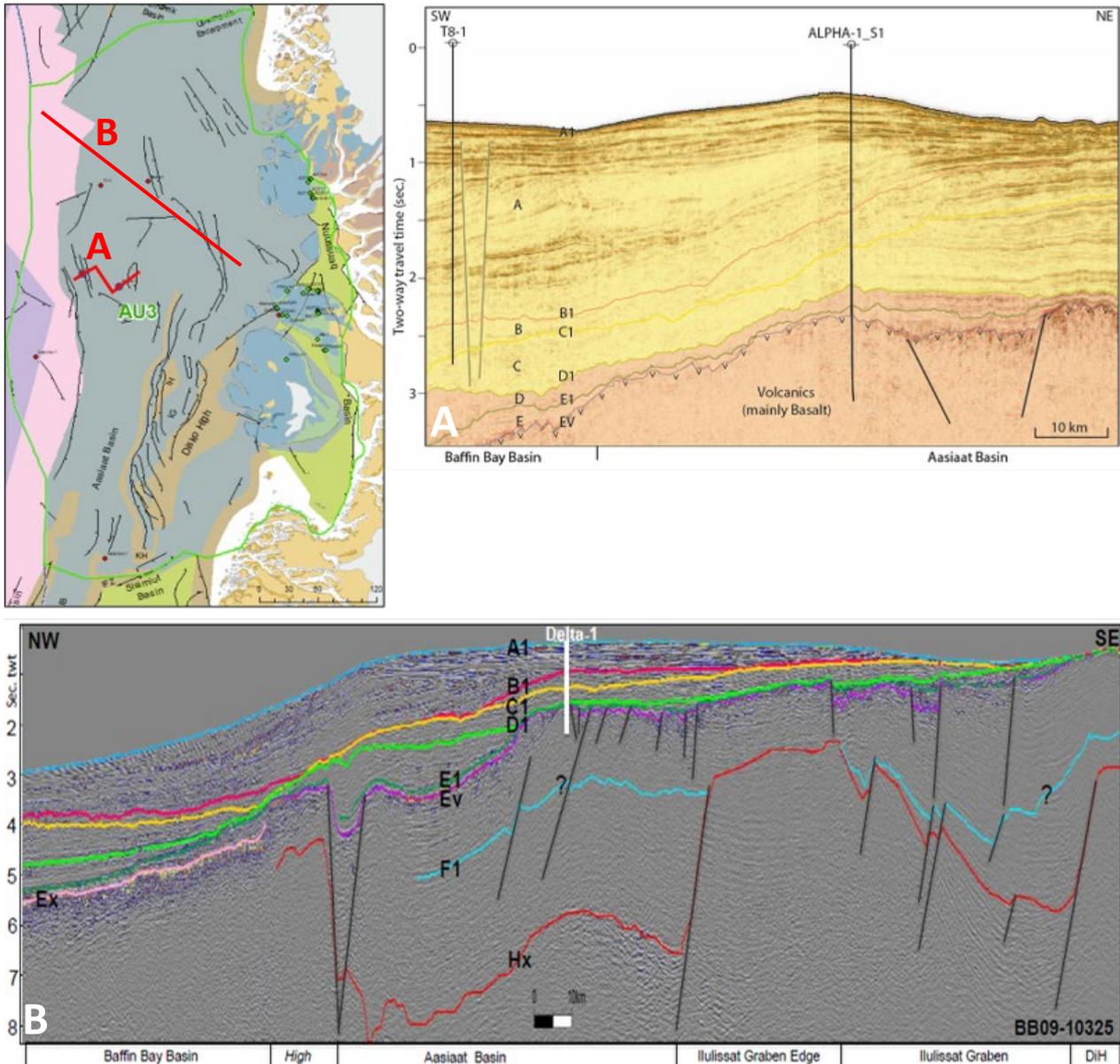


Figure 4 - Seismic sections with well-ties of the seismic stratigraphic horizons, tectono-stratigraphic mega-units. From Gregersen *et al.* 2019 and GEUS in-house reporting.

