Multiple Scenarios from Diverse Thermal Indicators: Contrasting Organic-Versus Mineral-Based Methods for a Frontier Intracratonic Basin in the Canadian Arctic*

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Search and Discovery Article #11164 (2018)**
Posted December 17, 2018

*Adapted from oral presentation given at 2018 International Conference and Exhibition, Cape Town, South Africa, November 4-7, 2018
 DOI:10.1306/11164Lavoie2018

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Abstract

The burial and thermal histories are critical elements in the evaluation of conventional and unconventional petroleum systems. For years, thermal parameters obtained through Rock-Eval and organic petrography have been the preferred approaches to understand the thermal evolution of basins. Various mineral-based methods have also been developed and increasingly applied to comprehend the thermal history of sedimentary successions. The Paleozoic Hudson Bay Basin in the Canadian Arctic is a large intracratonic basin and after an initial exploration phase (5 wells) in the 1970-1980 period, it was abandoned as based on Rock Eval 2 data, source rocks were deemed immature. However, all wells had gas kicks and bitumen-rich intervals. A research project by the Geological Survey of Canada aims at re-evaluating the petroleum systems of this basin with a particular attention to understanding its burial-thermal history. The burial-thermal research focuses on the Upper Ordovician stratigraphic interval at the base of the 2500 m preserved succession. Organic matter-rich source rocks and porous potential reservoir units (reef and hydrothermal breccia) occur over a short stratigraphic interval. These are particularly well exposed on Southampton Island at the northern reach of the basin where satellite and airborne radar images have identified nearby potential seawater oil slicks and hydrographic surveys have mapped seafloor pockmarks. The Upper Ordovician Type I-IIs shales are rich in TOC (up to 35%), with high HI value (average 630 mg HC/g TOC). New organic-matter based thermal indicators from Rock-Eval 6 and reflectance petrography indicate that the outcropping Upper Ordovician shales are immature (Tmax below 435°C and average Rvit-eq of 0.44%). Inverse modeling of apatite fission tracks data from basal Upper Ordovician sandstone suggest that the succession reach the early oil window with an acceptable temperature envelope of 65 to 85°C and best fit data of 72°C. Thermal

evolution from fluid inclusions microthermometry data in early and late carbonate cements from porous Upper Ordovician reefs has identified an early hydrothermal event (Th of 120°C) and late burial oil window conditions (Th of 93°C); clumped isotope temperature data from these cements are currently being acquired. Therefore, assuming proper analytical techniques, various organic and mineral-based thermal analyses could yield significantly different results.

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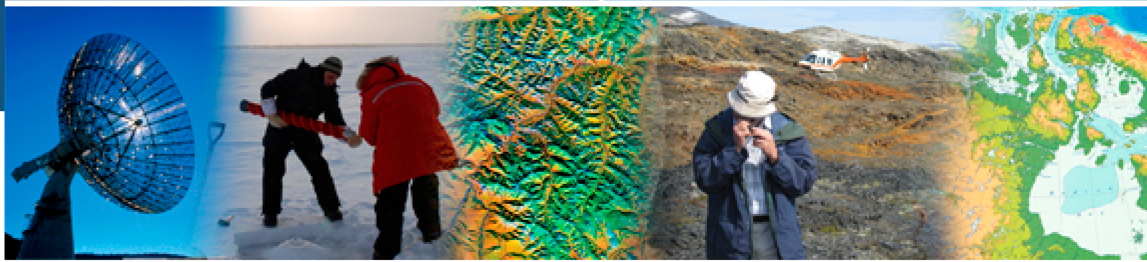
Multiple scenarios from diverse thermal indicators: contrasting organic- versus mineral-based methods for a frontier intracratonic basin in the Canadian Arctic.



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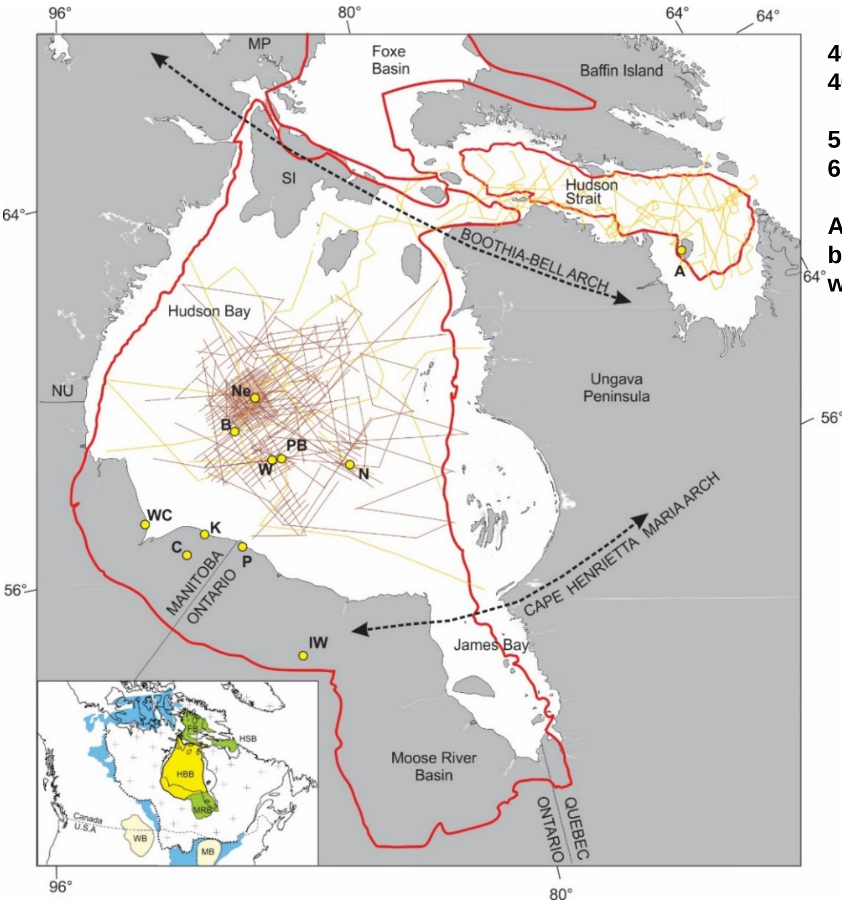
Outline

- **The Hudson Bay Basin – geological setting and hydrocarbon exploration history**
- **Evidence for hydrocarbon generation and expulsion (?)**
- **The thermal maturation issue in the Hudson Bay Basin**
  - Organic matter-based methods
    - Rock-Eval (T_{max}); Organic matter reflectance (VRo_{equ})
  - Thermochronological method
    - Apatite fission tracks (inverse modeling)
  - Calcite-based methods
    - Fluid inclusions microthermometry (T_h)
    - Clumped isotopes (Δ_{47})
- **The verdict ….**

