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Qualitative assessment of petroleum potential in Lancaster Sound region, Nunavut

E.A. Atkinson, M. Fustic, M.C. Hanna, and C.J. Lister

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Publications in this series have not been edited; they are released as submitted by the author.

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Executive Summary

The Government of Canada, through Parks Canada Agency (PCA) is proposing to establish a National Marine Conservation Area (NMCA) that includes much of Lancaster Sound in Nunavut. Natural Resources Canada (NRCan) has been tasked, under the Marine Conservation Targets[1] (MCT) initiative announced in Budget 2016, with evaluating the petroleum resource potential for areas identified for protection as part of the Government of Canada's commitment to conserve 10% of its marine areas by 2020. As part of this initiative, PCA requested that NRCan conduct a qualitative petroleum resource assessment for an area of Lancaster Sound and surrounding areas within which a NMCA would eventually be defined (Fig. 1).

This report provides the results of the 2017 qualitative assessment conducted by NRCan's Geological Survey of Canada's (GSC) for the Lancaster Sound region (referred to in this report as the NMCA Study Area). The report is an extension of a 2010 Mineral and Energy Resources (MERA) resource assessment done by the GSC to inform an earlier federal boundary proposal for a potential NMCA in Lancaster Sound (OF 6954, Brent et al., 2013 publication). The 2010 assessment covered 44,300 km^2 (Fig. 1) and identified an in-place mean resource potential of 4.5 billion barrels of oil and 13 trillion cubic feet of natural gas within the offshore study polygon. This report covers a total study area of approximately 636 000 km^2 and provides a qualitative assessment of the petroleum resource potential for a marine area of over 384 000 km^2.

The GSC interpretation, visually represented by a qualitative petroleum potential map (Fig. 1) suggests that the highest conventional petroleum potential is located in:

1. **Eastern Lancaster Sound and Baffin Bay (Baffin Fan area).** The high potential portion of the study area is comprised of up to 8 km of Mesozoic-Cenozoic clastic deposits (Fig. 1) and characterized by structural (extensional and compressional) and stratigraphic traps.
2. **Western Lancaster Sound.** This region is comprised of Paleozoic, carbonate dominated deposits, characterized by structural (salt tectonics related) and stratigraphic / diagenetic traps. The nearby Bent Horn Oil Field (Obermajer et al., 2010) hosted by age and depositional equivalent rocks strongly supports identified potential within the NMCA Study Area. However, the Bent Horn field is within the Sverdrup Basin, characterized by different and independent geological history from Lancaster basin.
3. In addition to the above areas of highest probability for significant conventional petroleum resources, the NMCA Area resources include:
    a. **Unconventional petroleum potential** such as gas hydrates, coalbed methane (CBM), and shale oil / shale gas;
    b. **Additional conventional petroleum resource potential** from potential resources located in areas characterized with limited data coverage (Fig. 2) which are currently assigned a moderate to low potential; and
    c. **Mineral resources** such as onshore identified lead, zinc, copper, iron, fluorite, barite, silver, gold, coal, gypsum, and micro-diamonds which are likely to extend offshore to parts of the Lancaster Sound. While development of offshore mine resources is not immediately

[1] The Marine Conservation Targets (MCT) initiative commits Environment and Climate Change Canada (represented by the Parks Canada Agency), Fisheries and Oceans Canada (DFO), and Natural Resources Canada (NRCan) to conserve 10% of Canada's marine and coastal waters within the 200 nautical mile limit by 2020.

foreseeable, potential future and current onshore mines (Fig. 3) are expected to be developed and to continue to operate adjacent to the final NMCA.

The new work done in this 2017 report confirms the spatial trends for petroleum potential identified in GSC Open File Report 6954 (Brent et al, 2013). In addition, the analysis has identified new areas of high petroleum potential at the mouth of Lancaster Sound and into western Baffin Bay (Fig.1).

1. Introduction

The petroleum potential in the NMCA Study Area proposed under the Marine Conservation Targets (MCT) initiative, was evaluated by a team of geoscientists at the GSC from December 2016 to March 2017. Objectives were to: (a) review, analyze, and integrate data from previous resource assessments and industry reports (Appendix 1), existing scientific literature, and available geoscience databases; (b) interpret 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 NMCA Study Area.

The results of the GSC work described in this report for the NMCA Study Area (Fig. 1), are primarily qualitative, as agreed to under the Marine Conservation Targets initiative. A GSC team with decades of cumulative research and industry experience in petroleum resource assessment conducted the analysis.

Based on practical geological considerations (tying to well control, for example), data were compiled and assessed for an area that is larger than that requested by PCA. This approach improves the detail and accuracy of GSC predictions. The larger study area was used in the qualitative assessment to tie to historical well data, indications of hydrocarbon potential (slick-like features, seeps, etc.), seafloor age data, and known onshore formation data extrapolated to the offshore.

GSC's qualitative assessment was based on available offshore two-dimensional seismic profiles (Fig. 2) and their integration with onshore geology, sea surface slick-like features, seafloor petroleum seeps, bathymetric surveys, extrapolation of western Arctic well data and the single shallow Ocean Drilling Program (ODP) well 645E in Baffin Bay.

Three distinct geological mega-sequences exist in the NMCA study area with a total sedimentary thickness of up to 12 km. (Fig. 3). In all three sequences, the presence of multiple source rocks, reservoirs, traps, and seals (Fig. 4), suggest the presence of fifteen potential plays (Table 1) which, over time, are estimated to have generated and pooled a substantial amount of petroleum. Over a billion years of geological time, these sedimentary deposits have undergone episodes of burial, uplift, erosion, re-deposition, and structural deformation that caused not only petroleum generation and accumulation but also alteration, remigration, and leakage of fluids to reach the seabed and sea surface. These natural geological processes have led to an abundance of present day petroleum indicators and numerous petroleum pool shapes, dimensions and distributions.

