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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 2015, GEM program has successfully carried out 14 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.

Activity Summary

The Canadian side of Baffin Bay, offshore Baffin Island represents a vast area with potential for viable petroleum systems within the layers of rock beneath the seafloor. These rock layers formed during opening of the North Atlantic Ocean and subsequent movement of Greenland relative to North America resulting in areas underlain by Cretaceous basins, oceanic crust, volcanic rocks, and extensive strike-slip and compressional features. Under the Baffin Project, the "Stratigraphic and Tectonic Framework for the Baffin Bay Petroleum Systems" activity aims to understand the fundamental geologic and tectonic evolution of the sedimentary basins in the Baffin Bay region and factors that control the petroleum potential. We will accomplish this by mapping the structure and stratigraphy of the sedimentary basins underlying the seafloor to map the thickness of sediment and to discover the timing of the key geologic elements needed to produce a complete petroleum system: source rocks, reservoir, seal, and migration pathways. Existing sampling and drilling of the stratigraphy is limited and thus requires a dependence on seismic imaging of the subsurface rock layers and a reliance on developing analogue studies. In this activity we are also studying the nearby Labrador margin because: a) this area evolved at the same time and through the similar processes as Baffin Bay; b) has a rich dataset of seismic and well data; and c) provides us with a valuable analogue for the formation of Baffin Bay. The Baffin Bay component of this activity is in the final stages of the compilation and reprocessing of modern and legacy seismic data and other geophysical and geological datasets. Initial results of the Labrador analogue study have provided new age constraints using biostratigraphy and an assessment of the wells from a sequence stratigraphic approach that can be combined with studies of the onshore stratigraphy, physical rock samples from ODP 645 and Geological Survey of Canada (GSC) drill cores, and knowledge from the conjugate Greenland margin.

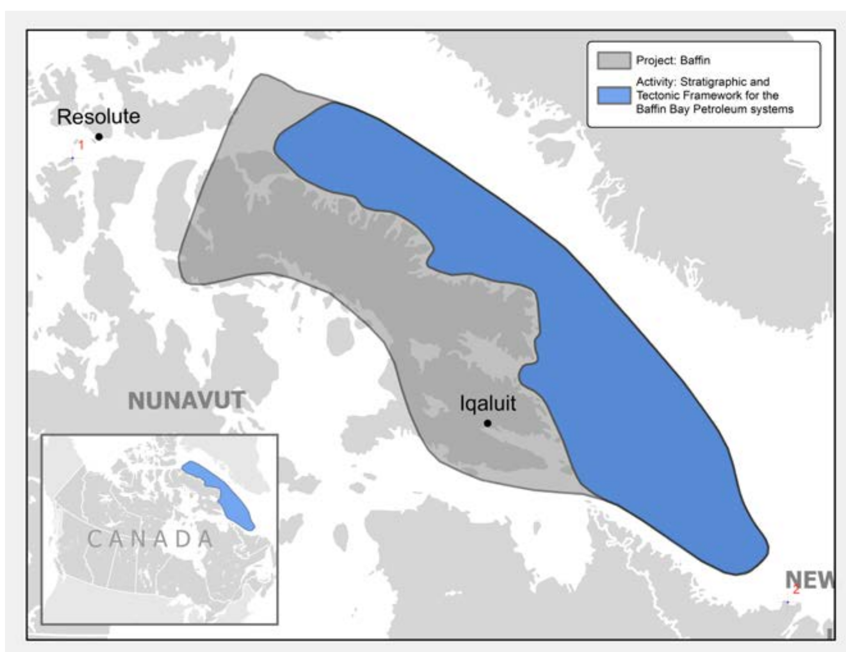

Figure 1: Location of the GEM 2 Baffin project area and activity associated with this report.

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 is reflected in the stratigraphy of the sedimentary basins and it 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 answer these scientific questions, this activity has been subdivided into 6 integrated subactivities that are described below in terms of their methodology, results and general conclusions or future work.

