Greenland Resource Assessment

Assessment Unit 1
Labrador Sea and Davis Strait

Project Summary

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or

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Greenland Resource Assessment, Labrador Sea and Davis Strait (Assessment Unit 1)

Executive Summary

A play-based resource assessment of conventional hydrocarbons has been performed for the Labrador Sea – Davis Strait continental shelf area, West Greenland (Assessment Unit 1, AU1). Four play levels have been assessed, with an estimated mean for the undiscovered resources of ~4,150 MMBOE risked recoverable for the northern area and ~1,400 MMBOE risked recoverable for the southern area based on the areal yield for the northern area.

The known prospectivity in the northern area includes 79 leads and 69 unevaluated features (fractured basement traps and stratigraphic traps) with Mean Case Risked Recoverables volumes of ~1080 MMBOE. The unidentified prospectivity has Mean Case Risked Recoverables volumes of ~3070 MMBOE resulting in an average area yield of ~30 MB/1000 km2 (risked). The unrisked Pmean volumes for the leads of the four evaluated play levels range from <1 to 1350 MMBOE.

The geologic probabilities for AU1 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.

The assessment results presented are based on all available data collected and interpreted by the industry, GEUS, NUNAOIL and the Greenland Ministry of Industry, Energy and Research (MIER) and reflect the state of geologic knowledge of the West Greenland part of the Labrador Sea - Davis Strait area at the time of the assessment. 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 methology 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 11 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

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.

Introduction

The AU1 Resource Assessment (Davis Strait and Labrador Sea, West Greenland) is the first 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 in order 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.

The project is mainly sponsored by NUNAOIL and is carried out as a collaboration between GEUS, NUNAOIL and the Greenland Ministry of Industry, Energy and Research (MIER) hosted

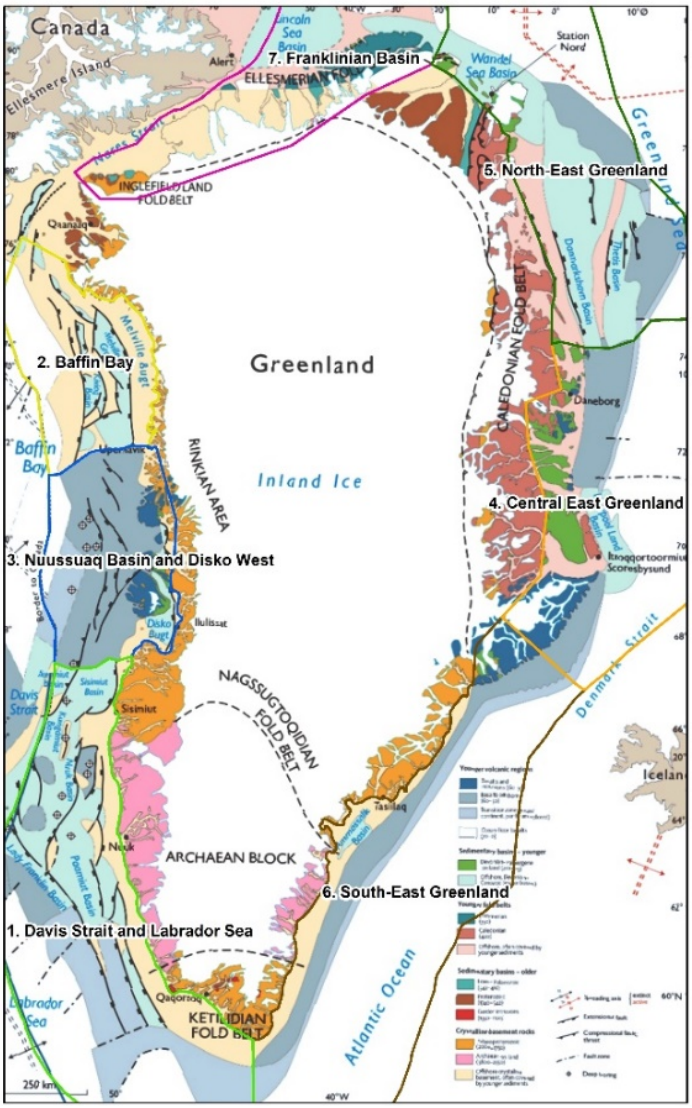


Figure 1. Geological map of Greenland with the seven assessment units indicated.

by GEUS. The work is based on all available existing data provided by the industry, GEUS, NUNAOIL and MIER. 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.

An oil and gas resource assessment of the West Greenland – East Canada province has previously been performed by the U.S. Geological Survey (USGS) in the Circum-Arctic Resource Program (Schenk 2017). However, the USGS assessment covers the areas north of the Arctic Circle, including only the northernmost part of AU1, and AU2 and AU3. No assessment has previously been published for the entire AU1 area.

Database

The database for AU1 includes an extensive 2D seismic data set of various vintages, two 3D seismic surveys, magnetic and gravity surveys, data from eight exploration wells numerous scientific publications and industry reports, and excellent outcrop analogues from the onshore Nuussuaq Basin and Bylot Island in eastern Canada (Figs 2, 3).