The regional seismic stratigraphic key horizons that have been mapped in Assessment Unit 3 are: **A1**: Seabed; **B1**: Plio-Pleistocene/Base Quaternary; **C1**: Late Miocene Unconformity; **D1**: Mid-Miocene Unconformity; **E1**: Mid-Eocene Unconformity and **EV**: Top Volcanics. Base volcanics; **F1**: Near base Cenozoic

Unconformity) has been estimated using seismic and potential field data. The deeper horizons, **G1**: mid-Cretaceous unconformity and **Hx**: Basement, have been constructed for basin modelling and reservoir effectiveness evaluations only. These are purely hypothetical horizons with a very large degree of uncertainty (Fig. 4).

Tectonostratigraphic Evolution

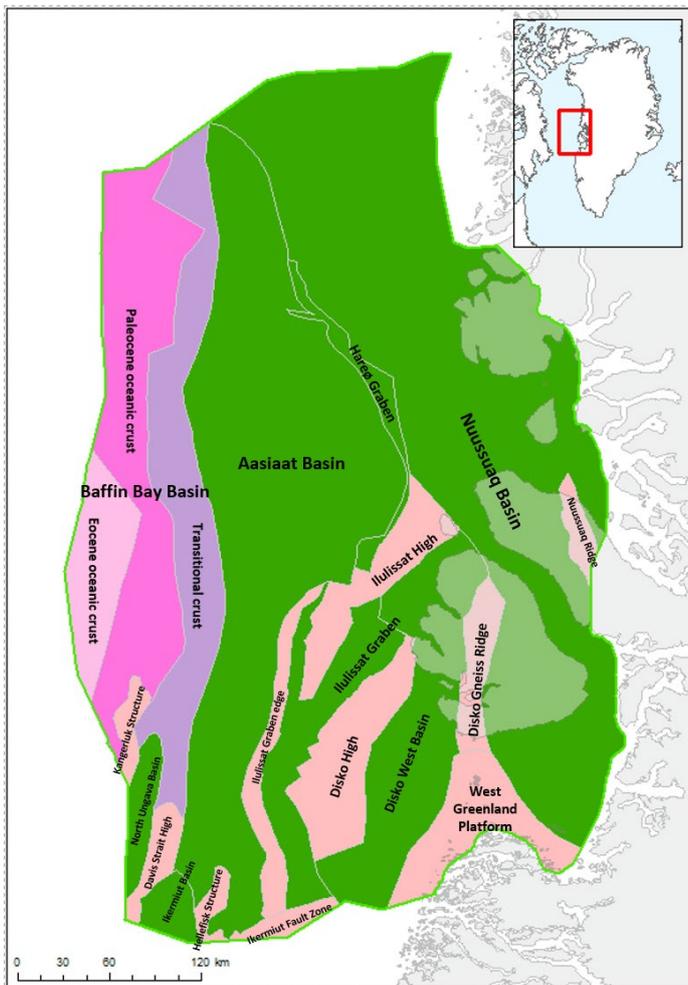


Figure 5 - Structural elements map of the central West Greenland margin (AU3). The eastern part of the area is dominated by Cretaceous rift basins covered by Palaeogene volcanic rocks (purple outline). In the western part of the region oceanic and transitional crust underlies the Palaeogene and Neogene sediments.

Disko High and Ilulissat High) are, however, mappable, and these were formed during the late rift phase in the Late Cretaceous whereas the minor structural highs in the southern part of the region (Kangerluk Structure, Davis Strait High, Hellefisk Structure and Ikermiut Fault Zone) were all formed by later compressional events during the break-up and drift phase (Fig. 5).

The tectonic evolution of the Labrador Sea – Davis Strait – Nuussuaq – Baffin Bay region is complex involving multiple phases of rifting related to the initial break-up of Greenland and Canada, transpressional movements, counter-clockwise rotation of Greenland, causing Late Paleocene – Early Eocene compression and inversion followed by Neogene – late Neogene uplift of the margins (e.g. Chalmers *et al.* 1999; Chalmers & Pulvertaft 2001; Dam *et al.* 1998, 2009; Funck *et al.* 2007; Gregersen *et al.* 2019; Japsen *et al.* 2005; Knutsen *et al.* 2012; Nielsen *et al.* 2011; Oakey & Chalmers 2012; Pedersen *et al.* 2018, 2019). Furthermore, the central West Greenland area is strongly affected by the North Atlantic Mantle Plume causing thermal uplift.