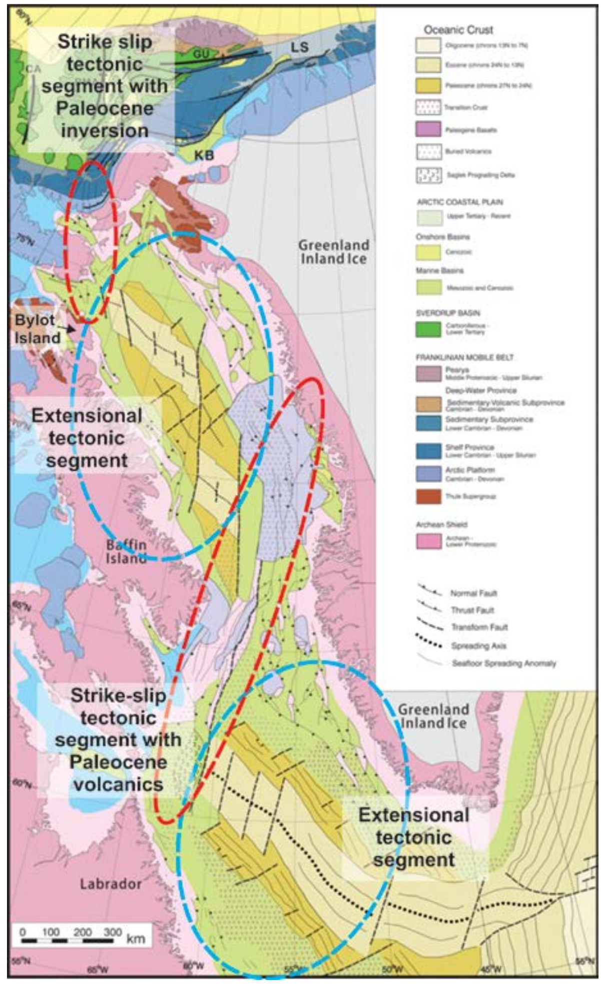

Figure 2: Regional geology map showing development of spreading centers and transform faults from Oakey and Chalmers (2012). The circled areas highlight the extensional margin segments (in blue) and areas of strike slip (in red).

1. Labrador Sequence Stratigraphy Analogue

Methods:

This subactivity utilizes the wealth of seismic and well data from the nearby Labrador margin to develop a robust sequence stratigraphic framework that can be applied northward into Davis Strait and Baffin Bay. A total of 37 core intervals were logged from 15 offshore Labrador wells including sedimentary Mesozoic and Cenozoic rocks and select Alexis Formation basalts and basement cores. Cores were assessed for lithology, sedimentary structures, and fossil material to provide depositional environment interpretations. Based on the core assessments, information in existing biostratigraphic reports, well history reports and cuttings logs, depositional environments are interpreted and major stratigraphic horizons are identified for 21 wells to date. These interpretations have been used to construct cross sections to link sedimentary packages and determine the nature of stratigraphic horizons in a sequence stratigraphic framework.

The core intervals were further sampled for palynology at approximately 1.5 m intervals producing over 90 individual samples. To refine our understanding of the uppermost Paleogene and Neogene section, we sampled and processed the complete wells of Corte Real P-85, Roberval C-02, and ODP 645 for palynology. In addition, existing GSC slides were analyzed for the Pothurst P-19 well.

Results:

The core logging assessments reveal a variety of paleodepositional environments recorded within the Bjarni Formation including both river- and wave-dominated deltas and brackish bay settings. As an analogue to the Baffin Bay rifted margin, the type of deltaic setting impacts the distribution of sandstone and thus the nature of potential reservoirs while brackish bay settings could be important in understanding Early Cretaceous source rock potential. Deltaic and shoreface sandstones are also prevalent in the more fully marine Markland and Gudrid formations, but drastic changes in relative sea level indicate rapid forced regressive and possibly stillstand shoreline development. Based on the stratigraphic results from the wells, at least 3 major sequence boundaries and at least 2 maximum flooding events can be identified in addition to a number of flooding surfaces.

