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GEM-2 Baffin Project

L.T. Dafoe, K. Dickie, G.L. Williams, N. Bingham-Koslowski, C.D. Jauer, J.W. Haggart, and J. Bates

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Foreword

The Geo-mapping for Energy and Minerals (GEM) program is laying the foundation for sustainable economic development in the North. The Program provides modern public geoscience that will set the stage for long-term decision making related to responsible land-use and resource development. Geoscience knowledge produced by GEM supports evidence-based exploration for new energy and mineral resources and enables northern communities to make informed decisions about their land, economy and society. Building upon the success of its first five-years, GEM has been renewed until 2020 to continue producing new, publically available, regional-scale geoscience knowledge in Canada's North.

During the 2017 field season, research scientists from the GEM program successfully carried out 27 research activities, 26 of which will produce an activity report and 12 of which included fieldwork. Each activity included geological, geochemical and geophysical surveying. These activities have been undertaken in collaboration with provincial and territorial governments, Northerners and their institutions, academia and the private sector. GEM will continue to work with these key partners as the program advances.

Project Summary

Offshore of Baffin Island, deep below the seafloor of Baffin Bay, there are sedimentary basins with as yet unknown potential for viable petroleum resources. As part of the GEM-2 Baffin Project, the desktop activity *Stratigraphic and Tectonic Framework for the Baffin Bay Petroleum Systems* aims to provide an understanding of the geological history and plate tectonic evolution of the sedimentary basins and the factors that control the petroleum resource potential. To help further understand basin distribution, the potential for deeply buried rocks, and the changing nature of the rifted margin of Baffin Bay, we are using the Labrador Sea margin to the south as an analogue. This area evolved contemporaneously with Baffin Bay and underwent similar geological processes. The Labrador offshore margin has been more thoroughly sampled by industry wells and modern seismic data and allows us to develop analogues for the crustal structure, nature of sedimentary basin fill, and characteristics of pre-rift Paleozoic basins. Additionally, the intervening Davis Strait region forms an important zone of strike-slip deformation with extensive volcanics, major structural highs, and large Paleozoic basins that contribute to factors influencing the petroleum system of that region. By integrating these studies with other GEM-2 Baffin activities, we can build an integrated tectonic and stratigraphic framework to better understand the timing of the key geologic elements required to produce a complete petroleum system in the Baffin Bay region: source rocks, reservoir, seal, and migration pathways.

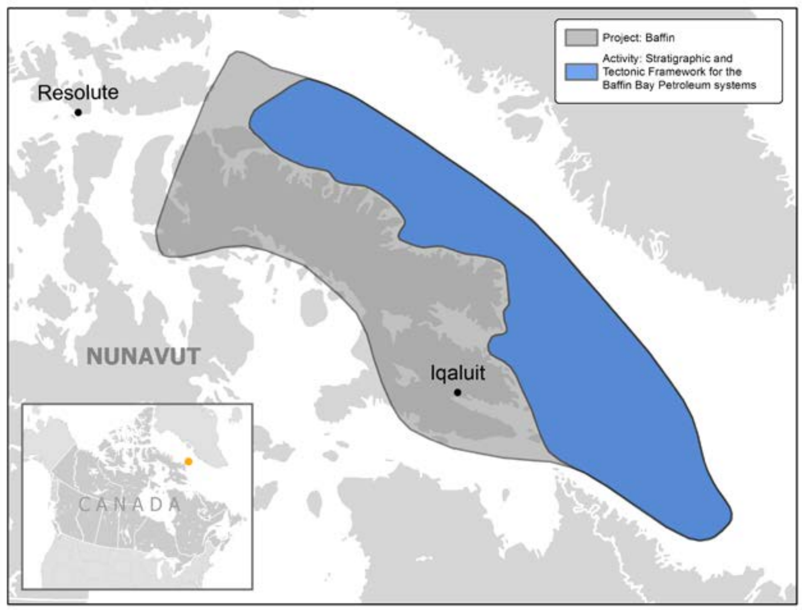

Figure 1: Location of the GEM-2 Baffin project area and activity associated with this report.