Assessment Unit 3 is covered by a very thick Paleocene volcanic succession extruded during initial sea floor spreading. The configuration of the Cretaceous basins is therefore largely unknown in most of the region. The major highs (Disko Gneiss Ridge, Nuussuaq Ridge,

In the western part of the region oceanic and transitional crust underlies the Palaeogene and Neogene sediments (Fig. 5).

Six major tectonostratigraphic phases have been recognized offshore West Greenland (Fig. 6; Gregersen *et al.* 2019).

The Pre-rift Phase includes Proterozoic and Palaeozoic successions.

The ?Aptian/Albian – earliest Cenomanian Early-rift Phase is characterized by the development of large extensional fault blocks and deposition of alluvial and lacustrine sediments.

A marine drowning episode separates the sediments of Early Rift Phase from the early Cenomanian – Early Campanian Subsidence (local rifting) Phase. This phase was characterized by deposition of marine muds and sands. The presence of a volcano of Late Cenomanian – Early Turonian age in the Nuuk Basin (Assessment Unit 1) indicates that local rifting took place during the early stage of this phase (Knudsen *et al.* 2020).

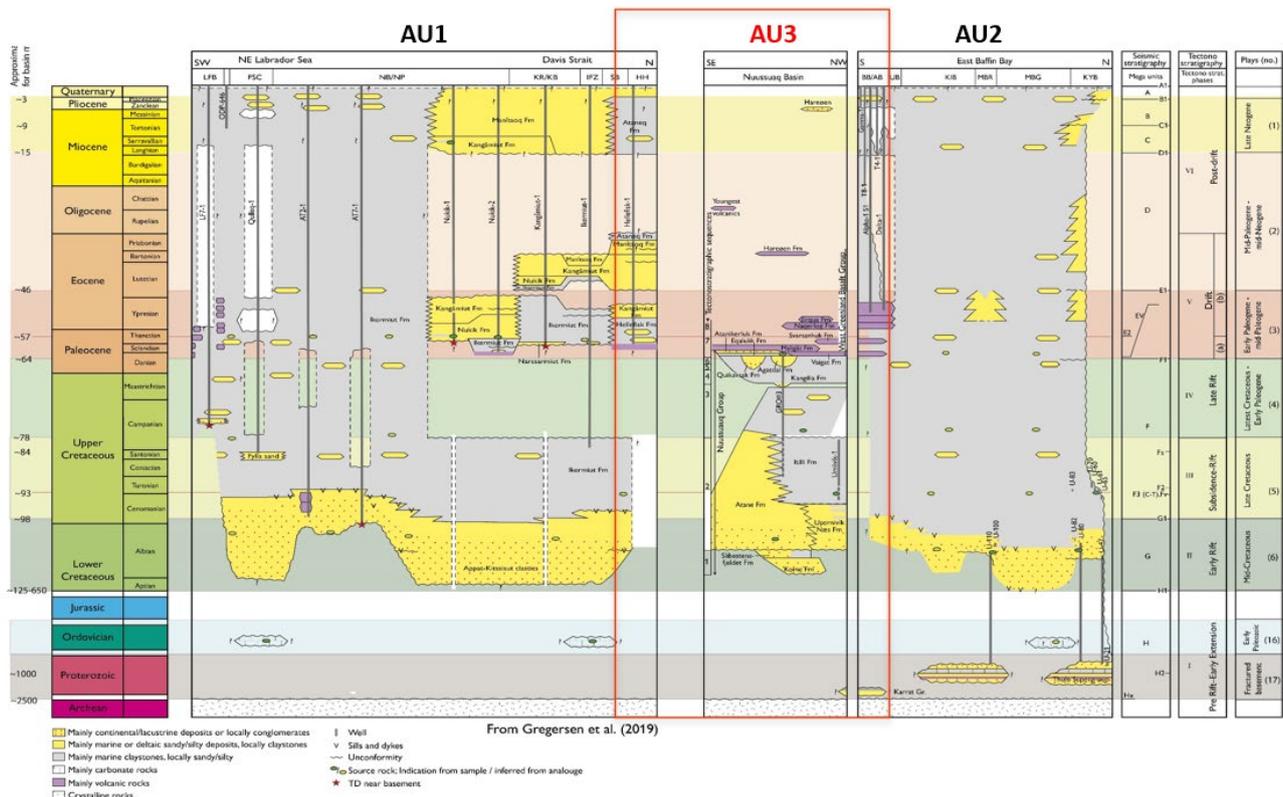


Figure 6 - Tectonostratigraphic evolution of West Greenland. From Gregersen *et al.* (2019).

A change in stress regime occurred during the initiation of the Early Campanian – Early Paleocene Late Rift Phase. In central West Greenland, the arrival of the North Atlantic Mantle Plume resulted in major uplift, erosion, and canyon incision. The Late Rift Phase was characterized by development of deep-water basins. Deposition of reservoir sands took place in basin-floor fans, turbidite slope channels and large canyons.

During the Early Paleocene – Eocene Drift Phase, formation of oceanic crust took place, causing separation of the continental margins of Greenland and Canada with north-east to northward movement of Greenland. From Paleocene to Eocene the central West Greenland Cretaceous – Early Paleocene basins were covered by volcanic rocks of the West Greenland Basalt Province while deep marine deposition took place in the Baffin Bay basins. Formation of oceanic crust was associated with compressional tectonics and the development of strike-slip and thrust faults, pull-apart basins, and inversion structures, most pronounced in the Davis Strait and Baffin Bay regions.