Palynological analyses of two Labrador Shelf wells, Corte Real P-85 and Pothurst P-19, have shown that both wells reached total depth in Eocene sediments. Corte Real P-85 possesses a considerable thickness of Lutetian-Bartonian section. The high degree of reworked Late Cretaceous dinocysts in the Lutetian could indicate that a major river system was bringing in sediment which was either deposited in a delta front or transported south by a proto-Labrador Current. Notable hiatuses in this well occur between the Rupelian and the upper part of the Early Miocene (equivalent to the Baffin Bay Unconformity) and within the Middle and Upper Miocene interval. Paleoenvironments in Corte Real P-85 ranged from open ocean (probably bathyal) throughout the Eocene, then gradually shallowing in the Oligocene. Neritic conditions prevailed in the Neogene, becoming more prevalent upwards. Similarly, Pothurst P-19 reached a total depth in lower Lutetian sediments and has several hiatuses, including the Lutetian-Bartonian, above the Rupelian and between Lower and Upper Miocene sediments. Paleoenvironmental data are not robust but do indicate open ocean, bathyal conditions in much of the well, with shallowing in the Plio-Pleistocene.

Palynological studies of conventional cores from several Labrador Shelf wells have led to more definitive ages and paleoenvironmental determinations for the intervals sampled. For example, spectacular Late Albian miospores were recovered from core 1 in Hopedale E-33 and Barremian-Aptian miospores from core 1 in North Leif F-05.

Future Work:

The next steps are to incorporate well interpretations from the remaining Saglek Basin wells that will prove to be important in understanding the shoreline proximal expression of the stratigraphy. In addition, interpretations from the wells will be combined with the seismic data to refine the stratigraphic model and correlations between wells. Palynological analysis on the Roberval C-02 and ODP 645 wells will also be completed. The final sequence stratigraphic framework will be utilized in Baffin Bay to understand the nature and age of stratigraphic horizons where stratigraphic control is limited to the shallow ODP 645 well and shallow bedrock drill cores collected by the GSC.

2. Seismic Interpretation in the Baffin Bay Area

Methods:

A significant part of this subactivity involves the compilation and processing of vintage (late 1960s through 1980s) and available modern seismic data. Owing to the age of much of the data, there are significant issues in resolving navigation and line identifications. Much of the data suffers from inadequate acquisition parameters, notably the use of short seismic streamers and undersized seismic sources. Consequently, the bulk of the data in the Baffin Bay and Davis Strait area is very low resolution. The best data available in Baffin Bay is a late 1970s industry dataset (Suncor) that was extensively reprocessed by GSC-Calgary including post-stack migration. As this is the best quality dataset available, it will be used as the reference for all the other seismic surveys in the Baffin Bay and Davis Strait areas.

The methodology for the compilation includes loading of data in seismic master projects, leveling data such that reflections (such as top of basement) are aligned within and between surveys, and processing data to enhance the quality. In addition, there are significant spatial gaps in the digital data coverage. These gaps were filled in by converting paper, microfiche and scanned data into seg-y formatted digital seismic profiles for use in the interpretation software. GSC-Atlantic has a significant set of legacy (1970s -1990s) high-resolution seismic lines in Baffin Bay and the Labrador Sea. These data were assessed to extract lines in relevant locations and with good penetration into the underlying rocks.

One of the most basic components of understanding the petroleum potential of an area is to produce a map of the sediment thickness between the basement and seafloor horizons. While the seismic mapping of sediment thickness depends on the grid of available seismic data, the resultant map is produced in two-way time. The map must be converted from two-way time to depth in kilometers in order to make predictions about the petroleum system. This conversion requires the compilation of available velocity data to be utilized in a velocity conversion model for the region, which is also underway for this activity.

Results:

Data loading, leveling and processing

The seismic project architecture for the GEM2 project was developed and consists of 3 types of workstation projects: 1) an "original seismic master" where data is loaded according to area and data ownership; 2) a "leveled seismic master" where data is copied from the original seismic masters, assessed for quality, leveled to a chosen reference survey and filtered to an optimal bandwidth for viewing basement and sedimentary horizons; and 3) an "interpretation seismic project" into which data is shared from the leveled seismic master and work is completed on the interpretations including mapping and gridding.