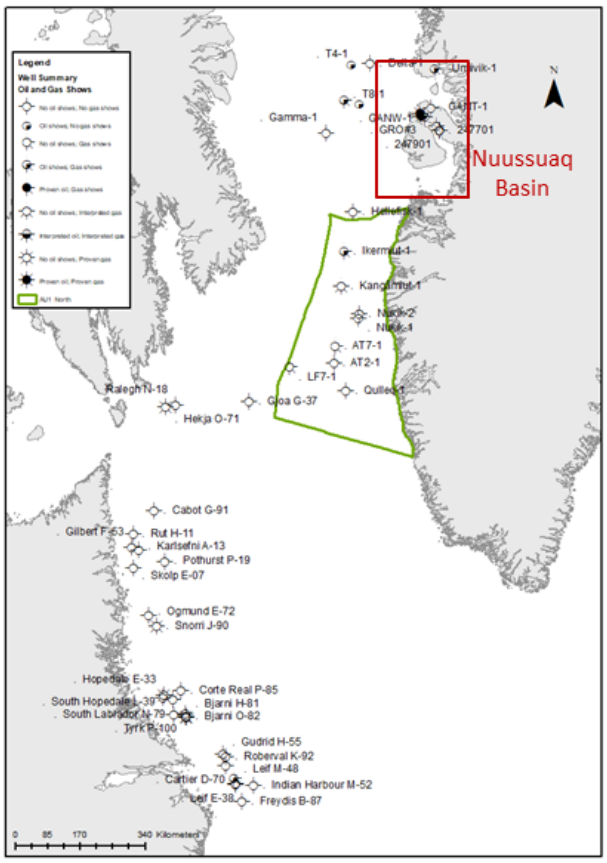


Figure 2. Outline of northern AU1 and Nuussuaq Basin and locations of wells and boreholes.

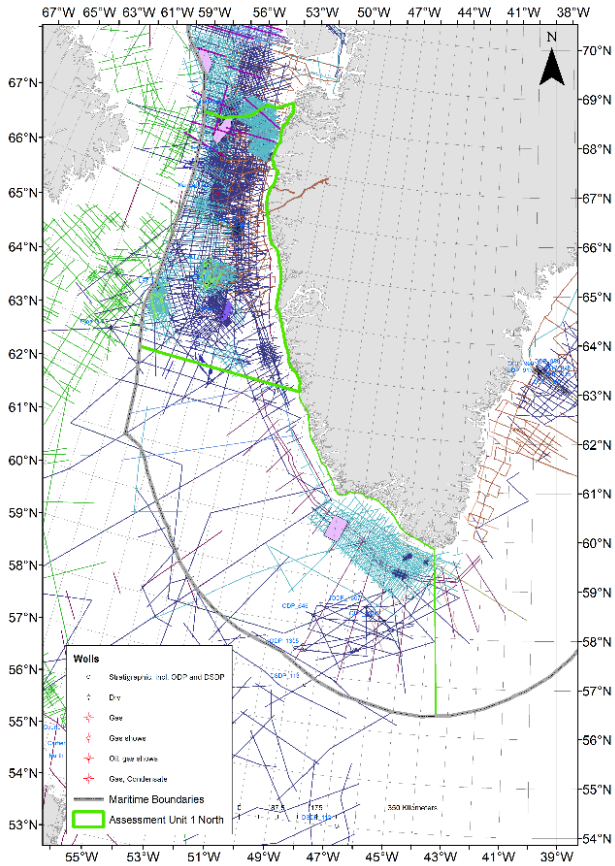


Figure 3. Seismic database with the northern and southern area of AU1.

Exploration History

Only limited exploration drilling has been carried out on- and offshore West Greenland and most of the West Greenland Continental Shelf can therefore be characterized as a frontier exploration region. Exploration efforts have been restricted to five periods (Christiansen 2011):

1. An offshore campaign 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 by a small Canadian company grønArctic in the 1990s including drilling of the GRO#3 exploration well
3. Offshore exploration in the 1990s by Statoil, Phillips, DONG and NUNAOIL, including drilling of the Qulleq-1 exploration well in 2000
4. New activities in the 2000s with a high level of seismic data acquisition by the seismic industry followed by a large number of licence awards and drilling of 8 exploration wells by Cairn in 2010-11
5. A major campaign in the Baffin Bay area in the 2010s with drilling of a series of shallow cores 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 of which eight were drilled in the AU1 area. No commercial discoveries have been made, but during drilling of the Kangâmiut-1 well, the well took major gas kicks in Paleocene submarine fan sandstones. The presence of gas constituents up to C4 suggests that gas is moderately wet which could indicate that the hydrocarbons in the sandstone is condensate or possibly oil. The drill stem test was inconclusive, probably due to mud invasion as a result of efforts to control the well, and the prospectivity of the Kangâmiut Ridge was therefore not adequately tested by the well (Bate 1997).

Figure 4 summarizes the post-well analysis of the eight wells drilled in AU1. Apart from the discovery in the Kangâmiut-1 well, three wells were off structure tests (Nukik-1, Nukik-2 and Ikermiut-1). LF7-1, Qulleq-1, AT2-1 and AT7-1 are all dry valid trap tests. In LF7-1 the main mid-Cretaceous and Late Cretaceous targets were not present.

The Qulleq-1 well was drilled on an amplitude anomaly that turned out to be related to a mineral phase-change transition from opal-CT to quartz. A post-well evaluation suggests that there is a risk that the

Qulleq-1 structure is located in a migration shadow. AT2-1 was drilled on a mid to Late Cretaceous target on what was believed to be the crest of a large rotated fault block. Post-well results indicate that it was drilled on a Late Cenomanian – Early Turonian volcanic feature (Knudsen. Post-well analysis of the AT7-1 well suggests that the presumed Cenomanian-Turonian source rock interval was developed in sandy facies and consequently the well had charge issues. Three wells have fluid inclusions (shown as partly charge in wells LF7-1, AT7-1 and Ikermiut-1).