Regional setting and historic background



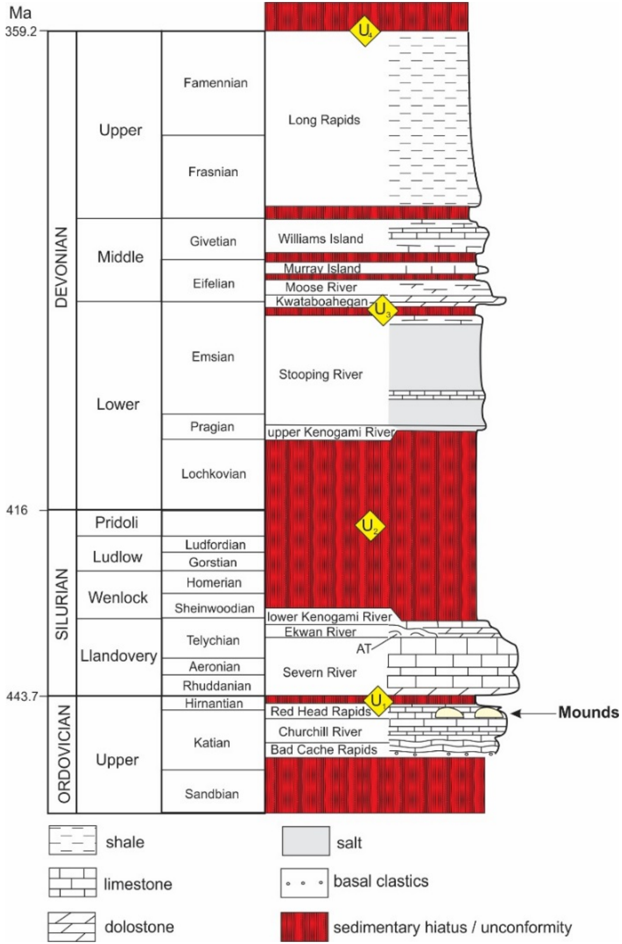
46 000 linear-km of industry seismic (1970's)
40 000 linear-km of GSC seismic (1980-1990)

5 offshore wells in Hudson Bay
6 onshore wells

All offshore wells had oil and gas shows, bitumen-impregnated samples, although none was tested.

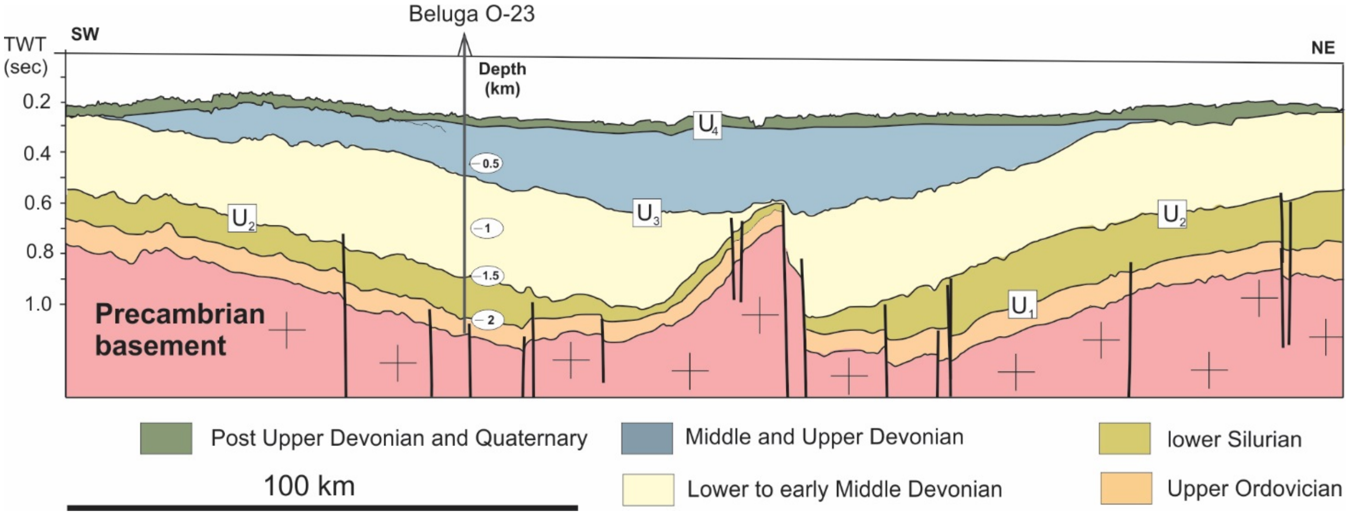
Stratigraphy

Upper Ordovician to
Upper Devonian
shallow marine platform carbonates,
shales and local reefs
----
variably thick, restricted marine
evaporites
----
variably thick, widespread
organic-rich shales
----
thin sections of
coastal plain sandstones
at base of the succession



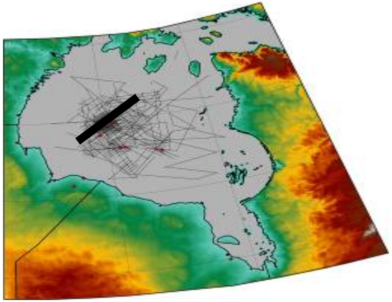
Lavoie et al. (2015)
AAPB Bull.

Basin geometry



4 major unconformities
- Ordovician-Silurian: U1
- Lower Silurian-Lower Devonian: U2
- Middle Devonian: U3
- Late Devonian: U4

Ordovician-Silurian active faulting



Pinet et al (2013)
Earth Sc. Rev.

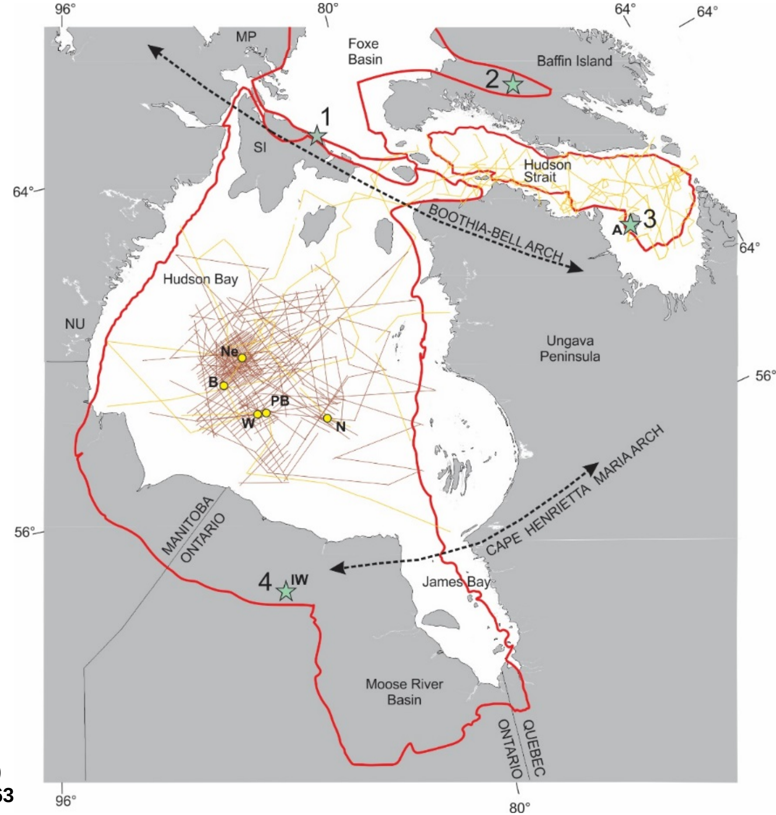
Source rocks (onshore immature)