Natural leakage of hydrocarbons is ubiquitous in sedimentary basins around the world both onshore and offshore. Hydrocarbons move within porous subsurface rock formations, or reservoirs, on a path of least resistance such as reactivated faulting associated with compromised traps. Since hydrocarbons are less dense than water and the pressure within a reservoir is higher than on the surface (seafloor or on land), under normal hydrostatic pressure conditions, hydrocarbons move to the top due to buoyancy and migrate out of the reservoir if a “leakage” zone is available.

2. Data

2.1 Literature:

The geology of Lancaster Sound and surrounding Arctic Islands was the subject of many GSC, National Energy Board of Canada (NEB), and industry reports (Appendix 1), as well as a wide range of earth science scientific publications (Appendix 3). While many of these were reviewed and integrated in this study, GSC Open File (OF) Report 6954 (Brent et al., 2013) and OF Report 3714 (Hannigan et al., 1999) produced quantitative resource assessments and therefore, were of primary importance. These two reports estimated the mean in-place resource potential for (a) offshore structurally trapped 719 $x10^6$ m^3 oil (4.5 Bbbls) and 368$x10^9$ m^3 gas (13 Tcf) within the previous 2010 MERA study polygon in the Lancaster Sound, and (b) onshore potential for 737 $x10^6$ m^3 oil (4.6 Bbbls), 330 $x10^9$ m^3 gas (1.17 Tcf) on Bathurst Island. A detailed list of supporting technical reports and scientific literature is supplied in Appendix 3.

2.2 Geophysical data:

Two-dimensional marine multichannel reflection seismic data in the NMCA Study Area were acquired by oil and gas companies between 1971 and 1979 (Fig. 2). However, not all these data were available for interpretation for this report and the quality of the available data ranged from poor to moderately good. Other geophysical data integrated into the qualitative interpretation for this report include various single-channel sub-bottom acoustic and bathymetric data acquired by the GSC from 1970 through 2008; high resolution bathymetric data acquired by the Université Laval-led ArcticNet research program from 2003-2008; a range of industry seismic mapping from reports submitted to the National Energy Board; velocity data; and various potential field data (gravity and magnetic data).

2.3 Analytical data:

The GSC's Sample Management System (SAMS) contains a wide range of easily searchable analytical data. Project-relevant data, such as source rock evaluation and geochemical composition of oil at seeps, were screened and interpreted in geological context and used to refine interpretations, including the extent of resource play polygons. SAMS was used for the Rock Eval data specifically in the Cretaceous samples on Bylot Island and Borden Basin shales located in Shale Valley (Arctic Bay formation). The SAMS database and Rock Eval data indicated significant potential for hydrocarbon generation from multiple source rocks.

3. Methodology

3.1. Scientific Reviews and Workshops

To ensure the sound integration of the geological data, several workshops were held by regional experts from GSC Calgary and GSC Ottawa. Developments of workflow, methodology, and mapping have been regularly reviewed by internally appointed project advisors. The results of the team's work were presented at an internal technical workshop at GSC Calgary on March 16, 2017 which represented the final stage of qualitative internal technical review.

3.2.Play Mapping

The sequences mapped from two-dimensional seismic data and constrained by outcrop and well data extrapolation resulted in a number of identified plays within those sequences (Table 1, Fig. 3, and Appendix 4 – Glossary of Terms). The maximum extent and sweet spot (high confidence area) for each play was defined by geologic trends, seismic interpretation and analogue data. Each play was assessed for, and weighted by probability of geologic success, and by a subjective estimate of potential size. The sum of all plays' potential was calculated to create the overall petroleum potential map (Fig. 1).

4. Results and interpretation

The presence of active petroleum systems in the NMCA Study Area is supported by (a) petroleum seeps in Scott Inlet (MacLean et al., 1981; Oakey et al., TBD) and Buchan Gulf (Levy et al, 1981); (b) numerous surface slick-like features (Budkewitsch et al., 2013); (c) seabed features indicative of fluid escape including numerous pockmarks and possible carbonate mounds (Fig. 3; Blasco et al., 2010); and (d) Bent Horn – a producing oil field located just outside the western margin of Lancaster Sound.

Since indirectly identified offshore petroleum accumulations have not been tested by drilling, interpretation and characterization was limited to offshore seismic, geologic outcrops, and analogue petroleum systems that have a similar geological history, such as the Beaufort Mackenzie delta and fan (Harrison et al., 2011).

Regional geological studies and subsurface mapping identified fifteen play types (Table 1) grouped within three geological mega-sequences (Appendix 2). Petroleum migration between different plays and mega-sequences is inferred. The petroleum potential map created by 'stacking and risking' identified plays suggests varying potential (Fig. 1), with the eastern (green/dark green) and western (yellow/green) ends of the NMCA Study Area having the greatest petroleum accumulation potential. The GSC study area for the Lancaster Sound region includes additional hydrocarbon potential in the Borden Basin sediments (1000 Ma) along with Cretaceous and younger (145 Ma to present day) stratigraphic hydrocarbon potential. The 2010 MERA (OF 6954, published in 2013) addressed facets of the structurally-trapped Cretaceous (145-66 Ma) to Paleozoic (541 Ma – 252 Ma) potential whereas the 2017 work identified 15 potential play types (Table 1) resulting in a higher potential area outboard of the Lancaster Sound into Baffin Bay (Fig. 1).

