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GEM 2 Hudson-Ungava Project

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2016

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FORWARD

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

During the summer 2016, GEM program has successfully carried out 17 research activities that include geological, geochemical and geophysical surveying. These activities have been undertaken in collaboration with provincial and territorial governments, northerners and their institutions, academia and the private sector. GEM will continue to work with these key collaborators as the program advances.

PROJECT SUMMARY

The Arctic is the last area with significant conventional hydrocarbon potential to be explored. A report by the United States Geological Survey indicates reserves of over 90 billion barrels of oil, 44 billion barrels of natural gas liquids and 1670 trillion cubic feet of natural gas (Bird et al., 2008), with a significant portion of these reserves located in the Canadian Arctic.

The Hudson Bay Basin is one of these under explored sedimentary basins in the Canadian Arctic. The basin is the largest intracratonic basin in North America and if other similar basins in North America (Michigan, Illinois, Williston basins) are world-class hydrocarbon producers, only nine exploration wells have been drilled in the Hudson Bay Basin (4 onshore and 5 offshore) between 1960s to early 1980s, with no commercial discovery. As part of the initial phase of the Geoscience for Energy and Minerals (GEM) program, a re-evaluation of historical exploration data and strategic acquisition of new hydrocarbon system data led to the conclusion that most of the key elements for a petroleum system are present in the Hudson Bay Basin, suggesting that its hydrocarbon potential has been under evaluated (Lavoie et al., 2013, 2015).

The Hudson Bay – Ungava project of the second phase of the GEM program aims to provide new information and models for the evolution of the Hudson Bay Basin which will serve as the cornerstone for a modern appraisal of the hydrocarbon prospectivity of the largest sedimentary basin in Canada (Fig. 1).

This report presents a summary of all laboratory works carried out in the 3 activities currently in progress for the energy component of the GEM-2 Hudson-Ungava project; stratigraphy, source and reservoir rocks and RADARSAT-2.

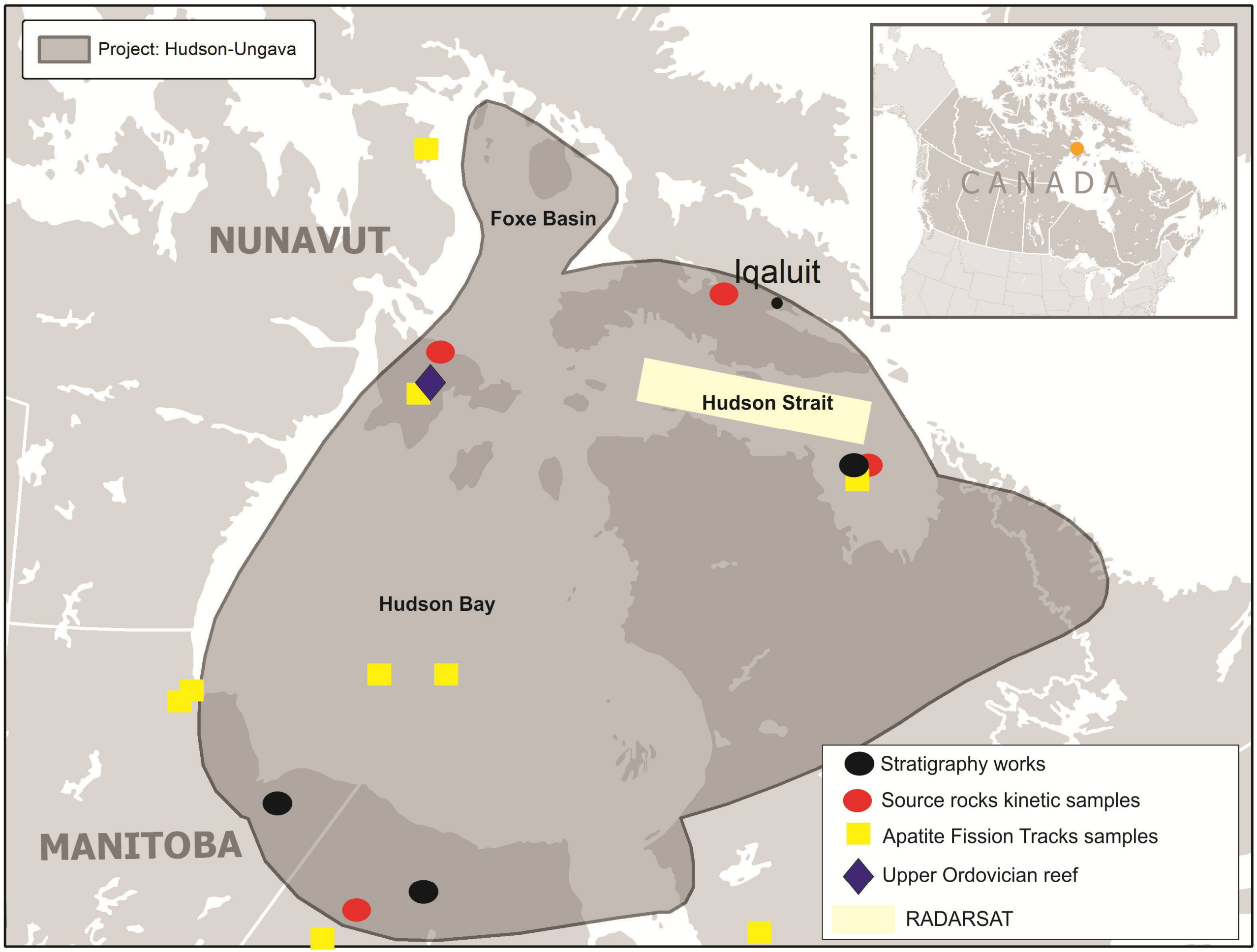

Figure 1. Localisation map of the Hudson Bay, Hudson Strait and Foxe Basin, together with areas of field data acquisition and/or studied samples for specific research activities discussed in the report.

INTRODUCTION TO HUDSON-UNGAVA 2016 ACTIVITIES

Integrated regional stratigraphy of petroleum basins of the Hudson-Ungava Project

Building an integrated regional stratigraphic framework is the natural continuation of the work completed as part of the first phase of GEM where specific local sedimentary successions were documented (Lavoie et al., 2013). The fine-scale correlations of these successions (Ontario, Manitoba, Nunavut, offshore Hudson Bay, onshore Foxe Basin, offshore Hudson Strait) is only possible through the use of a multidisciplinary approach that will combine detailed biostratigraphy, chemostratigraphy, sedimentology, petrophysics and geophysics.

This activity addresses two fundamental scientific questions:

1. How have geodynamic factors, such as faulting and/or variable burial and exhumation influenced the architecture and petroleum prospectivity of the Hudson Bay Basin?

2. Can sub-basins with distinct hydrocarbon prospectivity be identified in the Hudson Bay Basin?

In this 2016 report, biostratigraphic work on samples from Akpatok Island (Ungava Bay) and from Ontario will be discussed as well as chemostratigraphy and preliminary tectono-stratigraphy work from Manitoba Geological Survey in preparation for next year magnetotelluric survey in the Kaskattama Highlands area in Manitoba (Figure 2).

Understanding of hydrocarbon systems – source and reservoir rocks

The regional understanding of hydrocarbon systems (source and reservoir rocks, thermal maturation, hydrocarbon generation and expulsion, traps and seals) was initially addressed as part of the first phase of GEM with preliminary positive conclusions on the presence of all the above elements and events (Lavoie et al., 2013, 2015). A better knowledge of hydrocarbon systems for the entire Hudson Bay and Strait area is a critical element of the second phase of the GEM program. This will be accomplished through detailed field work combined with laboratory analyses (organic and inorganic geochemistry, thermal indicators, marine geophysical works and remote sensing).

Like the integrated stratigraphy activity, this activity addresses the same fundamental scientific questions:

1. How have geodynamic factors, such as faulting and/or variable burial and exhumation influenced the architecture and petroleum prospectivity of the Hudson Bay Basin?

2. Can sub-basins with distinct hydrocarbon prospectivity be identified in the Hudson Bay Basin?

In this 2016 report, laboratory works will be discussed and include, i) detailed source rock kinetic parameters based on modified hydrous pyrolysis, ii) thermal modeling based on apatite fission track data, iii) facies architecture and diagenetic evolution of potential hydrocarbon reservoirs and iv) limited new Rock Eval data from northern Ontario (Figure 1).

RADARSAT-2 image acquisition, interpretation, and methods development for identification of potential oil slicks

This activity involves a multi-year acquisition plan and interpretation of RADARSAT images over Hudson Bay/ Strait and Foxe Channel in order to record repeated occurrences of potential oil slicks in the same zones. The GEM-1 supported activity provided critical initial results and established a collection of historic data that is ultimately required as a basis for any further investigation or monitoring in the region (Decker et al., 2013). This GEM-2 activity will build upon these results by strengthening the baseline data to support further targeted investigations and will aid in improving knowledge of the subsurface geology and hydrocarbon potential in the Hudson Bay / Strait and Foxe Channel. Additional observations of spatially and temporally coincident dark features using satellite imagery raises the probability that natural seep occurrences exist and will provide valuable unconventional geoscience information about hydrocarbon resources.

This activity addresses the following fundamental scientific question:

1. Can sub-basins with distinct hydrocarbon prospectivity be identified in the Hudson Bay Basin?

In this report, images acquisition program for 2016 in the Hudson Strait and their preliminary interpretations will be discussed as well as the status of development of automatic system to identify potential oil slicks anomalies on RADARSAT images.