Two seismic master projects were generated to subdivide the area into: 1) the Rifted Margins master encompassing the Labrador Sea analogue and most of Baffin Bay, and 2) the Ungava Transform margin master encompassing southern Baffin Bay and Davis Strait (Fig. 2). In the Rifted Margins seismic master, 45 seismic surveys and more than 1400 seismic lines (over 50,000 line kilometres) were leveled and assessed for quality control. The locations of all the wells in the Baffin Bay, Davis Strait and the Labrador Sea, the main petrophysical logs and checkshot/velocity data were all loaded into this master. This master was replicated to produce the Ungava Transform master.

In the Rifted Margin master, the Suncor (1978 and 1979) surveys are being used as the reference surveys to level all vintage seismic data in Baffin Bay. The Suncor surveys form a large, complicated dataset consisting of 165 lines or line segments which had to be organized, loaded, and assessed for quality control and many lines required reloading, shifting and relabeling. The source of many problems with the overall dataset was the vintage nature of the data and incomplete or inaccurate documentation by the data owner.

Conversion of data to digital seg-y format

Much of the work thus far in the Ungava Transform margin seismic master (and some data in the Rifted Margin master) has involved conversion of data to a digital seg-y format (red lines, Fig. 3). Different software was tested to convert old multi-channel records into digital data with a final workflow involving quality control, conversion to seg-y, and a loading stage. Datasets in the Davis Strait and Home Bay were converted to digital format with the seismic data recovery and compilation effort including about 12,000 line kilometres of digital multi-channel seismic data. In the Ungava Transform seismic master, nearly 60 surveys have been compiled. Key lines from the Suncor dataset that were missing from the digital files were also converted to seg-y format for the Rifted Margin seismic master.

Single-channel data compilation

Selected high-resolution single channel lines were processed by reformatting shot point navigation in the trace headers to suitable parameters (sample rate, shot spacing) for use in the seismic interpretation software and integration into the seismic masters. Reprocessed single channel airgun lines from cruises 74026, 9325, 90013, 71032, 78029, and 85027 have been compiled with a total of 163 lines that are now ready for loading (blue lines, Fig. 3).

Constructing velocity models

Velocity data derived from seismic refraction, seismic reflection, borehole logging, and other data sources were compiled in the Baffin Bay area (e.g., yellow points, Fig. 3). This included reformatting velocity data from 85 of the 126 Suncor lines and 65 refraction lines in Baffin Bay. All available checkshot and velocity surveys for the Labrador and Davis Strait wells were compiled. Digital refraction velocity models were also obtained.

Algorithms were developed for the construction of velocity models and conversion of two-way time to sediment thickness. Seismic velocity models are constructed from the compiled data using different optimizing methods; for example, by ordinary least square method (to minimize errors in velocity *or* depth) and Reduced Major axis (RMA) and Deming methods (to minimize both velocity *and* depth errors). Nonlinear methods for two-way time to depth conversion are developed and ready for use in the Baffin Bay area.

New seismic data processing method

Common data processing methods such as stacking and prestack migration require the ability to detect bad traces or shots and fill data gaps by interpolating, particularly when the input data are noisy or are coarser than the required spatial sampling. A new method termed the *E-S* (eigenspace seismic) method for bad ensembles detection and interpolation in the eigenspace has been developed. This has included deduction of equations for the *E-S* method, programming codes, and processing sample offshore seismic data. The result is that offshore seismic survey data can be processed using the *E-S* method which has improved effectiveness and performance for bad trace or shot detection and interpolation.