Acknowledgments

The GSC Calgary MCT geoscience team sincerely thanks Tom Brent, Peter Hannigan, and Jim Dietrich for support and guidance during duration of the study; Keith Dewing, Lisel Currie, Chris Harrison, Thomas Hadlari, and Andy Mort for shared geological expertise, thematic workshops, critical reviews, and constructive feedbacks; Krista Boyce and Mark Obermajer for help with SAMS database; Lindsay Kung for ArcGIS assistance and Heather King, Yassir Jassim, and Faizan Shahid for their technical support. Many other GSC colleagues and Emeritus scientists are thanked for pointing to relevant literature, maps and data resources as well as for sharing their stories and thoughts about regional geology with us. Their insights contributed to the final presented version. Without their generous help, it would have been impossible to complete this project on time.

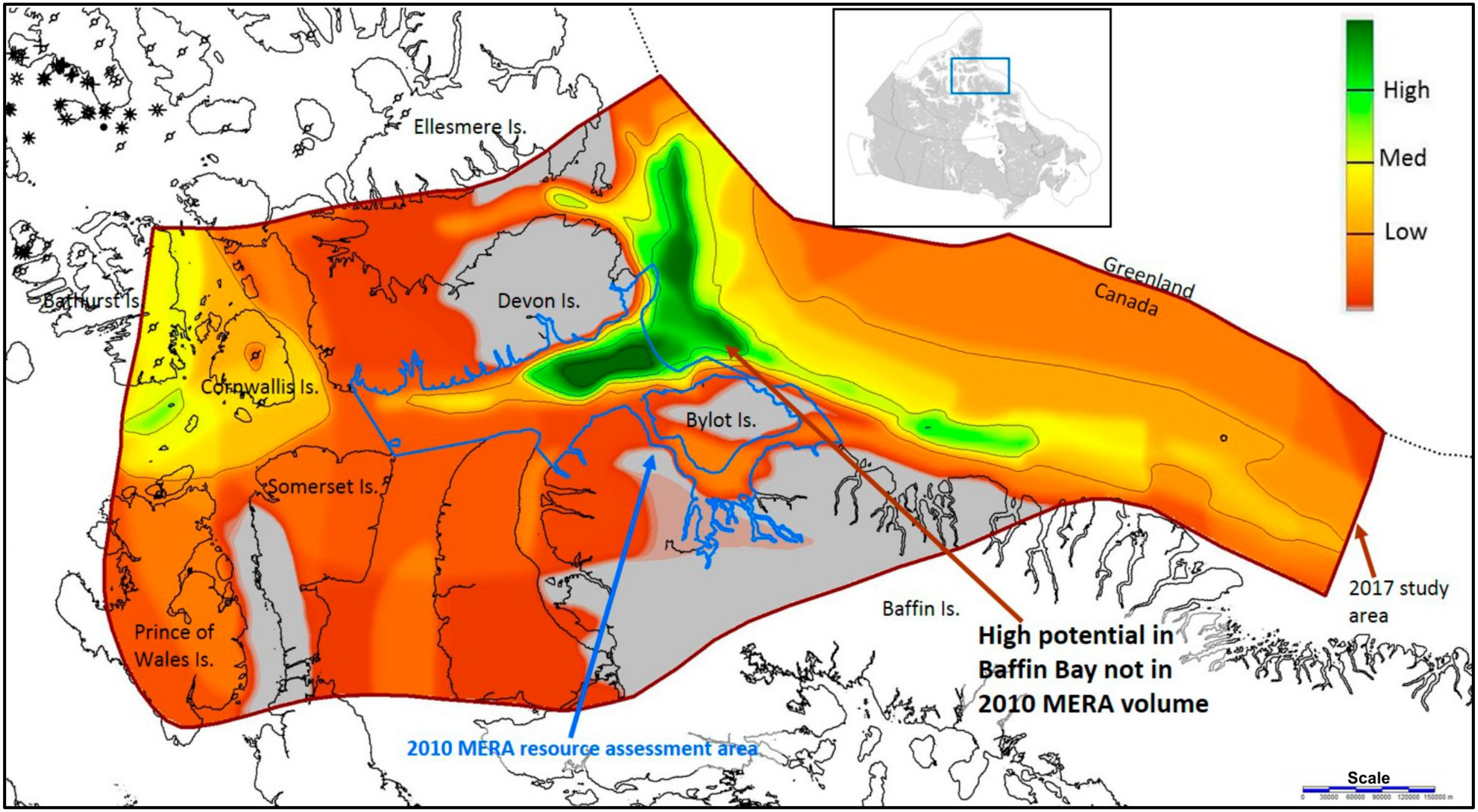

Figure 1. Petroleum Potential Map. Color code - gradation bar ranges from no potential (grey) to the highest potential (dark green). Black symbols are existing wells.