During the late Cenozoic – present-day Post-drift Phase tectonism diminished, though some intra-plate vertical adjustments occurred, and a series of uplift events took place along the passive margins. The latest basin development was characterized by formation of thick Neogene to Quaternary marine successions including contourite drifts and glacial related shelf progradation towards the west and south-west.

Plays and Play Elements

Based on seismic interpretation, well and outcrop data, 17 plays have been established for all seven assessment areas of the Greenland continental shelf. Seven of these plays are present in AU3 (Plays 1-6 and 17; Fig. 6) but only Plays 3–6 are evaluated as Plays 1 and 2 are not considered to have any exploration potential in the area. Six source rocks have been documented on the West Greenland continental margin and reservoir rocks are present virtually at all stratigraphic levels. High-quality regional seals are well documented in Cenomanian-Turonian, Campanian and Paleocene shales (Fig. 6).

Petroleum Systems

Six possible source rocks have been documented from geochemical analyses of oil seeps and mudstones in outcrops, dredge samples and well cores along the West Greenland continental margin (Bojesen-Koefoed 2011; Bojesen-Koefoed *et al.* 1999). Source rock intervals include Ordovician, Albian, Cenomanian–Turonian, Campanian, Paleocene–Eocene and Miocene. Several of these source rocks are also proven in eastern Canada from outcrops on Ellesmere Island, oil seepage in Scott Inlet and wells on the south-east Baffin Bay and Labrador continental shelves (Balkwill *et al.* 1990; Núñez-Betulu 1993; Fowler *et al.* 2005). The oil seeps described from the onshore Nuussuaq Basin (representing 5 distinct oil types, all pre-volcanic) and offshore East Canada, the Kangâmiut-1 gas kick and the gas discoveries on the East Canadian continental shelf provide evidence that, at least in those areas, petroleum systems are or have been active.

Based on geochemical evidence, the Niaqornaarsuk oil type of the Nuussuaq Basin was generated from deposits similar to Campanian non-source shales drilled by the GANT#1 well but developed in source quality facies (Bojesen-Koefoed *et al.* 1999). The known distribution of this oil type has hitherto been

restricted to a small area on the south coast of Nuussuaq, but recently, an inland discovery has enlarged the area significantly (Christiansen *et al.* 2020). The new discovery is situated on the flank of a large anticlinal feature, which may become a target for future exploration (Sørensen *et al.*, 2017). However, modelling of petroleum generation from the Campanian is pending further investigations.