METHODOLOGY

Biostratigraphy for Akpatok and Ontario samples

In order to evaluate the ages of the carbonate successions, 92 carbonate samples from Akpatok Island were studied for conodonts as well as 28 other from northern Ontario. Moreover, 4 samples for pollens from Silurian hosting crevice in-fill of poorly consolidated sand and mud from northern Ontario were studied for pollens to provide information on the age of diamond-bearing kimberlites emplacement.

Chemostratigraphy for Manitoba carbonate samples

The stratigraphy based on carbon isotope values ($\delta^{13}C$) or chemostratigraphy of carbonates, is a very useful tool for complementing the conventional biostratigraphy, especially for intervals devoid of macro- and micro-fossils. Isotopic results from 286 carbonate samples (calcite and dolomite) from 3 wells in Manitoba are reported.

Source rock kinetic study

Upper Ordovician limy shales to shaly limestones of the Boas River, Red Head Rapids, Amadjuak and Akpatok formations have been documented to be very rich hydrocarbon source rocks (Lavoie et al., 2013), but marginally mature to immature in outcrops at the margin of the Hudson Bay Basin. The objective of the study is to artificially bring these 4 rock units to higher maturation levels to evaluate their kinetic of hydrocarbon generation and the nature and volume of hydrocarbons potentially produced as it would be expected in the more deeply buried parts of the basin.

Apatite fission track study

The analyses and inverse modeling of apatite fission track allows better constraining the burial and exhumation history of sedimentary basins as well as providing critical information about the maximum burial temperature reach by the succession.

Upper Ordovician reef study

The study area is located 34 km SW of Coral Harbour on Southampton Island where a large massive reef mound of the Red Head Rapids Formation is exposed. The mound core facies is well visible, but flanking and inter-reef facies were eroded. 87 hand samples were collected in 0.5 m vertical increment at six representative sections located around the exhumed core. Samples were thin sectioned, polished, and stained with Alizarin red S and potassium ferricyanide (Dickson, 1965). The petrographic observations focused on the identification of the biotic and abiotic primary components of the mound core. Biotic and abiotic primary components were also sampled for δ13C and δ18O isotopic analysis. Nine fresh, polished slabs were microdrilled to generate powder. Analyses were performed with a Gas Bench II interfaced with a Finnigan Mat Delta XL mass spectrometer at the G.G. Hatch Laboratory, University of Ottawa. Data are reported as δ13C and δ18O in permil (‰) with respect to the Vienna Pee Dee Belemnite, or VPDB standard. The analytical precision is +/−0.1 ‰. This study forms part of a M.Sc. thesis at Ottawa University (Castagner, in prep.).

Rock-Eval analyses

Rock-Eval (RE) analysis is a well-accepted and cost-efficient geochemical analysis used for oil and gas exploration (Tissot and Welte, 1984). RE analysis was used in this study to evaluate the organic richness and thermal maturity of selected samples from northern Ontario. The key RE parameters measured are S1 peak (free volatile hydrocarbons in mg HC/g rock), S2 peak (residual petroleum generation potential in mg HC/g rock), S3 peak (CO2 from organic source, in mg/g rock), TOC (total organic carbon in %), PC [total pyrolyzable carbon (S1+S2+S3)], HI [hydrogen index, calculated, (S2 * 100/TOC) in mg HC/g TOC], OI [oxygen index calculated (S3 * 100/TOC) in mg S3/g TOC], Tmax (maximum temperature at S2 peak, in ^{o}C) and PI [production index (S1/S1 + S2)]. These measured and calculated RE parameters are the most extensively used geochemical data in petroleum exploration (Tissot and Welte, 1984).

RADARSAT-2 activity

An image acquisition plan for 2016 has been planned during ice free conditions. Preliminary visual interpretation of 87 RADARSAT-2 images for potential oil slicks detection over Hudson Strait was carried out. The activity also includes the development of algorithms and flow chart procedure for automatic images interpretation was actively progressing.

RESULTS

Biostratigraphy of Akpatok Island

A total of 92 carbonate samples were collected at 16 localities on Akpatok Island during the 2014 (13 samples) and 2015 (79 samples) field seasons. Samples cover the vertical interval between the lowest sea level and the highest point (280 m) on the island and thus the different stratigraphic levels considering the almost horizontal distribution of Upper Ordovician carbonate rocks; samples have been processed for conodont microfossils at both GSC Vancouver and Calgary microfossil labs. Of the 92 samples, 66 are productive of conodonts, from which over 22,000 well-preserved conodont elements have been recovered. Among these elements, 37 Late Ordovician conodont species have been identified.

Based on the recognised conodonts and the field observations, the preliminary results are:

The 280 m thick carbonate rocks exposed on Akpatok Island can be compared to the Upper Ordovician Bad Cache Rapids and Churchill River groups and Red Head Rapids Formation on Southampton Island, or to the Upper Ordovician Amadjuak, Akpatok and Foster Bay formations on Melville Peninsula, rather than just the Akpatok Formation as previously proposed by Sanford and Grant (2000).

The brown argillaceous and bituminous limestone rubble collected in creek contains conodont *Amorphognathus ordovicicus* Branson and Mehl; therefore, the brown argillaceous and bituminous limestone on Akpatok Island is biostratigraphically within the total range of *A. ordovicicus* that spans the entire Churchill River Group and lower part of the Red Head Rapids Formation on Southampton Island (Zhang 2011). From a lithostratigraphic point of view, this limestone is probably either in the upper Churchill River Group (= upper part of the Akpatok Formation), or lower part of the Red Head Rapids Formation (= lower part of the Foster Bay Formation), rather than being between the Amadjuak and Akpatok formations (Sanford and Grant, 2000) or in the lower Amadjuak Formation (Zhang and Mate, 2015).

All the recovered conodont elements have amber color, giving a Color Alteration Index (CAI) of 1, indicating that the brown argillaceous and bituminous limestone is immature for petroleum generation.

Biostratigraphy of northern Ontario

In the fall of 2015, 11 core and outcrop samples were submitted to the GSC's Paleontology Laboratory in Calgary for conodont analysis. Table 1 lists the station/well location, sample location and stratigraphic information for these samples. Further information and location map is presented in Armstrong (2015).

Three core samples are from a mineral exploration hole (Z11-1D1) drilled in 2011 by Zenyatta Ventures Ltd. in the western part of the Moose River Basin, south of the Albany River. These are interpreted to represent the lower Silurian Ekwan and possibly Severn River formations. Four outcrop samples from the Ekwan, Attawapiskat and Shashiskau rivers in the Moose River Basin represent the lower Silurian Ekwan and Severn River formations. The Shashiskau River is located in the southeastern part of the basin. Analysis of these Silurian samples is in progress.

Three core samples of Lower Devonian age were submitted from a stratigraphic test hole, Schlievert Lake OGS-93-8D, drilled in 1983 by the Ontario Geological Survey in the southern Moose River Basin. Samples were submitted from the Kwataboahegan, Stooping River and (?) Sextant formations. Results of conodont analysis for these Devonian samples reported by Gouwy (2016) confirm a late Emsian age for the lower Kwataboahegan and Stooping River formations (as per McGregor and Camfield (1976) and Uyeno and Bultynyk (1993)). The oldest/lowest sample, a sandy bio-grainstone thought to represent a basinward equivalent of the Sextant Formation, yielded conodonts of indeterminate age (Gouwy 2016).

Samples submitted for conodont analysis in 2014 are included in this report (Table 2) because results for Devonian samples were reported by Gouwy. (2016) Her analyses of outcrop samples in the Moose River Basin confirm a middle Eifelian to middle Givetian age for the Murray Island Formation at its type locality on the Moose River and a late Emsian age for the Stooping River Formation at its type locality near Fort Albany. Samples of the upper Kenogami River, Kwataboahegan, Williams Island and Moose River formations were either barren or contained conodont species of indeterminate age. Conodont analysis of Ordovician and Silurian age core and outcrop samples submitted in 2014 is in progress.

No.	Sample Name	Location Type	Location Remark	Datum	Easting	Northing	NTS sheet	Lithostratigraphic Name	Age estimate	Chrono-stratigraphy	Biostratigraphy	Paleo Report #
1	15DKA001L-07	Borehole	core drilled by Zenyatta Ventures Ltd in 2011	NAD83	637605	5672546	42N03	Ekwan River Formation?	early Silurian	*in progress*	*in progress*	*in progress*
2	15DKA001N-10	Borehole	core drilled by Zenyatta Ventures Ltd in 2011	NAD83	637605	5672546	42N03	Severn River Formation	early Silurian	*in progress*	*in progress*	*in progress*
3	15DKA001X-06	Borehole	core drilled by Zenyatta Ventures Ltd in 2011	NAD83	637605	5672546	42N03	Severn River Formation	early Silurian	*in progress*	*in progress*	*in progress*
4	15DKA008Z-04	Borehole	core drilled by Ontario Geological Survey in 1983	NAD83	360330	5602340	42J	Kwataboahegan Fm	middle Devonian	Early Devonian, Late Emsian	*serotinus*	4-SAG-2016
5	15DKA008AB-04	Borehole	core drilled by Ontario Geological Survey in 1983	NAD83	360330	5602340	42J	Stooping River Fm	lower Devonian	Early Devonian, Late Emsian	*serotinus*	4-SAG-2016
6	15DKA008AE-01	Borehole	core drilled by Ontario Geological Survey in 1983	NAD83	360330	5602340	42J	Stooping River Fm	lower Devonian	Early Devonian, Late Emsian	*serotinus*	4-SAG-2016
7	15DKA008AJ-06	Borehole	core drilled by Ontario Geological Survey in 1983	NAD83	360330	5602340	42J	upper Kenogami River Fm OR Sextant Fm	lower Devonian	indeterminate age	indeterminate age	4-SAG-2016
8	15DKA051A-15	Outcrop	north bank of river	NAD83	311359	5932635	43G	Severn River Formation	Lower Silurian	*in progress*	*in progress*	*in progress*
9	15DKA054A-05	Outcrop	south bank of river	NAD83	318627	5931792	43G	Ekwan River Formation	Lower Silurian	*in progress*	*in progress*	*in progress*
10	15DKA066B-06	Outcrop	southwest bank of river	NAD83	287528	5871448	43C	Ekwan River Formation	Lower Silurian	*in progress*	*in progress*	*in progress*
11	15DKA026A-08	Outcrop	west bank of river	NAD83	571863	5631791	32L	Severn River Formation	Lower Silurian	*in progress*	*in progress*	*in progress*