Introduction

To understand the petroleum systems of the Baffin Bay region (Fig. 1), the fundamental geologic and tectonic evolution of the sedimentary basins must be understood. The tectonic regime ultimately controls the development of sedimentary basins, which, in the case of the Baffin Bay area, formed as a result of rifting followed by subsidence from associated crustal thinning and cooling. This history, reflected in the stratigraphy of the sedimentary basins, provides insight into the development of the petroleum systems in these basins.

This GEM activity addresses the following scientific questions:

1) What is the nature and age of key stratigraphic surfaces, unconformities, and sedimentary packages in Baffin Bay?
2) How does the nature of the tectonic setting (extension and/or transform faulting; Fig. 2) change along the continental margin from the Labrador Sea into Baffin Bay and how does this influence the stratigraphy?
3) What is the impact of tectonic margin segmentation on the stratigraphic succession and petroleum potential in Baffin Bay?

To address these questions, this activity has been subdivided into six integrated subactivities with their ongoing progress described below.

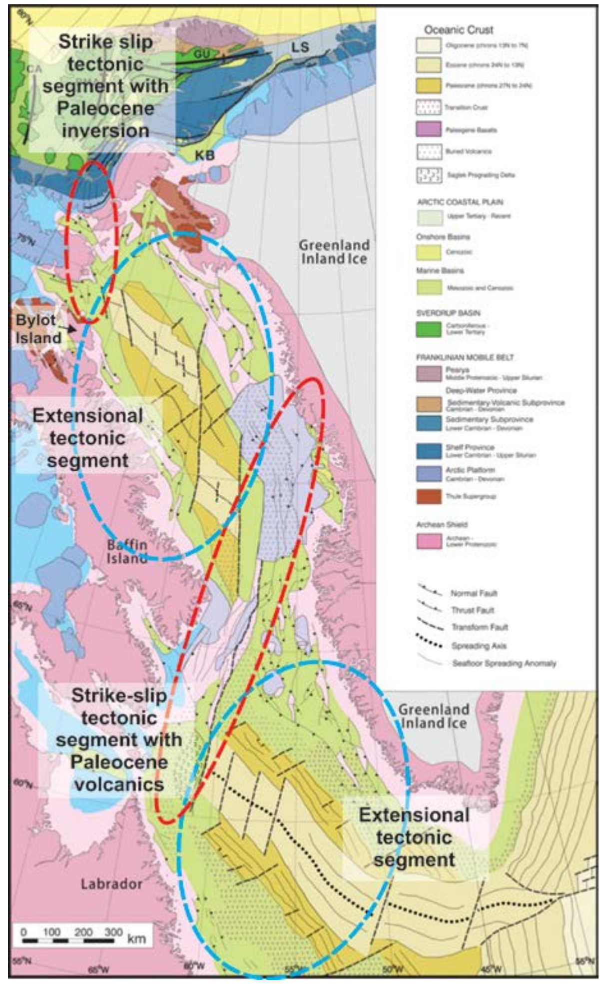

Figure 2: Regional geology map showing development of spreading centres and transform faults modified from Oakey and Chalmers (2012). The circled areas highlight the extensional margin segments (blue) and areas of strike slip (red).

Labrador Analogue

Biostratigraphy

During the year, two Open File reports outlining the palynomorph assemblages in four Labrador Shelf wells were published: the first on Corte Real P-85 and Pothurst P-19 (Williams, 2017a), the second on Roberval C-02 and Roberval K-92 (Williams, 2017b; Fig. 3). Both publications highlight the biostratigraphic and/or paleoenvironmental significance of observed palynomorphs. An additional Open File report is in preparation on the sedimentology and ichnological and palynological assemblages of all sedimentary conventional cores from the Labrador margin, as well as general descriptions of select basement cores and Alexis volcanics (Dafoe and Williams, in prep).