The Marraat oil type of the Nuussuaq Basin was generated from Paleocene deposits equivalent to the Eqlulik Formation drilled by the GRO#3 well. In the well the deposits are thermally immature, or marginally mature, and uplift-calculations based on vitrinite reflectance data suggest uplift in the order of 2 km. However, the widespread occurrence of Marraat-type seepage oils demonstrate that the source is oil window mature in large areas of onshore central west Greenland.

The source rock characteristics of each of the three main source rocks present in Assessment Unit 3 are summarized in Table 1.

Table 1. Characteristics of the three expected source rocks in AU3.

	Thickness (m)	TOC (wt-%)	Hydrogen Index	Kerogen type
Albian	100	5	250	III
Cenomanian–Turonian	100	3	300	II
Paleocene	100	4	200	(II-)III

These data have been used as input parameters to the kinetic model in the regional basin modelling study for the AU3 area.

Basin modelling indicates that both the Albian and Cenomanian–Turonian are most probably overmature in the offshore areas and have only reached thermal maturity in the Disko–Nuussuaq region. The maturity modelling suggests that Paleocene source rock interval are most probably overmature in the offshore areas expect for the southern part of the AU3 and have reached levels of thermal maturity sufficient for petroleum generation in the Disko–Nuussuaq region. Nevertheless, the charge model for the play analysis incorporates the possibility for charge from all three mature source rock intervals.

Basin modelling indicates that both the Albian and Cenomanian–Turonian are most probably overmature in the offshore areas and have only reached thermal maturity in the Disko–Nuussuaq region. Nevertheless, the charge model for the play analysis incorporates the possibility for charge from all three mature source rock intervals.

Assessment Process

The assessment process for the resource evaluation of AU3 is summarised in the “Yet-To-Find Triangle” shown in Figure 7. Basin evaluation is the basic activity describing the structural and stratigraphic framework leading into construction of Gross Depositional Environment (GDE) maps and identification of source rocks, reservoirs and regional seals that form the basis for definition of the plays. IES PetroMod v16.2 has been used to compile and setup a 3D basin reference model to assess maturity and possible migration for expected source rock intervals.

The results from the Basin Evaluation feed into the Play Analysis. In this analysis, numeric Common Risk Segment (CRS) and Composite Common Risk Segment (CCRS) maps have been constructed based on all available geological and geophysical data and exploration history data.

The following play risk elements have been assessed: Reservoir Presence (based on GDE maps), Reservoir Effectiveness (based on depth to interval maps), Seal Effectiveness (based on overburden thickness maps) and Charge-Migration (based on maturity and drainage maps), and Trap Presence (based on seismic line density).

