APPENDIX J
Review of the Potential Geological Risks from Commercial Development of Unconventional Hydrocarbon Reservoirs in Newfoundland

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Report to the
Newfoundland & Labrador
Hydraulic Fracturing
Review Panel

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POTENTIAL GEOLOGICAL RISKS FROM COMMERCIAL DEVELOPMENT OF UNCONVENTIONAL HYDROCARBON RESERVOIRS IN NEWFOUNDLAND

Summary

For Newfoundland and Labrador, the main focus of any practical commercial interest in fracturing unconventional reservoir rocks lies in western Newfoundland where reserves may be located, and where developments may affect the environment. Elsewhere in the province, the ancient igneous and metamorphic rocks are not considered petroliferous.

For Newfoundland, in general, and western Newfoundland, in particular, background information on the geology of glacial and post-glacial sediments (soils) and of bedrock show that there is a very close relationship between the thick layers of soils and the distribution of potentially petroliferous rocks. Bedrock geology determines, delineates and separates resistant igneous and metamorphic highlands from the softer sedimentary bedrock and soil covered lowlands. In lower lying places, and where sea level is rising, coastal and river erosion of unstable sediment slopes should be identified and accommodated before any private and industrial developments happen. Many of these unstable sediment deposits are easily recognised and, with financial matters duly considered on a "go" or "no go" basis, these coastal locations may or may not be practically engineered, developed for decades of use, and, after, properly decommissioned.

Recommendation 1: Design and engineering of infrastructures on coastlines and other unstable ground should include additional provisions for properly constructing and decommissioning sites in a timely manner, and in particular, in places that will one day be at or below sea level.

In addition to their physical and mechanical properties as foundations for construction, the soils of western Newfoundland form a significant part of the potentially arable lands on the island, and also contain significant groundwater deposits laying upon and in bedrock. At depth, and beneath the soil cover, the bedrock may contain conventional and unconventional hydrocarbons. Given the importance of both surface and bedrock deposits for growth and diversification of the Newfoundland economy, published and other government summaries of surface and groundwater resources, water collection and distribution are at a very basic level. They do not contain any or enough information to properly address the quantity and quality of the water available for use in western Newfoundland, and specifically for areas where it will become important for future commercial applications and for private homeowner use. Provincial water records contain few or no baseline measures for methane, other hydrocarbons, stable isotopes, and other complex chemicals in groundwater deposits. Nor were there any reports discovered for the stratigraphy of water and for explaining the regional distribution of water deposit chemistry.

Outcrop geology for the region leaves no doubt that there are many places where hydrocarbons are naturally leaking into the surface and groundwater environment. Likewise, in other local settings, both here and on the mainland, the major ion chemistry of some wells is indicating greater influences from deep and now modified phreatic water or leakage of ancient formation water. Measurement of methane, other hydrocarbons, and formation water leaking into phreatic water is important for appreciating where and how many fractured rocks are present in the subsurface and where subsurface flow preferentially moves through aquifers. At this time, we have no way to ascertain if or whether properly engineered development of unconventional hydrocarbon resources will have any impact upon groundwater supplies in this region. Be it for farming or hydrocarbons, our near total lack of appreciation of the chemistry, distribution and movement of water in bedrock is an important unresolved risk. Collecting appropriate data for constructing a broader knowledge base for the water laying upon deeply buried petroliferous rocks contributes to our regional understanding of this valuable resource and for establishing the baseline conditions needed and expected for both private and commercial use.

Recommendation 2: Government agencies tasked with looking after our groundwater resources should become more actively involved in gathering and interpreting the quantity, quality and availablility of this valuable resource. This

should include systematic regional studies of the stratigraphy of water, the influences of formation water chemistry (e.g. As, salts, and hydrocarbons) on potable water, and better data on sustainable production of groundwater.

Recommendation 3: Appropriate, statistically relevant, groundwater analysis should be completed before any fracking is started. In particular, baseline conditions regarding the quantity of hydrocarbons in the local water will become a standard to be used as a decision making tool.

In bedrock studies of strata and petroleum there are many signs indicating potential for both conventional and unconventional petroleum deposits in the Paleozoic strata laying on and around the shores of western Newfoundland. To date, conventional petroleum exploration discoveries and targets are focussed upon the ancient Ordovician platform carbonate rocks (the Autochthon) of the Anticosti Basin, a passive margin basin, and on somewhat younger Carboniferous sandstone deposits of the Deer Lake and Bay St George basins, two smaller transtensional/transpressional subbasins of a larger borderland basin, the Magdalen Basin. A recent Federal Government estimate of the potential conventional resource suggests eastern Canada Paleozoic basins that contain appropriate analytical data have an in-place potential (P50%) for $1170x10^9$ m^3 (41 Tcf) of natural gas and $403x10^6$ m^3 (2.5 Bbbl) of oil (Lavoie et al., 2009).