A further two Labrador Shelf wells, North Leif I-05 in the Hopedale Basin and Skolp E-07 in the Saglek Basin, were analyzed to determine the completeness of the Cretaceous section and to correlate the data with that from our lithologic and biostratigraphic studies of the conventional cores from the wells. The North Leif I-05 contains Aptian–Albian, Cenomanian–Turonian, Campanian and Maastrichtian sediments and represents one of the more complete Cretaceous successions on the Labrador Margin. North Leif I-05 also has a continuous section across the Cretaceous-Tertiary boundary, providing excellent correlation of the dinocysts with coeval assemblages in Europe. In the Cenozoic, there is a major dinocyst event marking the Paleocene-Eocene Thermal Maximum (PETM) as denoted by floods of a warm-water dinocyst genus. North Leif I-05 is the first Labrador Shelf well to show this distinctive concentration of species of *Apectodinium*. The well also has a thick middle

Eocene section and a major hiatus with the Chattian being absent. Paleoenvironments in North Leif I-05 include non-marine, marginal marine, and neritic to open ocean in the Late Cretaceous to Ypresian, and were probably bathyal throughout the Eocene, with gradual shallowing in the Oligocene. Neritic conditions prevailed in the Neogene, becoming more prevalent up section.

As in North Leif I-05, age control in Skolp E-07 is based primarily on dinocysts but the spores and pollen provide key biostratigraphic control, especially in the Aptian and Albian. The well shows a surprisingly complete Cretaceous section from Aptian to Maastrichtian. Like North Leif E-05, Skolp E-07 appears to have a more-or-less continuous section across the Cretaceous-Tertiary boundary. Much of the Palaeogene is missing especially in the Paleocene and Eocene, with only lower Danian, lower Ypresian, Rupelian and Chattian sediments being identified. Paleoenvironments in Skolp E-07 included non-marine, marginal marine, neritic and possibly open-ocean in the Late Cretaceous, with shallowing in the Cenozoic giving rise to marginal-marine to non-marine paleoenvironments in the Miocene. Such relatively shallow paleoenvironments are not common in Labrador Shelf wells.

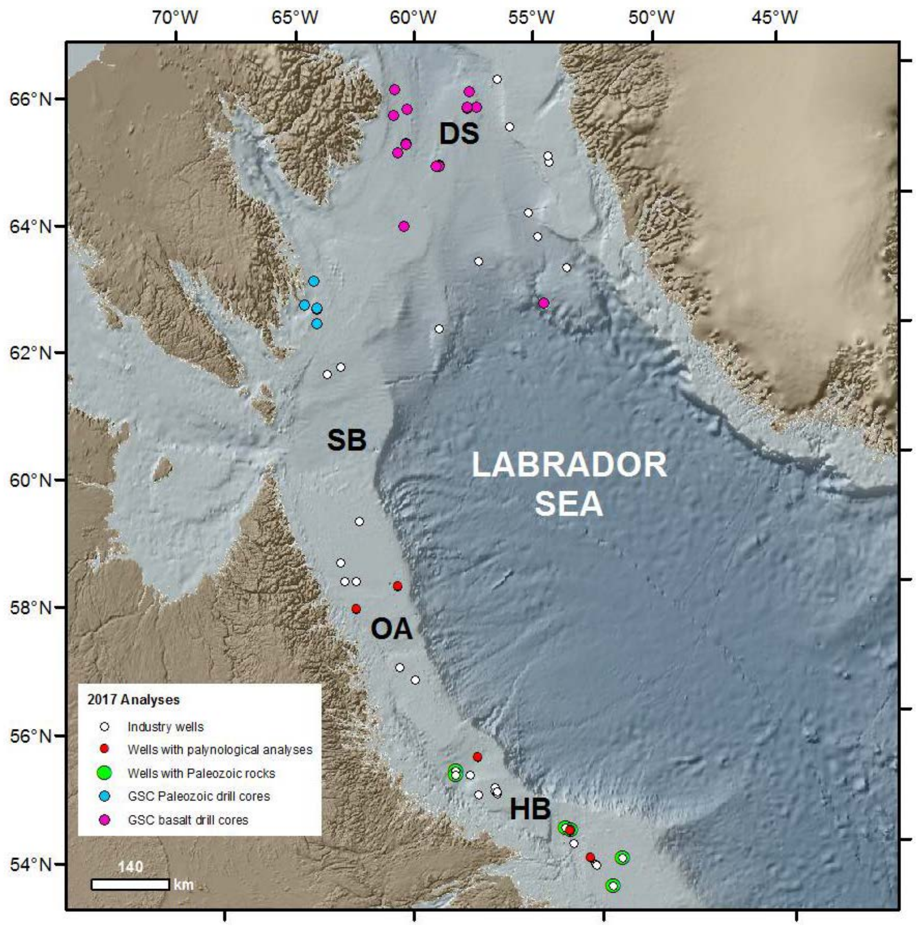

Figure 3: Map of wells and drill core materials analyzed under this study. DS=Davis Strait, HB=Hopedale Basin, OA=Okak Arch, SB=Saglek Basin.