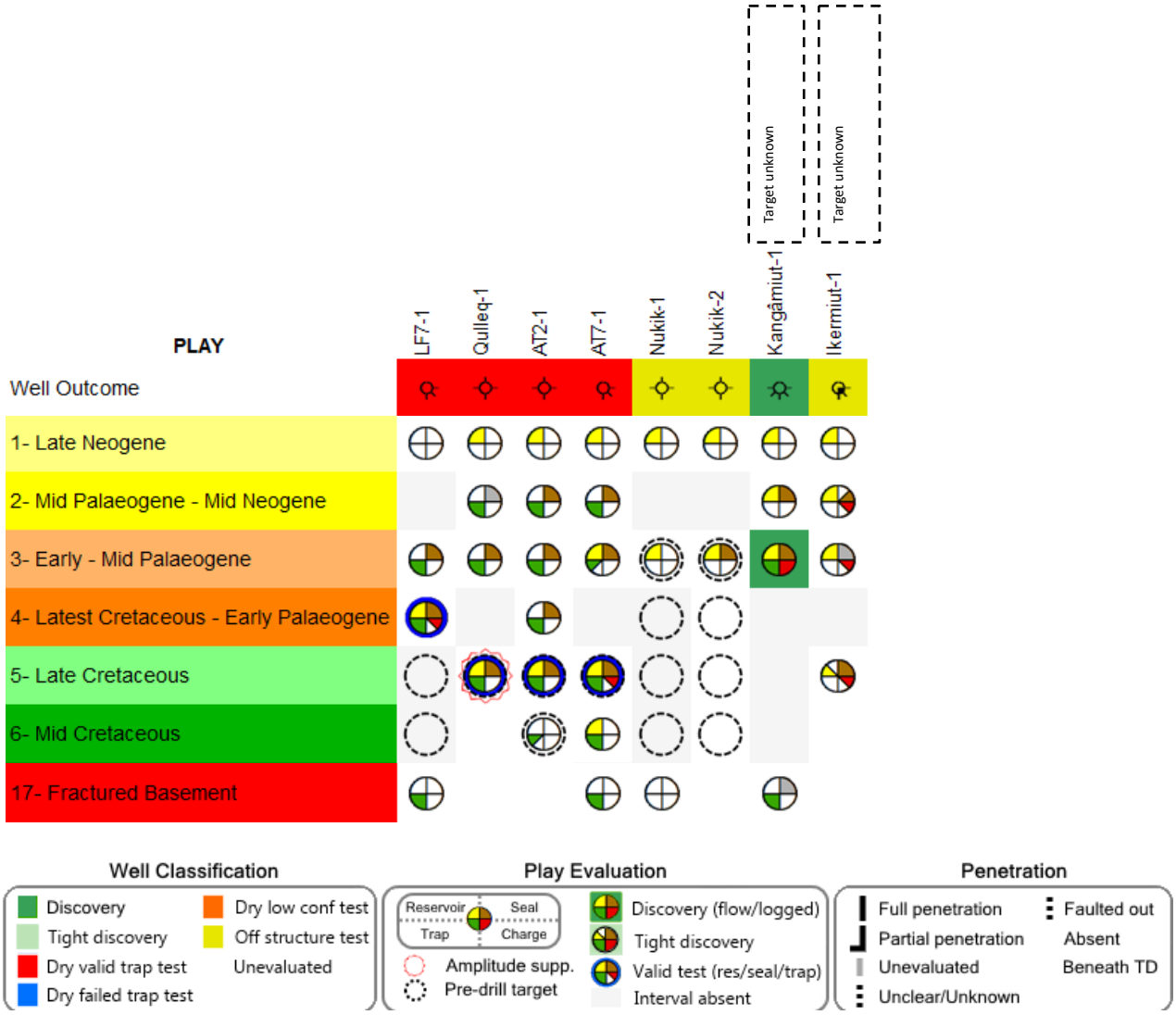


Figure 4: Post-well analysis of the eight exploration wells in AU1.

Seismic-Stratigraphic Interpretation

A regional seismic stratigraphic interpretation is based on GEUS and NUNAOIL in-house interpretation. Ten super-regional seismic stratigraphic key horizons have been mapped and tied to exploration wells and assigned to Plays (Figs. 5, 6). The ten seismic stratigraphic key horizons that have been mapped are: A1: Seabed; B1: Plio-Pleistocene/Base Quaternary; C1: Late Miocene Unconformity; D1: Mid-Miocene Unconformity; E1: Mid-Eocene Unconformity; E2: Late Paleocene; EV: Top Volcanics; F1: Near base Cenozoic Unconformity; G1: mid-Cretaceous unconformity; H1: Top Palaeozoic/Basement (Fig. 5).

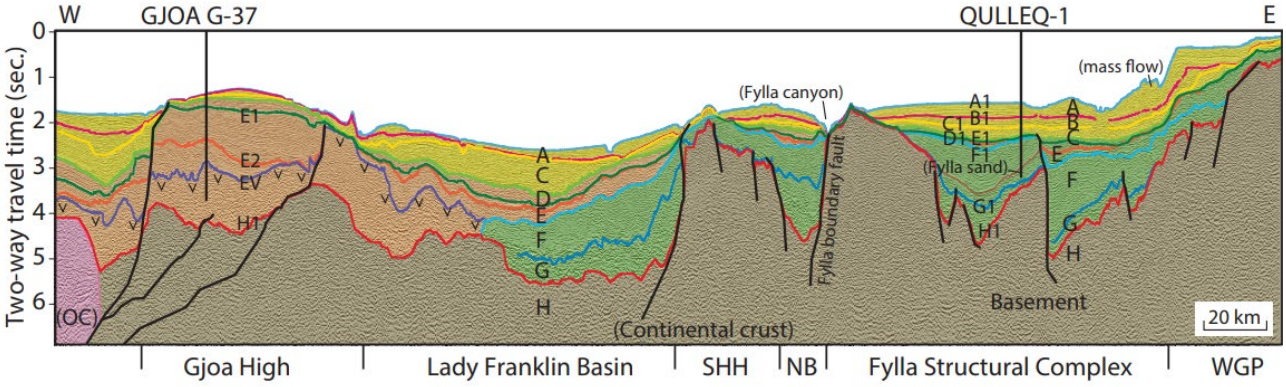


Figure 5. Interpreted E-W seismic section across the southern West Greenland continental shelf, including the Qulleq-1 well and the Gjoa G-37 well on the Canadian margin. From Gregersen et al. (2019).

