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Qualitative petroleum resource assessment of Peel Sound, Bellot Strait, Gulf of Boothia, Fury and Hecla Strait, and Foxe Basin, Nunavut

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EXECUTIVE SUMMARY

The Geological Survey of Canada (GSC) within Natural Resources Canada (NRCan) has evaluated the petroleum resource potential for Peel Sound, Prince Regent Inlet, Gulf of Boothia, Fury and Hecla Strait, and the northern portion of Foxe Basin, herein referred to as the study area (Figure 1). As part of the initiative to identify petroleum energy and mineral potential in Canada's offshore domain, the GSC has produced this report for the study area. These areas, located south of the Lancaster Sound assessment (Atkinson et al., 2017), have not been included in previous GSC petroleum resource assessment studies. Figure 1 identifies the qualitative petroleum potential for the study area and includes the previous Lancaster Sound qualitative petroleum resource assessment potential map published in Open File 8297 (Atkinson et al., 2017).

Data were compiled and assessed for an area that is larger than the offshore area only based on practical geological considerations. This approach improves the detail and accuracy of GSC predictions.

The petroleum potential for this area is very limited compared to Lancaster Sound and Baffin Bay (Atkinson et al., 2017). The GSC interpretation, covering an area from Peel Sound to the Foxe Basin, is visually represented in the petroleum potential map in Figure 1. A brief assessment of petroleum potential for each waterway of the study area follows:

1. **Gulf of Boothia and Prince Regent Inlet.** This region is comprised of Paleozoic carbonate dominated deposits, characterized by potential for structural and stratigraphic/diagenetic traps. Petroleum potential is considered low in this region. No petroleum exploration wells have tested rocks in this waterway.
2. **Foxe Basin.** This region is also comprised of Paleozoic carbonate dominated deposits, with potential for structural and stratigraphic/diagenetic traps. The Foxe Basin Rowley N-14 well, drilled in 1971 on Rowley Island in Foxe Basin, found no strong evidence of a working petroleum system. However, traces of bitumen (or dead oil) and oil staining were noted in the well report. Potential in Foxe Basin is considered low, although data coverage is limited.
3. **Peel Sound and Bellot Strait.** Peel Sound and Bellot Strait have little to no petroleum potential as these areas are underlain by Archean granite. Wells on Prince of Wales Island (Russell E-82, Young Bay F-62), west of Peel Sound, were drilled in the 1970s. Young Bay F-62 found evidence of an inactive petroleum system. However, the onshore Prince of Wales Island is fault separated from most of Peel Sound and Bellot Strait. The exception being Browne Bay, which may contain petroleum potential within Paleozoic carbonates.
4. **Fury and Hecla Strait.** This region is thought to be underlain by Mesoproterozoic shales and sands of the Fury and Hecla Basin similar to those mapped in the near shore of the strait. Therefore, the Fury and Hecla Basin has potential for Mesoproterozoic source and reservoir but there is little indication of an active petroleum system in this area.

The sedimentary succession of the study area is comprised of three distinct major geological mega-sequences; Archean, Proterozoic, & Paleozoic. The mega-sequences (Figure 2) do contain key petroleum system elements: source rocks, reservoirs, traps, and seals. However, interpretation and geological history in this area suggests limited petroleum potential. The four identified potential play types for this study area's work include: (i) Paleozoic fault blocks, (ii) Paleozoic hydrothermal dolomites (HTD) sourced by Paleozoic source rocks, (iii) Paleozoic reefs sourced by Paleozoic source and (iv) Proterozoic accumulations sourced by Proterozoic source rocks (Table 1). The presence and quality of source, reservoir, trap, and seal rocks qualify the potential for a working petroleum, system that may have led to the accumulation of oil and / or gas. However, the preservation potential of entrapped petroleum is reduced by many geological events since the Paleozoic including: (1) tectonic-induced faulting and inferred petroleum leakage along fractures, and (2) a significant amount of erosion associated with tectonic uplift that reduces seal integrity allowing for petroleum leakage (3) and inferred reservoir cooling and biodegradation of potential petroleum accumulations assuming petroleum generation and entrapment occurred.

This report also evaluates the potential for unconventional petroleum and mineral resources in the study area from published and publically known information. The unconventional energy resources evaluated include gas hydrates, coalbed methane (CBM), and shale oil/shale gas. This study area has little to no evidence to suggest these unconventional petroleum accumulations occur in the report study area.

Mineral resources may extend into the offshore waters of the study area. These would include undersea extensions of onshore identified lead, zinc, copper, iron, fluorite, barite, silver, gold, coal, gypsum, and micro-diamonds. Offshore mineral resources may be developed in the future but onshore mining could occur in the near future adjacent to the study areas. Figure 2 provides information on mineral occurrences and mines in the study area. The authors of this report are unaware of any regulatory framework that would allow offshore mineral mining currently in Canada.

1. INTRODUCTION

The petroleum potential in the study area was evaluated as an extension of the analysis conducted for Lancaster Sound in 2017 (Atkinson et al., 2017). Objectives were to: (a) review, analyze, and integrate geological data from existing scientific literature and available geoscience databases; (b) interpret, characterize, and map petroleum system elements and regional petroleum plays by applying sound geological principles; and, (c) provide a qualitative summary of the petroleum potential in the proposed protected area.

The results of the GSC work (Figure 1) are qualitative for the study area.

Based on geographic and tectonic considerations, offshore areas of the study area were grouped into three assessment regions, discussed in details in Appendices A, B, and C:

- Peel Sound and Bellot Strait (Appendix A)
- Prince Regent Inlet and Gulf of Boothia (Appendix B)
- Fury and Hecla Strait and Foxe Basin (Appendix C)

2. DATA

2.1 Literature

Although no previous GSC petroleum assessment studies have been published for the study area, the region was the subject of numerous regional studies published in a wide range of publications, and industry reports. The compilation of selected literature incorporated into the petroleum potential map (Figure 1) includes: (i) regional geological maps (Trettin, 1975, Okulitch, et al., 1991; Harrison et al., 2011; Jobin et al., 2017); (ii) geothermal maps (Grasby et al., 2011); (iii) reports (Mayr et al., 2004; Thorsteinsson and Tozer, 1962); (iv) scientific papers dealing with tectonics and sedimentation (Trettin, 1991; Mortensen and Jones, 1986); (v) basin thermal maturity (Dewing and Obermajer, 2009; Dewing and Obermajer, 2011); (vi) conversations with GSC experts on unconventional potential within the study area. A detailed list of supporting technical reports and scientific literature is supplied in Appendix D. A glossary of terms used in this report can be found in Appendix E.

2.2 Geoscience data

GSC's qualitative assessment was based on onshore surface geology: four onshore wells, onshore and offshore two-dimensional seismic lines, and their integration with bathymetric surveys along with gravity and magnetic data. The well locations, two-dimensional seismic lines, surface petroleum shows and slick-like features are identified in Figure 2.

Both onshore and offshore two-dimensional multichannel reflection seismic lines were used for interpretation work where data were available. Well data were tied to seismic for the Prince of Wales Island wells utilizing a synthetic tie which connected the geology as seen in both the wells and seismic data. Other geophysical data integrated into the qualitative interpretation for this report include single-channel sub-bottom acoustic and bathymetric data and various gravity (Jobin et al., 2017) and magnetic maps. However, there is limited seismic data coverage in Peel Sound and Prince Regent Inlet. There is no seismic data coverage in the Gulf of Boothia, Foxe Basin, Fury and Hecla Strait nor Bellot Strait.

Petroleum exploration includes:

> Onshore and offshore exploration: Four wells were drilled in the study area located on Prince of Wales Island, Russell Island, Somerset Island and Rowley Island in Foxe Basin. Although none of the wells encountered economic petroleum occurrences, subsurface indicators of petroleum presence (bitumen, pyrobitumen, oil staining, etc.) confirm a once present, though potentially limited, petroleum system. No offshore exploration wells were drilled. Very little structure can be seen due to the poor quality of seismic data covering Browne Bay within Peel Sound (Appendix B). Due to lack of identified potential

high-impact petroleum prospectivity, limited petroleum indicators (e.g. seeps, slick-like features) and limited onshore success, the overall offshore petroleum potential is limited for Peel Sound (Figure 1). Prince Regent Inlet and the Gulf of Boothia contain no well data. Slick-like features are noted in Foxe Basin near lineaments interpreted on potential field data (possible large scale basement faults). There is no seismic data coverage for Foxe Basin.

RadarSat data were assessed for evidence of surface slicks. Surface slick-like features may imply an active petroleum system or gas hydrate leakage and if these features are recorded repeatedly, their measurement supports higher confidence level of an active petroleum system. Data suitable for observing surface slick-like features were only available for part of the study area, in Foxe Basin (Figure 2).