1- Yields: 20-134 kg HC/ton rock
TOC: 5 - 35% - 5 meters

2- Yields: 16-99 kg HC/ton rock
TOC: 3 - 15% - 15 meters

3- Yields: 2-11 kg HC/ton rock
TOC: 4 - 5% - 12 meters

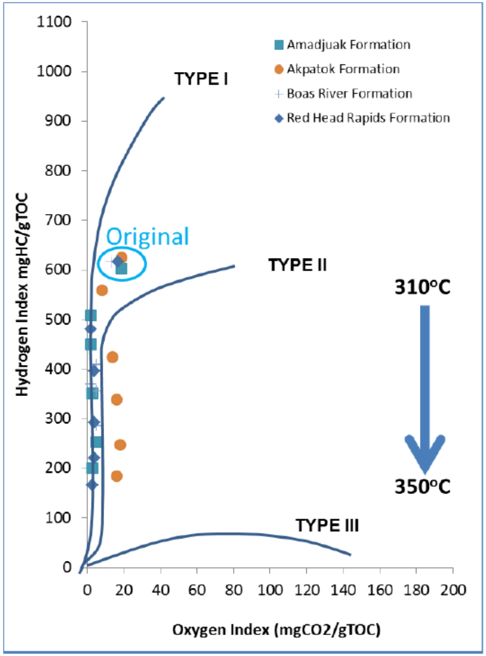
4- Yields: 13-74 kg HC/ton rock
TOC: 3 - 15% - 10 meters

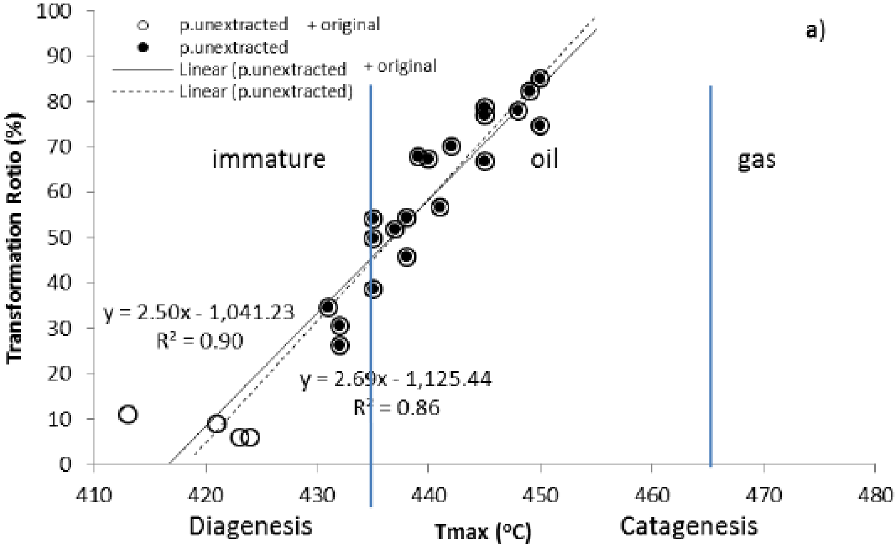


Lavoie et al. (2013)
GSC Open File 7363

Hydrocarbon generation at low temperatures

Artificial maturation through closed hydrous pyrolysis revealed that the immature source rocks (4 different units) start generating hydrocarbons at T_{max} of 435 to 439°C.
The overall quantity of generated hydrocarbons ranges between 22 to 166 mg HC/g TOC