Tectonostratigraphic Evolution

The tectonic evolution of the Labrador Sea – Davis Strait – Nuussuaq – Baffin Bay region is complex involving multiple phases of rifting related to the initial opening of the norther Atlantic, 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 and subsequent drifting.

Along the West Greenland continental margin major basins of Cretaceous (or possibly older age) developed separated by structural highs: the Sisimiut Basin, Kangâmiut Basin, Lady Franklin Basin, Nuuk Basin and several smaller basins related to the Fylla Structural Complex (Figs 6, 7). Towards the west in the northern part of the Labrador Sea and in Davis Strait, thick Paleocene volcanic successions extruded during initial sea floor spreading cover the Cretaceous basins. Oceanic or transitional crust is found in the central part of the Labrador Sea covering large areas of southern AU1 (Fig. 6).

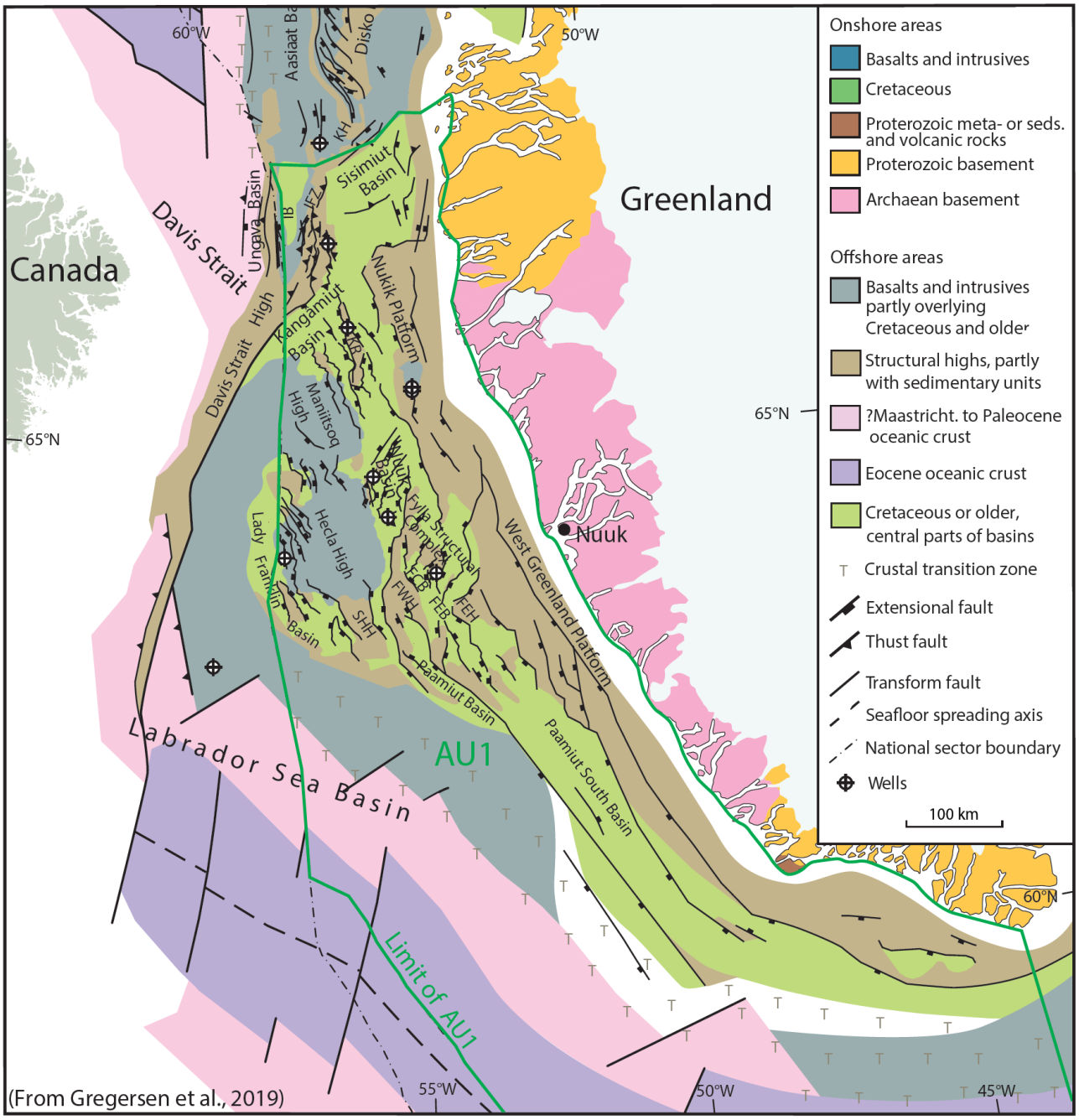


Figure 6. Tectonic elements map of the southern West Greenland margin in the Labrador Sea to Davis Strait area. The eastern part of the margin is dominated by Cretaceous rift basins and Cretaceous to Palaeogene structures. Further west in the region volcanic rocks and oceanic crust dominate the deeper geology. Map from Gregersen et al. (2019).

Figure 7 show the tectonostratigraphic evolution of the West Greenland continental margin where six tectonostratigraphic phases have been recognized (Gregersen *et al.* 2019).