Table 1. Preliminary conodont biostratigraphy of 2015 northern Ontario samples

No	Sample Name	Location Type	Location Remark	Datum	Easting	Northing	NTS sheet	Lithostratigraphic Name	Age estimate	Chrono-stratigraphy	Biostratigraphy	Paleo Report #
1	14DKA002-A4	Outcrop	low outcrop, west bank	NAD83	681106	5673778	42N01	Kenogami River Formation	early Devonian?	barren	barren	4-SAG-2016
2	14DKA003-C5	Outcrop	outcrop, south bank	NAD83	295591	5687383	42O05	Stooping River Formation	early Devonian	Early Devonian, Late Emsian	*serotinus*	4-SAG-2016
3	14DKA005-D6	Outcrop	outcrop, northwest bank	NAD83	324358	5669802	42O04	Kwataboahegan Formation	middle Devonian	barren	barren	4-SAG-2016
4	14DKA007-B5	Outcrop	large outcrop, northeast bank	NAD83	640040	5684135	42N07	Kenogami River Formation	late Silurian?	*in progress*	barren	ADM 2014 prelim
5	14DKA008-B3	Outcrop	large outcrop, east side of river	NAD83	713325	5545843	42K01	Ekwan River Formation?	early Silurian	*in progress*	Oz, platform, abund Pan	ADM 2014 prelim
6	14DKA008-C2	Outcrop	large outcrop, east side of river	NAD83	713325	5545843	42K01	Ekwan River Formation?	early Silurian	*in progress*	abund	ADM 2014 prelim
7	14DKA008-E5	Outcrop	large outcrop, east side of river	NAD83	713325	5545843	42K01	Kenogami River Formation	late Silurian	*in progress*	barren	ADM 2014 prelim
8	14DKA009-A8	Outcrop	outcrop, west bank	NAD83	438678	5776248	43A04	Stooping River Formation	early Devonian	Early Devonian, Late Emsian	*serotinus*	4-SAG-2016
9	14DKA010-A10	Borehole	drill core at Desolation Lake camp	NAD83	344831	5938498	43G11	Severn River Formation	early Silurian	*in progress*	Distomod, Oz, abun Pan	ADM 2014 prelim
10	14DKA010-F14	Borehole	drill core at Desolation Lake camp	NAD83	344831	5938498	43G11	Severn River Formation	early Silurian	*in progress*	Oz, abund Pan	ADM 2014 prelim
11	14DKA010-Z9	Borehole	drill core at Desolation Lake camp	NAD83	344831	5938498	43G11	Severn River Formation	early Silurian	*in progress*	Oul, Oz, abund Pan	ADM 2014 prelim
12	14DKA010A-C8	Borehole	drill core at Desolation Lake camp	NAD83	344831	5938498	43G11	Red Head Rapids Formation	upper Ordovician	*in progress*	com Oz, Pan	ADM 2014 prelim
13	14DKA027	Outcrop	outcrop, southeast side of island	NAD83	472518	5625069	42I14	Williams Island Formation	early late Devonian (Klapper et al. 2004)	indeterminate age	indeterminate age	4-SAG-2016
14	14DKA028-BC	Outcrop	outcrop, southern end of island	NAD83	479020	5629648	42I14	Moose River Formation	middle Devonian	indeterminate age	indeterminate age	4-SAG-2016
15	14DKA028-DE	Outcrop	outcrop, southern end of island	NAD83	479020	5629648	42I14	Murray Island Formation	middle Devonian	Middle Devonian, middle Eifelian - Middle Devonian, middle Givetian	*kockelianus - ansatus*	4-SAG-2016
16	14DKA030	Outcrop	low outcrop, northwest bank	NAD83	483718	5635016	42I14	Murray Island Formation	middle Devonian	Middle Devonian, middle Eifelian - Middle Devonian, middle Givetian	*kockelianus - ansatus*	4-SAG-2016
17	14DKA034-B	Outcrop	large outcrop, south side	NAD83	352215	5552825	42J03	Kenogami River Formation	late Silurian	*in progress*	barren	ADM 2014 prelim

Table 2: Preliminary conodont biostratigraphy of 2014 northern Ontario samples

Four samples of coarse to fine clastics sediments and potential coals from fissure and cracks in Silurian limestones near the Victor Mines kimberlite pipes were submitted for palynological age dating. Previous interpretation based on the presence of kimberlite clasts in the clastics suggested that the fissure fill is Jurassic in age. Only one sample had useful palynomorphs for dating and paleoevironmental analyses (Galloway, 2016). Due to the presence of angiosperm pollen, this specific sample is younger than Cretaceous. Moreover, based on the presence of possible Fagaceae pollen, the material is likely Eocene in age (Gallaway, 2016) and is in agreement with other studies of poorly consolidated, karst-filling or not, rocks in northern Ontario for which a Cenozoic age is proposed (Galloway et al., 2012; Galloway, 2015).

Chemostratigraphy Manitoba

In northeastern Manitoba, carbon and oxygen stable isotope ($\delta^{13}C$ and $\delta^{18}O$) sampling of select Paleozoic cores in the Hudson Bay Lowland portion of the Hudson Bay Basin was completed. The samples were sent for analysis in batches over the course of three years. To date, carbon and oxygen stable isotope ($\delta^{13}C$ and $\delta^{18}O$) results from core for the Sogepet Aquitaine Kaskattama Prov. No. 1, Houston Oils et al. Comeault Prov. No.1, and Merland et al. Whitebear Prov. (Fig. 2), referred herein as Kaskattama, Comeault and Whitebear, respectively, have been received and were plotted in the form of a vertical profile (Fig. 3). Details and results of these profiles are in Nicolas (2016 in press a and b). The $\delta^{13}C$ profiles for all three cores correlate well with the worldwide composite profiles in Saltzman and Thomas (2012). The $\delta^{18}O$ profiles for the cores are more difficult to compare to the worldwide composite profiles since they are based on allochem-specific (brachiopods or conodonts) standards as, as in Grossman (2012), and the herein results are dominantly from carbonate mudstone samples. The effect of diagenesis on the $\delta^{18}O$ values is also a factor that may render the interpretation more complex. Preliminary comparisons of the profiles to each other indicate that the cores have very similar profiles, and can be used to do stratigraphic correlations to other parts of the basin, as well as to cores and outcrop samples with uncertain stratigraphic assignments. Stable isotope results for the Foran Mining Kaskattama Kimberlite No. 1 (KK1) and Pennycutaway No. 1 cores, the middle Kenogami Formation interval of the Kaskattama core and outcrop samples collected along the Churchill River and Churchill coastal region are pending.

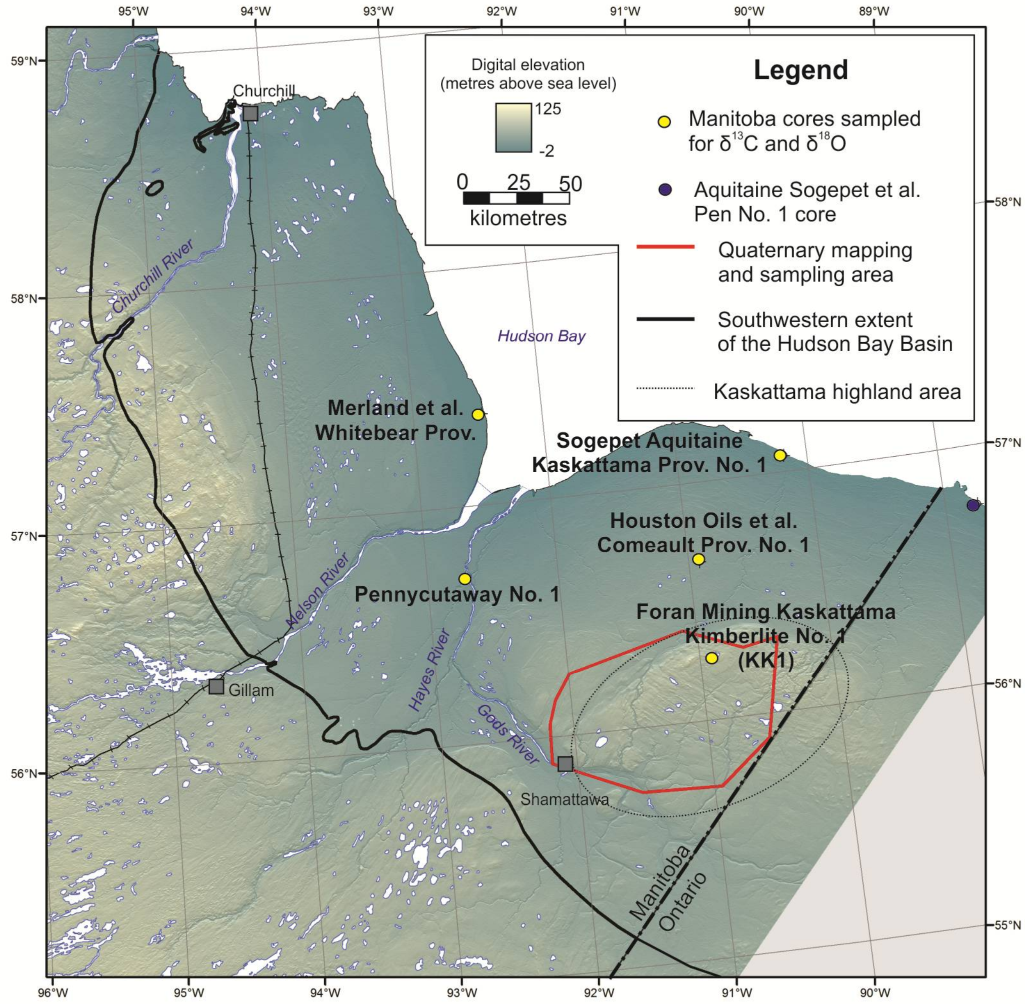

Figure 2. Digital elevation model (USGS 2002) of the Hudson Bay Lowland in northeastern Manitoba showing the location of (1) the approximate extent of the Kaskattama highland area, (2) the cores sampled for carbon and oxygen stable isotope profiling, and (2) the area of the Quaternary mapping program. Grey shaded area is outside of the limit of digital elevation model information.