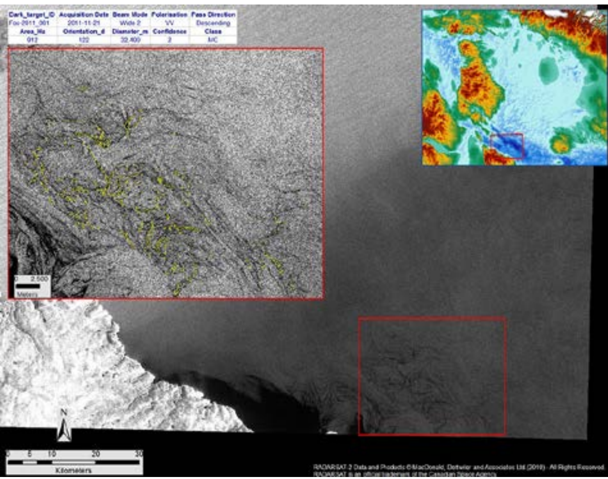


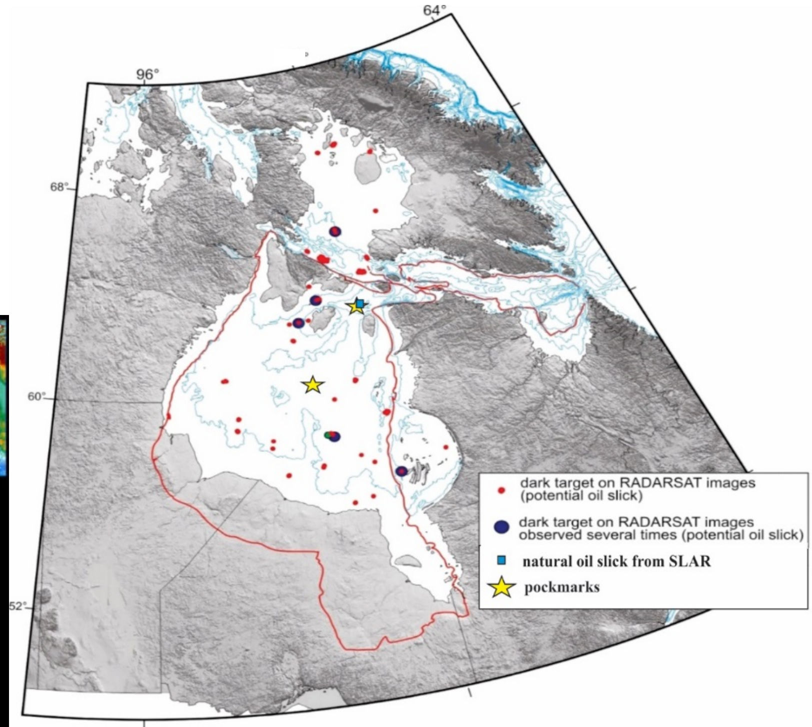


Reyes et al. (2016) GSC OF 8049 and (2017) Int. J. Coal Geol. V. 199, p. 138-151

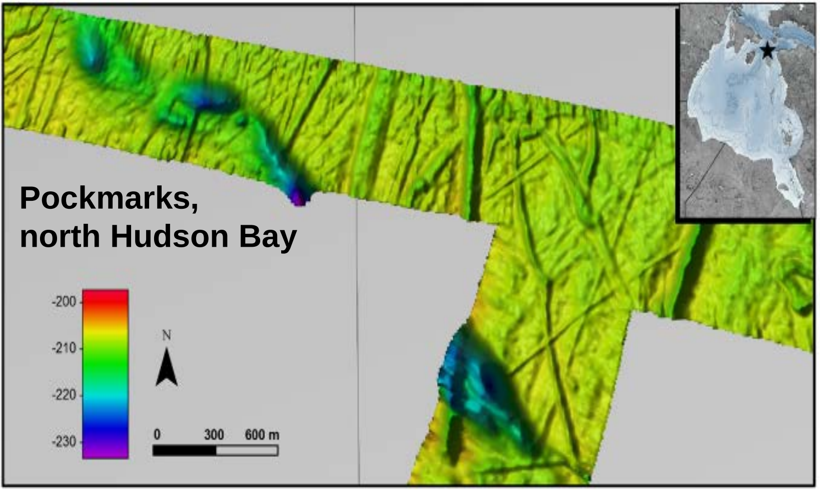
Hydrocarbon generation – Remote sensing

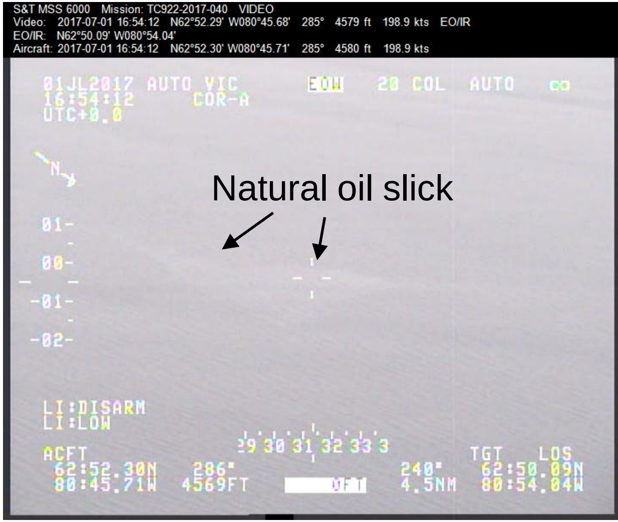
Abundant, potential oil slicks in the area as determined through RADARSAT images analyses; recent airborne SLAR slicks and pockmarks

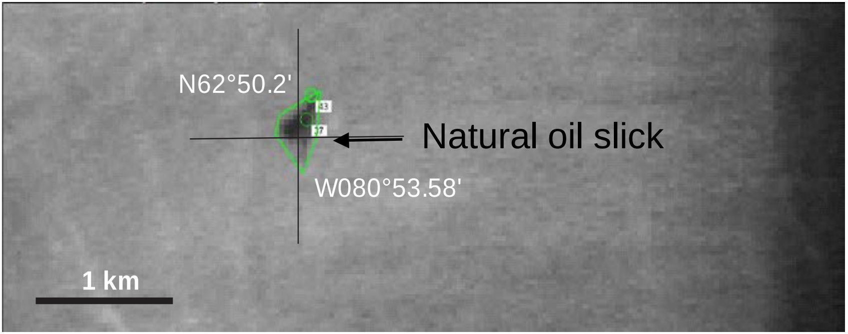




Decker et al. (2013) GSC Open File 7070







Hydrocarbon generation

A limited airborne SLAR survey – Natural oil slick coincident with seafloor pockmarks

The situation prior to the Hudson Bay project (<2008)

1. The marine seismic and wells indicated a thin (<2500 m) succession with assumed low geothermal gradient
2. Limited Rock-Eval2 analyses on OM- and HI-rich onshore source rocks samples suggested that they are immature

New thermal data 2008-2017

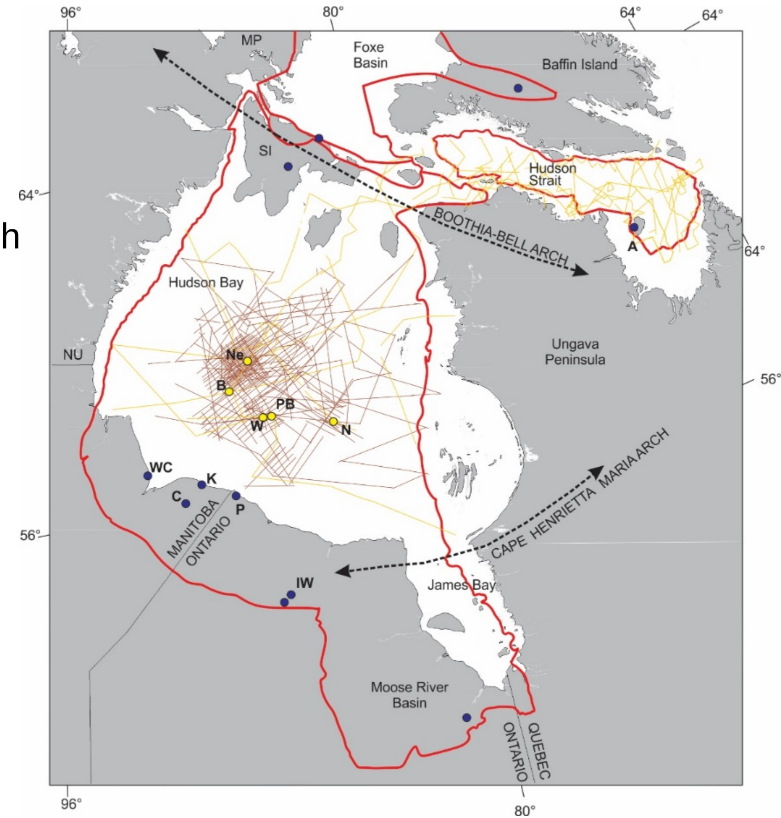
1. Extensive new Rock-Eval6 data from onshore and offshore samples
2. Organic matter reflectance study of 3 wells in central Hudson Bay and from onshore outcrops and wells
3. Apatite fission tracks from onshore and offshore samples
4. Fluid inclusion microthermometry in calcite cements from onshore reef
5. Clumped isotopes data in calcite cements from onshore reef

New Rock-Eval 6 T_{max} data

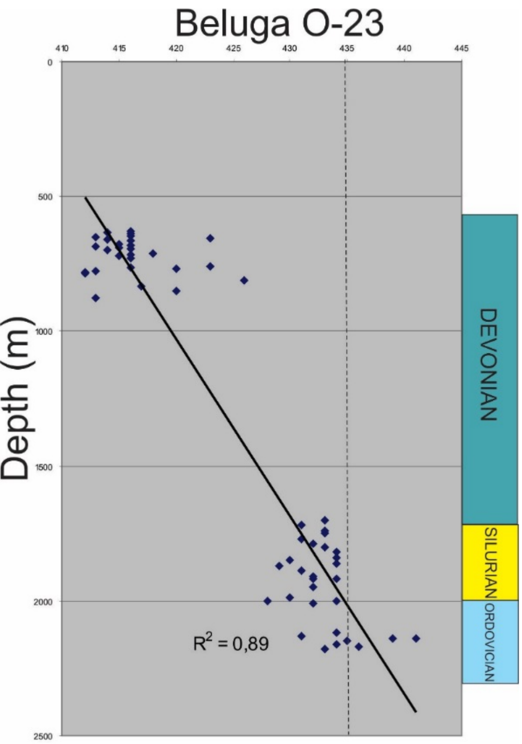
133 new samples from onshore of which **117** with S2 >0.35 mg HC/g rock