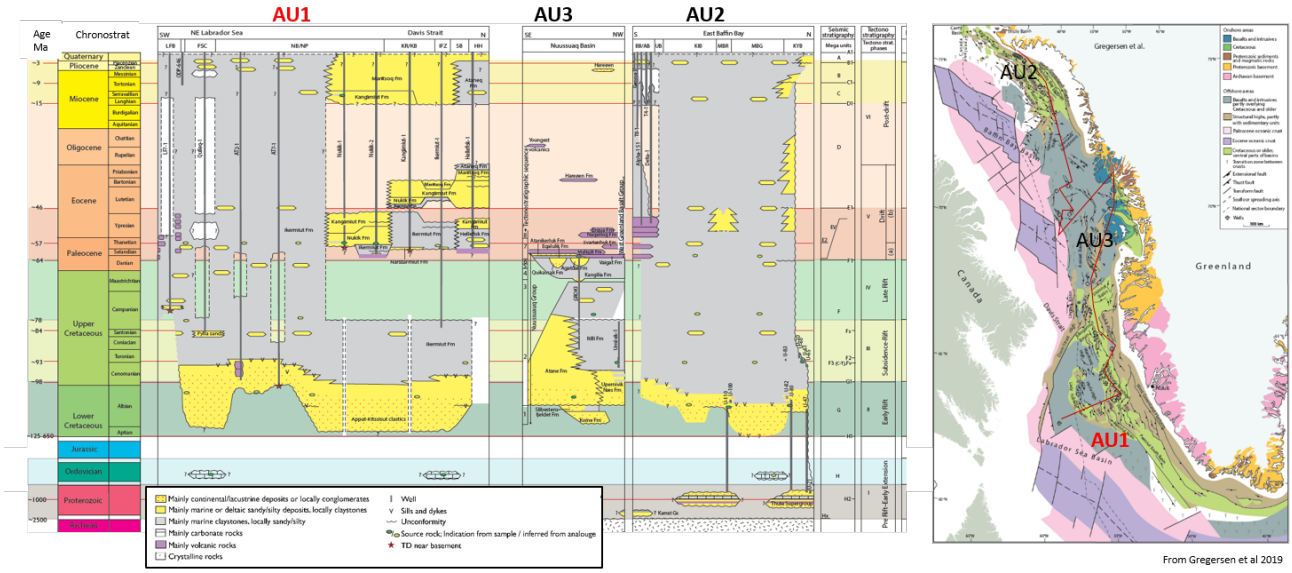


Figure 7. Tectonostratigraphic evolution of West Greenland. The red line on the geological map connects the exploration wells shown in the tectonostratigraphic framework.

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 indicates that local rifting took place during the early stage of this phase.

A change in stress regime occurred during the initiation of the Early Campanian – Early Paleocene Late Rift Phase and 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 large deep-water basins and deposition of reservoir sands took place in basin-floor fans, turbidite slope channels and large canyons.

During the Early Paleocene – Eocene Drift Phase, oceanic crust formation 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 North Atlantic Igneous Province. 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. Eight of these plays are present in AU1 (Plays 1-6, 16 and 17; Fig. 7). 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. 7).

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-Kofoed 2011; Bojesen-Kofoed *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).

Table 1. Characteristics of the six expected source rocks in AU1.

	Thickness (m)	TOC (wt-%)	Hydrogen Index	Kerogen type
Ordovician	25	8	600	II
Albian	100	5	250	II/III
Cenomanian-Turonian	100	3	300	II/III
Campanian	100	4	200	II/III
Paleocene-Eocene	100	4	200	II/III
Miocene	100	3	300	II/III

Basin modelling indicates that all source rocks, apart from the Miocene, may have reached thermal maturity throughout or in parts of AU1. Consequently, the charge model for the play analysis incorporate the possibility for charge from all five mature source rock intervals, which has been taking into account in the charge model. The oil seeps described from the onshore Nuussuaq Basin 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. The source

rock characteristics of each of the six expected source rocks are summarized in Table 1. These data have been used as input parameters to the kinetic model in the basin modelling study for the AU1 area.

Assessment Process

The assessment process for the resource evaluation of the northern part of AU1 (north of approximately 62°30'N) is summarised in the "Yet-To-Find Triangle" shown in Figure 8. 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 incorporating all available geological and geophysical data and exploration history data.