Mineral exploration includes:

Mineral resource exploration of the study area has been limited to the islands and mainly focused on gold, zinc, copper, diamonds, platinum group elements, and uranium (Figure 2; Indigenous and Northern Affairs Canada (INAC), 2016, 2017). However, in some areas studied, the onshore geology is different from the offshore geology (e.g. Prince of Wales Island Paleozoic carbonates compared to Peel Sound Archean granites, Figure 2). Therefore, extrapolation of the Paleozoic mineral assemblage for onshore Prince of Wales Island can not be carried into Peel Sound and Bellot Strait, which are interpreted to be floored by the Archean (Figure 2).

a) There are no current mining operations on Prince of Wales Island.
b) Mining operations exist south of the Boothia Peninsula such as Amaruk Gold (Adamera Minerals Corp.) and the Committee Bay area (North Gold Corp.) with diamond, gold and nickel prospects.
c) Mining potential includes Mississippi Valley Type (MVT) mineral potential of Zn-Pb-Cu for onshore Prince of Wales Island and parts of northern Somerset Island (Figure 2; Dewing et al., 2007).
d) Concentrations of Uranium in the Fury and Hecla Basin (Figure 2) have been mapped by Long and Turner (2012).
e) The offshore mineral potential in the Foxe Basin is unknown. A speculative MVT deposit may occur in the centre of the basin where large basement faults may have acted as conduits for mineral rich fluids. Onshore (Figure 2), to the east of the Foxe Basin Commander Resources holds a series of gold showings on Baffin Island (N.W.T. & Nunavut Chamber of Mines, 2012). To the west of the Foxe Basin on the Melville Peninsula diamonds, base metals, and iron are the primary mineral holdings (N.W.T. & Nunavut Chamber of Mines, 2012).

2.3 Unpublished analytical data

GSC's Sample Management System (SAMS) contains a wide range of easily searchable analytical data. Project-relevant data, such as source rock evaluation, were screened and interpreted in geological context and used to refine interpretation, including extent of resource play polygons.

3. METHODOLOGY

3.1. Internal Scientific Reviews

To ensure sound integration of the geological data, GSC area experts were frequently consulted for direction and feedback, which provided access to additional knowledge, unpublished interpretations, and subject matter expertise.

3.2. Play Mapping

Previously published work did not include evaluation of petroleum system elements. The authors of this report identified plays in the study area and defined those elements based on geologic and tectonic trends, seismic interpretation, and analogue data (Table 1). Each play was assessed individually and a chance of geologic success was assigned for each occurrence of a petroleum system element (source, reservoir, trap, and seal). A 1D basin model was generated for the Young Bay F-62 well to estimate source rock maturity (Appendix A, Figure A-3) and used to influence Chance of Success (COS) mapping. Petroleum system elements were multiplied to produce a COS map for each play. In addition, plays were then weighted by an internally-developed global scale factor (GSF), which is a subjective estimate of how the play compares with respect to potential volumes of petroleum resources, on a worldwide scale. Thereby a GSF of 1 reflects confidence for the presence of a large petroleum accumulation, i.e. 7.95e+7m³ or 500 MMBOE. Lower GSF therefore reflects lower confidence of the presence of a large accummulation. The sum of all plays' potential was then calculated to create an overall qualitative petroleum potential map (Figure 1). The resource assessment methodology (COS) used by the GSC is discussed in detail in Lister et al. (in press). Similar types of analyses are widely used throughout the petroleum industry.

4. RESULTS AND INTERPRETATION

The potential presence of petroleum systems in the study area is quite limited and restricted to occurrences in the Gulf of Boothia, Prince Regent Inlet and Foxe Basin.

Subsurface mapping identified four play types (Table 1), each with very limited petroleum potential:

(i) Paleozoic fault blocks,
(ii) Paleozoic hydrothermal dolomites (HTD) sourced by Paleozoic source rocks,
(iii) Paleozoic reefs sourced by Paleozoic source rocks,
(iv) Proterozoic accumulations sourced by Proterozoic source rocks.

The petroleum potential map, created by multiplying the petroleum system elements of reservoir, source, seal and trap in each play type (Table 1) and giving each segment a scale multiplier, resulted in identified plays of varying petroleum potential. The chance of success maps are then added together to create the final qualitative petroleum resource assessment map (Figure 1).

Foxe Basin (Appendix C) and Prince Regent Inlet/Gulf of Boothia (Appendix C) is estimated to be in between medium to low potential (orange). The remaining study area contains very low to nil petroleum potential, red and grey (Figure 1). Specifically, in Peel Sound (with the exception of Browne Bay) and Bellot Strait the seafloor is thought to be Archean granite, containing no hydrocarbon potential (Appendix B). In the Gulf of Boothia and Foxe Basin, the thinner Paleozoic carbonates have limited hydrocarbon potential, as do the Proterozoic sediments of the Fury and Hecla Strait (Appendix C). The grey areas of Figure 1 indicate no petroleum potential.

Unconventional resources were investigated for their energy potential possibly including: gas hydrates, coal-bed methane, oil shale, and shale gas. Based on previous publications and provincial reports, unconventional resource potential is considered very low in offshore parts of the study area. Oil shale and coal-bed methane are not considered to be prospective as an unconventional resource in onshore parts of the study area due to interpreted immature source rock. There are no publications that indicate regions of potential methane hydrate stability in the study area.

The overall petroleum potential of this report's study area is very limited compared to the 15 identified play types in Lancaster Sound and their estimated potential (Atkinson et al., 2017).

5. CONCLUSIONS

Petroleum potential is estimated to be very low in Peel Sound, Bellot Strait, Gulf of Boothia, Fury and Hecla Strait into Foxe Basin due to:

1. Peel Sound and Bellot Strait are underlain by Archean sediments with very limited areas for the combination of source, reservoir, trap and seal, which is necessary for an effective petroleum system.
2. Gulf of Boothia does not contain a sufficiently thick succession of carbonate platform to support an effective petroleum system (i.e. source rock not buried deeply enough to generate hydrocarbon).
3. Fury and Hecla Strait have limited Proterozoic sedimentary coverage (Fury and Hecla Strait) but are too old to have preserved hydrocarbons.
4. Foxe Basin is characterized by an absence of identified high-quality source and reservoir rocks known to date.
5. Unconventional petroleum resource potential is assessed to be very low.
6. MVT deposits may occur in the offshore areas of the study area based on extrapolation from known onshore deposits. Other mineral potential includes base metals, gold, diamond, and nickel.

6. ACKNOWLEDGMENTS

This work was conducted by Natural Resources Canada under the Marine Conservation Targets (MCT) initiative as part of the Government of Canada's commitment to conserve 10% of Canada's marine and coastal waters within the 200 nautical mile limit by 2020.

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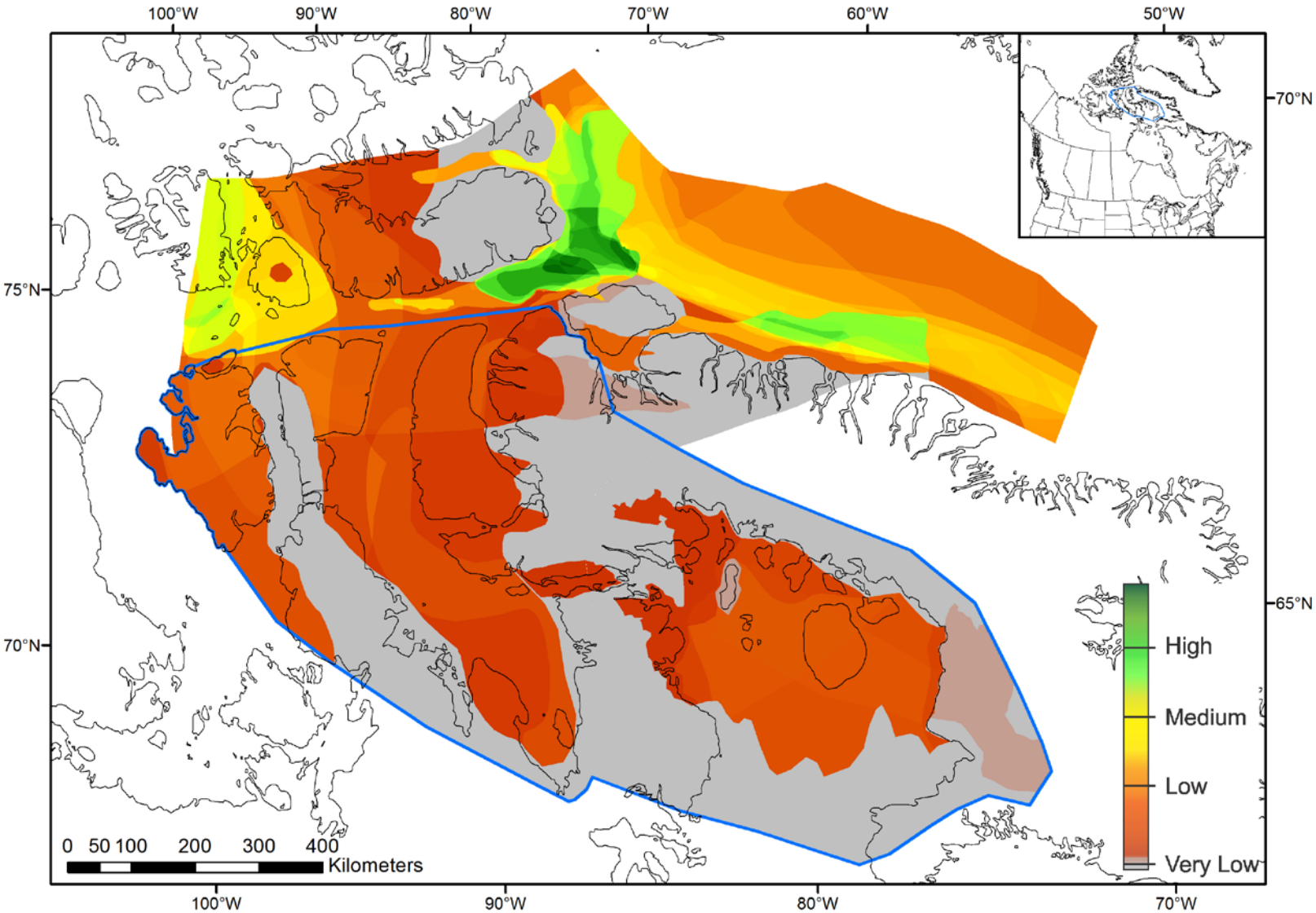


Figure 1. Petroleum Potential Map for the current study area (blue outline) joined with the Lancaster Sound assessment. The previously published Lancaster Sound assessment map (Atkinson et al., 2017) has been updated and regenerated using the methodology described in Lister et al. (in press). Color code – gradation bar ranges from no potential (grey) to the highest potential (green). No high potential areas exist in this study area. Inset map shows location of study area (blue outline).