464 new samples from offshore and onshore wells of which **230** with S2 >0.35 mg HC/g rock

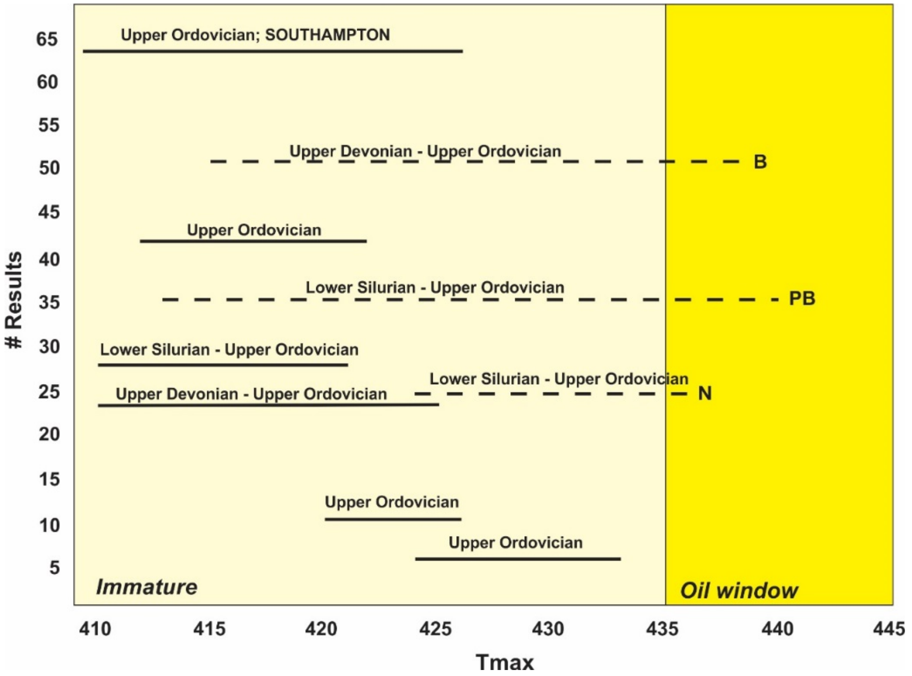
Detailed data in Lavoie et al (2013) GSC Open File 7363



New Rock-Eval 6 T_{max} data

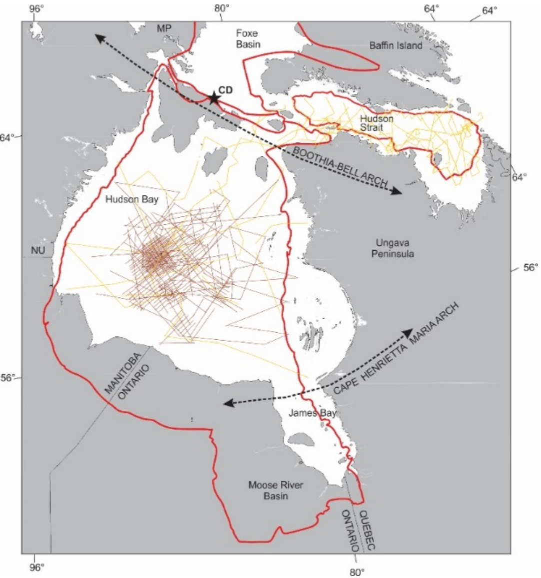


Offshore wells have average and maximum T_{max} values higher than outcrops – Few over 435°C



Organic matter reflectance data - Southampton Island

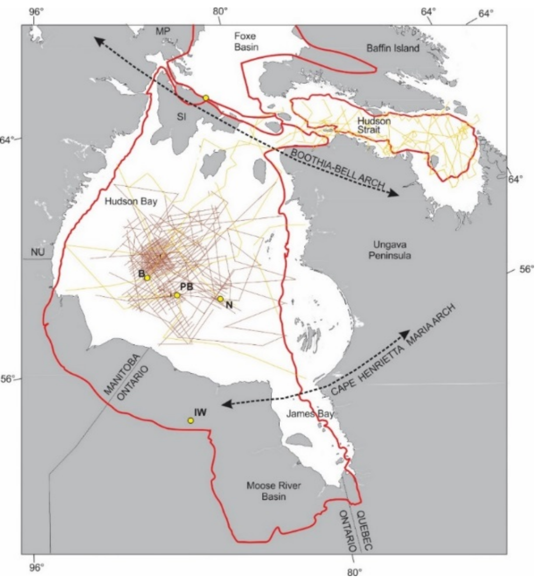
6 shale samples from 3 units at Cape Donovan (CD)
VRo_{equ}, T_{max} and extracts (Weatherford)



Interval	VRo_{equ} %	T_{max} °C	Pr/Ph ratio
Upper	0.43	418	0.48
Upper	0.40	415	0.75
Middle	0.35	417	0.62
Middle	0.43	415	0.73
Lower	0.56	415	0.54
Lower	0.49	412	0.57

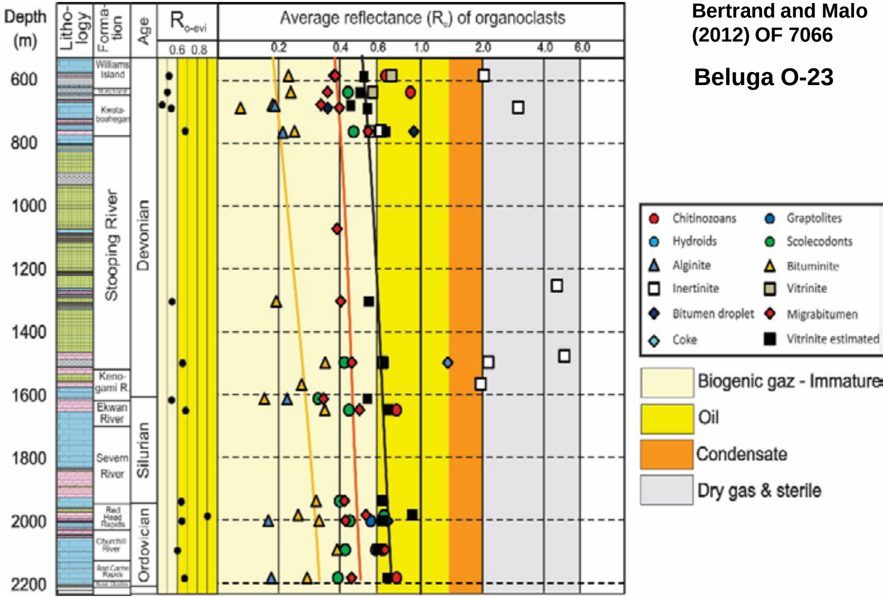
Organic matter reflectance data – Central Hudson Bay

58 samples from 3 wells in central Hudson Bay.
All organoclasts Ro% values were transformed in VRo equivalent %