The major unconventional exploration targets in Newfoundland and Labrador occur in the organic rich, mudstone and thin carbonate successions of the Cow Head and Northern Arm groups (Allochthon). Secondary unconventional targets may one day be identified in Labrador Group and St George Group rocks of the Anticosti Basin, in foreland basin deposits of the Winterhouse Formation beneath the Gulf of St Lawrence, and in Carboniferous mudstones of the Deer Lake and Bay St George basins and farther offshore in the St Anthony Basin northeast of Newfoundland. The Federal Government analysts (Lavoie et al., 2009) suggest that none of these rocks contain appropriate background data for calculating a fully risked in-place potential.

For those rocks that are under consideration at this time, and wherever they are seen, the strata of the Allochthon are very deformed from syndepositional tectonics (slumps) and from multiple episodes of structural deformation during the different phases of mountain building. In western Newfoundland, there is no particular controversy about the formation and occurrence of “source rock reservoir” hydrocarbons in the Allochthon in this region. There are very different views about the quantity of hydrocarbons and whether recovery from intensely fractured rock is possible. In any particular place where the Allochthon is seen in outcrop as exposed thrust fault bounded slices, the fine-grained petroleum bearing rocks are now significantly deformed and with laminae, beds, folds and slices often separated from one another by many water wet fractures. Oils shows are a common occurrence across this region. Basically, these rocks are unlike many, if not all, other unconventional reservoirs. In those places elsewhere in North America and where commercial, unconventional recovery is achieved from petroleum systems known as “continuous, basin centred accumulations” and from “source rock reservoirs”, the strata are organized, layered with other surrounding seal rocks and interstitial water, and simply jointed. Together, this keeps hydrocarbons in place – that is trapped by lithologic and hydrostatic seals. For rocks in the allochthon, on the west coast of Newfoundland, and where fractures are much more complex – that is ranging in size from regional thrust faults to microscopic cracks along and across bedding and grain boundaries, it is not clear if any significant lithologic seal exists – it may simply be an imperfect, and leaky hydrostatic seal.

To work toward understanding if any seal exists to keep hydrocarbons trapped and what if any actions can be taken to recover hydrocarbons, a much better appreciation of physical and hydrodynamic properties of this entire body of rock is required. In my opinion, at this time, this body of data is very limited and of little use in guiding large developments. At some point subsurface demonstration tests will have to be conducted to determine if commercial recovery is possible without compromising any of the surface and potable groundwater environment. Commercial success in this programme offers the prospect for large rewards, but should only happen if adequate precautions are demonstrated. In my opinion, and with our limited understanding of trace elements, pathogens and hydrocarbons that are naturally present in the local surface waters (a Government matter) and with the products that may be released from inadequately engineered hydrocarbon exploration and development (an industry and Government matter affecting the public), we are not at a point where general approvals should be granted.

Recommendation 4: Government efforts towards building greater industrial capacity in this part of Newfoundland and Labrador should include work with industry to understand these natural resources and to help define appropriate and safe recovery strategies. Logically, this should include better measures of (1) the size, shape and quality of this potential resource, and (2) measures to confirm recovery is possible in rocks with complex structures and without compromising the quality of the surface and groundwater environments.

DISCLOSURE

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1. I hold the following degrees:
   a. B. Sc. (Honours) Geology (1974) University of Toronto, Toronto ON.
   b. M. Sc. Geology (1978) University of Toronto, Toronto ON.
   c. Ph. D. Geology (1982) University of Calgary, Calgary AB.

2. I am a registered professional:
   a. Professional Geologist (P. Geo.) Province of Newfoundland and Labrador

3. I am a member of the following professional and scientific organizations:
   a. Professional Engineers and Geoscientists of Newfoundland and Labrador (PEGNL)
   b. Geological Association of Canada (GAC)
   c. American Association of Petroleum Geologists (AAPG)

4. In total, the largest part of my research has been directed towards understanding the regional stratigraphy, sedimentology, age and thermal maturation of petroliferous strata in eastern Canada. I do not currently hold any grants from oil industry sources. For the last 15 years, my grants from Federal and Provincial agencies (GSC and PEEP) are tied to understanding the geology and resources of Paleozoic sedimentary strata on and around Newfoundland and Labrador and in support of field and laboratory training for undergraduate and graduate students.