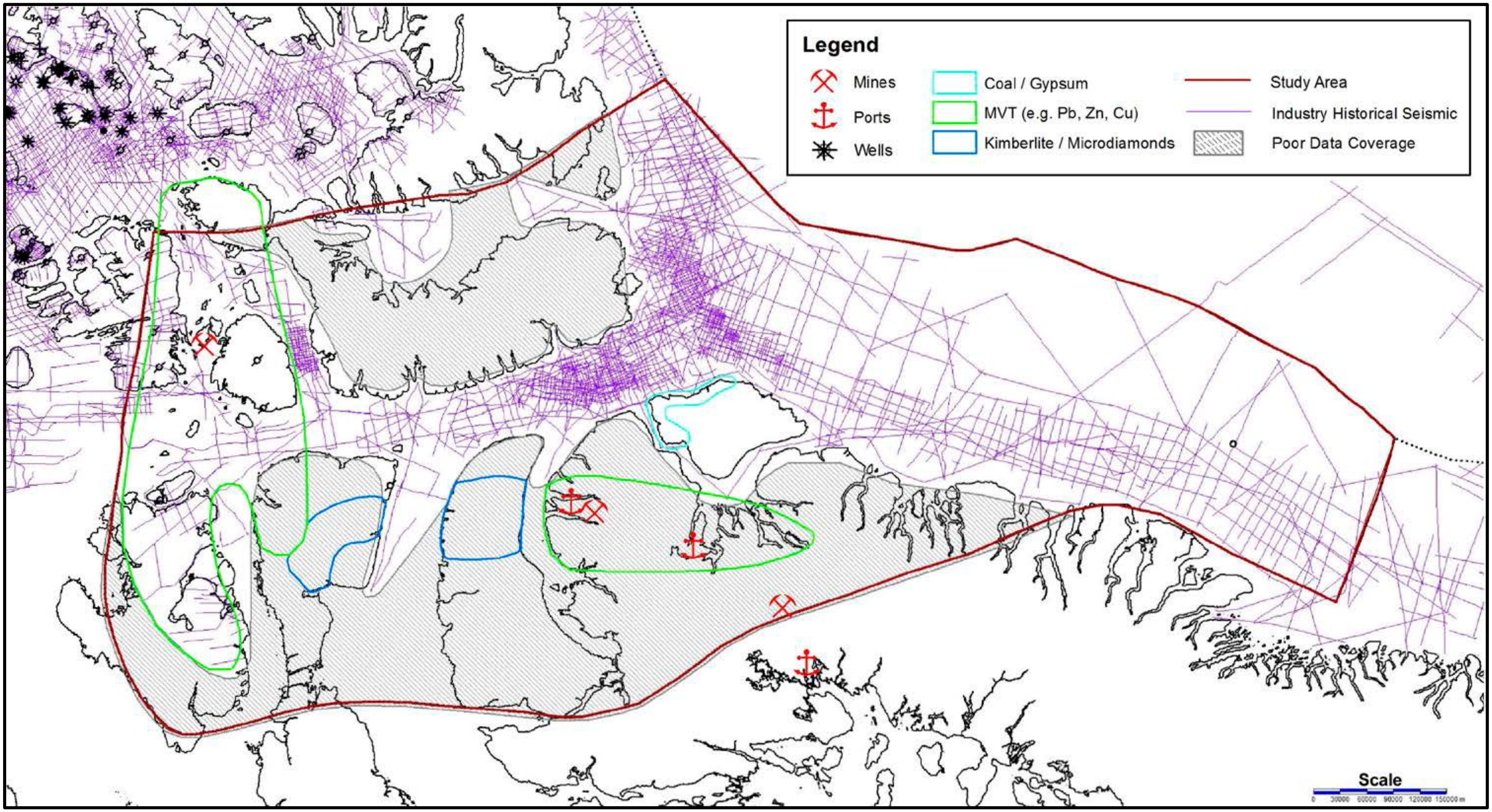

Figure 2. Location of industry two-dimensional multichannel seismic lines and mineral overlays.