Bertrand and Malo (2012) OF 7066

Beluga O-23

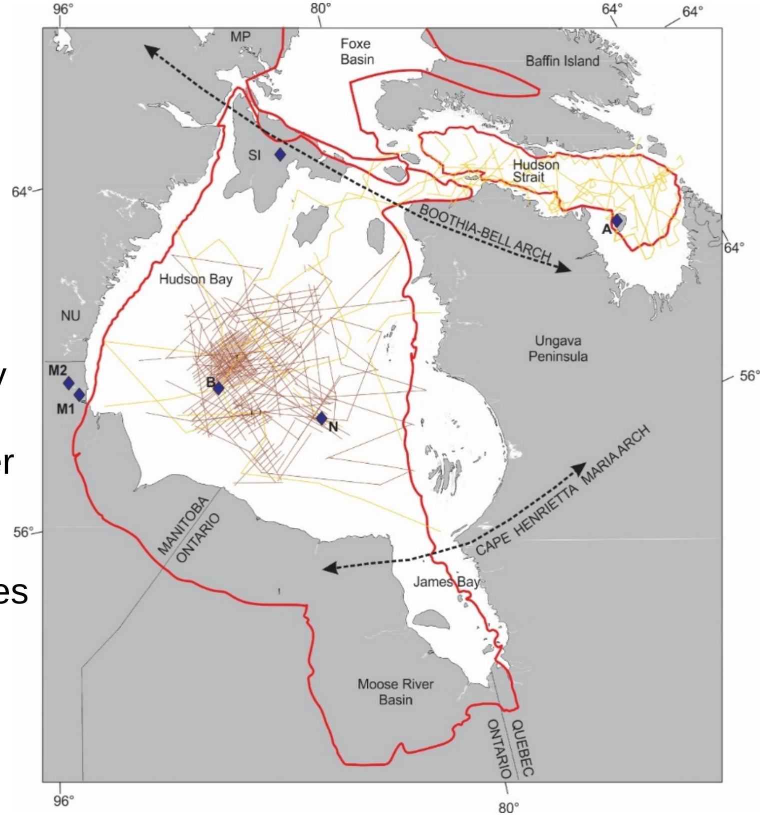


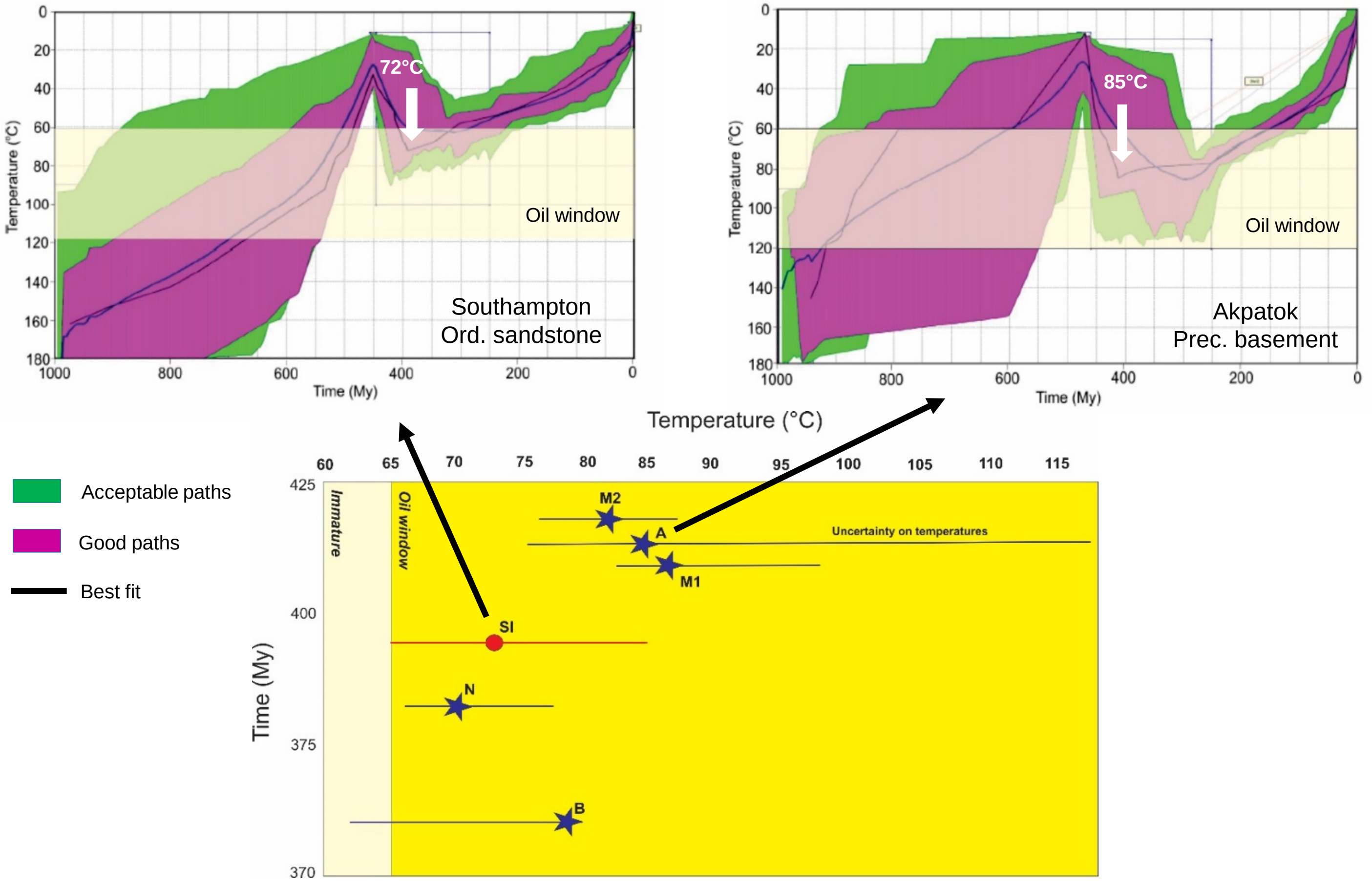
Based on VRo_{equ}, for the wells in central Hudson Bay, the threshold to oil window is in Lower Silurian

Apatite Fission Tracks (AFT)

Inverse modelling of AFT data provides a range of accepted and a best-fit values for maximum temperatures and time of maximum burial. Tracks length and density are controlled by partial to total annealing processes between 60 and 120°C and over 120°C, respectively