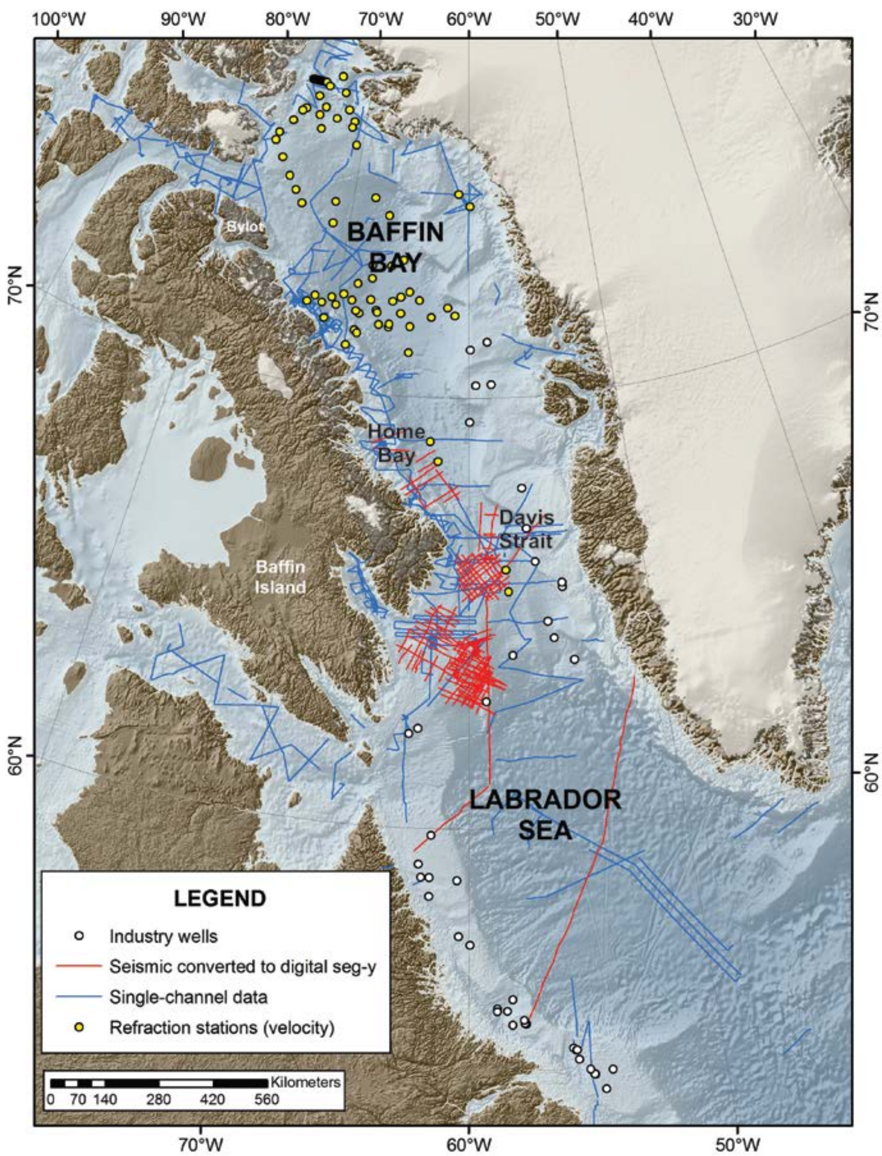

Figure 3: Map of the Baffin Bay area showing the locations of data converted to seg-y (red), processed single-channel data (blue) and some of the compiled velocity measurements (yellow).

Seismic Interpretation

Initial seismic interpretation has been undertaken in the Rifted Margins seismic master. This has included an evaluation and integration of horizons and fault models from previous work on the Labrador Shelf and in the Labrador Sea. The Rifted Margins master was updated to include this year's preliminary biostratigraphic assessments for the Pothurst and Corte Real wells and the preliminary depositional environment assessment for the Gudrid well. Early interpretation work was focused on mapping objectives set out by the Green-CAP project (see section 4 below), but have since shifted to the extensional margin in the northern Labrador Sea and the extensional margin in Baffin Bay.

A preliminary gross sediment thickness map for Baffin Bay has been generated by compiling and spatially enabling industry maps generalized from National Energy Board reports, and modified by selective re-interpretation of seismic which is presently ongoing. The general methodology to create the grid is to subtract the water travel time from time structure mapping referenced to a sea level datum, making it a sediment travel time map, and then the map is converted to thickness with a velocity function. Significant revisions to both the time structure mapping of basement and the depth conversion method are still to come. In addition, the nature and orientation of basement ridges and sediment thickness will require substantial revision in the currently poorly defined area in central Baffin Bay.