5. I am not currently consulting for any mining companies, oil companies, environmental service companies and agencies, or for government surveys. Work completed for these organizations has been directed towards understanding the distribution and quality (age and maturation) of a proven or probable resource or target, or for a modern environment assessment.

POTENTIAL GEOLOGICAL RISKS FROM COMMERCIAL DEVELOPMENT OF UNCONVENTIONAL HYDROCARBON RESERVOIRS IN NEWFOUNDLAND

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Introduction

Asked by the Newfoundland and Labrador Hydraulic Fracturing Review Panel (NLHFRP) to prepare and offer an opinion on the geological risks and rewards associated with unconventional hydrocarbon developments in NL, the following report is a summary of surface and bedrock conditions that may have some potential risk for an unacceptable outcome if due diligence, care and consideration of long term ramifications are not addressed. Some of the conditions identified here are practical matters surrounding such things as roads, water- and oil-well construction. Other broader questions are tied to decommissioning of old infrastructures (and this may also include other industries outside the oil and gas sector) and to understanding the hydrology and maintaining the integrity of subsurface hydrocarbon reservoirs and other fluids during and after extraction is completed. In application, these matters are likely to be nuanced government policy matters best answered by our elected legislated institutions. The larger part of this summary examines my opinion of the state of bedrock and surface geology studies, the level of research that has been completed and on specific research that should be completed if unconventional exploration and development approvals are granted.

The following material is divided according to the medium being evaluated, with some properties of surface materials and water being addressed before bedrock and their hydrocarbons. In both sections there are geographic places and topics where it is not always possible to easily separate the contribution of bedrock, formation water and petroleum from influences upon surface materials.

Quaternary and Recent Surficial Materials – Soils and Water

Surface geology and hydrology questions to be addressed in this report:

(a) Risks associated with the disposition and nature of Quaternary and post-glacial sediments
(b) Risks associated with the hydrological and hydrogeological disposition of potable or useful surface and subsurface water, including the presence of known brine springs and oil seeps.
(c) Geomorphological risks related to siting of multi-well development sites.

Background on Surficial Materials

In Canada, and in glacial times, glacial ice formed and moved from two major sources – alpine glaciers and ice sheets. As the name implies, alpine glaciers occur in mountainous regions and still exist in the in western Canada, Nunavut and northern Labrador. The larger body of glacial ice cover over North America formed as massive, very thick ice sheets radiating from specific regions of Canada (Dredge et al., 2014); the Cordillera, east and west of Hudson Bay, Ellesmere Island, Baffin Island and Newfoundland (Fig. 1). The Newfoundland Ice Cap formed over the island sending radiating glacial lobes and sediment into the Gulf of St Lawrence to the west, the Laurentian channel off the south coast of the island, east onto the Grand Banks and northeast into the North Atlantic (Dredge et al., 2014). Steep sided fiords and large bays and finger lakes are clear evidence for glacial ice carving along paths of least resistance. Less obvious are changes to the elevation of the land and coastlines from (a) relatively rapid rebound of the Earth's crust below formerly glaciated regions and (b) slow sinking of the Earth's crust after the rebound finished and seas filled with glacial melt water. In northern parts of the island of Newfoundland and all of Labrador, Baterson and Liverman (2010) show the crust is still rising, whereas in southern and eastern Newfoundland, the Earth's crust finished its post-glacial rebound and is now slowly sinking (Fig. 2).

