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Report of activities for the Stratigraphic and Tectonic Framework for the Baffin Bay Petroleum Systems (2016)

GEM-2 Baffin Project

L.T. Dafoe, K. Dickie, G.L. Williams, C.D. Jauer, Q. Li, S. Dehler, D.P. Potter, S. Hynes, E. Patton, J. Bates, J.W. Haggart, and K. Clark

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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 investment in responsible 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 summer 2016, GEM program has successfully carried out 17 research activities that include 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 collaborators 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 Baffin Project, the desk-top 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 factors that control the petroleum resource potential. To begin to understand basin distribution, the potential for deeply buried rocks, and the changing nature of the rifted margin of Baffin Bay, we have developed a regional compilation of sediment thickness, the first of its kind for the Baffin Bay region. Sediment thickness was interpreted from 2D images (digital representations of vertical slices through the basin's rock layers) generated from existing seismic reflection data. The compilation is an important milestone as it provides the basis for further detailed work such as ongoing crustal studies utilizing gravity inversion analyses. The sediment thickness compilation is being combined with limited available information on Baffin Bay geology including: existing Geological Survey of Canada (GSC) samples (bedrock drill cores, dredge samples, and piston cores), onshore stratigraphy (Bylot Island), Ocean Drilling Program Site 645 reports, and conjugate Greenland margin published works. Immediately south of Baffin Bay, the Labrador Sea margin has been more thoroughly sampled by industry wells and modern seismic data. Because this area evolved at the same time as Baffin Bay and underwent similar geological processes, it can be used an analogue. Components of this part of the activity include updated age constraints from biostratigraphy, development of a sequence stratigraphic framework with regional implications, and an improved understanding of the rift history of the Baffin Bay – Labrador Sea region from deep crustal studies. This

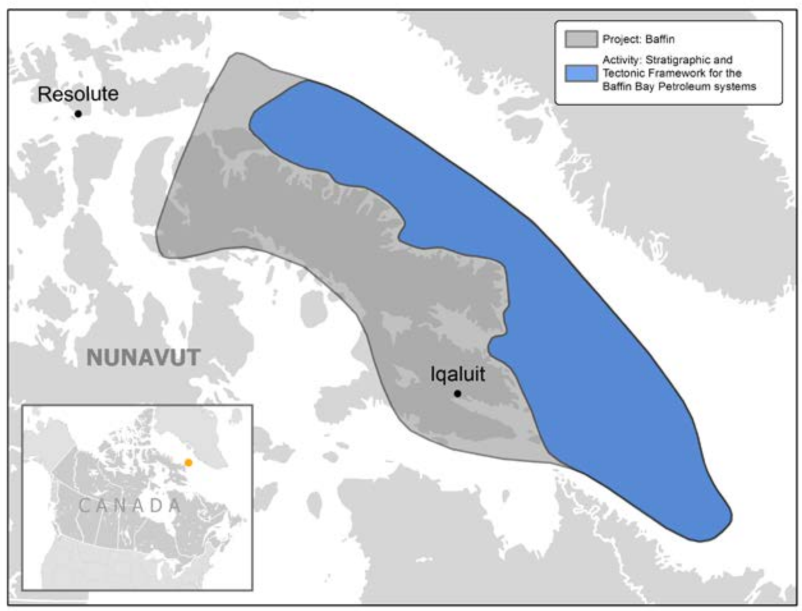

Figure 1: Location of the GEM-2 Baffin project area and activity associated with this report.

activity's goal is to develop a stratigraphic and tectonic 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.

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 6 integrated subactivities described below.