Future Work:

Future work includes further seismic processing, such as post-stack time migration, to aid in the data interpretation. In addition to the work already completed on the Suncor dataset, 33 lines or line segments still require migration. Two approaches have been tested, both involving finite difference migration. Initial tests have shown that the data does not seem to be of sufficient depth range or quality to require anything more than a single velocity; however, on more complicated lines multiple velocities might be necessary. In addition to the Suncor data, there are over 200 lines previously converted to digital seg-y format that would benefit from migration, as well as key single-channel lines.

Future seismic interpretation in the Ungava Transform master will focus on the top Eocene volcanics, tied in from the Gjoa G-37 and Hekja O-71 wells to the south with at least one Miocene seismic marker to be determined from the ODP 645 well to the north. There are regional tie lines extending to wells on the Greenland side from which some additional seismic horizons will be interpreted.

3. Tectonic Margin Segmentation

This subactivity relies on the assessment of the seismic data from the above work. Early results suggest a significant relative difference in the scale of structures from the rifted margin in the Labrador Sea to that in Baffin Bay. With no industry wells on the Canadian margin of Baffin Bay, determining the timing of events and using the analogue study from the Labrador margin will be critical to understanding the nature of basin infills in Baffin Bay. Based on the nature of the stratigraphy and initial assessment of the seismic data, the Miocene and younger section from Labrador will be a good analogue for Baffin Bay.

4. Integrated Stratigraphic Framework for Baffin Bay

Methods:

Ongoing work on the Cretaceous and younger sedimentary rocks on Bylot Island, northeastern Baffin Island (GEM 1 & 2) are integral to the understanding of the stratigraphy in the offshore. In addition, the closely aligned Green-CAP Tectonostratigraphic Atlas will have implications for a regional perspective by combining the knowledge of both the Canadian and Greenland margins of the Baffin Bay and Labrador Sea area.

Results:

Petrography of onshore sedimentary strata, Bylot Island region

Preliminary petrographic analysis of Cretaceous-Paleocene sandstones cropping out on Bylot Island and northern Baffin Island has been undertaken, to assess diagenesis and reservoir potential, and to lay the foundation for provenance studies. The Cretaceous-Paleocene succession of the region consists of more than 1 kilometre of interstratified sandstones and mudstones. Much of these strata are interpreted as non-marine to nearshore marine in origin, based on sedimentology and palynology, and are considered to be proximal equivalents of strata preserved in the offshore regions of northwestern Baffin Bay.

Sandstones in the Cretaceous-Paleocene succession show stratigraphic changes in composition, maturity, and diagenesis. Porosity and permeability of sandstones in much of the section are considered very good, although some intervals show a greater proportion of lithics and feldspars, thus degrading the reservoir quality of these sandstones. Textural maturity of the sandstones also varies stratigraphically, potentially related to variations in source terrane and depositional environments. A model of petrographic evolution of the succession is being developed, which will identify preferred target intervals for hydrocarbon exploration.

Bylot Island palynological analyses

The analysis of 33 North Bylot Trough samples from the Maud Bight area on the east coast of Bylot Island primarily involved cross-checking the occurrence of taxa and preparing detailed analysis tables. This stratigraphic section is critical to establishing correlations with independently dated, midcontinental Campanian and Maastrichtian North American spore and pollen assemblages. In addition, a preliminary scan of 114 palynology slides from the Q-section samples from the Twosnout Creek area, west-southwest coast of Bylot Island was conducted and preliminary ages have been inferred. Further microscope study is required although this is simplified by a reduced spore and pollen diversity in most samples from this mostly marine section. Occurrence data is being loaded into GSC Calgary's corporately managed database, and spore and pollen data will demonstrate tectonically induced time gaps.

Ongoing work from the Bylot Island area also includes manuscript preparation on the Albian to Paleocene biozones and the initial conclusions of their correlations with existing North American biozones based on terrestrial (nonmarine) taxa. Another manuscript in preparation includes a more detailed study on *Porosipollis* and a specific example of how the phylogenetic understanding of pollen and spore complexes serve as a tool in refined cross-continental correlations and hence the biostratigraphic value of such studies.