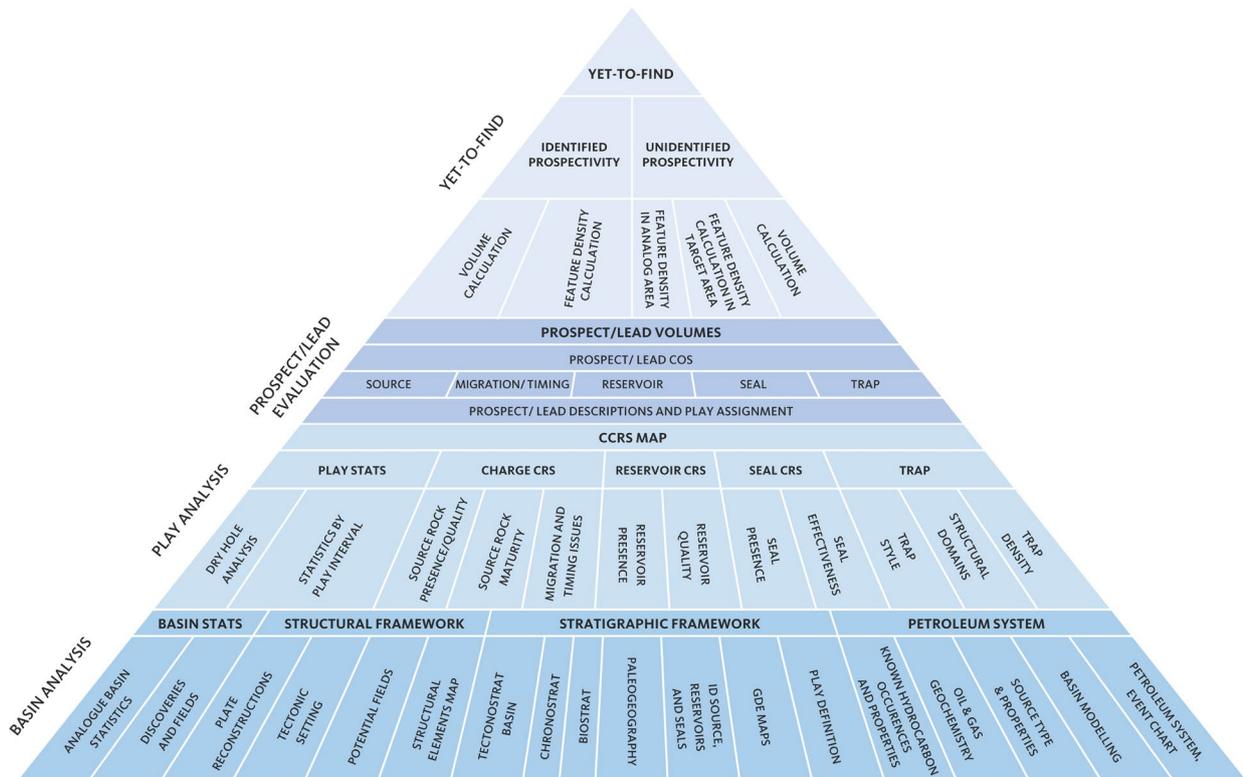


Figure 7 - Resource evaluation workflow used in the Greenland Resource Assessment.

A multiple charge scenario is applied for each play since three main source rock intervals have been identified on the West Greenland shelf: Albian, Cenomanian–Turonian and Paleocene (Bojesen-Koefoed

2011). This means that for each play a specially designed composite charge workflow is applied to assess the charge-migration risk. A detailed description of this process is found in the PowerPoint presentations available on the data portal.

Volumes for leads mapped by the industry, GEUS and NUNAOIL have been integrated into the play evaluation and the identified prospectivity has been calculated. For the volume calculations of individual leads the oil-water contact has been picked halfway between the top of the structure and spill point, since source rock quality analysis does not support fill-to-spill scenarios.

The Yet-to-Find analysis is based on a feature (lead) density calculation approach for each of the identified play intervals. In Assessment Units 1 and 2 south and north of Assessment Unit 3 estimates of Analog Feature Density for each play were based on observed feature densities in areas with relative high exploration activity and where an almost complete mapping of possible leads could be anticipated.

This approach could not be used in AU3, since exploration here failed due to:

1. Map Cretaceous structures in the offshore areas since seismic imaging below the thick volcanic pile proved to be unsuccessful.
2. Confirm exploration models in the Palaeogene succession overlying the volcanics.

Feature density and field size evaluations for Assessment Unit 3 are therefore based on the estimates obtained in Assessment Unit 2 to the north which has a similar geological and structural evolution as AU3.

Based on these estimates the unidentified prospectivity has been calculated for the AU3. Due to the high exploration risks encountered in Assessment Unit 3 and the high degree of uncertainty associated with especially any possible charge, maps showing the Mean Case Risked MMBOE Recoverable per unit area have not been produced in this case.

Resource Assessment

The resource assessment provides an estimate of the play-based Yet-to-Find potential of conventional hydrocarbons. The assessment includes Plays 3, 4, 5 and 6 (Fig. 6). Plays 1 and 2 are located at very shallow depths below seabed and are therefore not considered prospective.

Known Prospectivity

The first step in the Yet-to-Find Assessment was to make Gross-Rock Volumes for the leads mapped by the industry, GEUS and NUNAOIL in AU3. A total of 24 leads have been evaluated in Assessment Unit 3 (Fig. 8). Gross-Rock Volume calculations were made in Player® based on area-depth pairs from the top of structure to spill-point. Area-depth pairs were derived from either mapping of the structures in Petrel or digitizing of

closure and contour lines in ArcGIS from company reports. For identified structures without area/depth pairs (unevaluated leads), area yield values have been applied.