Stratigraphic Framework

We have integrated a detailed paleoenvironmental analysis of the wells with new and existing biostratigraphic data and multi-channel seismic interpretation to build upon previous stratigraphic work on the Labrador Margin. As the Baffin Bay margin experienced a similar rift history, but is poorly sampled by wells, we can apply our Labrador margin framework to this area using seismic interpretation and identification of seismic packages as a primary tool.

Our focus is on the overall regressive and transgressive phases affecting the Labrador margin, especially within the Upper Cretaceous through Cenozoic section. We have been able to map the location of shoreline (e.g. deltaic) clinoforms and shelf-edge break clinoforms primarily within the Hopedale Basin along the southern Labrador margin and to a lesser extent within Saglek Basin to the north (Dafoe et al., 2017). We note overall backstepping during deposition of the Upper Cretaceous

Freydis Member (Markland Formation) shoreline sandstones with a subsequent major regression during deposition of the Gudrid Formation (Selandian-basal Ypresian) where a thin sandy shoreline prograded seaward. The following transgression resulted in a stillstand, Ypresian clinoform developed in a highly proximal position. Renewed regression took place in the Bartonian with deposition of the Leif Member of the Kenamu Formation in which clinoforms are long-wavelength, thin and laterally extensive. Another major transgression forms the base of the Mokami Formation within which a number of flooding surfaces are evident during gradual shoreline progradation that primarily takes place landward of current exploration wells. The Saglek Formation represents two Oligocene-Miocene regressive sandstone units that form large, well-defined clinoforms resembling shelf-edge deltas with correlative fan deposits. The final sandstones along the margin reflect glacial lowstand during the Plio-Pleistocene. Early results suggest that this framework can be applied to the Baffin Bay margin within both tectonically formed graben fills and the eustatically influenced Cenozoic sedimentary wedge.

Paleozoic Basement Rocks: Labrador and Davis Strait

Prior to the formation and subsequent rifting of the supercontinent Pangea, which resulted in the formation of the Labrador-Baffin Seaway, Paleozoic sediments accumulated in the Iapetus Ocean and now form important pre-rift basement successions. Insights into the depositional environments that existed in the Iapetus Ocean can be gained by studying the Paleozoic strata sampled in drill cores from offshore southeast Baffin Island and the Davis Strait, as well as in exploration wells drilled along the Labrador margin. Six Paleozoic, limestone drill cores from the southeast Baffin shelf (4 drill cores) and the Davis Strait (2 cores) regions were collected during 1975 and 1977 GSC cruises, respectively and have recently been re-examined and described (Fig. 3). Additionally, 21 thin sections originating from the drill cores, were also described in order to accurately identify faunal, compositional, and diagenetic elements. The results from the thin section analysis will be combined with the drill core descriptions in order to refine paleoenvironmental interpretations for the region. Seven wells located along the Labrador margin intersect Paleozoic strata with recovery of six conventional cores from four of the wells (Fig. 3). These cores have been described in detail with 44 thin sections for all the 7 wells remaining to be analyzed, but will provide further information on detailed lithology and faunal assemblage. These results will be combined with the core descriptions to interpret the Paleozoic depositional environments of the Labrador margin.

Paleozoic biostratigraphic analysis along the Labrador Margin was largely completed in the 1970s and produced inconsistent results both in terms of methodology and age determination. As such, the seven wells that contain Paleozoic strata in the region have various (Ordovician, Devonian, Carboniferous) to unknown age dates (indeterminate Paleozoic), with several wells reporting low confidence in the reported age. The advancements in biostratigraphic processing since the 1970s and the current poor state of Paleozoic age constraints, resulted in the undertaking of a new, Paleozoic biostratigraphic study. Samples from the 7 wells will be sent for processing and analysis and will be combined with our detailed facies analysis.