A comparison of the isotope profiles from one core to the other shows that the profiles are similar and that the Hirnantian isotopic carbon excursion (HICE) interval can be identified on each profile (Fig. 3). Preliminary comparisons to the carbon isotope profile done by Armstrong et al. (2013) on the Aquitaine Sogepet et al. Pen No. 1 core, located in Ontario just east of the Kaskattama core, indicate that isotopic profiles exhibit similar trends; however there are some minor discrepancies in stratigraphic assignment of formation boundaries. Resolving these discrepancies and doing the basin-wide correlations is part of the next phase of work on this project.

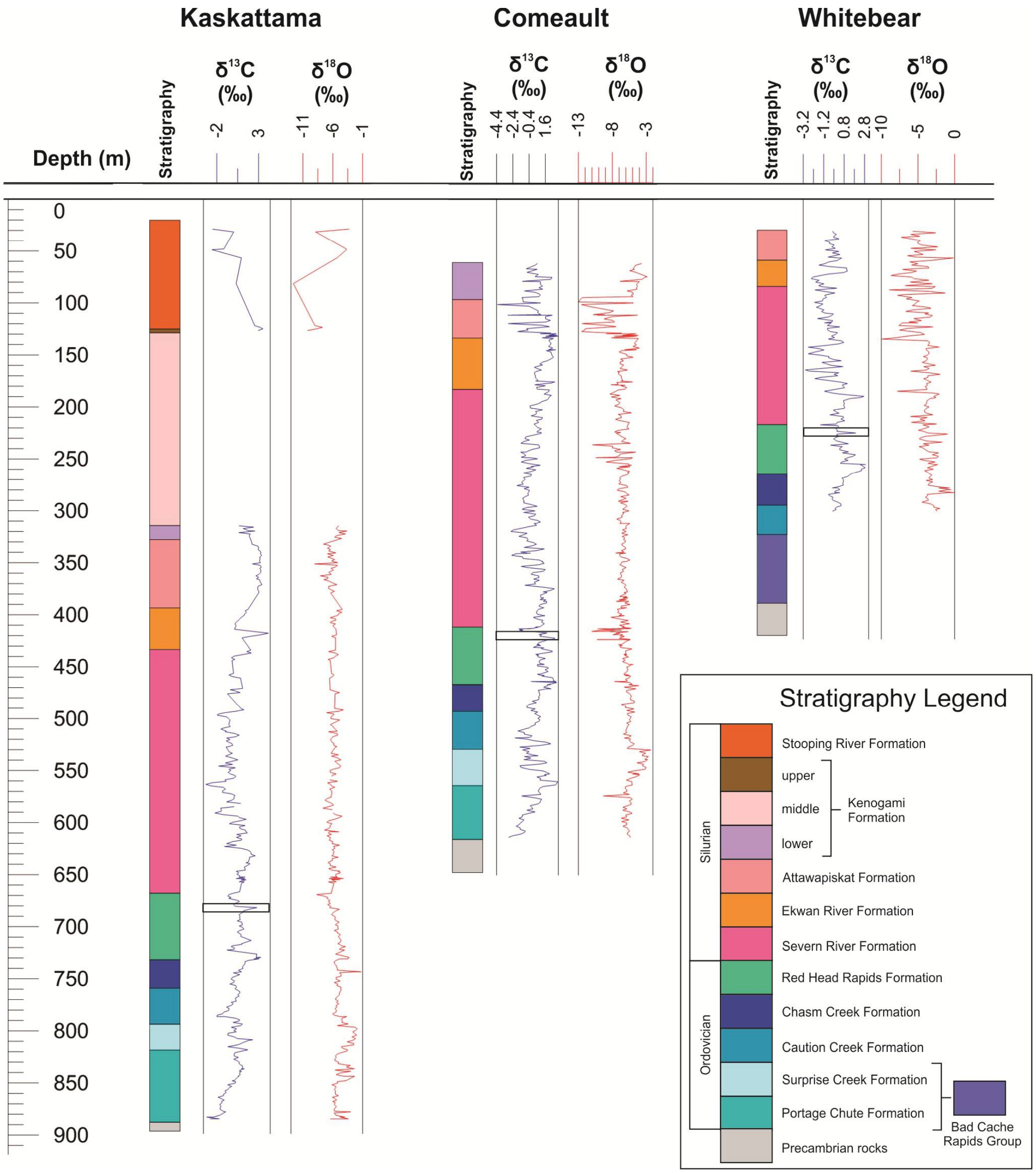

Figure 3. Carbon and oxygen stable isotope ($\delta^{13}C$ and $\delta^{18}O$) profiles for the Sogepet Aquitaine Kaskattama Prov. No. 1, Houston Oils et al. Comeault Prov. No.1 and Merland et al. Whitebear Prov. cores; boxed areas on the $\delta^{13}C$ indicate the location of the HICE for each core.

Nicolas and Clayton (2015) lineament mapping of the Hudson Bay Lowland was done by remote-sensing methods through the analysis of multiple GIS information layers to help understand the possible trends of basement fractures masked by recent sediments. The dominant fracture orientations, along with predicted bedrock strike direction, will be used to develop a grid for a magnetotelluric (MT) geophysics survey that is planned for the summer of 2017. This survey will be over the Kaskattama highland, northeast of the First Nation community of Shamattawa in the Hudson Bay Lowland in northeastern Manitoba (Fig. 2). In further preparation for this MT survey, the Manitoba Geological Survey conducted a large Quaternary stratigraphy and sampling program on the Kaskattama highland in

August 2016. Fieldwork allows documenting the Quaternary stratigraphy along natural river-cut exposures and sampling the surficial sediments across the study area at a reconnaissance-scale (Hodder and Kelley, 2016 in press). During the 2016 field season, 14 new stratigraphic exposures were logged and 22 surficial stations visited. A total of 57 till samples, each weighing 2-3 kg, were collected from C-horizon tills for till-matrix geochemistry and grain-size analysis. In addition, 30 sample sites had 9.5 L of till collected for kimberlite-indicator minerals (KIM) analysis

Source Rock Kinetic

Four samples of Upper Ordovician source rocks collected from outcrops at the margin of the Hudson Bay (Boas River and Red Head Rapids formations), Foxe (Amadjuak Formation) and Hudson Strait (Akpatok Formation) basins were studied (Fig. 4). These four units were shown to be excellent source rocks (Lavoie et al., 2013), but given their organic geochemical parameters, were considered to be immature. The ultimate goal is to evaluate the evolution and timing of hydrocarbon generation throughout deeper burial.

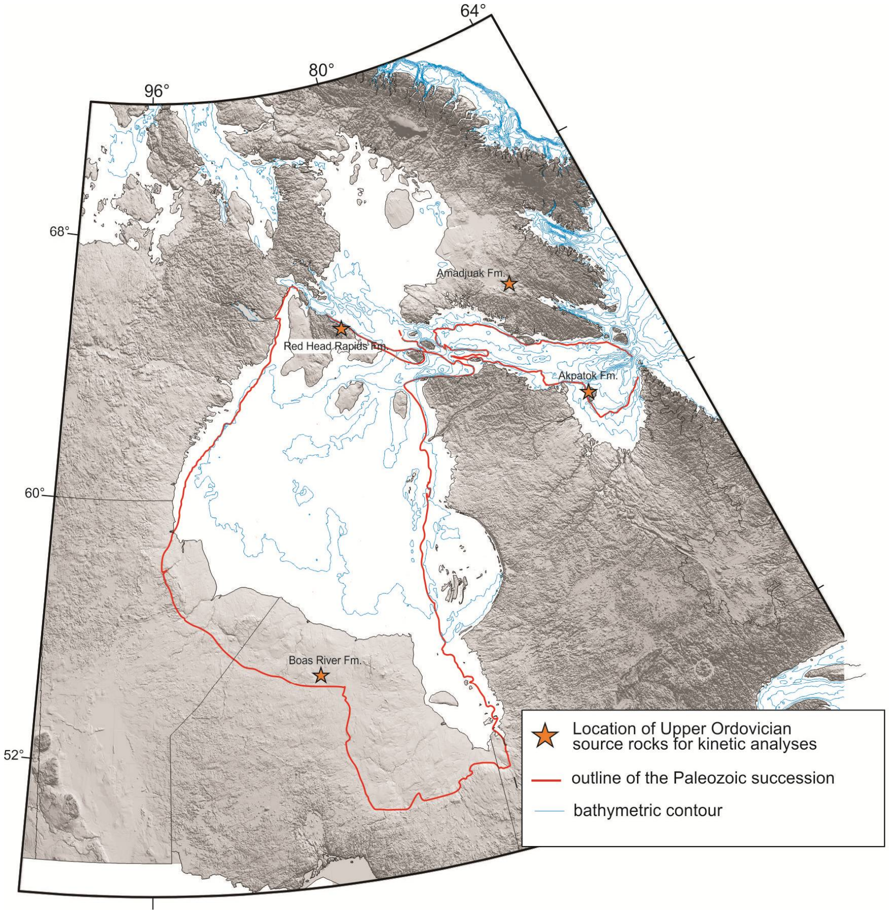

Figure 4: Location of source rock samples for kinetic study. Modified from Lavoie et al. (2015).