For the hydrocarbon volume calculations the following input parameters have been considered for all leads: 1) Porosity, 2) Gross and net sand thicknesses and Net-to-Gross Ratio, 3) Oil Saturation, 4) Oil formation volume factor (Bo), 5) Recovery Factor (RF), and 6) Gas expansion factor (E). These input parameters are based on well data, information about water depths, interpretation of petrophysical well-logs, saturation curves, and information from publications etc.

The known prospectivity appears from integrating the calculated identified lead volumes (see section above) with the CCRS maps providing the risked volumes for the leads.

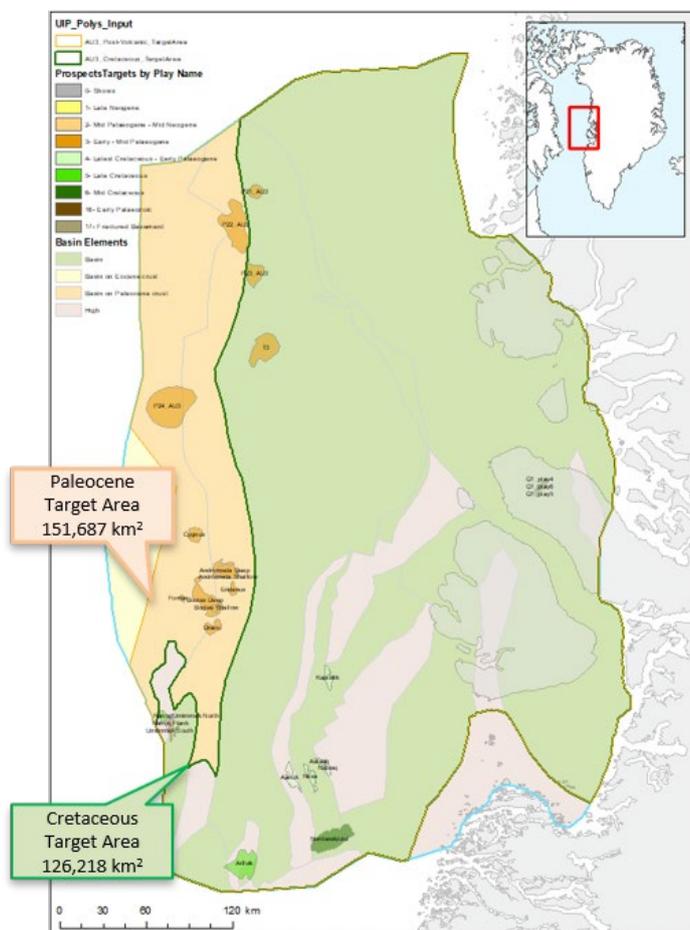


Figure 8 - Identified leads in AU2. Analog and target areas for the Yet-to-Find calculations are also shown.

Unidentified Prospectivity

As mentioned above, the unidentified prospectivity analysis is based on the Feature Density (FD) calculation for each of the identified play intervals carried out in Assessment Unit 2, due to the severe lack of data in Assessment Unit 3 (Fig. 8).

The “Future Target Area FD (per play)” = “Analog Area (FD)” ÷ “Identified Target Area FD”.

Target area for Plays 4-6 is the area underlain by Cretaceous basins. The target area for Play 3 is the entire region west of the West Greenland Platform except the area furthest to the west where Eocene oceanic crust is present.

The unidentified prospectivity is the “Future Target Area FD (per play)” × “Mean volume per Feature MMBOE”.

A summary of the results by Play Interval (Identified Prospectivity) and results by Play Interval (Unidentified Prospectivity) is shown in Table 2.

It should be noted, that although the total risked reserves may seem relatively high, the mean risked volume per feature is as low as 5 MMBOE.