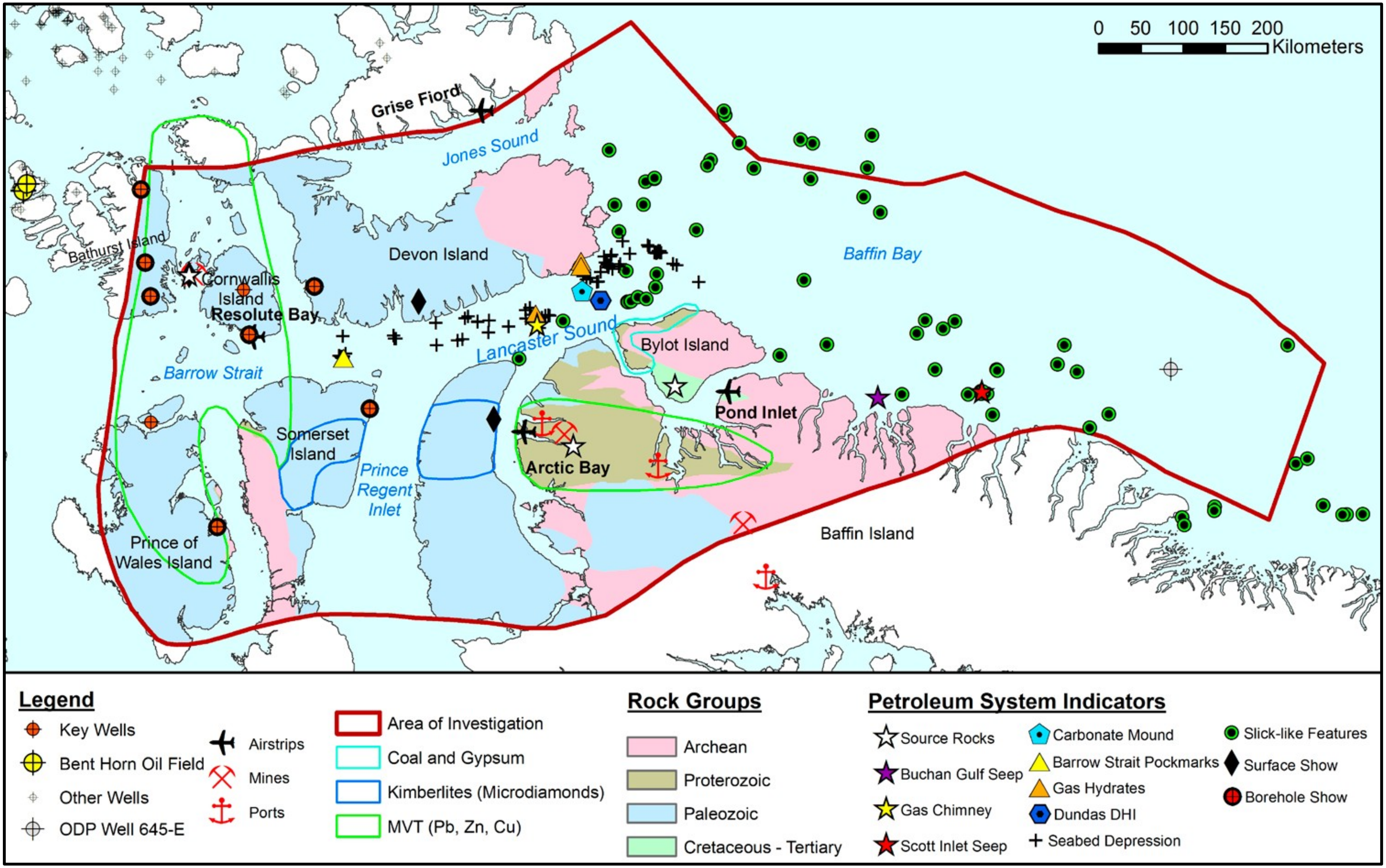

Figure 3. Location map with posted wells, petroleum indicators, geographic landmarks, and stratigraphic subdivision, modified after Brent et al., 2013 – their Figure 9.

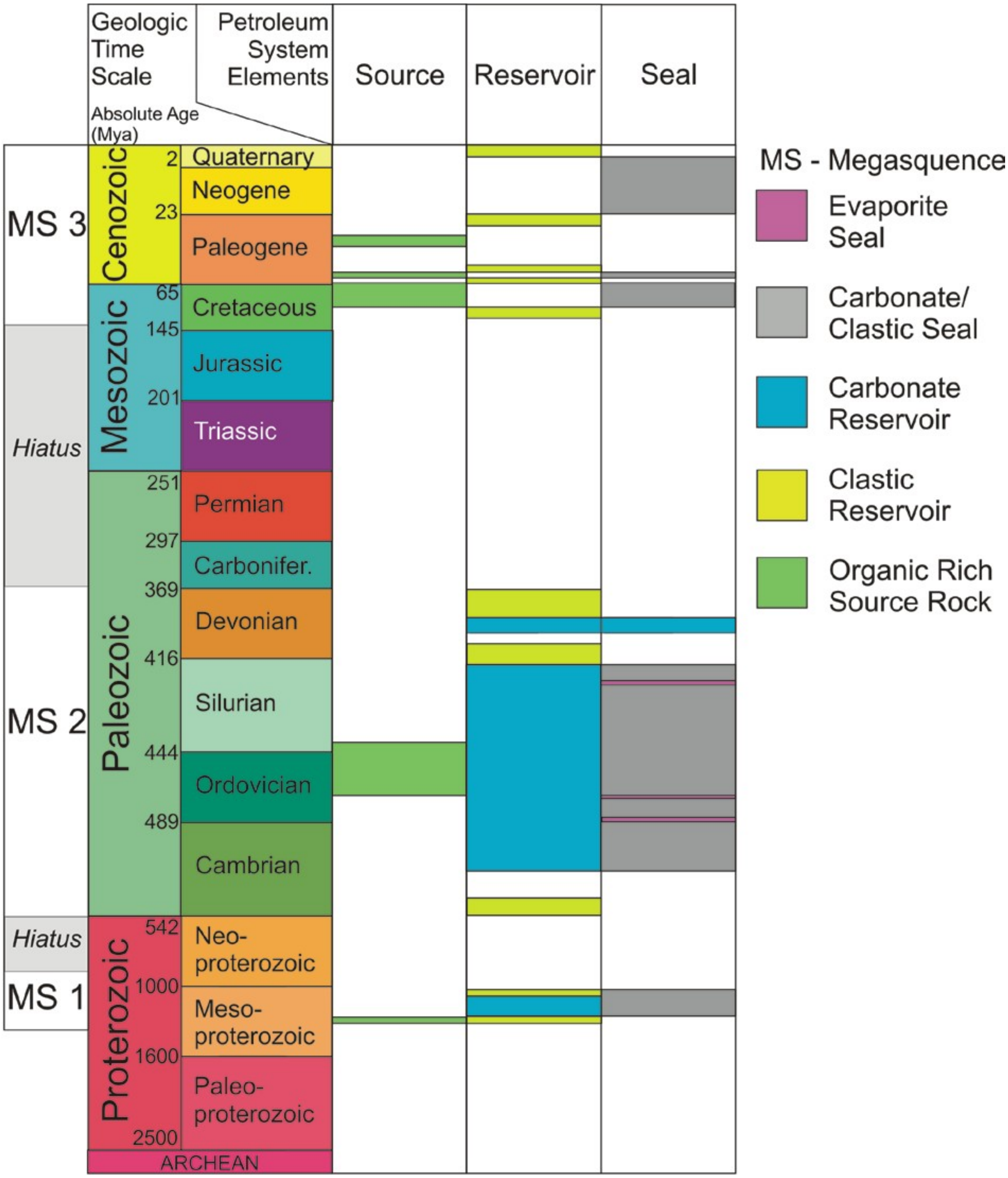

Figure 4. Simplified stratigraphic column showing petroleum system elements and their relation to mega-sequences 1 through 3. Key: Carbonifer. – Carboniferous; Mya – million years ago.