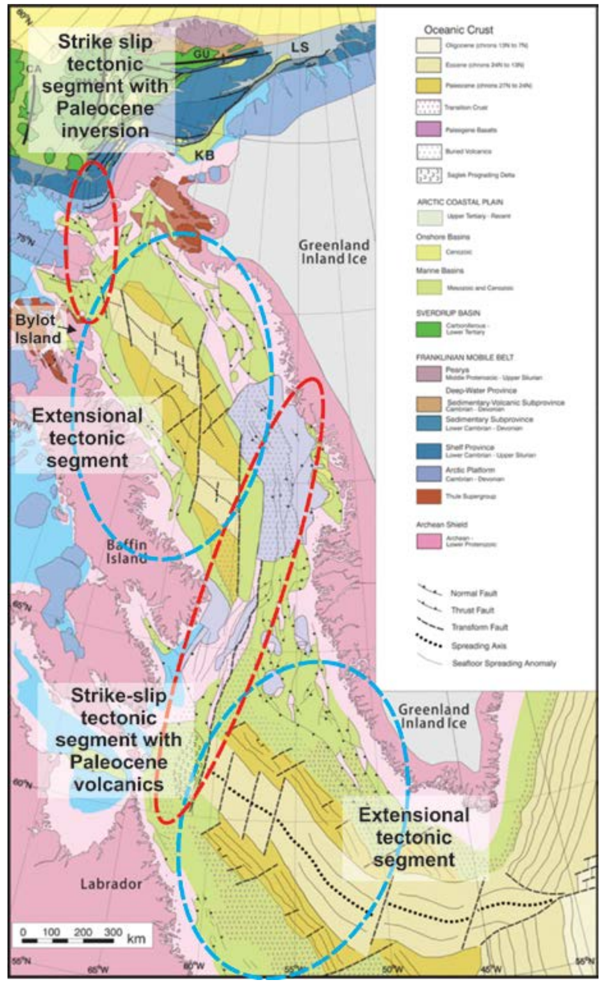

Figure 2: Regional geology map showing development of spreading centres and transform faults modifed from Oakey and Chalmers (2012). The circled areas highlight the extensional margin segments (blue) and areas of strike slip (red).

Labrador Analogue

Stratigraphic Framework

As the Labrador margin experienced a similar rift history to Baffin Bay, an analogue stratigraphic framework is being developed to help understand the poorly sampled stratigraphy in Baffin Bay. Changes in paleodepositional environments were assessed in 28 industry wells (Fig. 3) by logging of available conventional cores (37 core intervals) and synthesizing information in existing biostratigraphic reports, well history reports, and cuttings logs. Eight semi-regional cross-sections were constructed using these data with stratigraphic horizons identified from changes in paleoenvironments and instances of missing section (reflecting gaps in time). This information, combined with new biostratigraphic (palynological) results, led to the development of a sequence stratigraphic framework. Major (2nd order) sequence boundaries were defined within the Cretaceous and Cenozoic section. Key findings include the presence of a maximum flooding event in the middle to late Maastrichtian based on both lithological and palynological results. The Gudrid Formation sandstones represent shallow-water, forced regressive lobes in the southern portion of the Hopedale Basin and southern portion of the Saglek Basin. A Lutetian break in section corresponds to a flooding surface within overall shelfal deposits. Furthermore, the Leif Member sandstones represent a lowering of sea level and are constrained within the Bartonian. Finally, age constraints for the late Paleogene–Neogene section help delineate three major sequence boundaries that can be mapped seismically.

Biostratigraphy

Two open file reports outlining the palynostratigraphy and paleoenvironments of four Labrador Shelf wells are planned for release this fiscal year. The first report covers Corte Real P-85 (124 samples) and Pothurst P-19 (116 samples), and the second compares the same data in Roberval C-02 (77 samples) and Roberval K-92 (171 samples), two wells that are closely adjacent (black dots, Fig. 3). Corte Real P-85 and Pothurst P-19 reached Eocene sediments at total depth, whereas the two Roberval wells extended into Cretaceous rocks. One significant discovery was the presence of a thick Lutetian section in the Corte Real and Pothurst wells. Palynological analysis of 81 conventional cores from 13 Labrador Shelf wells including Roberval K-92 shed considerable light on the ages, especially in the Lower Cretaceous sections.