Play Interval	Number of Prospect Targets	Unrisked BOE (mmboe)	Risked BOE (mmboe)
3- Early - Mid Palaeogene	12.00	3,282.54	36.94
4- Latest Cretaceous - Early Palaeogene	6.00	546.97	11.63
5- Late Cretaceous	3.00	1,514.33	25.11
6- Mid Cretaceous	2.81	935.99	33.27
Totals:	23.8	6,279.8	107.0

Table 2. Summaries of Identified and Unidentified Prospectivity in Assessment Unit 3. The Total Risked Recoverable (Mean Case) is 3,650 MMBOE.

Play Interval	Number of Unidentified Features	Unrisked BOE (mmboe)	Risked BOE (mmboe)
3- Early - Mid Palaeogene	168.13	31,440.60	188.87
4- Latest Cretaceous - Early Palaeogene	191.23	70,373.81	1,112.21
5- Late Cretaceous	193.72	71,288.19	1,123.14
6- Mid Cretaceous	194.97	71,748.10	1,133.03
Totals:	748.1	244,850.7	3,557.3

Portfolio Analysis

Due the high exploration risk encountered everywhere in the offshore areas of AU3 at all play levels (Fig. 9) a portfolio analysis to highlight the most prospective areas has not been carried out for Assessment Unit 3, since de-risking initiatives are not possible to carry out in the offshore areas with present-day seismic imaging technologies.

It should, however, be noted, that the leads onshore Nuussuaq can be de-risked significantly at relatively low cost and that these therefore may provide viable exploration targets.

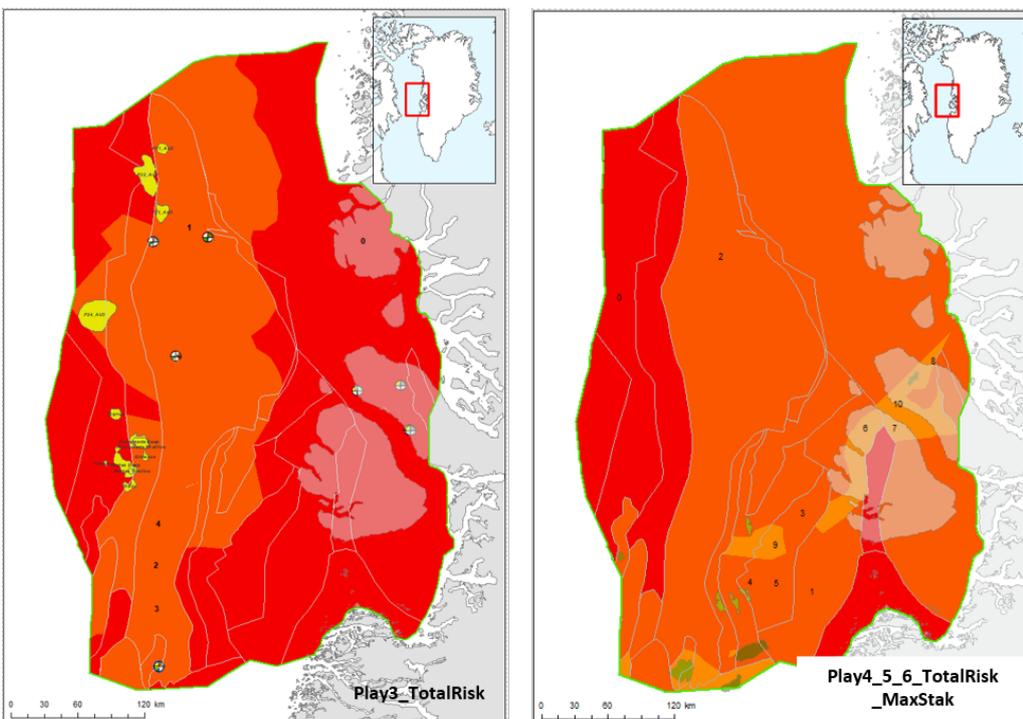


Figure 9 - Total play risk for Play 3 and maximum risk value stack for Plays 4–6. Note that play risks in the offshore areas is generally less than 5% without possibilities of de-risking with present-day technologies. However, the onshore leads may be de-risked to represent viable exploration targets.

Deliverables

The results from this study including a Player® ArcGIS project and an extensive slide pack are available for the petroleum exploration industry by contacting [Thomas Varming](#) at NUNAOIL,

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