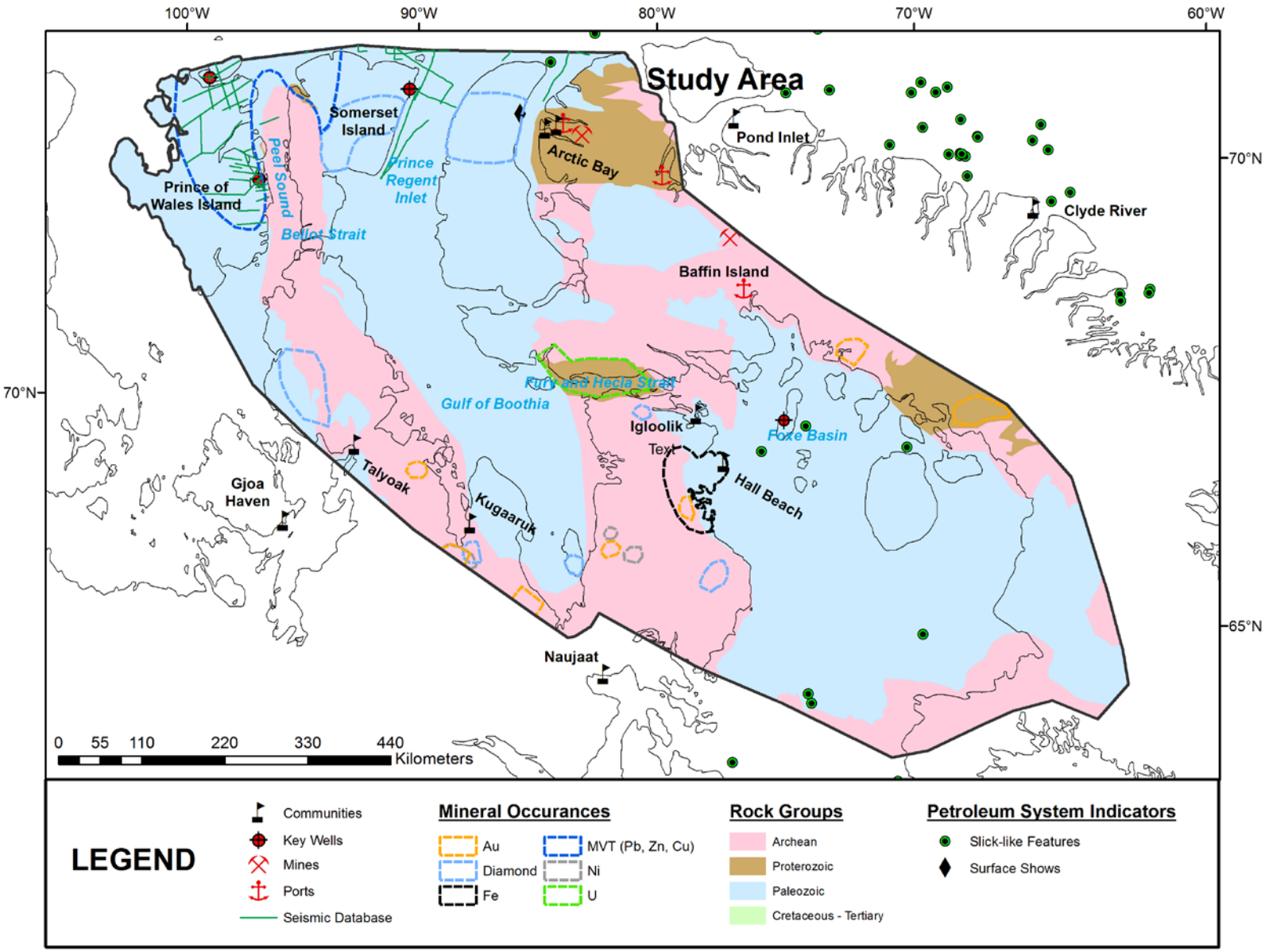


Figure 2. Location map with main tectono-stratigraphic and mega-sequence (rock groups) subdivision. Overlays include well locations; mineral zones (Dewing et al., 2007; Indigenous and Northern Affairs Canada (INAC), 2016 and 2017 and Long and Turner, 2012), petroleum indicators (Brent et al., 2013); and geographic landmarks.

Peel Sound to Foxe Basin potential chance of success summary							
Age (Ma)	Play	Reservoir	Trap	Source	Seal	Highest Uncertainty	Global Scale Factor
393	Paleozoic - in ext/invert fault blocks	Carbonates, Clastics	Structural	Cape Phillips, other Paleo/Ordovician	Tight carbonates, shales	Breach/ Preservation	1.000
426	Hydrothermal Dolomite (HTD)	HTD Carbonates	Stratigraphic	Cape Phillips, other Paleo/Ordovician	Tight carbonates, shales	Preservation	0.6/.45
426	Paleozoic Reef	Reefs	Stratigraphic	Cape Phillips, other Paleo/Ordovician	Tight carbonates, shales	Preservation	0.500
999	Proterozoic structure	Clastics or Carbonates	Folds, Subcrop	Agu and Arctic Bay formations	Proterozoic intra-formational shales	Preservation	0.5/.45

Table 1. Petroleum plays including risk assessment for Peel Sound to Foxe Basin. Note: In this study area, only four play types from Atkinson et al. (2017) have been identified (8, 11, 13, and 15). In plays 426 and 999, the global scale factors (GSF) change depending on location of the study area. The larger GSF numbers in plays 426 and 999 (0.6 and 0.5 respectively) reflect the areas near Lancaster Sound. The smaller GSF numbers in this study area (0.45) for plays 426 and 999 reflect the Foxe Basin.

APPENDIX A – PEEL SOUND AND BELLOT STRAIT

Summary

The geology and economic potential of Eastern Prince of Wales Island was reported in detail in GSC Bulletin 574 (Mayr et al., 2004). No resource estimates were given, but based on available sparse data overall petroleum potential was considered low to unknown. Extrapolated onshore geology coupled with onshore and offshore seismic lines and gravity surveys (Jobin et al., 2017) supports the lack of petroleum potential in Peel Sound. The exception is Browne Bay, where petroleum potential may exist, but is evaluated to be low. Bellot Strait, confined by and underlain by Archean rocks, has no petroleum potential.

Background

Location, tectono-sedimentary setting, and geological history: Peel Sound is a shallow depression (<400 m deep) bounded by Archean granites on Boothia Peninsula and Somerset Island in the east and patchy Precambrian exposures thrusted onto the Lower Paleozoic carbonates on the eastern side of Prince of Wales Island (Figures 2 and A-1A).

Geologic mapping (Figure A-1A, Harrison et al., 2011) suggests that Peel Sound is underlain by basement rocks with no petroleum potential. Our interpretation of seismic line 717U_X-65 (Figure A-1B) suggests the possible patchy preservation of a relatively thin (<700 m thick) sedimentary cover likely comprised of Proterozoic and/or Paleozoic rocks. The thin sedimentary cover is supported by gravity data (Figure A-2, Jobin et al., 2017). Considering its small thickness and isolation from other sedimentary rocks, it is very unlikely that this unit would have any petroleum potential. Bellot Strait, a narrow waterway cut through one of the major west-east trending faults is confined by and underlain by Archean rocks and thus has no petroleum potential.

Onshore Boothia Peninsula, Somerset and Prince of Wales Islands have sedimentary successions including Proterozoic and Paleozoic carbonates and clastics. Proterozoic rocks belong to remnants of the Huntington-Aston Basin (Long and Turner, 2012; Mayr et al., 2004; based on Campbell and Cecile, 1981; Jackson and Ianelli, 1981; and Young, 1981), while the Paleozoic succession is dominated by an extensive Ordovician and Silurian carbonate platform with Devonian clastics (Mayr et al., 2004).