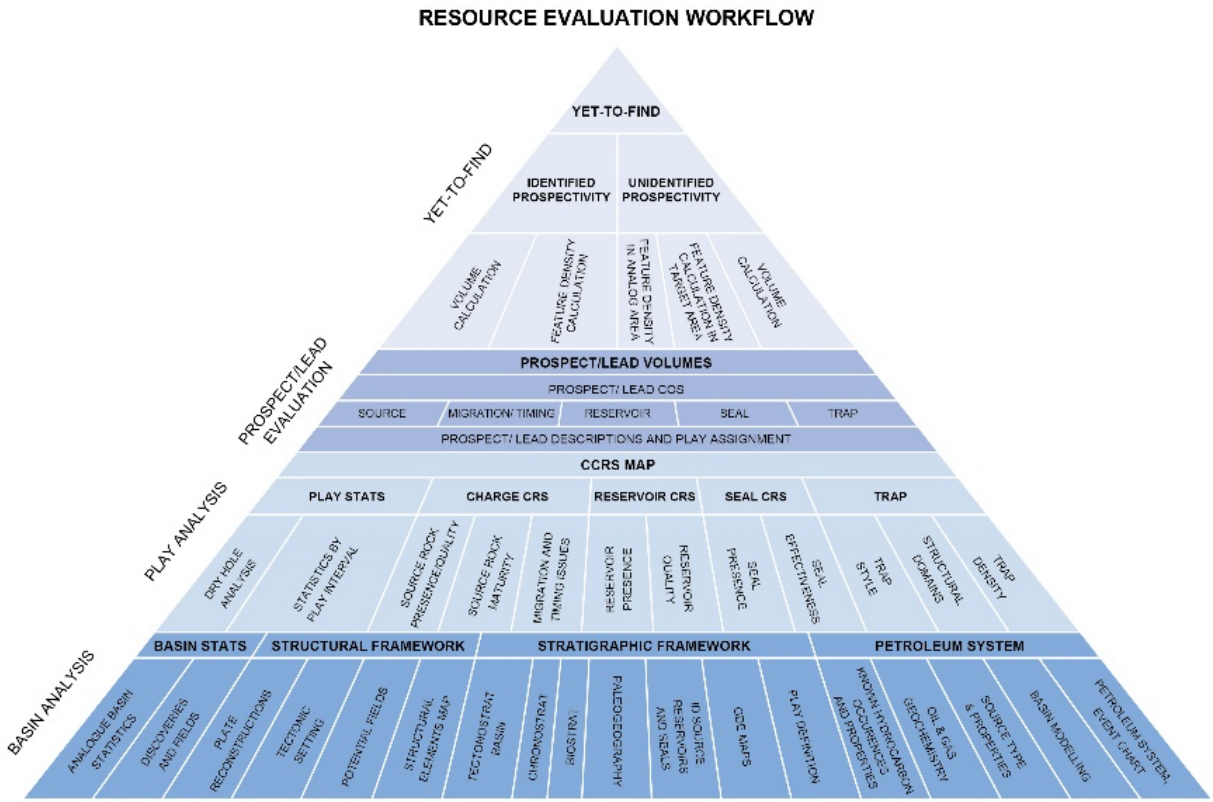


Figure 8. Resource evaluation workflow used in the Greenland Resource Assessment.

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).

A multiple charge scenario is applied for each play since five source rock intervals have been identified on the West Greenland shelf: Ordovician, Albian, Cenomanian–Turonian, Campanian and Paleocene (Bojesen-Koefoed 2011). This means that for each play a specially designed composite charge workflow is applied in order 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 calibrated with data from the most extensively explored previous licence areas (analogue areas) in AU1.

Based on these analogue areas the unidentified prospectivity has been calculated for the underexplored areas. Having calculated both identified and unidentified prospectivity, the Mean Case Risked MMBOE Recoverable per unit area can be estimated and the roll-up of all play intervals provide the Total Mean Case Risked MMBOE for AU1. In this way, information on which blocks are the most prospective is now available.

Resource Assessment

The resource assessment provides an estimate of the play-based Yet-to-Find potential of conventional hydrocarbons. Due to large variations in data coverage, AU1 has been divided into a northern and southern part (Figures 2 and 3). The northern area is characterized by having very good seismic data coverage, eight exploration wells have been drilled, and it has been possible to carry out a full play analysis. In the southern area, the data coverage is extremely sparse and no exploration wells have been drilled. This prevents the possibility for making an in-depth play analysis and basin modelling that can feed into the Yet-to-Find analysis. In order to calculate the Yet-to-Find for the southern area the average area-yield in the northern area, has been used to calculate the resources for the southern area.

In the northern area, the assessment only includes Plays 3, 4, 5 and 6 (Fig. 8). Plays 1 and 2 are located at very shallow depths below seabed and are therefore not considered prospective. Similarly, volume calculations for Play 16 – Early Palaeozoic (Ordovician) – and Play 17 – Fractured Basement – leads have not been carried out due the lack of knowledge and the complex nature of these plays. These are therefore considered as concepts only. However, the possible Ordovician source rock has been included in the geological model for the petroleum source rocks possibly sourcing overlying plays.

Northern AU1

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 AU1. A total of 79 leads have been evaluated in the northern part of AU1 (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 1) Mapping of the structures in Petrel, or 2) Digitizing of closure and contour lines in ArcGIS from company reports.

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.