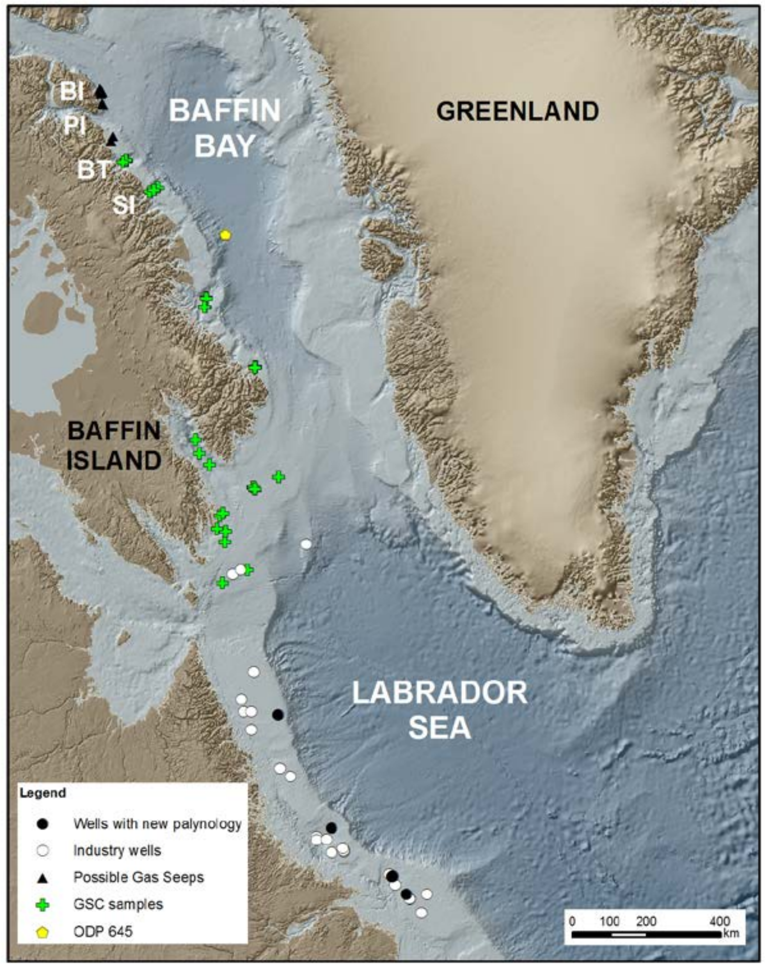

Figure 3: Regional study area with location of well and sample data. BI=Bylot Island, BT=Buchan Trough, PI=Pond Inlet, and SI=Scott Inlet.

The palynological analysis of the North Leif I-05 well is ongoing. One striking discovery has been the presence of abundant specimens of the dinocyst *Apectodinium* in the sample from 2220–2230 m, denoting that the sediments were deposited during or close to the Paleocene–Eocene Thermal Maximum (PETM). This event, recognized in many areas of the Northern and Southern hemispheres, reflects the time of maximum temperatures in the Cenozoic. The signal in North Leif I-05 is by far the strongest in the Labrador Sea, not surprisingly considering its location in the southern part of the Hopedale Basin. North Leif I-05 should provide better stratigraphic control in the Cretaceous, which will help in unravelling the biostratigraphy of Bylot Island and Baffin Bay.

Seismic Interpretation

Mapping of basement offshore Labrador has been completed and refined to incorporate recognition of significant changes across tectonic zones. These zones include: the extended continental margin; a zone of hyperextended crust; a zone of exhumed continental mantle; a proto-oceanic domain; normal oceanic crust; and a volcanic margin to the north. This work aids in understanding the overall rift history of the Baffin–Labrador Sea area, and similar zones may be mappable in Baffin Bay. In addition, shoreline and shelf edge breaks in the Cenozoic section were mapped using seismic data in central Hopedale Basin by integrating paleoenvironmental interpretations determined from lithological and palynological analyses. These important paleoenvironmental settings aid in identification of major regional transgressions and regressions most likely to extend as far as Baffin Bay.