Structurally, a series of sub-parallel N and NE-trending thrust faults separate basement rocks on Somerset Island and in Peel Sound from a thick Paleozoic succession to the west on Prince of Wales Island (Figure A-1A). Thrusting occurred during the Boothia Foldbelt event in the Late Silurian to Early Devonian (Mortensen and Jones, 1986). The thrust faults placed Precambrian basement over Silurian sedimentary rocks (Mayr et al., 2004; Figure A-1C) and the thrust blocks are separated by series of NE-trending tear faults (Mayr et al., 2004). Sediments from thrusted blocks were rapidly deposited in the newly formed foreland basin (Figure A-1C). During the Late Devonian Ellesmerian Orogeny, basement blocks that were thrusted to the west during the Late Silurian were reactivated by S-directed compression which led to the development of NE-trending folds, both adjacent to and within the area of the Boothia Foldbelt (Harrison et al., 1993; Kerr, 1974; McNair, 1961). These folds are offset by en échelon sinistral strike-slip faults (Harrison, 1995; Jober et al., 2007; Figure A-1A).

Since the Early Devonian, the Peel Sound area has experienced extensive periods of uplift and associated erosion. The present day morphology was initiated by major easterly-flowing rivers during the Paleogene-Neogene (Tertiary; Fortier and Morley, 1956; Pelletier 1966; Trettin, 1991) and modified by glacial movement during the Quaternary.

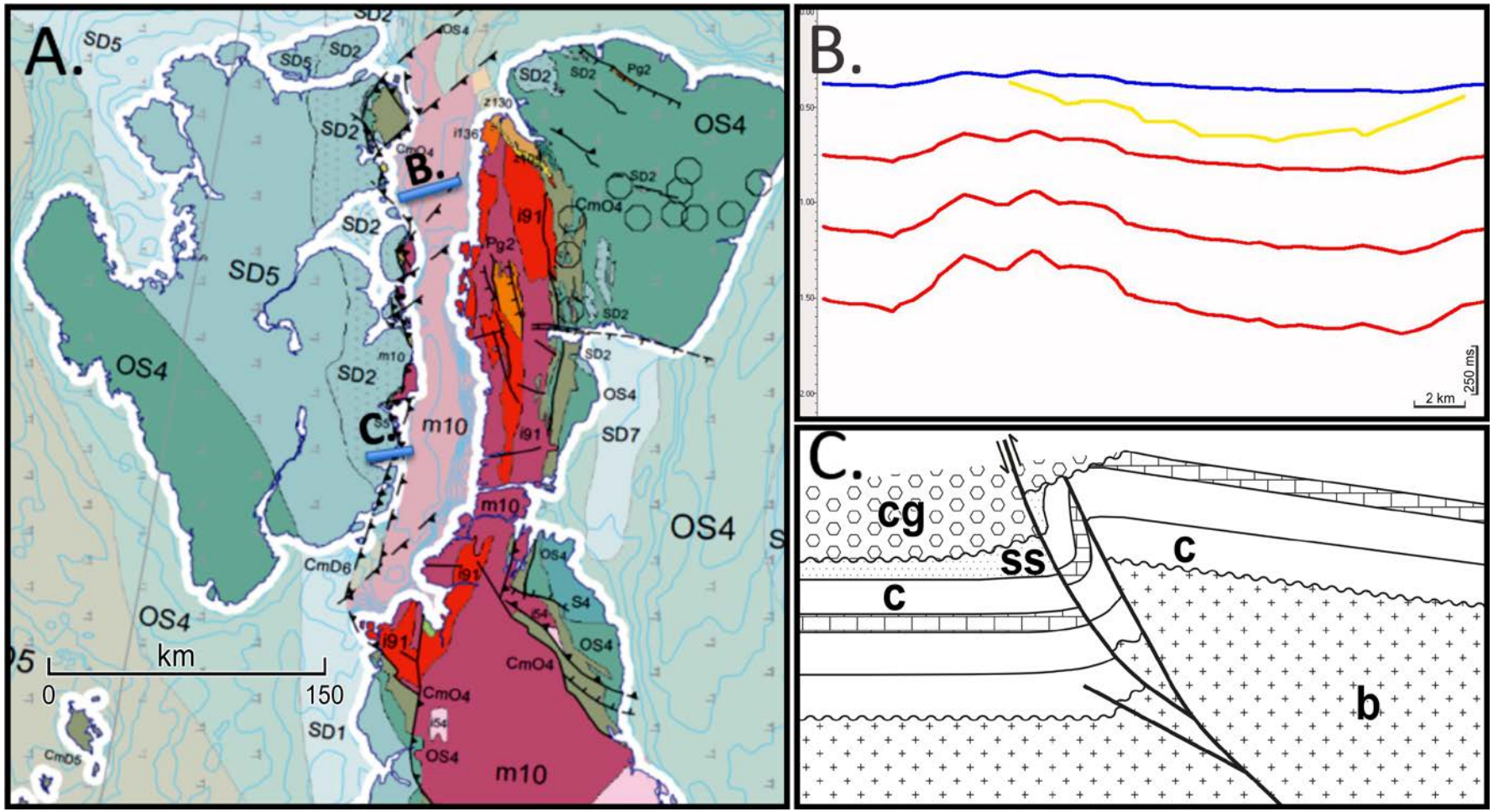


Figure A-1. Peel Sound and Bellot Strait geology A) geologic map (from Harrison et al., 2011), Blue lines: approximate location of figures shown B and C; B) cartoon of seismic interpretation on Kenting's line 717U_X-65 Key: Red: water bottom multiples, Yellow: interpreted shallow basement; data is from National Energy Board report 693-09-10-0052 submitted by Kenting, data image is publically available from NEB C) schematic (not to scale) cross-section through Strzeleski Block (From Mayr et al., 2004, Figure 22).

Key mapped units (Figure A-1A):

m10 undivided Archean and Proterozoic (4000-542 Ma)
i91 granodiorite to granite metagabbro, gabbroic anorthosite, anorthosite … Caledonian Orogen
OS4 carbonates, undifferentiated Ordovician-Silurian (488-415 Ma)
SD1 Silurian and Devonian (444-359 Ma)
SD2 clastic, continental, Silurian-Devonian (444-359 Ma)
SD5 carbonates, Silurian-Devonian (444-359 Ma)
SD7 Silurian-Devonian (444-359 Ma) marine sedimentary, undivided

Lithology key for Figure A-1C: b – basement, c – carbonates, ss – sandstone, cg – conglomerate.

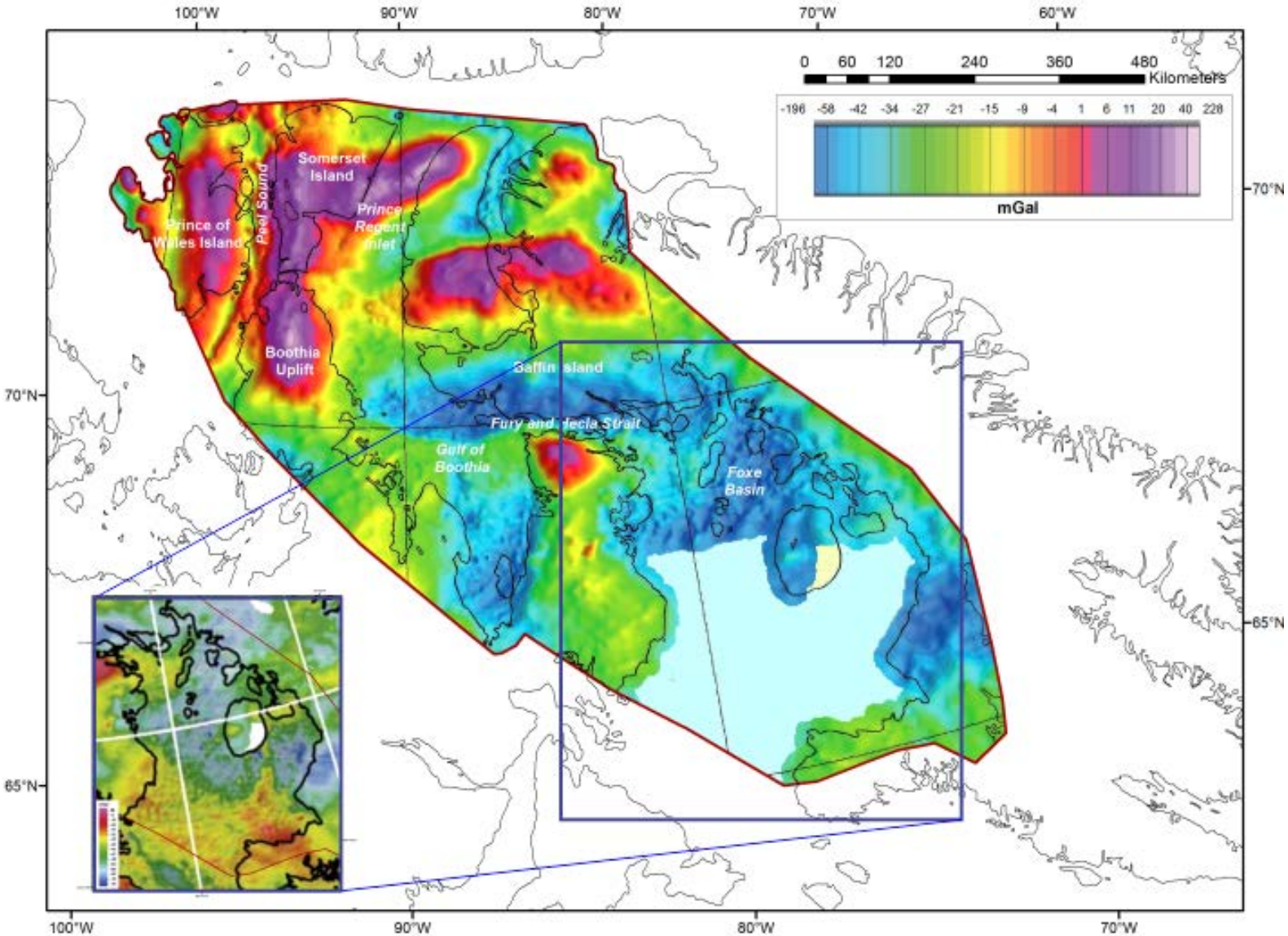


Figure A-2. Isostatic residual gravity anomaly map of the study area (modified from Jobin et al., 2017) showing regional gravity lows (blues) in the Gulf of Boothia, which may indicate thicker sedimentary cover in this area. The Foxe Basin inset (bottom left) is a Bouguer Anomaly map from the work of Pinet et al. (2013).