5 basement and 1 basal sandstone samples have generated data

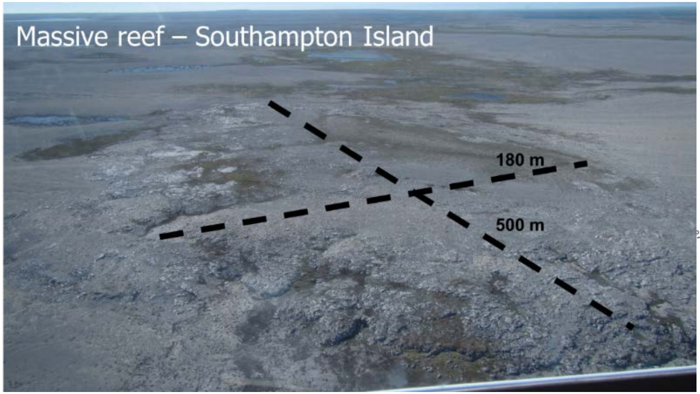


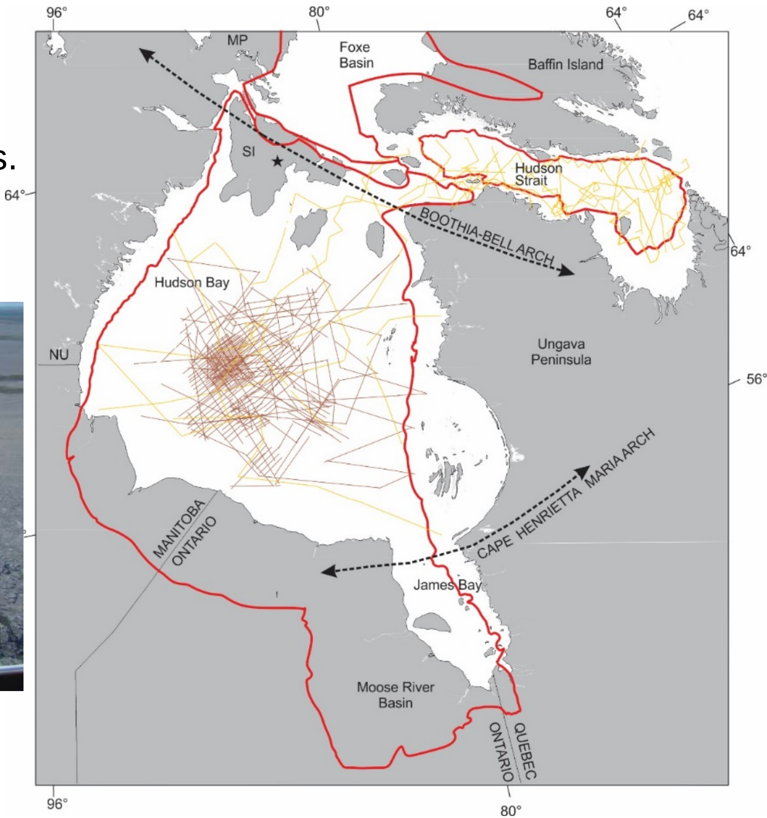


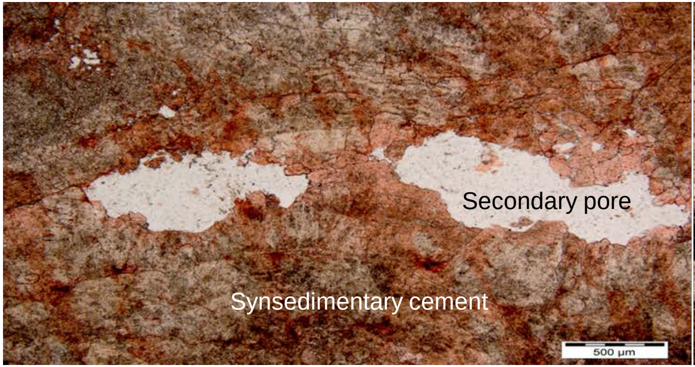
Pinet et al (2016) GSC Open File 8110

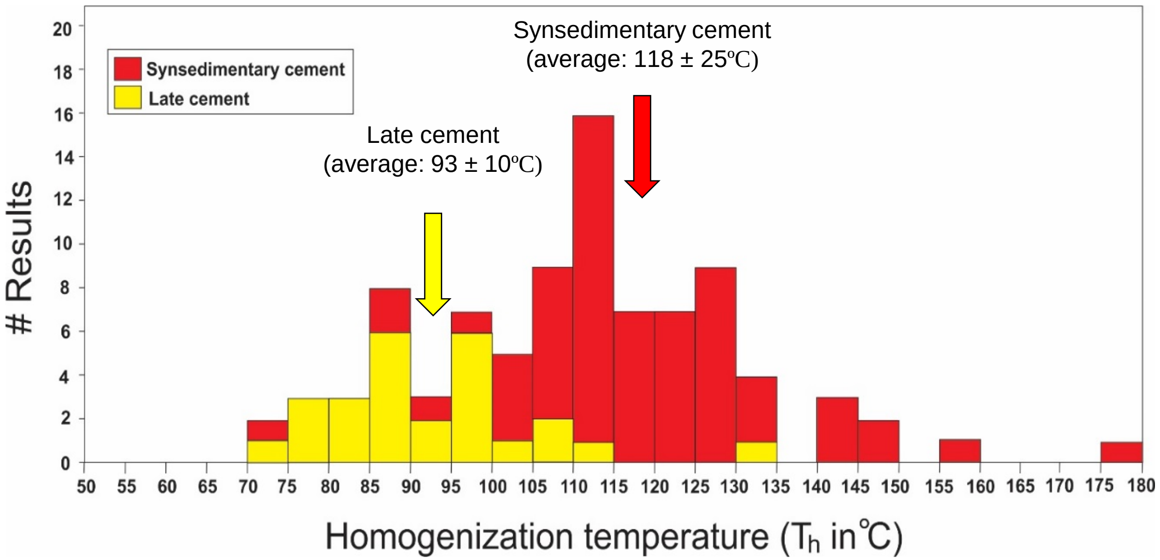
Fluid Inclusions

T_h and T_m measurements in 94 inclusions. Two type of cements, 1) synsedimentary marine and 2) late burial cements