The chitinozoan- and organic-rich very limy shales were artificially matured using modified hydrous pyrolysis (HP) to determine and understand the thermal maturation indices, phases and kinetics of petroleum generation for these source rocks. The 72 hours pyrolysis temperatures were 310, 320, 330, 340 and 350°C; these temperatures correspond to peak thermogenic hydrocarbon generation. Quantitative and qualitative geochemical (Rock–Eval - RE) and petrographic (organic petrology – OP) analyses of the solid pyrolyzates indicate that all immature (from whole rock Tmax) source rocks reached thermogenic hydrocarbon generation after the first 310°C pyrolysis temperature. The original measured Tmax of 424°C increased to 437-450°C after completing the HP. Moreover, the results following organic solvent extraction and the subsequent Rock-Eval (RE) analyses show the Tmax reaches 441 to 454°C. This indicates that the high amount free volatile hydrocarbon and soluble solid bitumen (asphaltenes) in the solid pyrolyzates suppressed the true Tmax (Reyes et al., 2016).

In the absence of true vitrinite macerals in Late Ordovician times, chitinozoan and bitumen reflectance and the measured Tmax were also used to detect changes of thermal maturity after each stage of hydrous pyrolysis. Using several well-known conversion equations, the estimated vitrinite reflectance equivalent (VReqv) increased from an initial value of 0.20-0.68%Roeqv, to 0.65-1.46%Roeqv after pyrolysis, depending on which equations were used. The overall RE and OP results indicate that 0.65 to 1.19%Roeqv is the best accurate estimates of thermal maturity. Hydrocarbons were expelled from the source rocks after the first stage of pyrolysis and peaked at 340°C (Tmax of 447°C) at an expulsion rate of 56.93 mg HC/g TOC. The estimated transformation ratio (TR) ranges from 34 to 65% for HI and up to 75% for S2. However, solvent extraction shows that the actual TR of HI and S2 ranges between 59 and 75% and from 65 to 86%, respectively, suggesting that there was a significant underestimation of the TR from whole rock analyses. The underestimation of HI and S2 is higher in early stage of catagenesis and declines exponentially as the bitumen thermally cracks into lighter oil and insoluble pyrobitumen. The underestimation continues to decline as the thermal maturity reaches the gas window in the latter stage of catagenesis (Reyes et al., 2016).

Apatite Fission Track

The Canadian Shield is an iconic example of a cratonic area characterized by an old, thick, cold and stiff lithosphere. As with most continental interiors, the Canadian craton is considered stable, and most geological models infer a slow and more or less continuous exhumation punctuated by minor sedimentary and ice sheet loading events. However, several lines of evidence (presence of Phanerozic outliers, sedimentary xenoliths in kimberlite pipes, sparse organic maturation data) imply that younger sedimentary units have been deposited and subsequently eroded away from vast areas. Quantification of the thickness, age and geographical distribution of the missing geological record is not an easy task, but has major implications for the geological history and hydrocarbon prospectivity of the Hudson Bay Basin.

New apatite fission track (AFT) results from the Hudson Bay area indicate that AFT ages are younger than the age of the host rocks indicating that samples experienced significant annealing and were subjected to temperature > 60°C during the Phanerozoic. The AFT study applied an inverse modeling strategy taking into account the subsidence history for basement samples from the bottom of hydrocarbon wells and the fixed geometrical relationship for the samples from a 3.6 km vertical profile in the LaRonde mine in Abitibi (Quebec).

Thermal histories from AFT data record cycles of heating and cooling that are coherent with the sedimentary record preserved in the Hudson Bay Basin, but also indicate temporal and geographic variations in the timing and degree of Phanerozoic heating episodes. The maximum temperature experienced during the Paleozoic is relatively well constrained but the respective effects of higher surface temperatures, changes in the paleo-thermal gradient and changes in depth due to burial remain difficult to assess as well as the timing of maximum heating. The fact that some samples located at the present-day edge of the basin experienced temperatures of the same order of magnitude or even higher than samples from the central part of the basin is particularly noteworthy (Pinet et al., 2016).

Moreover, a new interpretation has been proposed in which the evolution of the NNW-trending Hudson Bay Central High (HBCH) which corresponds to a normal fault array extending for a minimum length of 500 km is linked to Paleozoic tectonic events that shaped the Appalachian orogen on the eastern side of the North American craton (Fig. 5). In this interpretation, stresses applied to the continental margin during the Silurian-earliest Devonian Salinic orogeny were transmitted over a distance of > 1400 km in the continental interior where they induce the normal-fault reactivation of older structural discontinuities. The shutdown of tectonic activity along the HBCH during the uppermost Early Devonian to lowermost Middle Devonian is interpreted as resulting from a change in the direction of plate convergence during the Acadian orogeny (Pinet, 2016).

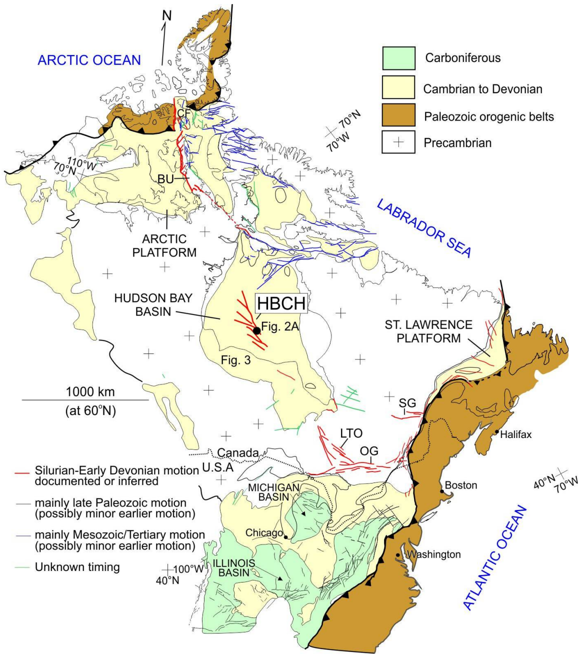

Figure 5. Map showing faults with documented or inferred Paleozoic motions, northeastern North America. BU—Boothia uplift; CF—Cornwallis fold belt; HBCH—Hudson Bay central high; LTO—Lake Timiskaming outlier; OG—Ottawa graben; SG—Saguenay graben. From Pinet (2016)

Upper Ordovician Reef

Upper Ordovician reefs represent one of the major untested petroleum plays identified in the Hudson Bay Basin (Lavoie et al., 2015). We report here on the sedimentological and diagenetic characteristics of a large reefal structure exposed on Southampton Island, Nunavut. The study area is located approximately 34 km southwest of Coral Harbour (64°2’34.8”N, 83°49’33.60”W) and corresponds to the locality #13 in Zhang (2010). This locality shows a large, resistant domal mound at the top of the Red Head Rapids (RHR) Formation. The mound (Fig. 6) is approximately 400 m long in a NW-SE direction, 250 m wide and 10 m thick. In total, 87 hand samples were collected at 0.5 m vertical increments along six representative sections located around the exhumed reef core. The main reef facies comprise boundstone and cementstone composed of various proportions of early-calcified sponge tissues, microbial encrusters, synsedimentary aragonitic cement and small colonial metazoans (Fig. 7). The RHR reef developed in a restricted and hypersaline basin following the End-Ordovician glacioeustatic sea-level fall cumulating into the regional development of the Ordovician-Silurian unconformity within the Hudson Bay Basin (Pinet et al., 2013). The reefs, in which microbialites dominate but coexist with metazoans, were more widespread in the Early Ordovician prior to the Middle to Late Ordovician expansion of skeletal-dominant reefs (Castagner et al., 2016).

The RHR reef, porous and locally bitumen impregnated, underwent early marine, near-surface and progressive burial diagenesis; reducing its primary porosity but significantly increasing its secondary porosity. All depositional and diagenetic carbonate phases (n= 44) of the RHR reef were sampled using a microdrill for δ^{13}C and δ^{18}O analyses (Fig. 8). The primary components of the RHR reefs (sponge, microbial component, early marine cement) have relatively enriched δ^{13}C values close to those expected for the late Ordovician seawater while their δ^{18}O values have a wider range. δ^{13}C and δ^{18}O trends support progressive stabilization of the primary carbonate phases under a period of subaerial exposure and subsequent burial (Hudson 1977). Future fluid inclusion and clumped isotope studies should help to constrain the temperatures and salinities of various diagenetic fluids as well as their original δ^{18}O values.