Petroleum Exploration Activities and Offshore Potential

Two onshore petroleum exploration wells were drilled in 1971 by Sunoco (Panarctic Russell E-82) and in 1975 by Kerr-McGee (Young Bay F-62) just west of the Peel Sound and the regional thrust-fault belt within the easterly tilted foreland basin (Okulitch et al., 1991; Harrison et al., 2011).
The Young Bay F-62 well was drilled into a seismically-identified bright spot. Although neither Young Bay F-62 (on Prince of Wales Island) nor Russell E-82 (on Russell Island) encountered commercial petroleum accumulations, the bitumen in the Lower Devonian/Silurian Read Bay limestone (-325 m to -355 m subsea) and in the Silurian/Ordovician Allen Bay dolomite (-812 m to -965 m) in Young Bay F-62 well, confirms the presence of a petroleum system. A 1D model was created for the Young Bay F-62 well (Figure A-3).However, this area of exploration is separated from most of Peel Sound by the structure described above: a large fault system separating Prince of Wales Island geology and Peel Sound geology. The potential exceptions are Browne Bay and other embayments located west of the thrust-fault belt, in submerged parts of tilted foreland basin along the East Coast of the Prince of Wales Island (Figure A-1A). There, the thick sedimentary succession may contain all petroleum system elements including source, reservoir, traps, and seals, but still with limited petroleum potential (Mayr et al., 2004). In most of Peel Sound, considering the patchy nature of sediments coupled with their limited thickness and tectonic history described above, it is reasonable to suggest that generation, entrapment and particularly preservation of any petroleum accumulation is very unlikely.

Source Rock

The bitumen encountered in Young Bay F-62 was either (a) sourced by an older underlying Ordovician or even a Proterozoic source (Mayr et al., 2004); (b) migrated long distances from matured Cape Philips shale to the west (Dewing and Obermajer, 2009); and/or (c) migrated short distances from organic rich strata within Devonian-Silurian Drake Formation (Rock-Eval data from all three available samples indicate thermal maturity in the early oil generation window [SAMS database; Table A-1]). Furthermore, the palynology report (SAMS database) suggests that samples are age-equivalent to organic-rich Eids and Devon Island formations in the Eastern Arctic and Kitson Formation in the Western Arctic.

ID	TOC	Tmax	period	age
C-008244	2.58	430	NA	NA
C-008256	1.14	432	Emsian	E. Devonian
C-039399	0.96	433	Ludlow	Silurian

Table A-1. SAMS database from northwest onshore Prince of Wales Island.

The interpreted burial history for the Young Bay F-62 well (Figure A-3), calibrated with available vitrinite reflectance data (SAMS database) and coupled with T_{max} data from the Silurian-Devonian Drake Formation outcrop (Table A-1) suggests that both the Lower Paleozoic and Precambrian rocks have reached the oil-generation window that peaked ~365 Ma in the Devonian (Figure A-3). The model has taken into account elevated geothermal gradient throughout the Peel Sound (Grasby et al., 2011), and increased basin temperature during Proterozoic rifting and Franklinian igneous event (723 Ma). Results show that if present, source rocks could have generated oil that charged the extensive porous Paleozoic dolomite reservoirs.

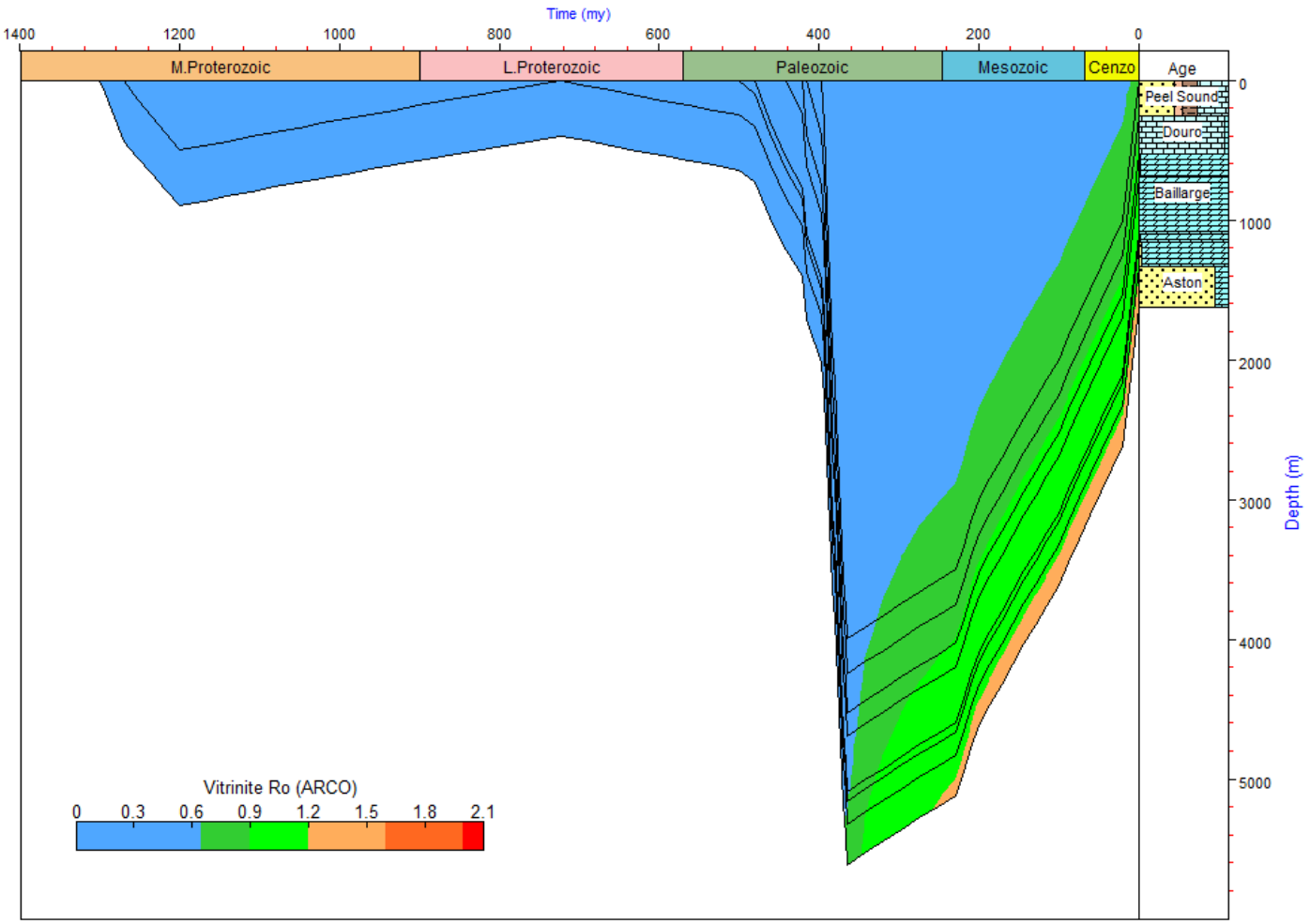


Figure A-3. Burial History Chart for well Young Bay F-62, showing calculated thermal maturity in colour. Green to light orange shades indicate the oil window. Dark orange to red are in the gas window. Late Proterozoic uplift is attributed to the reactivation of the Shale Hill fault (post 720 Ma, Turner, 2011). 4 km of sediment were deposited (over 30 Ma) during the Devonian, modeling the (relatively) rapid clastic deposition of the Devonian clastic wedge.

Reservoir

The presence of reservoirs within Devonian/Silurian carbonates initially inferred from bright spots identified on seismic sections are confirmed by well logs and drill cuttings. Hydrothermal dolomitization was the primary cause of porosity development. Although not documented nor evaluated as reservoir rocks in literature, Devonian Peel Sound Formation sands eroded from uplifted Archean and Proterozoic rocks and deposited in the newly formed foreland basin should have good reservoir properties. Based on 1D modeling the peak temperature of the Douro formation was >104°C at ~342 Ma, during peak generation (365 Ma), the reservoir temperature would have been ~95°C. Since 142 Ma, the reservoir temperature has remained below 70°C, which means any potential pooled hydrocarbon may be biodegraded.