Central Labrador Sea: magma-poor margin

The presence of serpentinized mantle along the ocean-continent transition in the central segment of the Labrador magma-poor margin, was first identified by Chian et al. (1995) from anomalously high velocities on their seismic refraction profile. We have been able to extend the mapping of this zone for over 200 km along strike (Keen et al., 2017; in review). Our work is based on new, modern seismic reflection data which is tied to previous refraction velocities and integrated with potential fields. It reveals a characteristic subdued seismic expression in this zone along with the presence of a volcanic layer lying above basement.

The insights into the structural characteristics of this margin also indicate the presence of a zone of proto-oceanic crust showing that the earliest phase of seafloor spreading started here around chron 31, developing into normal thickness oceanic crust by chron 27. The timing of the initiation of seafloor spreading in this segment has proved to be elusive until now.

Landward of the serpentinized mantle zone we show images of hyper-extended crust with its complex block-faulting in which faults sole into decollement zones that merge with Moho. This represents extreme crustal thinning with thinning factors greater than 3.5 and embrittlement of the entire crust. We present the complexity of this margin segment and make comparisons with the West Greenland conjugate as well as the Newfoundland-Iberian margin and also discuss its anomalous aspects and what mechanisms might be responsible for rifting of such old (Archean), cold cratonic lithosphere.

Davis Strait Transform Margin

Seismic and Structural Interpretation

Our geophysical analysis of the Canadian side of the Davis Strait shows a good fit with the current understanding of the eastern part of the region (Sorenson, 2006). The marine Bouguer gravity map (Fig. 4), shown as contour lines, is a keystone to integrating the vintage seismic that shows structural details and the magnetic data that show regional geological trends. The compilation of data used to study this structurally complex strike-slip margin with overprinted volcanics will show further details on the revised structural mapping of the Ungava Fault Zone and the adjacent Davis Strait High and will also provide new insights into crustal type and geophysical features like Bouguer gravity anomalies and various magnetic features. The potential for hydrocarbon exploration of the adjoining sedimentary basins with reference to possible sea-surface oil slicks will also be discussed.

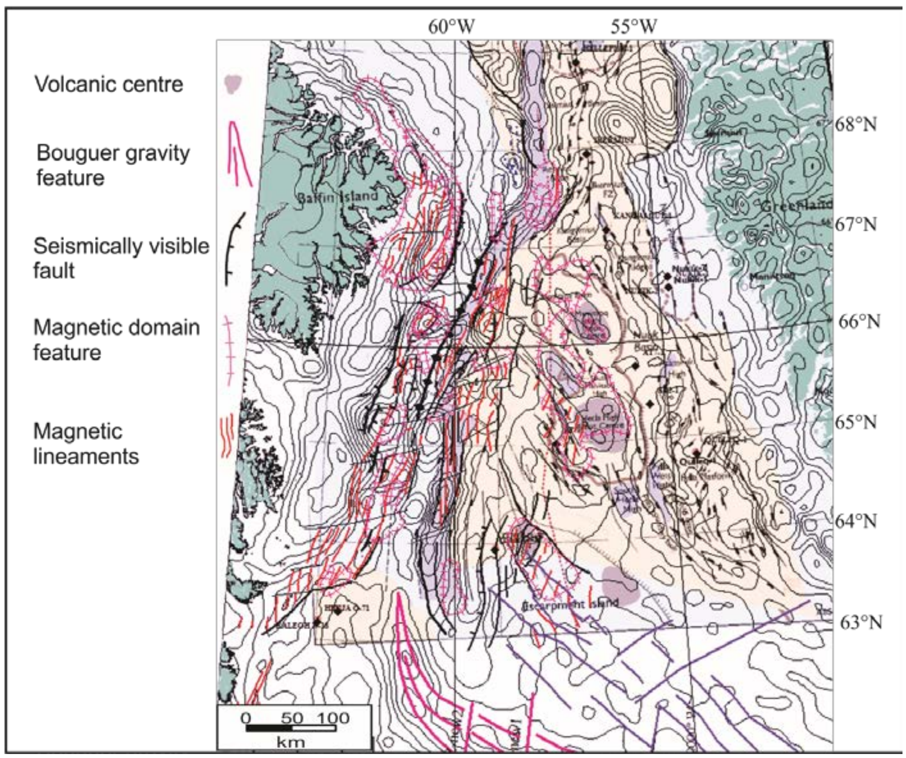

Figure 4: Map of the Davis Strait region with key structural elements indicated on the map. Contours represent Bouguer gravity. The Greenland side of the region is modified from Sørensen (2006).