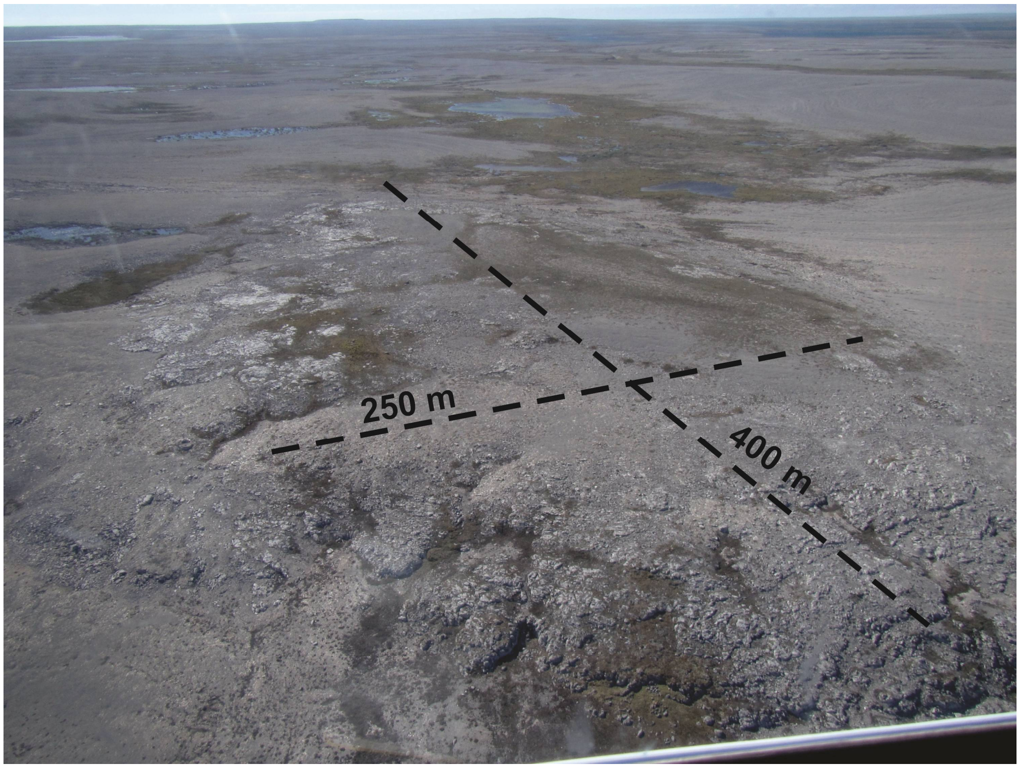

Figure 6. Aerial view of the massive reef core of the Red Head Rapids Formation on Southampton Island.

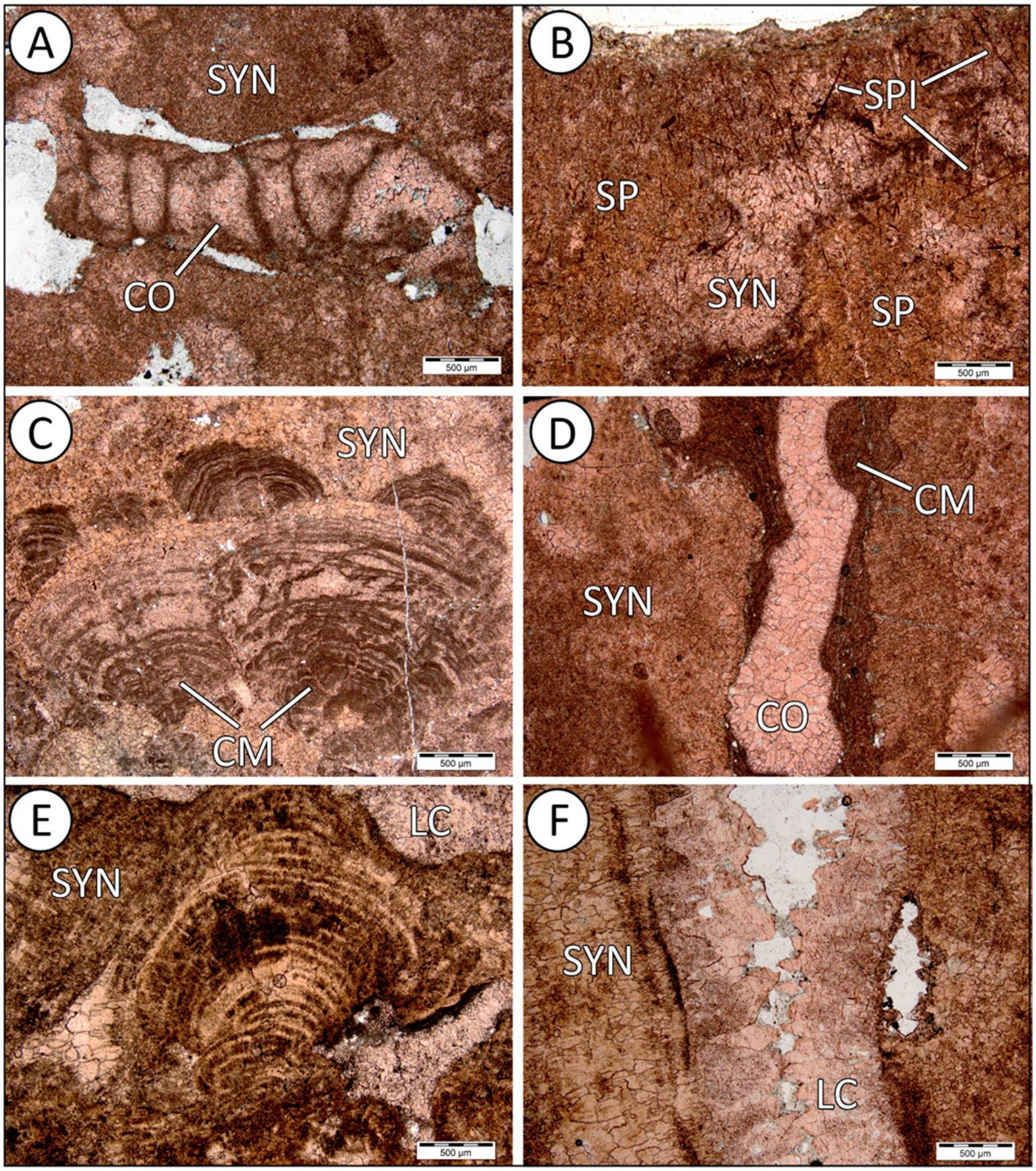

Figure 7. Photomicrographs showing primary and diagenetic carbonate phases present in the RHR reef exposed on Southampton Island. A – Poorly preserved colonial coral (CO) with distinct septa cemented by a synsedimentary inclusion-rich neomorphic spar (SYN). B – Neomorphic replacement of sponge tissue (SP) with poorly preserved spicules (SPI) intergrown with an inclusion-rich, brownish, pleochroic spar cement (SYN). C – Calcimicrobial laminae (CM) growing in alternance with the synsedimentary inclusion-rich spar cement (SYN). D –Dissolved colonial coral (CO) encrusted by calcimicrobes (CM) and synsedimentary inclusion-rich spar cement; space in now filled by an inclusion-poor, drusy calcite cement (LC). E – Synsedimentary inclusion-rich spar cement showing a botryoidal growth form (SYN) and final pore occluding, inclusion-poor drusy calcite cement (LC). F –Synsedimentary inclusion-rich spar cement (SYN) locally showing square crystal terminations (formerly aragonitic) postponed by an inclusion-poor, drusy calcite cement (LC) partially filling a dissolution vug.

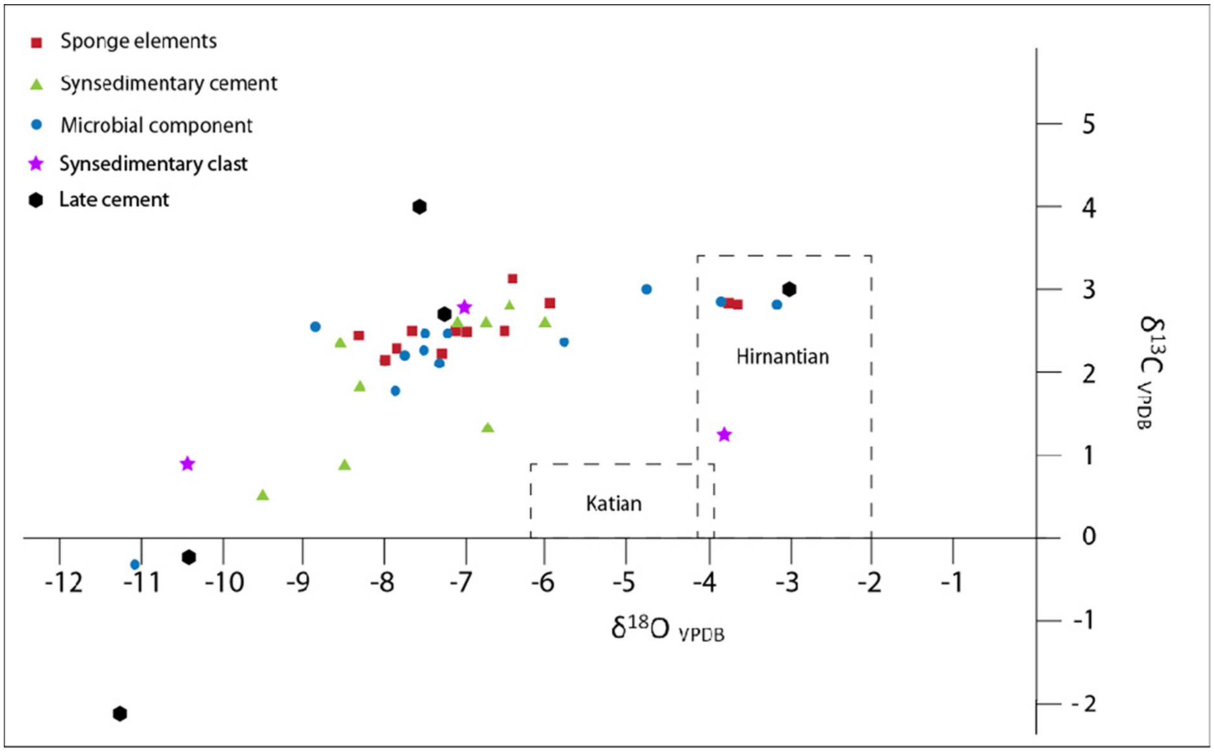

Figure 8. Cross plot of δ^{13}*C versus* δ^{18}*O of various depositional and diagenetic carbonate phases present in the RHR reef exposed on Southampton Island. Dashed boxes show variations in the expected* δ^{13}*C and* δ^{18}*O values for the Katian and the Hirnantian seawater (Shields et al., 2003). Stable isotope analyses were performed with a Gas Bench II interfaced with a Finnigan Mat Delta XL mass spectrometer at the G.G. Hatch Laboratory at the University of Ottawa. Data are reported as* δ^{13}*C and* δ^{18}*O in permil with respect to the Vienna Pee Dee Belemnite, or VPDB standard with an analytical precision of ±0.1‰.*