Trap

The main trapping potential in Browne Bay and other embayments in eastern Prince of Wales Island exists in hydrothermal dolomites. Higher amplitudes have been observed on onshore seismic lines which may represent porosity in the Paleozoic platform and can be interpreted to be hydrothermal in origin (Davies et al., 2006). Hydrothermal dolomite potential is also suggested by related MVT lead and zinc deposits in the region (Figure 2). There is also some limited chance of stratigraphic traps in Proterozoic rocks beneath the angular sub-Cambrian unconformity.

On the east side of Prince of Wales Island there is a significant reverse fault that carries Archean rocks over the Paleozoic platform. Very little deformation of the Paleozoic carbonates is observed in the footwall of this reverse fault. There is no petroleum potential in the Archean rocks in the hanging wall of this fault, and potential for structural traps in the footwall is very limited due to the limited deformation and unfavourable strata geometry (Figure A-1B).

Seal

Extensive, non-dolomitized carbonate platform units would act as a seal for Paleozoic hydrothermal dolomite plays. Any significant accumulation in Peel Sound reservoirs would have been lost due to the absence of an overlying seal.

Bellot Strait, which separates the Boothia Peninsula from Somerset Island, is an up to 2 km wide and 25 km long natural passage. It is interpreted as one of many west-east trending faults (lineaments) created during Late Silurian to Early Devonian tectonic uplift (Boothia uplift). Both sides of this narrow passage have been mapped as Archean granite. Considering Bellot Strait has a shallow water depth of 22 meters and using geologic trends, such as the overall North-South orientation of the uplift and compressional thrust faults (Okulitch et al., 1991), it is assumed that Archean granites underlie the strait and that chances of finding any petroleum accumulations within Bellot Strait are extremely low.

APPENDIX B – GULF OF BOOTHIA AND PRINCE REGENT INLET

Summary

The Gulf of Boothia and Prince Regent Inlet, located in the middle of the Arctic carbonate platform (Figures 2 and B-1) are underlain by Ordovician and Silurian carbonates similar to those exposed on the adjacent Brodeur Peninsula (Baffin Island) and Somerset Island (Figure B-1). Parts of the coastal regions are underlain by Archean granites and the Proterozoic sediments of the Fury and Hecla Strait (located in the Fury and Hecla Strait; Figure B-1). Due to inferred limited petroleum potential, throughout the Gulf of Boothia there is limited seismic data and no petroleum exploration wells have been drilled. However, ~2000 m deep Garnier O-21 well drilled on Somerset Island encountered oil staining and bitumen in Paleozoic carbonates. Onshore mapping and gravity maps (Figure A-2) suggest limited structures (fault blocks) within both Prince Regent Inlet and the Gulf of Boothia. Regional gravity lows in the Prince Regent Inlet and the Gulf of Boothia (Figure A-2) allow the possibility of slightly thicker preserved sediments, and thus a very speculative extension of the fault block and hydrothermal dolomite plays discussed in the Lancaster qualitative resource assessment (Atkinson et al., 2017).

In the Gulf of Boothia, the petroleum potential is estimated to be very low due to: (i) limited thickness of the carbonate platform successions (~2 km); (ii) limited extent of Proterozoic sediments (Fury and Hecla Strait); (iii) absence of identified high-quality source rocks; and (iv) absence of surficial petroleum indicators.

In Prince Regent Inlet, the petroleum potential is estimated to be low due to (i) limited thickness of the carbonate platform successions (~2 km); (ii) unknown extent and thickness of underlying Proterozoic sediments (i.e. inferred offshore extent of Borden Basin (Atkinson et al., 2017); (iii) absence of identified high-quality source rocks; and (iv) absence of surficial petroleum indicators.

Background

Location, tectono-sedimentary setting, and geological history: Prince Regent Inlet and the Gulf of Boothia are one, large, connected north – south oriented body of water. The geographic name change for the waterways is based on separate discovery of the southern and northern extent of the area. Combined, the seaway is over 700 km long, 270 km wide (at the widest point), and averages 275 m deep. It separates Baffin Island from Somerset Island and the Boothia Peninsula (Figure B-1). Baffin and Somerset Islands are predominantly underlain by Paleozoic carbonates similar to the adjacent Brodeur Peninsula (Baffin Island) and Somerset Island (Figure B-1). Further south in the Gulf of Boothia the coastal regions are underlain by Archean granites and the Proterozoic sediments of the Hecla and Fury Basin (located in the Hecla and Fury Strait; Figure B-1). The deepest parts follow channel orientations suggesting that these are erosional remnants of a major Paleogene-Neogene (Tertiary) drainage system, modified by south-north flowing glaciers during the Quaternary (Trettin, 1991). Due to the absence of major modern drainage systems, Holocene deposition is minimal and is likely dominated by bioclastic sedimentation from the water column and sediment input from relatively small seasonal streams.

Petroleum Exploration Activities and Offshore Potential

Due to inferred very low petroleum potential, the Gulf of Boothia has not been evaluated by seismic and/or offshore well drilling. Panarctic Oils Ltd. drilled exploration well Garnier O-21 in 1971 at the northern extent of Prince Regent Inlet on Somerset Island. While it did not encounter commercial accumulations, occurrences of oil stains and bitumen (dead oil) are reported.

The map of sedimentary basins of Canada (Mossop et al., 2004) shows that the entire assessment area is underlain by the Prince Regent basin. The Government of Nunavut estimates that this basin is up to 2 km thick and contains 0.3 billion barrels of oil and 2 trillion cubic feet of gas, which ranks the

Prince Regent basin as one of the least prospective areas identified by the Government of Nunavut (Mossop et al., 2004).

Evidence of porous Paleozoic dolomite and oil staining and bitumen in Garnier O-21 implies the presence of both potential reservoir and petroleum migration through the Paleozoic carbonates.

A regional thermal maturity map (Dewing and Obermajer, 2009) suggests that if present, the Cape Phillips Formation would be in the oil generation window within Prince Regent Inlet. However, due to lack of data, Dewing and Obermajer (2009) did not map regional maturity south into the Gulf of Boothia and the eastern margins of the map have some uncertainty (K.Dewing, pers. comm. 2017). Furthermore, the Cape Phillips Formation has not been identified in outcrops on Somerset Island and its presence in subsurface remains speculative.

Proterozoic sediments of the Fury and Hecla Basin in the southeastern Gulf of Boothia contain age-equivalent clastics and carbonates to mega-sequence 1 of the Borden Basin described in the Lancaster Sound report (Atkinson et al., 2017). A potential source unit in the Agu Formation and reservoir in the Whyte Formation are discussed in Appendix C.

Source Rock

Although the Lower Paleozoic and underlying Proterozoic units may have reached the oil generation window (Dewing and Obermajer, 2009), and the presence of any source rock including Proterozoic and Cape Phillips (Lower Paleozoic) cannot be totally excluded, source rock presence and quality remains speculative.

Reservoir

No reservoir properties have been analyzed, but based on basin analogy, numerous documentation of dolomites on geological maps (Harrison et al., 2011) it is expected that dolomitized reservoirs are common throughout all carbonate successions.

Trap

Negative gravity anomalies in the eastern Gulf of Boothia (Figure A-2) may be related to thicker sedimentary packages possibly due to faulting. No seismic data exist in the Gulf of Boothia to inform this interpretation. Dolomite may also act as a trap, particularly in Prince Regent Inlet, as that area contains more mapped faults that increases the possibility of dolomitizing fluids.