Davis Strait Transform Margin

Seismic Interpretation

The completed compilation of seismic data in the Davis Strait transform margin area comprises more than 15,000 line kilometres of vintage seismic data. Using this compilation, the top of the basement was mapped regionally. This surface often represents the top of Eocene basalt flows that were intersected in the Gjoa G-37 well. A gridded isochron map of sediment thickness (two-way seismic travel time between the seafloor and the top of basement) was then produced at 3,500 m resolution. The map of sediment thickness in the Davis Strait area was then compared with the Natural Resources

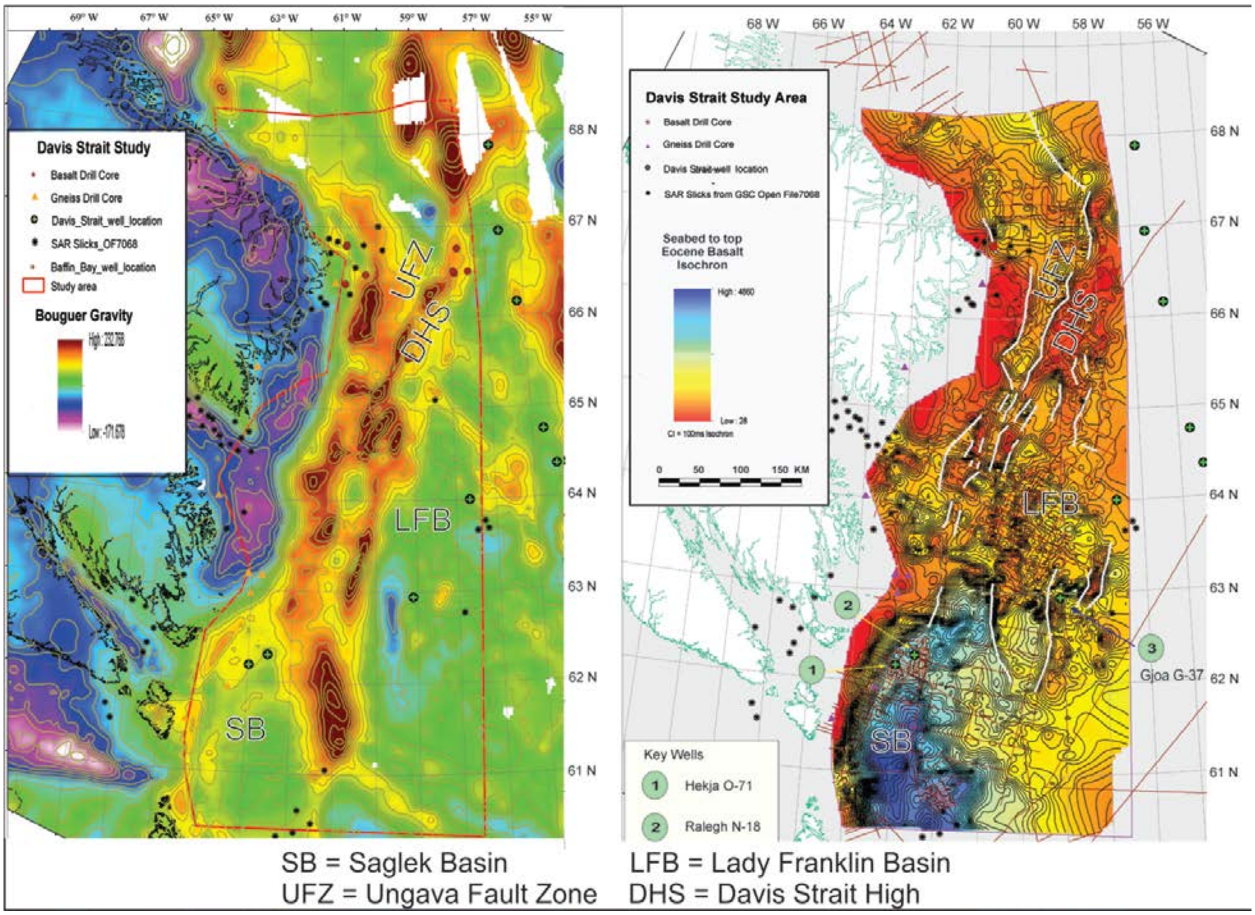

Figure 4: NRCan Bouguer gravity anomaly map (left) and sediment thickness map from seismic interpretation in two-way time (right).