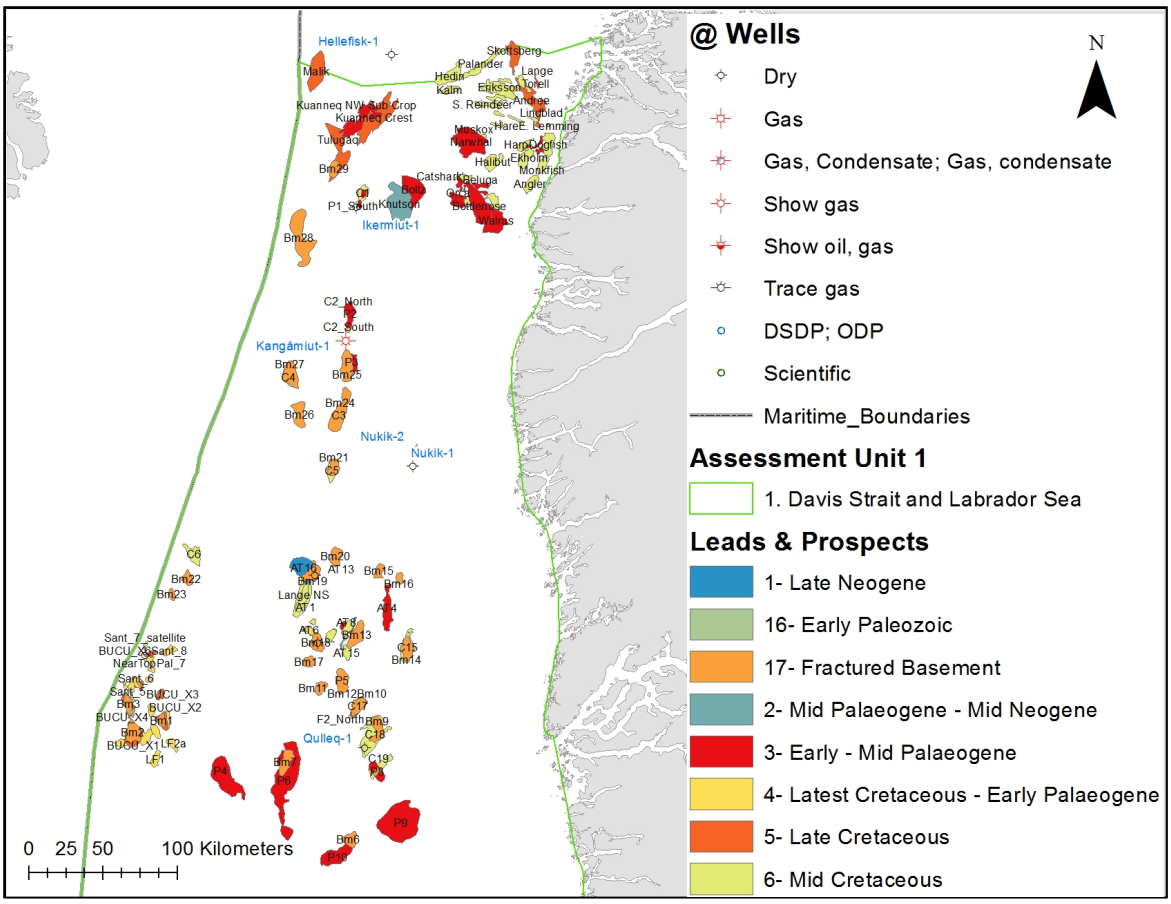


Figure 8. Identified leads in the northern part of Assessment Unit 1.

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.

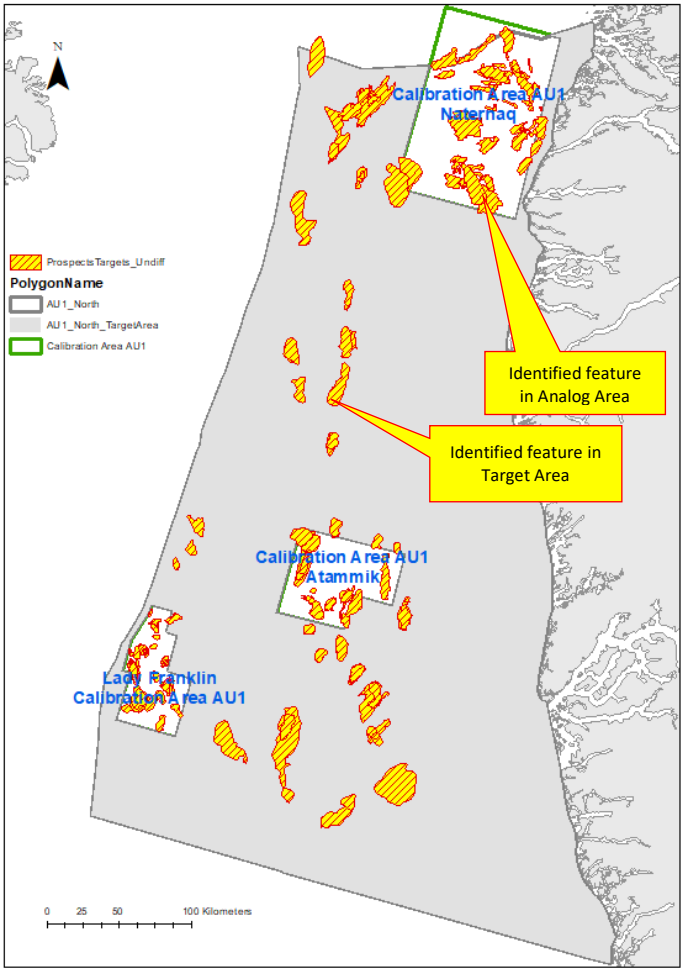
Unidentified Prospectivity

The unidentified prospectivity analysis is based on a Feature Density (FD) calculation approach for each of the identified play intervals, calibrated with data from the most extensively explored previous licence areas in AU1 (Plays 4-6) or mapped basement high areas (Play 3).

The most extensively explored licence areas in AU1 are:

- Naternaq, 11,192 km^2
- Atammik, 4,052 km^2
- Lady Franklin, 2,962 km^2

Total Calibration Area is 18,206 km^2 for Plays 4-6 (Fig. 9).



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

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

A summary of the results by Play Interval (Identified leads) and results by Play Interval (unidentified prospectivity) is shown in Table 2.

Figure 9: Calibration and target areas for Yet-to-Find analysis for Plays 4-6.

Table 1. Summaries of Identified and Unidentified Prospectivity in the northern part of AU1.The Total Risked Recoverable (Mean Case) for the northern area is 4,150 MMBOE.

Summary of Results by Play Interval (Identified Prospects)

Play Interval	Number of Prospect Targets	Unrisked BOE (mmboe)	Risked BOE (mmboe)	EMV (M$)
3- Early - Mid Palaeogene	10,00	3.468,18	97,38	0,00
4- Latest Cretaceous - Early Palaeogene	17,00	427,37	74,22	0,00
5- Late Cretaceous	9,00	2.078,10	201,50	0,00
6- Mid Cretaceous	43,00	5.793,76	710,10	0,00
Totals:	79,0	11.767,4	1.083,2	0,0

Summary of Results by Play Interval (Unidentified Prospectivity)

Play Interval	Number of Unidentified Features	Unrisked BOE (mmboe)	Risked BOE (mmboe)	EMV (M$)
3- Early - Mid Palaeogene	0,00	0,00	0,00	0,00
4- Latest Cretaceous - Early Palaeogene	95,38	3.624,53	84,39	0,00
5- Late Cretaceous	56,36	12.963,11	734,58	0,00
6- Mid Cretaceous	259,52	35.035,38	2.254,69	0,00
Totals:	411,3	51.623,0	3.073,7	0,0

Portfolio Analysis

Northern AU1

Main basic assumptions for Yet-To-Find and Portfolio analyses:

1. Stratigraphic traps and fractured basement/Ordovician carbonates are not considered due to high risk associated with these trap types. Such traps generally represent unique opportunities that are difficult to predict and assess, especially in frontier regions, where such trap types have not yet been tested or documented.
2. Partial fill of structures halfway between top and bottom.
3. Paleocene structural traps only on top of structural highs.