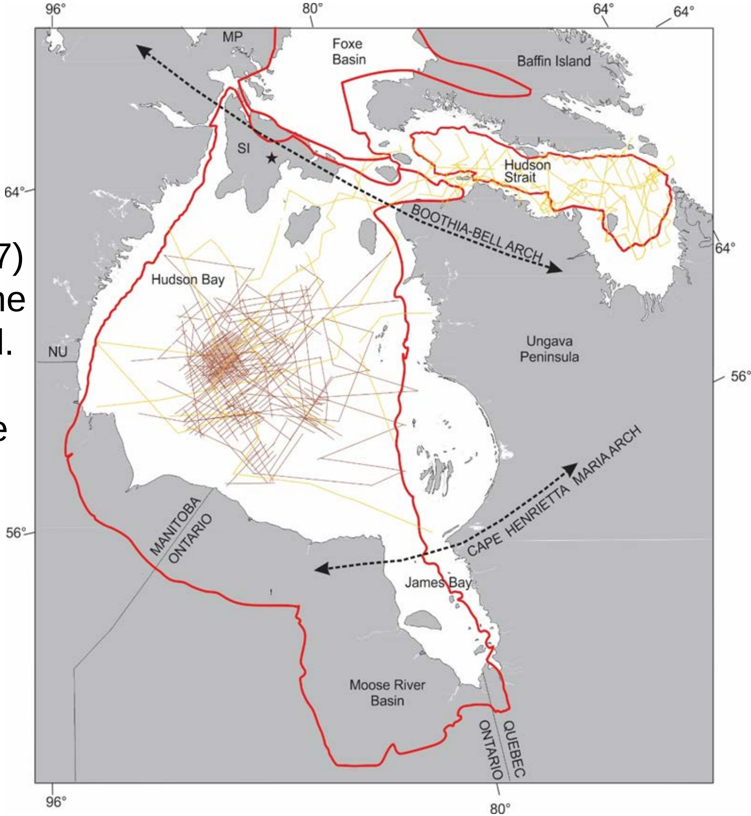


Lavoie et al. (2018)
Sedimentary Geology

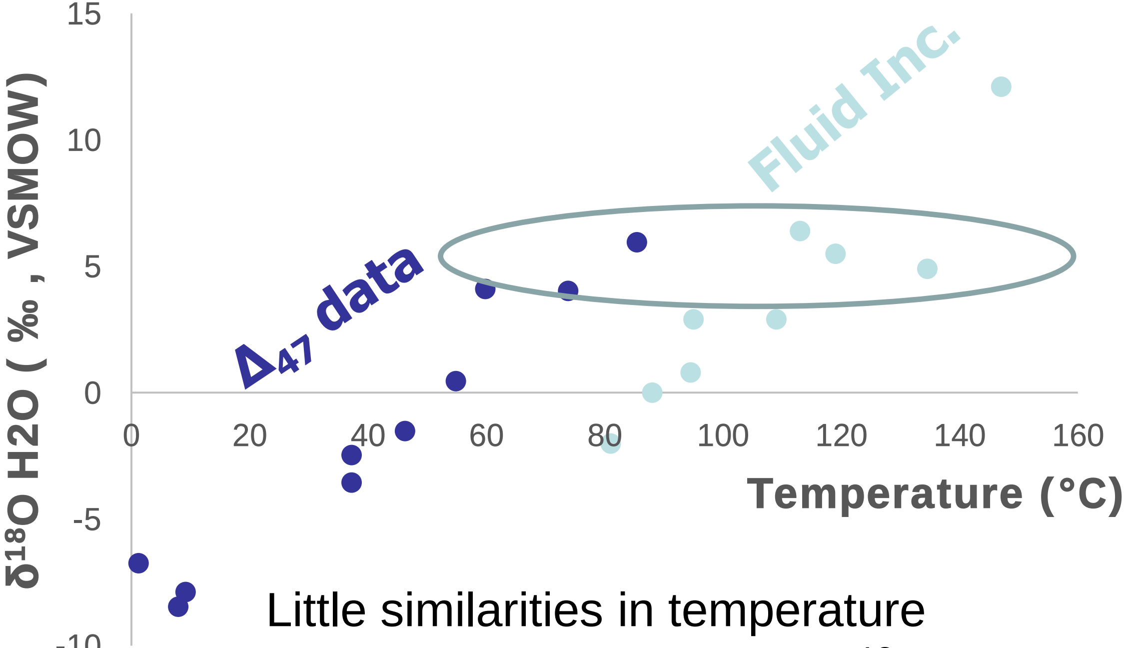
Clumped Isotopes

Bounded or clumped oxygen and carbon rare heavy isotopes in a carbonate crystal (Δ_{47} ratio in CO_2 (^{13}C+^{18}O+^{16}O) or mass 47) is thermodependant and independant of the isotopic composition of the diagenetic fluid. In contrast, the $\delta^{18}O$ ratio of calcite is controlled by both the temperature and the composition of the diagenetic fluid

Δ_{47} ratio was measured in early and late calcite cements in the Upper Ordovician reefs on Southampton Island from which fluid inclusions thermal data are available



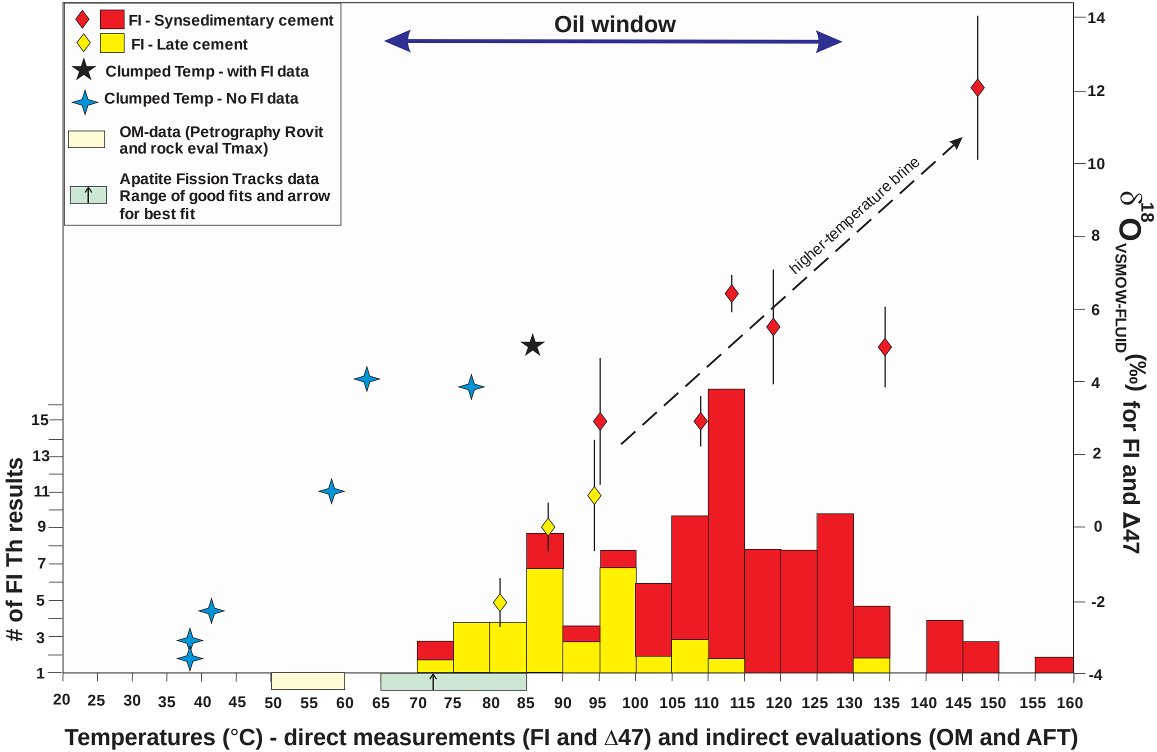
Preliminary parent water $\delta^{18}O_{VSMOW}$ estimates and temperatures from Fluid Inclusions and Δ_{47}



Little similarities in temperature

But the highest Δ_{47} suggest ^{18}O-rich brines

Divergent data sets from Southampton Island



Rock Eval (T_{max}) and reflectance (Vro_{eq}) *Immature -* Upper Ordovician source rock

Apatite Fission Tracks and Fluid inclusions (T_h): *oil window -* Upper Ordovician basal sandstone and reef late cements

Fluid inclusions (T_h) and Clumped isotopes (Δ_{47}): *Hydrothermal and high to low Temp* Upper Ordovician reef cements

Conclusions – The Verdict

The available data from Southampton Island for the evaluation of thermal history from diverse lithologies and material suggest that some approaches are imprecise or do not record properly the thermal history:

Organic matter in shale (Rock-Eval) and/or dispersed in rocks (OM Reflectance)

Uranium-rich apatite in sandstone and crystalline basement

Fluid inclusions in carbonates

Oxygen and carbon clumped isotopes in carbonates

Assuming proper analytical techniques, various organic- and mineral-based thermal analyses could yield significantly different results

Interpretation of thermal history has to be done with great care

THANK YOU !