Canada Bouguer anomaly gravity map (Fig. 4). The dominant NE–SW striking pattern of the Ungava Fault Zone and the adjacent Davis Strait High are visible on the Bouguer gravity map and can be seen delineated by fault trends on the sediment thickness map. The boundaries of the Lady Franklin Basin along the western flank of the Davis Strait High and the northern end of the Saglek Basin to the south are now better defined. Smaller basin features within the Davis Strait are typically shallow compared to the Saglek Basin where known petroleum potential exists. A lack of thick subbasin infills will be an important factor in assessing the potential for any petroleum occurrences in the transform margin area.

Time to Depth Conversion Function

A seismic velocity model has been constructed based on sediment compaction theory to transform two-way travel time (TWT) into sediment thickness in depth (km). The procedure involved an initial compilation of available seismic velocity data sources including: borehole sonic logs, seismic refraction models, stacking velocities from seismic data, and check-shot velocities. These data were then evaluated for quality, resulting in 816 high-quality velocity measurements (Fig. 5) sampling different depths within the stratigraphic column and sourced mainly from borehole sonic logs and check-shot samples. Sonic logs and check-shot samples underwent quality analysis, median filtering and resampling at a comparable resolution to seismic reflection data in order to filter out noise and eliminate spatial aliasing. Resampled velocity measurements also show a reasonable compaction trend proving that the moving window average and resampling window are accurate. The reduced major axis fitting technique was then used to characterize minimizing errors in both velocity and depth to construct the seismic velocity model (equation 1) and estimate its 95% confidence level (shown as black dashed lines in Fig. 5). The correlation coefficient is as high as 0.86 for the fit. Finally, the TWT seismic profiles and GIS gridded isochron map of sediment thickness are transformed by solving nonlinear equations with iteration methods. The nonlinear equations are solved quickly (convergence) and accurately (assigned accuracy) producing a map of sediment thickness in depth.

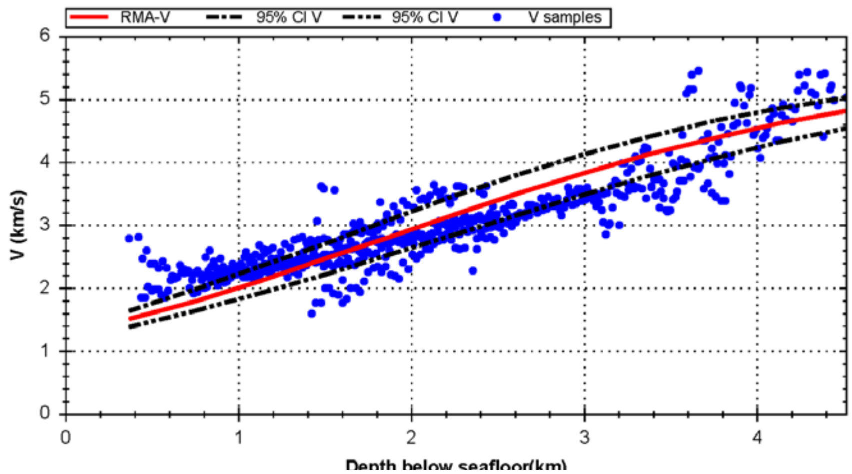

Figure 5: Compilation of velocity data points versus depth below seafloor.