The northern part of AU1 has been divided into graticular blocks (30'x 30', *c.* 650 km^2). Figure 10A shows the roll-ups for Plays 3, 4, 5 and 6 Mean Case Risked MMBOE/Block Recoverable. The total roll-up for Mean Case Risked MMBOE/Block Recoverable for Plays 3-6 is shown in Figure 10B. The number in each block represents the calculated known and unknown Mean Case Risked MMBOE/Block Recoverable.

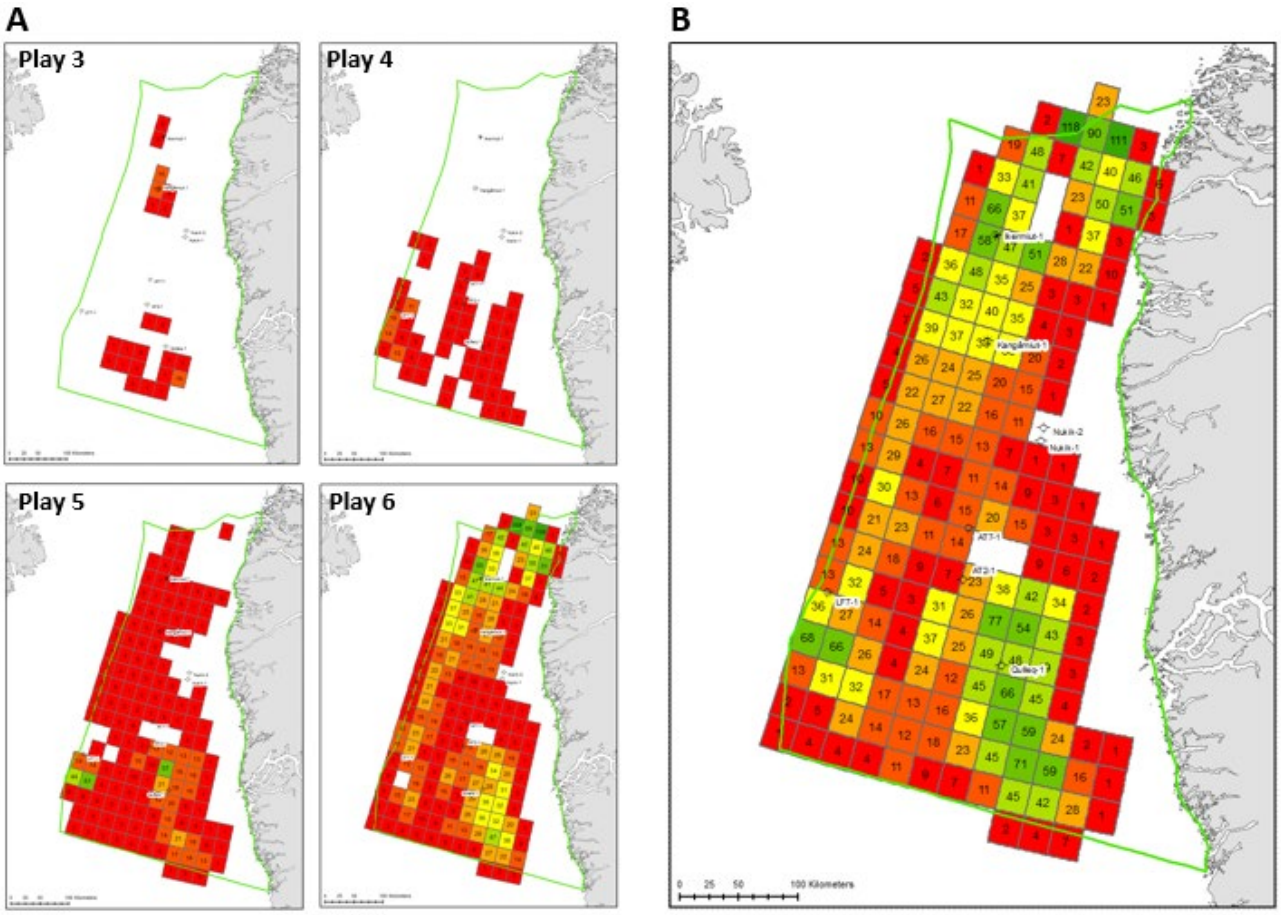


Figure 10. Risked mean recoverable (MMBOE) per block, northern part of assessment unit AU1. A: Individual plays, B: Total roll-up for plays 3-6.

The total roll-up in Fig. 10B suggests that the most prospective areas are the Kangâmiut/Sisimiut Basins and the Fylla Structural Complex/Fylla East Basin. From the roll-up per play level in Fig. 10A it is evident that for the Kangâmiut/Sisimiut Basins the most prospective plays are Play 3 and Play 6, whereas for the Fylla Structural Complex/Fylla East Basin the most prospective plays are Play 5 and Play 6.

Southern AU1

For the southern area, with very little data, the average area yield for the northern area has been used to assess the unknown prospectivity. The average yield (risked recoverable) for the northern area is 30 MMBOE/1,000 km^2. The size of the sedimentary basin area in the southern part of AU1 is 46,000 km^2.

Thus, the Total Risked Recoverable (Mean Case) for the southern area is estimated at ~1,400 MMBOE.

The assessment results presented here are based on all available data and reflects the state of geologic knowledge of the West Greenland part of the Labrador Sea – Davis Strait area at the time of the

assessment. Future drilling and evaluation of the petroleum systems based on new data within this area will add to the geologic knowledge base, and will lead to a refinement of these assessment results.

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 managing director of NUNAOIL, Signe Ulfeldt Hede.

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