GSC Legacy Basalt Drill Core Samples

To aid in the seismic and tectonic interpretation of the Davis Strait region, we have studied the GSC legacy seabed drill cores listed as containing basalt bedrock in the GSC Expedition Database. In the Davis Strait region, the 21 samples are grouped into 6 sub-regions: Cape Dyer, mid Davis Strait, southeast Cape Dyer, Davis Strait High, southern Davis Strait High, and West Greenland margin (Fig. 3). The cores have been logged and thin sections were acquired for studying mineralogy. Due to the recovery, current condition of the materials, and ability of the drill to core large clasts resting on the seabed, each of the drill cores was assessed to determine if bedrock had been drilled. Of the 21 samples studied, 6 contain most likely basalt bedrock, 10 contain possible basalt bedrock, and 5 contain no basalt bedrock. Of these drill cores, 8 have been identified for further analysis based on their likelihood of encountering basalt bedrock, location, and the presence of sufficient material for further sampling. Basalts displaying the least amount of alteration and/or infilling of vesicles were selected for compositional analyses (3) and Ar-Ar (8) age dating, which are currently in progress. These results will help us to understand the timing of volcanism in the region and related tectonics.

Baffin Bay Interpretation

Seismic Interpretation

Since completion of our data compilation in Baffin Bay, we have refined the interpretation of the basement horizon and gridded using the convergent algorithm supplied in the Geoframe interpretation software (Fig. 5). In southern Baffin Bay, interpolated grid values were deleted in regions lacking seismic data coverage. In northern Baffin Bay, the edge of the grid corresponds to the end of our seismic data coverage or where basement became so deep it dropped below the base of the seismic section. This grid forms a contribution to the gravity inversion work in Welford et al. (in prep).