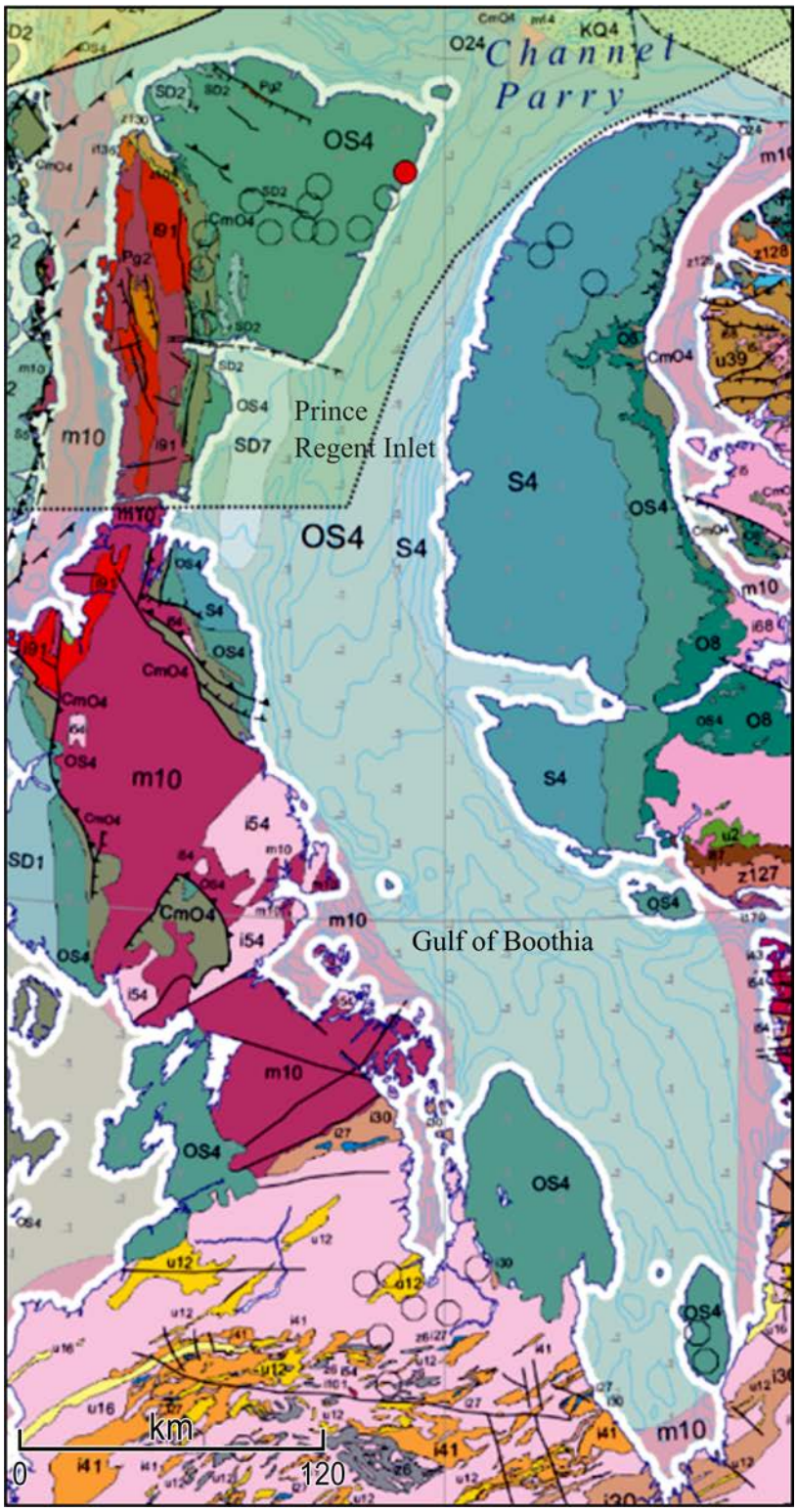
Seal

Seal presence and quality is unknown. Undolomitized carbonates can form seals. Faulting may cause seal failure through fracturing of brittle carbonates.

Figure B-1. A detail from the geological map of the Arctic (Harrison et al., 2011) centred on the Gulf of Boothia and Prince Regent basin. The red dot is the location of the Garnier O-21 well, and the green shaded area shows oil generation window of the Cape Phillips Formation (from Dewing and Obermajer, 2009).

Key mapped offshore units:

- **SD7** Silurian-Devonian (444-359 Ma) marine sedimentary, undivided
- **S4** Silurian (444-416 Ma) carbonates
- **OS4** undifferentiated Ordovician-Silurian (488-415 Ma) carbonates
- **127** Limestone, dolostone, quartz arenite, shale: undivided (Proterozoic)
- **m10** Archean to Paleoproterozoic (4000-1600 Ma) granites, granodiorite, gneiss, migmatite



APPENDIX C – FURY AND HECLA STRAIT AND FOXE BASIN

Summary

The Foxe Basin consists primarily of sediments of the Arctic carbonate platform (Figures 2 and C-1, Ordovician and Silurian carbonates). Parts of the coastal regions are underlain by Archean granites and the Proterozoic sediments of the Fury and Hecla Basin (Figure C-1). Due to inferred limited petroleum potential throughout the Fury and Hecla Strait and Foxe Basin there are no seismic data and only one exploration well has been drilled (Rowley Island N- 14, Figure C-1) by Aquitaine and partners in 1971. The Paleozoic section in Foxe Basin is comprised of middle Cambrian, Ordovician to Lower Silurian carbonates, sandstones and minor shale formations (Trettin, 1975). The Rowley N-14 well shows limited petroleum potential, being thermally immature and low in organic carbon (Zhang et al., 2008). Regional gravity lows in the Gulf of Boothia (Figure A-2) extend into Foxe Basin and allow the possibility for slightly thicker preserved sediments, and thus a very speculative extension of the fault block and hydrothermal dolomite plays discussed in the Lancaster Sound study (Atkinson et al., 2017). The water depths in Foxe Basin range from 100 m in the northern part of the basin to approximately 400 m in Foxe Channel, a narrow East-West oriented structural feature that parallels Southampton Island (Figure C-1). This area is considered to have very low petroleum potential, which potentially could increase, towards the southern Foxe Basin into the Southampton Island sub-basin. The petroleum potential of the Foxe Channel is not assessed in this report.

Background

Location, tectono-sedimentary setting, and geological history: Paleozoic sedimentation within Foxe Basin began in the middle Cambrian (Trettin, 1991) and this succession consists mainly of sandstones and dolostones for the first and second sedimentation cycles (Trettin, 1975). This is followed by another sedimentation cycle of Ordovician age consisting of dolomitic limestones (Trettin, 1975). The last Paleozoic cycle has been correlated to the Lower Silurian Severn Formation which is mostly comprised of limestone (Zhang et al., 2008). The Rowley N-14 encountered the entire Paleozoic section in the well where the total thickness encountered was 512 m and the total depth of the well terminated in Precambrian igneous and metamorphic rocks.

Within the Upper Ordovician and Lower Silurian sediments, offshore wells in Hudson Bay generally have greater sediment thicknesses than their onshore counterparts as compared to onshore Manitoba and Ontario (Zhang, 2010 and Trettin, 1975). Therefore, it could be inferred there is greater thickness within the Foxe Basin as compared to the Rowley N-14 well. However, the Government of Nunavut (Government of Nunavut, 2018b, p. 2, chart entitled "Nunavut petroleum sedimentary basins potential for exploration and discovery") believes the total thickness of Foxe Basin sediments to be 2000 m, which is less than Hudson Bay (3000 m). A greater offshore sediment thickness could allow for thicker deposited shale intervals, which could be a source for hydrocarbon or petroleum generation. When present, faults may act as conduits for oil migration from a theoretical mature source rock into potential reservoir rock but such faulting has not been identified due to the absence of seismic data. Potential field data (Figure A-2) show trends that may be consistent with large basement faults.

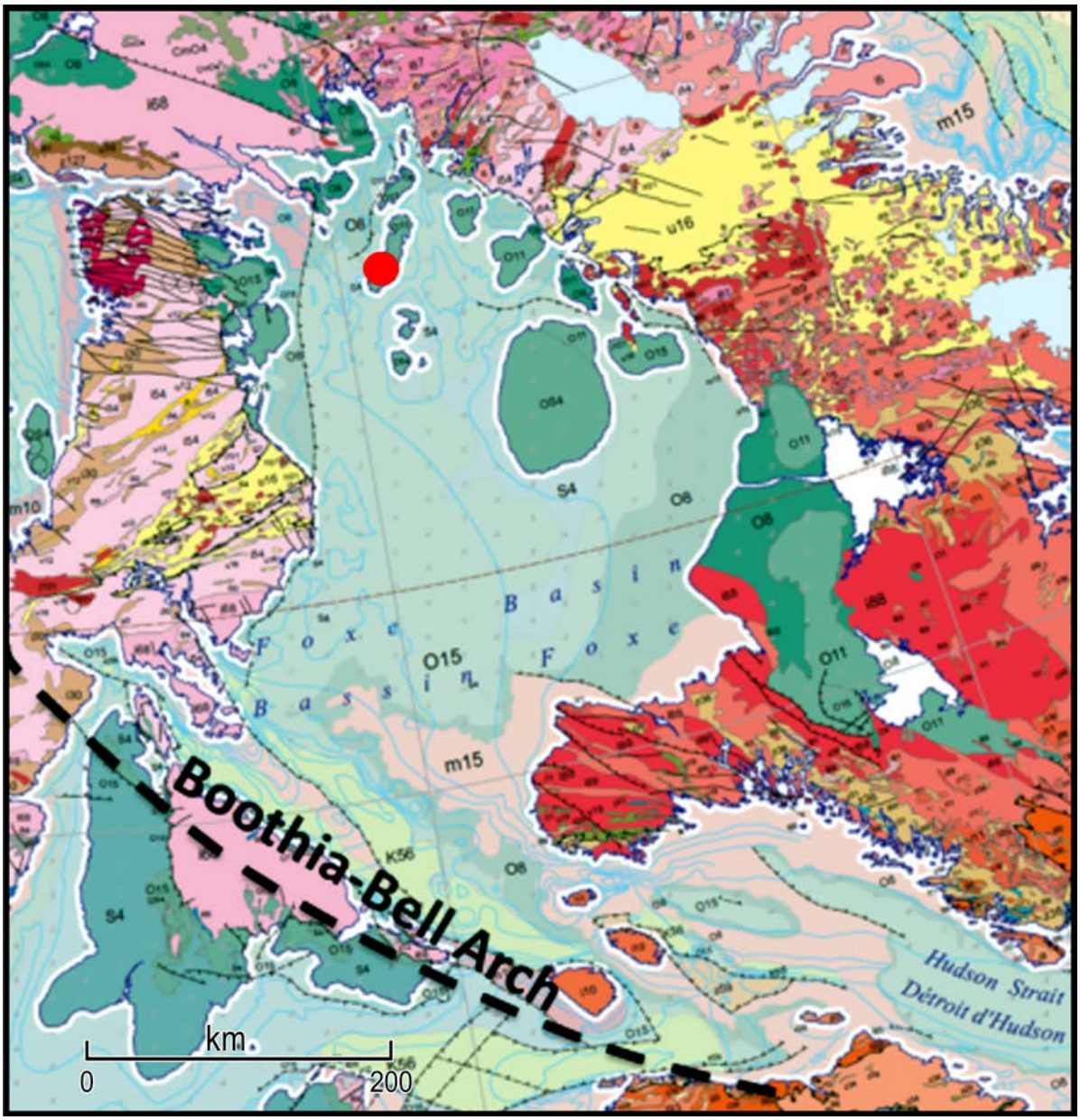


Figure C-1. Geological map of the Arctic (Harrison et al., 2011) centred on the Foxe Basin with Rowley N-14 well marked as the red dot. Boothia-Bell Arch from Lavoie et al., 2015.