$$V(h) = \frac{5.65}{1 + e^{1.26832 - 0.66912 * h}} \qquad (1)$$

Baffin Bay Interpretation

Legacy GSC Sample Study

Drill core, dredge and piston core samples collected by the GSC during marine cruises from 1976 to 1985 in the Davis Strait and Baffin Bay areas were reassessed to provide new insights into the subsurface stratigraphy and for comparison with rock units on the Labrador margin (green crosses, Fig. 3). Samples reported as sedimentary in nature were studied to determine if they represented potential bedrock material: the samples consisted of 23 drill cores (one inch diameter), three piston cores, and two dredge samples. Of the drill cores analyzed, ten were confirmed as bedrock, eight likely represent bedrock (based on similarities to more definitive samples), three are possibly bedrock, and two were determined not to represent bedrock material. Shale fragments within two soft-sediment piston cores and one mudstone dredge sample were confirmed to be of likely bedrock origin. The most intriguing results are from the silty mudstones from the Buchan Trough area (Fig. 3), which contain well-defined trace fossil suites of the *Cruziana* and *Zoophycos* Ichnofacies, confirming an outer shelf to prodelta depositional setting suggested by palynological analyses. To the south of Buchan Trough, the Scott Inlet (Fig. 3) contains an active seep. In this area, drill core 80028-49 was confirmed as bedrock following palynological analysis. The dinoflagellate cysts in this sample indicate a Lutetian age and show affinities with coeval Labrador Shelf assemblages. This is the first evidence of middle Eocene sediments on the Baffin Shelf. Future sampling of dredge sample 78029-22 may provide more information on the source rock in Scott Inlet.

Data Compilation

All the available multi-channel seismic data in Baffin Bay have been converted to SEG-Y format and loaded into the interpretation workstation. The converted dataset includes over 8,000 line-kilometres of vintage stacked (unmigrated) data distributed over 10 different projects. To reduce the effect of the diffractions on these stacked sections, "provisional" migrated sections were produced for over 17,000 line-kilometres of data using constant velocities of 1,800 m/sec and 3,000 m/sec, and in some areas, sections migrated at 2,500 m/sec. Since these older datasets are of generally poor to fair quality, this approach to migration was the most expedient.

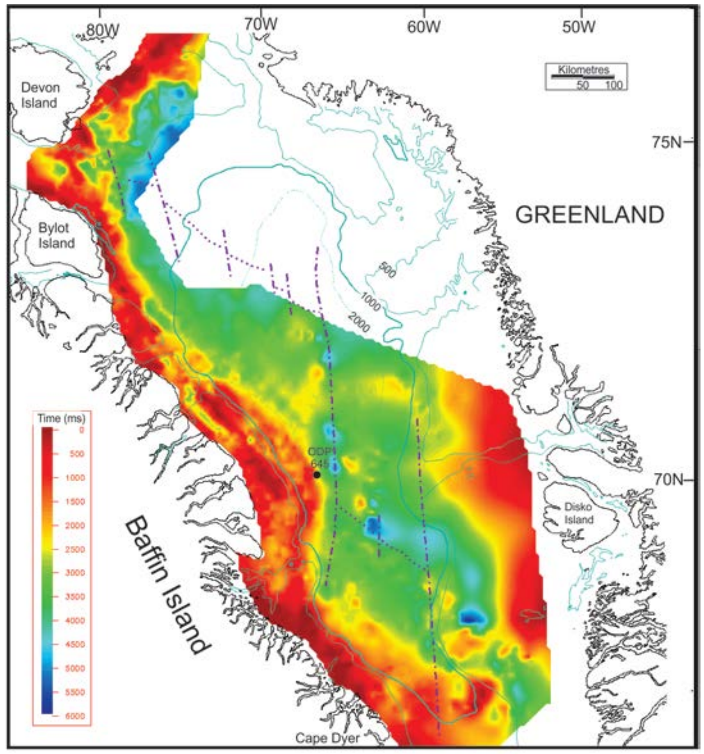

Figure 6: Preliminary sediment thickness map of Baffin Bay. Bathymetric contours of 500 m, 1000 m and 2000 m are shown in green. Some features of oceanic crust (Oakey and Chalmers, 2012) are shown as purple lines: fracture zones (dashed) and spreading axis segments (dotted). The location of the ODP 645 well is indicated by the black dot.