Lancaster Plays Summary

	Age (Ma)	Play	Reservoir	Trap	Source	Seal	Major Risk	Prospect Risk (Scale 0-30)	Risk Weight (0-1)	Size Weight (0-1)	Sweet Spot combined weight (0-1)
		Hypothetical GREAT play						30 *	1	1	1.00
		* Prospect risk of 30% scores full weight of 1, estimated prospect risks for plays are divided by 30 to obtain risk weight						30/30	= 1	x 1	= 1
1	0	Plio-Pliestocene	Clastics	Stratigraphic	Kanguk / post-Cretaceous	Tert. shales	Seal	10	0.333	0.500	0.167
2	3	Mio-Pliocene Channels	Channel Fills	Stratigraphic	Kanguk / post-Cretaceous	Tert. shales	Seal	12	0.400	0.500	0.200
3	5	Miocene	Clastics	Stratigraphic	Kanguk / post-Cretaceous	Tert. shales	Seal	15	0.500	0.600	0.300
4	34	Eocene	Clastics	Stratigraphic, Structural	Kanguk / post-Cretaceous	Tert. shales	Reservoir, Seal	15	0.500	0.700	0.350
5	56	Paleocene	Clastics	Stratigraphic, Structural	Kanguk / post-Cretaceous	Tert. shales	Reservoir, Seal	15	0.500	1.000	0.500
6	92	Mesozoic - in ext/invert fault blocks	Clastics	Stratigraphic, Structural	Kanguk / post-Cretaceous	Meso/Tert. shales	Breach, Reservoir	20	0.667	1.000	0.667
7	365	Devonian clastic wedge	Clastics	Stratigraphic, Subcrop	Cape Phillips	Shales/Tight Sands	Seal	3	0.100	0.500	0.050
8	393	Paleozoic - in ext/invert fault blocks	Carbonates, Clastics	Structural	Cape Phillips, other Paleo, Kanguk	Tight Carbonates, Shales	Breach/ Preservation	20	0.667	1.000	0.667
9	426	Cornwallis Salt Detached Folds	Carbonates, Clastics	Structural	Cape Phillips, other Paleo	Tight Carbonates	Source	20	0.667	0.800	0.533
10	426	Cornwallis Sub-Salt	Carbonates	Normal Faults	Cass Fjord, Eleanor River	Salt	Source	10	0.333	0.700	0.233
11	426	Hydrothermal Dolomite	Carbonates	Stratigraphic (ampltidues)	Cape Phillips, other Paleo	Tight Carbonates	Preservation	15	0.500	0.600	0.300
12	426	Silurian Reef Front	Reefs	Stratigraphic	Cape Phillips, other Paleo	Basinal Facies	Preservation	10	0.333	0.500	0.167
13	999	Proterozoic source, Paleozoic Reservoir	Carbonates	Stratigraphic or Combination	Arctic Bay etc, Borden Basin	Tight Carbonates	Timing of Maturation	4	0.133	0.500	0.067
14	999	Proterozoic structure traps, younger source	Clastics??	Structural	Cape Phillips, other Paleo, Kanguk	Tight Carbonates	Reservoir	3	0.100	0.500	0.050
15	999	Proterozoic source and reservoir	Clastics or Carbonates	Folds, Subcrop	Arctic Bay etc, Borden Basin	Tight Carbonates, Shales	Preservation	2	0.067	0.500	0.033
16		Gas hydrates									
17		unconventionals									

Table 1. Petroleum plays including risk assessment.

Appendix 1 – Industry Activity

1) **Petroleum.** Historical petroleum exploration includes:

   a) *Onshore exploration:* Nine wells were drilled on islands in (or near) Barrow Strait between 1963 and 1975 and although none of these wells encountered economic hydrocarbon occurrences, seven of the nine wells contained at least one indicator of petroleum presence (Fig. 3: bitumen, pyro-bitumen, oil staining, etc.).

   b) *Offshore exploration:* Despite interest for offshore petroleum developments, none of the geologically identified high-impact prospects has ever been tested by drilling. Many factors, including environmental considerations and stakeholder issues, influenced exploration companies' delays to drill. For example, in 2016, Shell relinquished 8,000 km^2 of exploration permits in the Lancaster Sound region.

2) **Mining.** Onshore mine operations in the proximity of the NMCA Study Area include:

   a) *Polaris and Nanisivik* (recently abandoned) mines which have produced more than 33 million tonnes of lead-zinc ore.

   b) *Mary's River iron mine* (located on western Baffin Island) operated by Baffinland Iron Mines Corp. which currently is permitted to produce 18 Million tonnes of ore per year and is permitted to ship 4.2 Million tonnes of ore annually through Milne Inlet for a 21 year period (Baffinland Iron Mines Press Release, 2015). In 2016, Bafflinland proposed an increase from 4.2 Million tonnes annually to 12 Million tonnes, which includes expansion of port facilities (Press Release, 2015).

   c) *Numerous onshore prospects* for kimberlites (micro-diamonds), iron, lead-zinc, and other minerals have been identified, but for various reasons have not yet moved to exploitation phase. Offshore mineral deposits and offshore mine development potential are inferred from geological maps by extrapolating onshore mineral provinces and mineralization trends. However, a quantitative offshore mineral resource assessment is beyond the scope of this project work.