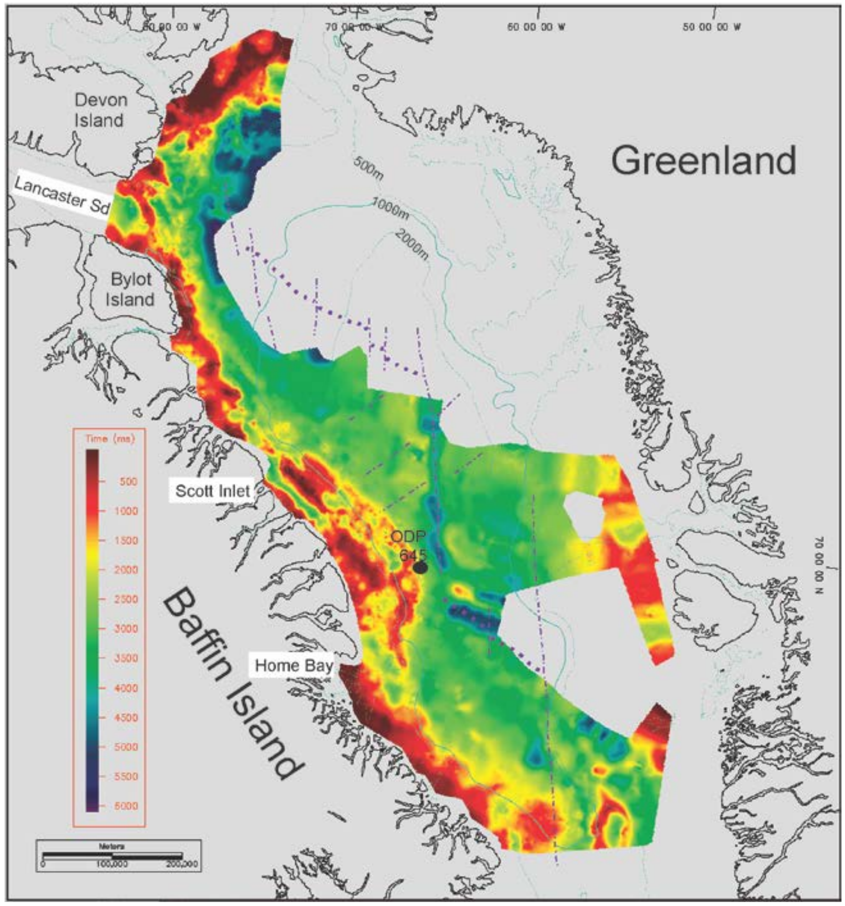

Figure 5: Sediment thickness map of Baffin Bay in two-way time. Bathymetric contours of 500 m, 1000 m and 2000 m are shown in green. Some features of oceanic crust (Oakey and Chalmers, 2012) are shown as purple lines: fracture zones (dashed) and spreading axis segments (dotted). The location of the ODP 645 well is indicated by the black dot

Sediment thickness is greatest along the spreading center and major fracture zone (Oakey and Chalmers, 2012) in southern Baffin Bay, while the northern Baffin Bay margin is covered by the thick Baffin Fan (Harrison et al., 2011). The shelf regions show a distinct offset between the southern and central Baffin Island shelf, around Home Bay. This corresponds to a similar offset along the central Baffin Bay fracture zone offshore. The central Baffin Island shelf, between Home Bay and Scott Inlet, appears to be the widest segment (over 120 km) along western Baffin Bay and is cut by a number of grabens. North of Scott Inlet, the margin narrows to become less than 50 km wide off Bylot Island. The northern Baffin Bay shelf exhibits much more complex structures across the mouth of Lancaster Sound and northward where it becomes a transform margin that was later inverted in the Eocene when Greenland converged with Ellesmere Island.

Integrated Stratigraphic Framework

Stratigraphic Analysis of Onshore Stratigraphy

Cretaceous-Paleocene stratigraphic equivalents of strata preserved in the offshore of Baffin Bay, including Lancaster Sound and the continental shelf of Baffin Island, are preserved onshore on Bylot Island and adjacent areas of northeastern Baffin Island. Fieldwork was undertaken in these onshore regions during 2017 to: 1) establish the stratigraphic framework of the Cretaceous-Paleocene strata and assess their depositional environments; 2) determine the precise biostratigraphic ages of the strata and assess their sequence stratigraphic history; 3) assess the structural overprint affecting the strata; 4) assess the provenance of the strata; and 5) interpret the uplift history of the region. Understanding the sequence stratigraphic history of these onshore strata, and the geological history which controlled their accumulation, provides a model for sedimentation in the offshore basins. Summary details of the 2017 onshore field program can be found in the companion report by Haggart et al. (2017).

Tectonic Margin Segmentation

Utilizing the wealth of geophysical data along the Labrador margin to study the crustal structure and nature of rifting will be valuable in understanding the development of the Baffin Bay margin. While refined gravity inversion techniques suggest a wider zone of oceanic crust or a transitional zone (Welford et al., in prep), initial results from seismic interpretation suggest the presence of margin segments similar to that of Keen et al. (2017) reported along offshore Labrador.

Summary and Petroleum Potential

Delineating the petroleum potential of the Baffin Bay region relies on understanding the underlying crustal structure as well as the overlying sedimentary basins. With limited data available from the Canadian margin of Baffin Bay, the Labrador Sea provides a unique opportunity to develop and explore analogue studies as the two areas share a similar geological history. Our Labrador studies provide insight into: crustal structure and the timing of seafloor spreading; the stratigraphy of the basin infill, age of key events, and location of sandstone reservoirs; and the geology of pre-rift Paleozoic basins also known to form part of the petroleum system. The intervening Davis Strait region is a zone of complex transform plate motion related to the change in seafloor spreading direction. Here, extensive volcanics are important in understanding the heat flow of the region, large Paleozoic basins may contribute to the presence of possible sea-surface slicks, and major structural boundaries are now better constrained. Studies of the onshore stratigraphy on Bylot Island provides an additional proximal analogue to the poorly sampled Baffin Bay margin. Along the Baffin Bay margin itself, significant sediment thickness variation is, at least in part, controlled by tectonic segmentation of the margin similar to that of the Labrador margin to the south. Our ongoing studies will help to shape the geological and tectonic understanding of the Baffin Bay margin and its petroleum potential.

Acknowledgments

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