Seismic Interpretation

A preliminary sediment thickness map for Baffin Bay is shown in Figure 6. It was produced from seismic interpretation using a combination of migrated and unmigrated data and will be refined once the migrated data have been incorporated into the project. The thickest sediments were deposited in the deepest part of Baffin Bay over oceanic crust, as indicated by the fracture zones and spreading axes (Oakey and Chalmers, 2012). Thinner successions of sediment trend along the shelf with some deeper grabens indicated, especially along the central part of the Baffin Island margin.

Gravity Inversion and Crustal Structure

A 3-D model of density anomaly structure was generated for the Baffin Bay region by inverting free-air gravity data using constraints from bathymetry and sedimentary thickness data. A density anomaly isosurface within the model is used as a proxy for the base of the crust, allowing depth to Moho and crustal thickness variations across Baffin Bay to be investigated and compared with published models based on seismic refraction data. Preliminary inversion results clearly show a pattern of northward thinning of oceanic crust that compares favourably with the seismic models, and also shows a zone of transitional crust along the Baffin Island side of Baffin Bay that extends further westward than previously defined.

Integrated Stratigraphic Framework

Bylot Island Biostratigraphy

Analyses of previously collected samples from Bylot Island (Fig. 3) are ongoing and include a detailed study of the dinocysts and acritarchs and preliminary evaluation of the spores and pollen in 108 samples from the Q section at Two Snout Creek. An events chart was generated, which highlights the first, or oldest, and last, or youngest occurrences. The section ranges in age from middle Albian–Cenomanian to middle to late Paleocene. All of the Late Cretaceous stages are represented, with the possible exception of the Turonian; although, a short interval appears to be Turonian–Coniacian in age. Evidence that the section is tectonically disturbed is indicated by the fluctuations in dinocyst assemblages. These assemblages seem to indicate that there is repetition of the section in the upper part, with Campanian, and in one sample Coniacian–Santonian, sediments occurring within the Maastrichtian. Within the early Cenozoic, Paleocene strata include Danian and Selandian sediments, but Thanetian sediments have not been confirmed. Paleoenvironments range from non-marine in the Albian–Cenomanian to outer neritic or even open water in the later Cretaceous. During the Paleocene, paleoenvironments fluctuated, being outer to middle neritic in the Danian but becoming shallower marine and then non-marine later. Ongoing analyses and future samples will be key to further understanding the nature of missing section and paleoenvironments of deposition.

Petroleum Systems

Under a Memorandum of Understanding, the Canadian Hydrographic Service (CHS) provided bathymetry data in the form of digital files, log books, and echosounder records from the Canadian margin of Baffin Bay. With significant effort, the echosounder records could have been registered to their spatial location in Baffin Bay to provide a high resolution grid of the seafloor. However, the digital compilation included field sheet data that were gridded to form a high quality image of the seafloor, and these data were determined to be of sufficient resolution for gravity inversion and seismic interpretation studies. The 127 echosounder records for 1985 and 1986 field sheets off Bylot Island and Pond Inlet were scanned and assessed for direct hydrocarbon indicators. Overall, the data were of low quality and only 11 possible gas seeps emanating from the seafloor were identified from the records (Fig. 7).

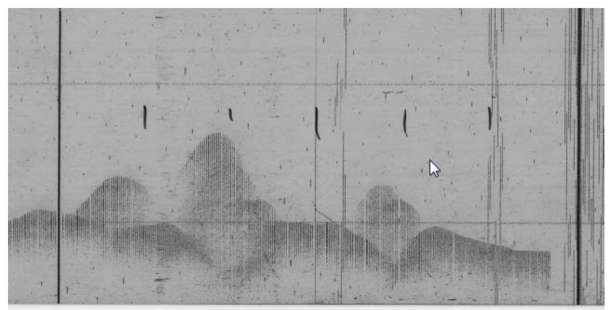

Figure 7: Possible gas seeps emanating from the seabed on a CHS echosounder record, Baffin Bay.