Onshore-offshore correlations & thermal modeling, Bylot Island area

In the Bylot Island area integration of onshore geology maps (in large part based on previous research), multibeam sonar seafloor bathymetry maps and re-interpreted seismic sections are combined to identify major faults that cut crystalline basement and correlate offshore seismic stratigraphic units with formations mapped onshore. Normal faults in the Bylot Island area generally strike NW-SE, NE-SW or E-W. The orientation of the NW-SE striking faults is most likely controlled by pre-existing fabrics in the basement rocks. Faults with this orientation have a long history that started in the Mesoproterozoic (formation of the Milne Inlet trough) and continued with reactivation just before or during the early Cambrian, in the Late Cretaceous, and possibly recently. The E-W faults are steeper than, and postdate movement on the NW-SE striking faults. Basement-cored horsts are more common in the Bylot Island area than previously thought, suggesting that structural hydrocarbon traps may be more plentiful in the offshore than has been appreciated in the past. The improved understanding of the preferred orientations and timing of faulting in this area will inform future seismic section interpretations and especially the correlation of faults between 2D seismic lines.

Thermal modelling of new apatite fission track age and track length data (AFT) and apatite and zircon (U–Th–Sm)/He age data (AHe and ZHe) provides insight into the contrasting thermal histories of the crustal blocks that are bound by the basement-cutting faults mentioned above. Thermal modelling of AFT, AHe and ZHe data has resulted in model thermal histories that provide insight into the thermal history of this area from 1.7 Ga to 70 Ma and locally constrains the timing of fault movement to late Cretaceous time, coeval with the opening of Baffin Bay.

Green-CAP Tectonostratigraphic Atlas Project (on hold as of July, 2015)

The Green-CAP Tectonostratigraphic Atlas is a collaborative project between the Geological Survey of Canada and the Geological Survey of Denmark and Greenland (GEUS). Each survey has agreed to compile data and provide geological and geophysical interpretations for each half of the margin to produce an overall integrated dataset and understanding of the Labrador Sea-Baffin Bay area. The regional compilation will provide foundational information in frontier exploration areas and guide future decisions in the Baffin Bay area. A Task Shared Agreement has been signed which outlines the responsibilities of each organization, and a number of the atlas deliverables closely align with this GEM activity. As the project was set to begin in April 2015, initial workshops were held to discuss the atlas and begin the planning stages. We contributed to the planning and participation in workshops and 5 individuals were tasked with co-leadership of work packages, which involved compilation of detailed work package outlines for the final atlas. Even though the atlas project has now been postponed, plans for this project will provide a regional context for this GEM activity.

5. Petroleum Systems Assessment

CHS bathymetric field notes and echo sounder records

The signed Memorandum of Understanding between the Canadian Hydrographic Service (CHS) and the GSC has been completed to provide the GSC with access to echo sounder records and related data along the northern Baffin Bay shelf. The raw digital files of navigation and bathymetry have been provided by CHS, and high-resolution scans of 9 field sheets for the northern Baffin Shelf have been georeferenced. Next steps include: completing the scanning of 17 field log books; cross-referencing field log book contents with digital navigation and bathymetry files; evaluation of the spatial accuracy; and scanning of the ~400 echo sounder records. These scanned records will then be integrated with the digital navigation and interpreted for direct hydrocarbon indicators (e.g. pockmarks, mounds, gas venting).

6. GIS and Information Management

The compilation of GIS data and information management for the project is ongoing. Existing datasets have been revised and updated, new datasets are being acquired from several sources such as the GSC, international government organizations and provincial surveys, and project-relevant legacy data have been spatially enabled. The GIS layers are being expertly managed in a robust ArcSDE project space on an Oracle server at GSC (Atlantic). The vector and raster data are accessible to all project participants for viewing, analysis and synthesis in ArcGIS software and for download and incorporation into other GIS and seismic interpretation software packages. To date, a total of 24 datasets have been uploaded into the Baffin Bay ArcSDE user-schema geodatabase and an additional 20 datasets are ready for upload into the ArcSDE instance. An organized effort is being made to complete metadata records for all data managed in the ArcSDE server as a measure to adhere to good information management protocols.

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