Appendix 2 – Mega-sequence petroleum system analysis

Mega-sequence 1: Proterozoic (1,300 to 950 million years old; Turner, 2009) clastic-dominated sedimentary succession, exposed on Baffin, Bylot, Somerset, and Devon islands (Fig. 3) indicate a significant likelihood that they are present offshore within the NMCA Study Area (Long and Turner, 2012). A review of the literature suggests limited documentation about Proterozoic basins petroleum systems and their potential. Mega-sequence 1 (Fig. 4) was not included in OF 6954 (Brent et al., 2013). However, literature on Proterozoic Borden Basin tectonics (Long and Turner, 2012; Turner et al., 2016), paleo-seeps (Hahn et al., 2015), dissolved metal systematics in black shales (Turner and Kamber, 2012) and carbonate sedimentary systems (Turner, 2009; 2011) suggests that Proterozoic Borden Basin contains all petroleum system elements. Mega-sequence 1 may still be an important contributor to petroleum resources within the NMCA Study Area. Poor resolution of historical offshore seismic data were of a limited usage for mapping Proterozoic internal stratigraphy.

- *Source Rock.* GSC's geochemical database coupled with data from basin evolution of the Arctic Bay Formation (Turner and Kamber, 2012; Turner, 2016) suggests that source rock quality of that unit varies from poor at Alpha River to superb at the Shale Valley locality (Fig. 3) where the residual TOC average of 200m thick exposure is >4%. Terrestrial plant material evolved in the Late Silurian (454-418 Ma), therefore the source rock in these older rocks had to be dominated by oil-prone Type I and/or II. Organic-poor sediments (i.e., Alpha River) are interpreted as shallow strata deposited along the basin margins (Turner pers. comm. 2017). Although early rift sediments are structurally separated at the base, black organic-rich shale at the top of the Arctic Bay Formation is interpreted to be connected basin wide (Jackson and Iannelli, 1981). Source rock is mostly over-mature (SAMS unpublished data; Turner and Kamber, 2012).
- *Reservoir.* Potential reservoirs include porous intervals in strata underlying (a) the Adams Sound Formation sandstones and overlying (b) carbonate dominated Society Cliffs Formation [recently divided into Iqqittuq, Angmaat, Nanisivik, and Ikpiarjuk (dolostone mounds) formations, Turner, 2009] and Victor Bay Formation, and (c) Nunatsiaq Group (Strathcona Sound and Athole Point; Aqigilik; and Sinasuvik formations) sandstones (Turner, 2009; Turner et al., 2016). Although, data documenting reservoir properties are lacking, it is reasonable to infer that Adams Sound Formation, interpreted as fluvial to marine sandstone (Long and Turner, 2012) was characterized by good primary porosity, which was later reduced under burial pressure. Described carbonate reservoirs, and in particular dolostone mounds of the Ikpiarjuk Formation, should have excellent primary porosities, which have been diagenetically cemented (Hahn and Turner, 2017). A range of porosity types are expected within the carbonate succession, particularly in paleo-highs under the unconformity surface separating Nanisivik from Victor Bay Formation (Turner pers. comm. 2017). Sandstones of the Nunatsiaq Group should be good reservoirs.
- *Trap.* Considering the described depositional and tectonic setting, a range of trap types is expected within the NMCA Study Area including stratigraphic pinch-outs, as well as diagenetic and structural traps. Interpreted paleo-gas accumulations at erosional highs and under subtle unconformity surfaces were used as evidence for formation of (Zn-Pb-Ag) ore deposits (Turner, 2011). Destruction and tilting of many Proterozoic traps by subsequent Paleozoic and Mesozoic tectonic events would have caused oil remigration into younger traps or paleo-leakages. Evidence of locally extreme burial (i.e., Tmax of up to 600°C at Shale Valley locality) suggests that entrapped oil under these conditions would have been thermally cracked to fundamental components e.g., coke and methane/hydrogen. In summary, petroleum generated from Proterozoic source rocks may be trapped in a range of Proterozoic and younger strata, but the majority of generated oil is lost by natural leakages and thermal cracking.

- *Seal.* Regional seals would have been formed by tight facies such Victor Bay Formation mudstones and laterally extensive cemented zones could have formed several localized seals within sandstones or carbonates.

Mega-sequence 2: Paleozoic carbonate sediments are mapped in Barrow Strait, Somerset Island, and Bathurst Island regions. The strong reservoir potential of this unit is inferred from the proximity of Bent Horn Oil Field (Fig. 3) which, from analogous rocks from 1985 to 1993, produced a total of 321,469 m^3 (~ 2 million barrels) of light crude (47° API Gravity; Obermajer et al., 2010). Regionally, this mega-sequence (Fig. 4) is mapped from Lancaster Sound to Barrow Strait, and is interpreted to be the most prospective between Bathurst, Devon, and Prince of Wales Islands (Fig. 1 and 3). It is comprised of several stacked interpreted petroleum systems.