These reefs likely have excellent potential as reservoir facies judging by their porous nature (up to 15% by visual estimation) and stratigraphic position immediately above high TOC Type IIs source rocks. These reefs are identified in seismic profiles and even if the precise timing of pore space evolution with respect to hydrocarbon generation and expulsion is still elusive, dead oil and pore-coating bitumen have been reported (Heywood and Sanford, 1976).

Rock Eval analyses – northern Ontario

Thirteen samples were submitted for Rock Eval 6 and TOC analysis in 2015 (Table 3). Six are core samples from the Zenyatta Z11-1D1 core and are from the Silurian age lower Kenogami and possibly middle Severn River formations. Both of these units were deposited in restricted shallow water environments. The samples are thin brown to black bituminous shales, limestone and dolostones. Four of these samples yielded TOC values from 4.42 to 7.21 wt%. Tmax values are all less than 428°C and their IP values <0.1 (0.01 to 0.04) indicate that all samples are immature. All samples plot in the Type II field on a S2 vs TOC plot (Fig. 9), Three core samples were from the Schlievert Lake core, from the Lower to Middle Devonian Stooping River, Kwataboahegan and Williams Island formations. The Kwataboahegan and Stooping River samples had TOC values less than 2 wt%, whereas the Williams Island sample was 6.54 wt% TOC. As for samples from the Zenyatta well, these samples are immature as they all have Tmax values lower than 435°C (414 to 421°C) and IP lower than 0.1 (0.02 to 0.03).

The remaining 4 samples were collected from outcrops of lower to middle Devonian age units. All except one sample had low TOC values (<1.0 wt%). However, the nearshore carbonaceous shale of the Sextant Formation yielded the highest TOC values, 13.54 wt%. Interestingly this sample plots in the Type II field (Fig. 9) despite containing what appeared to be abundant plant fragments. If the Type II assignment is true, the latters are seemingly subordinate to marine-derived kerogen. Tmax values for outcrop sample are all low, except for an anomalous value for a sample with very low TOC. Moreover, this outcrop sample (15DKA031D-03) has no S1 values and PI of 0, suggesting that the Tmax of 450°C is erroneous.

The most organic rich samples are typically thin seams from units deposited in shallow restricted environments. These units are generally widespread in the Moose River Basin. From this limited dataset, the lower Silurian Severn River and the Lower Devonian Sextant formations have the best HC genetic potential for these immature samples.

Sample ID		Location Information							Sample Information			Rock Eval results									
Sample #	Sample Name	Sample Type	Well / Station Name	Datum	Well / Outcrop Location (Latitude)	Well / Outcrop Location (Longitude)	Map Sheet	Depth - From (m)	Depth - To (m)	Stratigraphy	Tmax	S1	S2	S3	PI	S2/S3	PC(%)	TOC(%)	HI	OI
1	15DKA001B-04	core	Zenyatta Z11-1D1	NAD83	51.187745	-85.030926	042N	71.85	71.85	lower Kenogami River Fm	427	0.31	12.01	0.97	0.02	12.38	1.12	4.63	259	21
2	15DKA001B-06	core	Zenyatta Z11-1D1	NAD83	51.187745	-85.030926	042N	72.15	72.15	lower Kenogami River Fm	424	0.02	1.00	0.16	0.02	6.25	0.10	0.44	227	36
3	15DKA001B-09	core	Zenyatta Z11-1D1	NAD83	51.187745	-85.030926	042N	76.95	76.95	lower Kenogami River Fm	418	0.57	19.35	0.91	0.03	21.26	1.75	4.67	414	19
4	15DKA001O-07	core	Zenyatta Z11-1D1	NAD83	51.187745	-85.030926	042N	163.7	163.7	middle Severn River Fm?	417	1.46	40.53	1.55	0.03	26.15	3.61	7.21	562	21
5	15DKA001P-02	core	Zenyatta Z11-1D1	NAD83	51.187745	-85.030926	042N	164.25	164.25	middle Severn River Fm?	424	0.93	21.71	0.98	0.04	22.15	1.97	4.42	491	22
6	15DKA001P-08	core	Zenyatta Z11-1D1	NAD83	51.187745	-85.030926	042N	168.64	168.64	middle Severn River Fm?	422	0.12	2.94	0.23	0.04	12.78	0.29	0.86	342	27
7	15DKA008J-01	core	OGS-83-8D Schlievert Lake	NAD83	50.556292	-88.971799	042J	168.32	168.37	Williams Island Fm	416	0.61	20.60	2.67	0.03	7.72	1.95	6.54	315	41
8	15DKA008V-09	core	OGS-83-8D Schlievert Lake	NAD83	50.556292	-88.971799	042J	287.82	287.87	Kwataboahegan Fm	414	0.09	3.69	0.59	0.02	6.25	0.36	1.39	265	42
9	15DKA008AAB-08	core	OGS-83-8D Schlievert Lake	NAD83	50.556292	-88.971799	042J	323.65	323.67	Stooping River Fm	421	0.06	2.90	0.35	0.02	8.29	0.27	0.89	326	39
10	15DKA020C-02	outcrop	15DKA020	NAD83	50.211123	-81.650078	042I			Sextant Fm	428	0.16	69.63	1.16	0.00	60.03	5.98	13.54	514	9
11	15DKA022A-01	outcrop	15DKA022	NAD83	51.017293	-80.539687	042P			Kwataboahegan Fm	425	0.01	1.34	0.54	0.01	2.48	0.15	0.95	141	57
12	15DKA031A-02	outcrop	15DKA031	NAD83	50.398997	-81.569962	042I			Williams Island Fm	426	0.03	2.66	0.52	0.01	5.12	0.26	1.03	258	50
13	15DKA031D-03	outcrop	15DKA031	NAD83	50.398997	-81.569962	042I			Williams Island Fm	450	0.00	1.35	0.17	0.00	7.94	0.12	0.27	500	63
repeat	15DKA020C-02r	repeat						repeat			427	0.16	76.61	1.23	0.00	62.28	6.57	14.63	524	8

Table 3. Rock Eval results from Silurian to Devonian samples from northern Ontario.

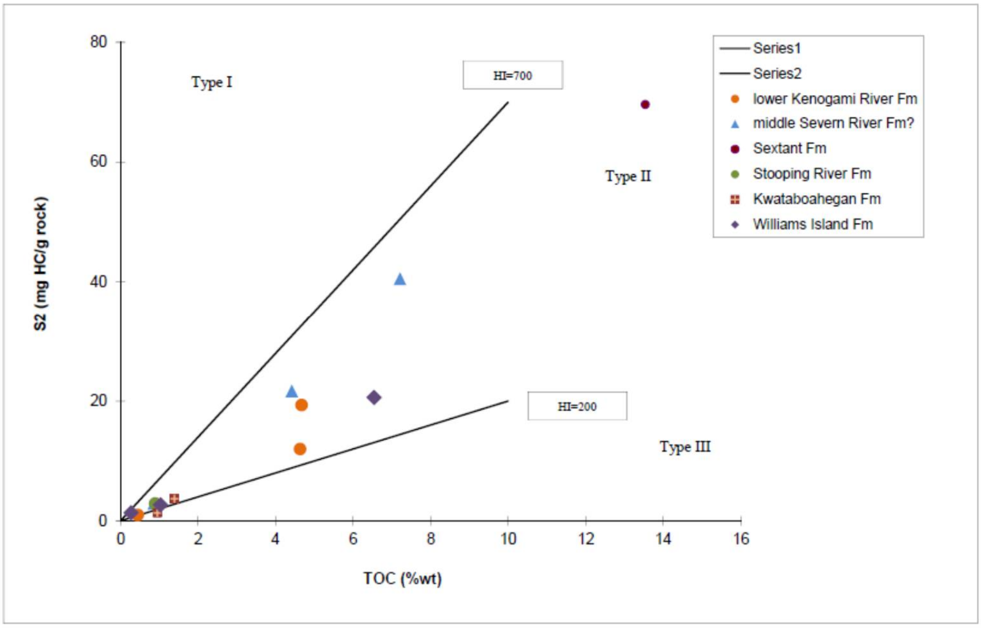

Figure 9. S2 versus TOC plot of samples from Northern Ontario. All samples plot in the Type II marine kerogen-type.

RADARSAT-2

Image analyses - The green rectangles in figure 10 show the distribution of the image footprints for 2016. There are 87 images (Fig. 10) in total (VV polarization, 12.5 m pixel spacing).