Key mapped offshore units:

O8	Early and Middle Ordovician carbonates (488-461 Ma)
O11	Middle Ordovician carbonates (472-461 Ma)
OS4	carbonates, undifferentiated Ordovician-Silurian (488-416 Ma)
S4	Silurian carbonates (444-416 Ma)
O15	Middle and Late Ordovician carbonates (488-461 Ma)
K56	Cretaceous clastics (145.5 – 65.5 Ma)
m15	undivided mylonites, paragneiss, gneiss, granodiorite, migmatite, diatexite, and amphibolite
i170	diorite, gabbro; Hornby Bay and Amundsen Basin
i68	paragneiss, migmatite, diatexite, gneiss, diorite and gabbro
z127	Limestone, dolostone, quartz arenite, shale; Fury and Hecla Strait

Petroleum Exploration Activities and Offshore Potential

Fury and Hecla Strait

The Fury and Hecla Strait separates the Melville Peninsula from Baffin Island and connects Foxe Basin with the Gulf of Boothia (Figure 2). It is a narrow (2 – 20 km wide), 140 km long natural passage underlain by Proterozoic sediments of the Fury and Hecla Basin. This basin contains age-equivalent clastics and carbonates to mega-sequence 1 of Borden Basin (described in Atkinson et al., 2017) and are considered to have very low petroleum potential.

Source Rock

The Agu Bay Formation, a 75 m thick black shale, has been mapped in the Fury and Hecla Basin (Chandler, 1988). The presence of well-preserved microfossils (Butterfield and Chandler, 1992) implies that the shale did not exceed the temperatures in the oil window (>160°C). However, paleo-gas accumulations at erosional highs and under subtle unconformity surfaces are mapped in the Borden Basin (Turner, 2011).

Reservoir

No reservoir properties have been analyzed, but the Whyte Inlet Formation (clastics with sandstones) of the Fury and Hecla Basin can reach over 3 km in thickness and sits on top of the Agu Bay shale (Chandler, 1988). The Whyte Formation makes up over half of the mapped Fury and Hecla Group and is thought to exist under the Fury and Hecla Strait. It is predominantly white to purple fine-grained arenite (Chandler, 1988). Intraformational conglomerates and shales (Chandler, 1988) would reduce reservoir effectiveness where present.

Trap

As the Fury and Hecla Basin is coeval with the Borden Basin trap types may be similar to those discussed in Atkinson et al. (2017) and Turner (2011). For the purpose this report, Proterozoic faulting is thought to be the most likely cause of trap formation.

Seal

The sandstone-rich Whyte Formation dominates the upper stratigraphic succession of the Fury and Hecla Basin (Chandler, 1988), therefore the presence of a regional seal is questionable. The most likely type of seal would be intraformational shales within the Whyte Fm. (Chandler, 1988); however, the age of the sediments and subsequent tectonic history makes seal preservation seal unlikely.

Foxe Basin

Due to inferred very low petroleum potential, the Foxe Basin has not been evaluated by seismic and only one well exists: the Rowley N-14 well, drilled by Aquitaine in 1971. While the well did not encounter commercial accumulations, occurrences of oil stains and bitumen (dead oil) are reported, confirming the presence of a petroleum system.

The Government of Nunavut estimates that the Foxe Basin is up to 2 km thick with no estimated petroleum resources (Government of Nunavut, 2018b, p. 2, chart entitled "Nunavut petroleum sedimentary basins potential for exploration and discovery"). The presence of porous Paleozoic dolomite and oil staining and bitumen in Rowley N-14 may provide evidence for the presence of both potential reservoir and petroleum migration through the Paleozoic carbonates. However, petroleum potential is considered to be very low.

Source Rock

Although the Lower Paleozoic and underlying Proterozoic units may have reached the oil generation window (Dewing and Obermajer, 2009), and the presence of any source rock including Proterozoic and Cape Phillips (Lower Paleozoic) cannot be totally excluded, substantial source rock presence and quality

remains speculative in this study area. Very thin organic rich beds have been recorded in the Rowley N-14 well, and on South Baffin Island, near Amadjuak Island (Macauley et al., 1990).

Reservoir

No reservoir properties have been analyzed, but based on basin analogy, numerous documentation of dolomites on geological maps (Harrison et al., 2011) it is expected that dolomitized carbonates are common reservoirs throughout the succession.

Trap

Negative gravity anomalies in Foxe Basin (Figure A-2) may be related to thicker sedimentary packages possibly due to faulting. No seismic data exists to inform this interpretation. Linear features observed in potential field data may indicate large-scale basement faults which may act as conduits for dolomitizing fluids. Therefore, dolomitized units may act as traps.

Seal

Tight Silurian carbonates seals may fail by faulting thereby fracturing brittle carbonates.

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APPENDIX E – GLOSSARY OF TERMS

(* from or modified from Schlumberger Limited's The Oilfield Glossary, http://www.glossary.oilfield.slb.com)

***Carbonate:** A class of sedimentary rock whose chief mineral constituents (95% or more) are calcite and aragonite (both $CaCo_3$) and dolomite [$CaMg(CO_3)_2$]. Limestone and chalk are carbonate rocks.

Cenozoic: Geological Era approximately 66 million years ago to present.

***Clastic:** Sediment consisting of broken fragments derived from pre-existing rocks and transported elsewhere and redeposited before forming another rock. Examples of common clastic sedimentary rocks include siliciclastic rocks such as conglomerate, sandstone, siltstone and shale. Carbonate rocks can also be broken and reworked to form clastic sedimentary rocks.

***Formation:** A body of rock that is sufficiently distinctive and continuous, and can be mapped.

***Hydrate:** An unusual occurrence of hydrocarbon in which molecules of natural gas, typically methane, are trapped in ice molecules. More generally, hydrates are compounds in which gas molecules are trapped within a crystal structure. Hydrates form in cold climates, such as permafrost zones and in deep water. To date, economic liberation of hydrocarbon gases from hydrates has not occurred, but hydrates contain quantities of hydrocarbons that could be of great economic significance. Hydrates can affect seismic data by creating a reflection or multiple.

***Maturation:** The process of a source rock becoming capable of generating oil or gas when exposed to appropriate pressures and temperatures.

Mesozoic: Geological Era approximately 145 to 252 million years ago.

***Migration:** The movement of hydrocarbons from their source into reservoir rocks.

Paleozoic: Geological Era approximately 252 to 541 million years ago.

***Petroleum System:** Geologic components and processes necessary to generate and store hydrocarbons, including a mature source rock, migration pathway, reservoir rock, trap and seal. Appropriate relative timing of formation of these elements and the processes of generation, migration and accumulation are necessary for hydrocarbons to accumulate and be preserved.

Play: A family of prospects and/or discovered pools that share a common history of hydrocarbon generation, migration, reservoir development, and trap configuration; forms a natural geological population limited to a specific area.

***Pool:** A subsurface oil accumulation. An oil field can consist of one or more oil pools or distinct reservoirs within a single large trap. The term "pool" can create the erroneous impression that oil fields are immense caverns filled with oil, instead of rock filled with small oil-filled pores.

Proterozoic: Geologic eon encompassing ages of 2500 – 541 million years ago. This eon represents the youngest portion of the Precambrian and is sub-divided into three geologic eras: Paleoproterozoic (oldest), Mesoproterozoic and Neoproterozoic (youngest).

***Reservoir:** A subsurface body of rock having sufficient porosity and permeability to store and transmit fluids. Sedimentary rocks are the most common reservoir rocks as they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

***Seal:** A relatively impermeable rock, commonly shale, anhydrite or salt that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system.

***Sequence:** A group of relatively conformable strata that represents a cycle of deposition and is bounded by unconformities or correlative conformities.

***Source rock:** A rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter.

***Trap:** A configuration of rocks suitable for containing hydrocarbons and sealed by a relatively impermeable formation through which hydrocarbons will not migrate. Traps are described as structural traps (in deformed strata such as folds and faults) or stratigraphic traps (in areas where rock types change, such as unconformities, pinch-outs and reefs). A trap is an essential component of a petroleum system.

***Unconventional resource**: An umbrella term for oil and natural gas that is produced by means that do not meet the criteria for conventional production. What has qualified as unconventional at any particular time is a complex function of resource characteristics, the available exploration and production technologies, the economic environment, and the scale, frequency and duration of production from the resource. Perceptions of these factors inevitably change over time and often differ among users of the term. At present, the term is used in reference to oil and gas resources whose porosity, permeability, fluid trapping mechanism, or other characteristics differ from conventional sandstone and carbonate reservoirs. Coalbed methane, gas hydrates, shale gas, fractured reservoirs, and tight gas sands are considered unconventional resources.