- *Source Rock.* The Cape Phillips Formation is a proven Upper Ordovician/Lower Silurian source rock (Dewing and Obermajer, 2009) exposed on Cameron Island (~200 km NW of the western side of the NMCA Study Area). The basal member of the Cape Phillips Fm. is an organic rich carbonaceous shale that was deposited regionally. In addition to regional thermal maturity map (Dewing and Obermajer, 2009), evidence of petroleum generation includes hydrocarbon shows in seven of nine wells drilled near the NMCA Study Area (including oil staining, gas, bitumen, and pyro-bitumen) and the presence of bitumen in outcrop, recorded at the Polaris Mine [Selby et al., 2005 and in outcrop on Devon Island (NEB report 2236)] and the Brodeur Peninsula (NEB report 2260). Although the Cape Phillips Fm. is documented as a regional source rock it is possible that other units may contain source rock intervals.
- *Reservoir.* Regional reservoir units in mega-sequence 2 are primarily Ordovician to Silurian carbonates with Devonian clastics thought to exist locally near eastern Bathurst Island. Carbonate reservoir distribution is highly variable and affected by numerous lithologic and diagenetic influences. The two major reservoir facies identified are Paleozoic reef fronts and hydrothermal dolomite. Silurian reef fronts have been mapped west from Devon Island continuing through Cornwallis, and Bathurst Islands (de Freitas et al., 1999). Hydrothermal dolomite occurs when hot fluids intrude a carbonate facies and alter pre-existing minerals. This type of reservoir is a prolific hydrocarbon producer in North America (Davies and Smith, 2006) and has been recorded at Polaris Mine (Reid et al., 2013) and has been seismically imaged in the subsurface of Prince of Wales Island (Mayr et al., 2004). Devonian clastic sediments are preserved along the eastern and southern shore of Bathurst Island (Embry, 1991; Harrison et al., 1998).
- *Trap.* There are a variety of trap types within the Paleozoic carbonate plays. The most prospective trap types are salt detached folds and subsalt structures. Regional evaporites are mapped onshore and in seismic profile near Bathurst Island. The structures created in the Cornwallis Fold Belt have been imaged by Harrison (in press) and are excellent hydrocarbon prospects. Exploration wells were drilled in the area but none of these wells penetrated units between or below salt horizons. Hydrothermal dolomite (considered a reservoir and stratigraphic trap) has been mapped across the western area of the NMCA Study Area. Paleozoic carbonates have been mapped on structural highs in NMCA Study Area Sound; since this places them above younger, Cretaceous source rock it is possible that there are Paleozoic carbonates sourced by Cretaceous shales.
- *Seal.* Seal is the highest risk element in mega-sequence 2, and seals in the NMCA Study Area are varied. The evaporites offer the greatest chance for hydrocarbon preservation as they are ductile and may have survived multiple deformation episodes. Hydrothermal dolomites could have been sealed by overlying carbonates; however carbonates are brittle and may have fractured during post hydrocarbon generation deformation.

Note – Paleozoic carbonates in the Canadian Arctic are proven hydrocarbon systems (Bent Horn Field). In the NMCA Study Area there is strong supporting evidence of all major components for a working petroleum system. Source rocks of Ordovician/Silurian age are thought to be regionally extensive with oil staining, bitumen/pyro-bitumen, and gas tests in exploration wells indicating the generation of hydrocarbon. Prospective trap and seal combinations in the western area of the NMCA Study Area, near Bathurst and Prince of Wales Islands, have not been tested by exploration wells.

Mega-sequence 3: Mesozoic and Cenozoic clastic sediments associated with early rifting and the development of the Baffin Bay Fan. This is the youngest and most prospective area within the NMCA Study Area, located along the western margin of Baffin Bay (Fig. 1 and 3). It is comprised of several stacked interpreted petroleum systems (Fig. 4).

- *Source Rock.* Potential source rocks include: (a) Upper Cretaceous Kanguk Formation, which is regionally extensive, and generates petroleum in the Sverdrup Basin (Hülse et al., 2015). Kanguk outcrops on Bylot Island (Haggart et al., 2010) contain high total organic carbon (TOC) which supports its petroleum potential within the NMCA Study Area; (b) additional Cretaceous and post-Cretaceous source rocks likely include age and setting analogues to source rocks documented onshore western Greenland (Bojesen-Koefoed et al., 1999).
- *Reservoir.* Clastic reservoir units comprised of sediment derived from westerly sourced continental scale drainage and local island highlands were deposited from the Cretaceous until the Pleistocene. During the Cretaceous and Early Cenozoic, sediments were deposited in ancient river valleys (including the current Lancaster Sound) and deltas draining into the early rifting Baffin Bay. As relative sea level rose, the Baffin Bay Fan was deposited in deepwater setting. Cretaceous reservoir units exposed on Bylot Island show superb reservoir properties such as porosity and permeability (Miall et al., 1980) and similar reservoir characteristics are inferred to exist offshore. Good reservoir quality of deepwater deposits is inferred from analogue studies including age equivalent Beaufort Mackenzie fan deposits (Harrison et al., 2011). Seismic interpretation in Lancaster Sound and Baffin Bay shows a complex of inter-fingering and stacked paleo channels and delta-fan architectural elements, suggesting good reservoir properties and connectivity. Additional reservoirs are possible in underlying Paleozoic carbonates (analogues to Mega-Sequence 2).
- *Trap.* Numerous types of petroleum traps are identified on seismic or inferred including: (a) extensional traps; (b) structural traps against uplifted Paleozoic and Proterozoic basement highs; (c) stratigraphic pinch-outs; (d) porous Paleozoic carbonate highs covered by shale; and (e) compressional inversion anticline traps (e.g., Dundas and Hope structures).
- *Seal.* Multiple, thick, laterally extensive Cretaceous and Cenozoic shale deposits are interpreted as potential seals. Potential sealing rock units have been identified on Bylot Island (e.g., Cretaceous Navy Board rock formation), in ODP 645E well, and correlated with offshore seismic (Harrison et al., 2011). The inferred presence of seal rocks comes from interpreted depositional setting and analogues (i.e., Beaufort Mackenzie and Gulf of Mexico). Shales would seal age equivalent sandstone reservoirs (syn-depositional) and Paleozoic carbonates when deposited directly on top of the potential reservoir intervals.

Appendix 3 – Reviewed Documents

BOLD: Key Reference Documents

Anglin, C.D. and Harrison, J.C. (ed.), 1999. Mineral and Energy Resource Assessment of Bathurst Island Area, Nunavut: Parts of NTS 68G, 68H, 69B and 79A; Geological Survey of Canada, Open File 3714, 242 p. (10 sheets) https://doi.org/10.4095/210386

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Appendix 4 – Glossary of Terms

(* from or modified from 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.

***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 66 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.

***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.