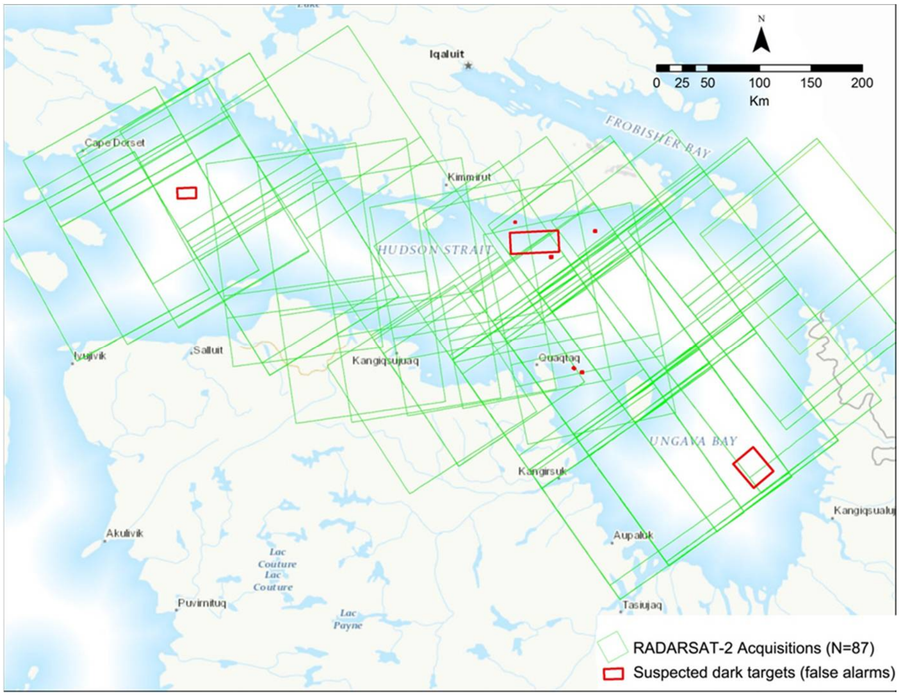

Figure 10. Distribution of RADARSAT-2 images acquired for the project. Suspected oil slicks (red boxes and dots) are most likely false positives.

The entire image mosaic was inspected visually on a large monitor. This was achieved by displaying the mosaic, a small portion at a time, and using visual enhancement techniques if necessary. An experienced interpreter proceeded to the detection and delineation of potential oil slicks. The locations of the potential slicks were vectorized and registered into a GIS database.

The interpretation reveals only a few slick candidates with very low confidence levels. No observations are considered to be potential natural oil seeps. It is noteworthy mentioning that ice was still present in the strait during the image acquisition period, making the interpretation more difficult as it is as oil slicks are often associated with a darker surrounding.

Figure 11 displays the best dark target example found over the entire RADARSAT-2 mosaic. It is a low confidence oil slick candidate. The bright elongated zone inside the disk-shaped dark area contradicts an oil slick origin and suggests a link with the presence of floating ice. The lack of potential slick candidate over this area is surprising given the abundance of dark features in the adjacent Foxe Channel to the west (Lavoie et al., 2015).

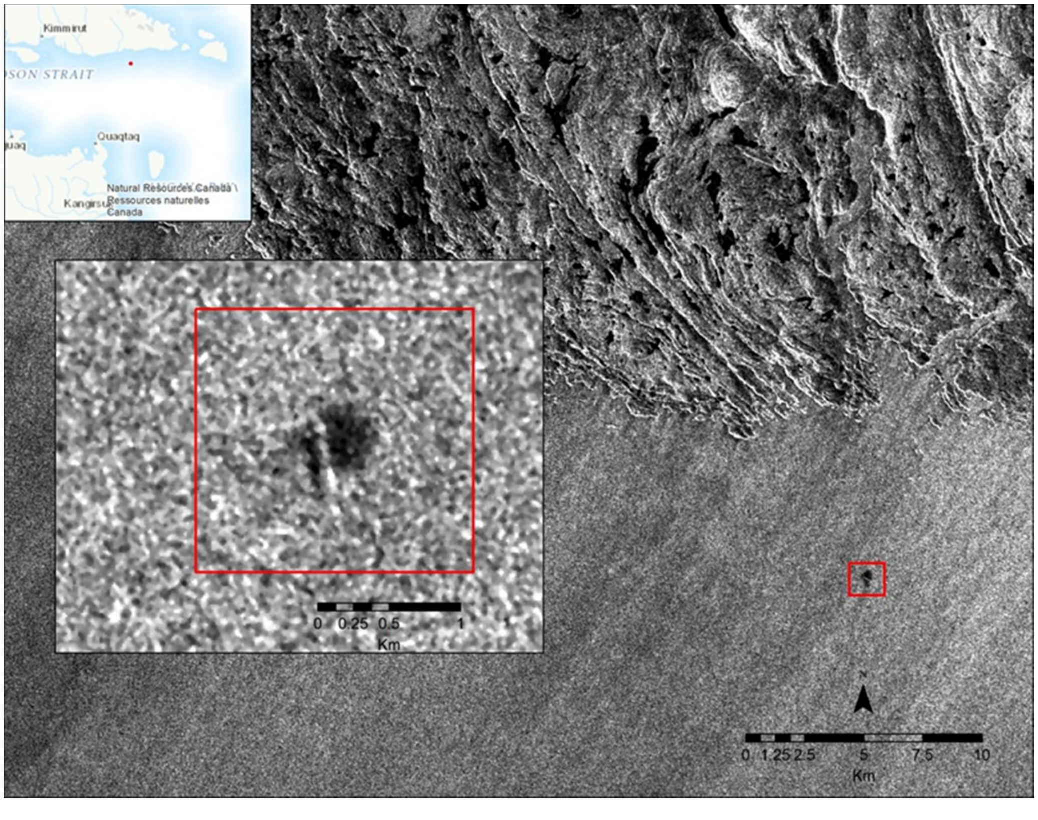

Figure 11. Black element at the surface of the Hudson Strait waters, south of Baffin Island. The dark feature is considered to be a false positive.

Dark target detection in SAR images for oil seep recognition an automated approach - The main steps of the method that is presently implemented, but still under test, are shown in figure 12. The goal is to first subdivide the entire image into smaller and more homogeneous regions (boxes 6 and 7) to optimize the application of a statistical distance measure for dark target detection (box 8). Background correction and contrast enhancement is first required (boxes 3, 5). Characterization of each detected dark spot (geometry, radiometry, context; boxes 9, 10) is used for preliminary look-alike screening (box 11).

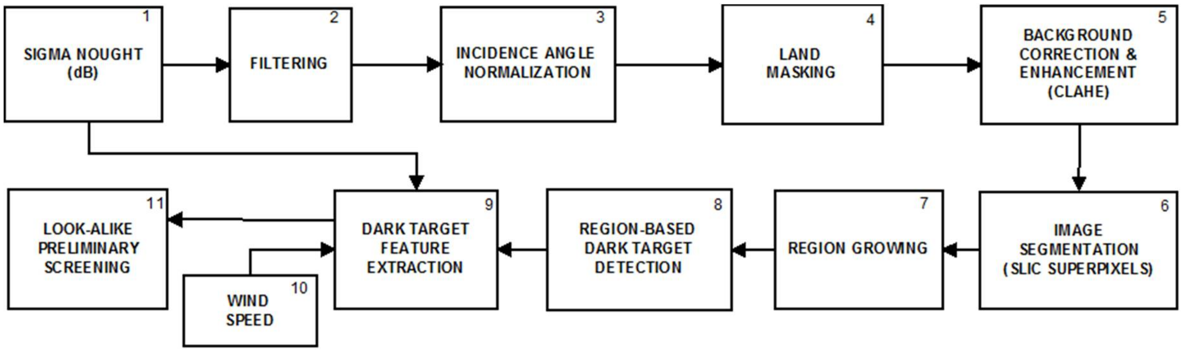

Figure 12. Dark target processing chain for oil seep discovery.

In more details,

- Boxes 1, 2: SAR data pre-processing include geocoding, calibration and image filtering.

- Box 3: Backscattering measured by SAR sensors over ocean is characterized by a progressive decreasing of brightness along the range direction. A correction is applied to normalize the image backscatter, based on the CMOD5 model (Hersbach et al., 2007) with a wind speed of 3 m/s.

- Box 5: SAR images of sea exhibit large spatial variability. The contrasted limited adaptive histogram enhancement (CLAHE) algorithm (Zuiderveld, 1994) is adopted to reduce the large scale background variability and to enhance the local contrast.

- Boxes 6 and 7: The CLAHE image is partitioned into homogeneous regions with the Simple Linear Iterative Clustering (SLIC) algorithm (Achanta et al., 2012). Because each region must be much larger than the targeted dark features, a hierarchical region growing algorithm is utilized next to merge spatially connected regions so that all region sizes must be larger than a specific size (~16 × 103 ha).

- Box 8: The detection of dark pixels is based on robust estimation of location (median) and scale (the median of absolute deviation) within each region of the partitioned CLAHE image. A threshold is used to isolate pixels (dark targets) away from the region median, in unit of median of absolute deviation.

- Boxes 9, 10: Backscatter characteristics within and surrounding dark targets are computed (e.g. mean, standard deviation, area, etc.) for discrimination analysis. Same extraction process is applied for wind data (National Synthetic Aperture Radar (SAR) Winds (NSW) Products, Environment Canada).

- Box 11: Thresholds are applied on extracted features to eliminate dark targets with characteristics incompatible with those of oil seeps.

Future works (not included in Fig. 12)

The preliminary list of suitable dark targets will be integrated within a GIS environment for multi-temporal spatial coincidence analysis with the aim of eliminating a large number of look-alikes. Utilization of auxiliary data, such as phytoplankton bloom maps, will be explored to further remove look-alikes.

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