Tectonic Margin Segmentation

The analogue study for offshore Labrador has provided insight into the timing and nature of Cretaceous rift packages, the nature of the crust underlying sediments, and a refined understanding of the Cenozoic section. Early results suggest that the morphology of rift packages are comparable with Baffin Bay and new results from legacy GSC drill core samples will provide improved age constraints within Cretaceous grabens, such as Scott Inlet. The 3-D model of density anomaly structure constructed from gravity inversion in Baffin Bay suggests that thin crust is likely present further west than previously thought and may correspond to a wider zone of oceanic crust or transitional crust similar to that observed offshore Labrador.

GIS and Information Management

GIS data and information management has focused on the completion of spatially enabled project-relevant legacy datasets (such as scanned figures and maps), file conversions between GIS and seismic interpretation software packages, updating and revising existing vector and raster data, and enhancing vector data to add query and visualization functionality to aid in analyses (see Fig. 8). These efforts will provide the basis for the GEM-2 Baffin Region Atlas activity.

GIS data are being expertly managed following established data management principles. Data are conforming to project standards in terms of projection and extents. Raster and vector GIS layers are managed in a robust ArcSDE geodatabase on an Oracle server at GSC (Atlantic). An organized effort is being made to complete metadata records for GIS data to adhere to good information management protocols.

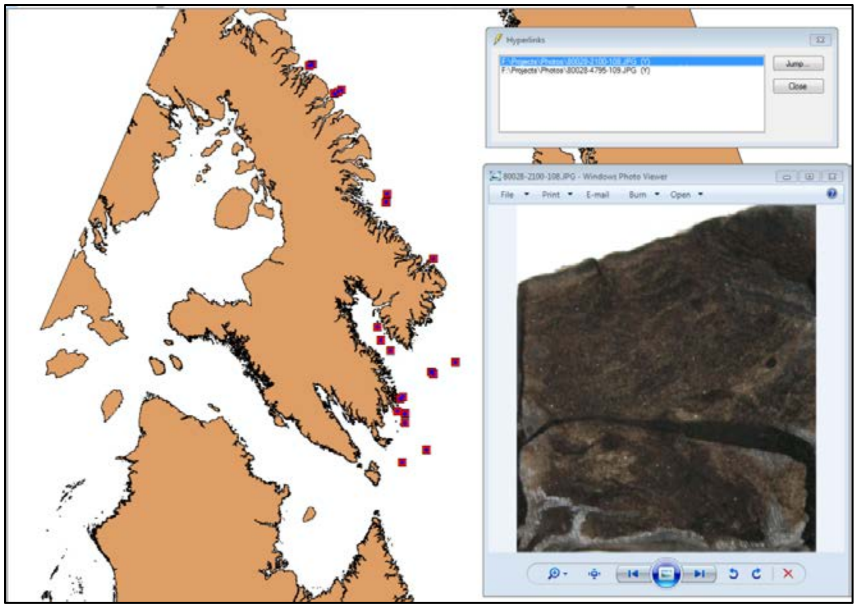

Figure 8: Example of hyperlink display: photo of legacy GSC drill core sample (right) aside location map.

Conclusions

Building on this GEM-2 activity, field activities will commence in 2017 to further ground-truth the science with additional sampling. This will include a marine cruise in 2017 that will focus on collecting data to help support community and government decisions on the presence and nature of suspected natural oil seeps on the seafloor and provide geological insights regarding these occurrences. Onshore field activities are further proposed in 2017 and 2018 to assess stratigraphic successions and depositional environments of Cretaceous-Paleogene strata exposed on northern Baffin Island and adjacent Bylot Island. In preparation, a community visit to Pond Inlet was conducted in March 2016, documentation in support of the proposed field activity has been submitted to various agencies following the community visit, delivery of helicopter fuel has been arranged, and an additional community visit is planned in late 2016 or early 2017.

Acknowledgments

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