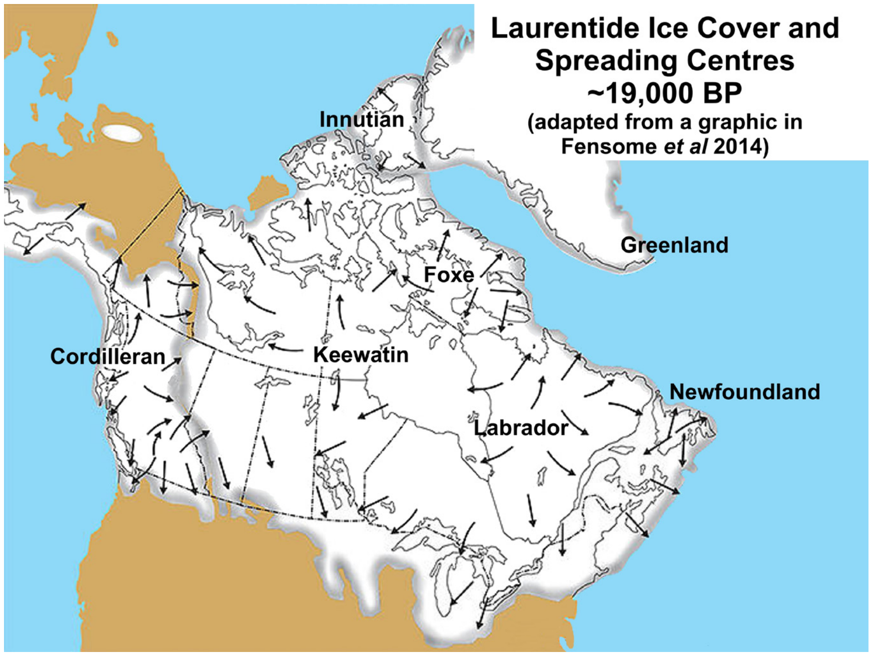

Figure 1. Glacial map of Canada shortly after the peak of the last glaciation and showing the major spreading centres for glacial ice. Two ice caps are present in Newfoundland and Labrador. The Labrador ice cap has its spreading centre over northern Quebec. The Newfoundland Ice Cap positioned over central Newfoundland sent ice radiating into the Gulf of St Lawrence, the Laurentian Channel, Grand Banks and the North Atlantic northeast of the island. Adapted from Fensome et al. (2014).

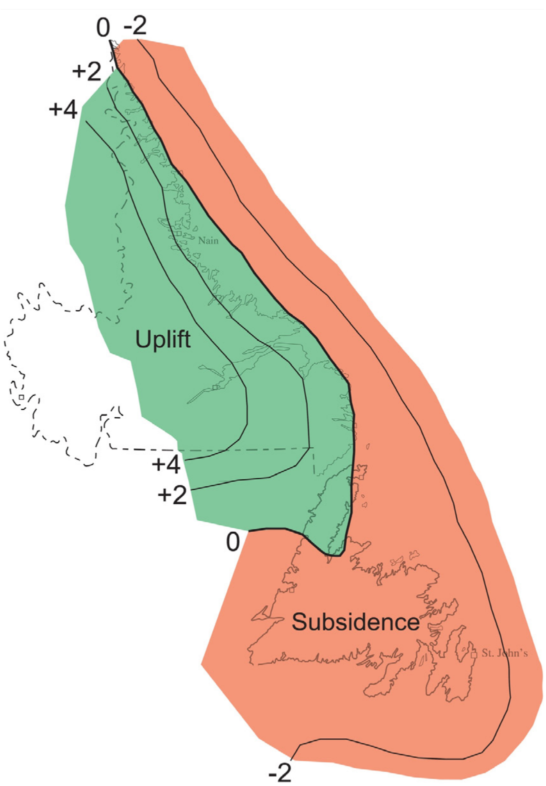

Figure 2. Generalized map of present day crustal uplift and subsidence (mm/year) from isostatic rebound (Batterson and Liverman, 2010).

In addition, during glacial times when polar regions were covered with up to 4 km of ice, the seas were more than 100 m shallower and large parts of our continental shelves were exposed. With significant amounts of glacial ice melting from about 20,000 to 7,000 BP, Shaw et al., (2002) show the sea slowly climbed across the edges of the continents (e.g. the Grand Banks) and to about their present positions (Fig. 3). With the combined changes from the rebound of the Earth's crust and seas rising, and under normal post-glacial conditions, parts of Newfoundland and Labrador are continuing to rise and stay ahead of sea level change (Labrador), whereas other places, in the south and east of the province, coastal areas are slowly returning to the sea. For example, Shaw et al. (2002) show in the last 7,000 to 8,000 years, as glacial rebound slowed, sea levels have steadily climbed 20 to 30 m up the ancient coast of the Avalon and Port au Port Peninsulas (Fig. 4). On shorelines delineated by sea cliffs this is hardly noticed. In contrast, on low lying coasts, as, for instance the Port au Port Peninsula or the St Lawrence Lowlands at Riviere du Loup (Quebec), the evidence for sea-level rise across beaches and salt marshes is everywhere.

In relatively recent times and with climate models indicating a changed and rapidly warming world, glaciers and ice caps will melt faster, warmer ocean water will expand and occupy a larger volume, and sea levels will rise at a relatively faster rate. With additional water from ice melting from Greenland and Antarctica, all low lying coastal areas of Newfoundland and Labrador will begin to be flooded more rapidly by the rising seas. In a Batterson and Liverman (2010) assessment for Newfoundland and Labrador, and using changes predicted from the IPCC (2007) as guidance for provincial and community planning strategies, in the next 100 years, the most southern and eastern parts of the province will experience a sea level rise of more than 1 m; western and northern Newfoundland will have about 1 m of sea level rise; and most of Labrador may experience less than 1 m change (Fig. 5). This rate of change is more than two times faster than that measured from the 20th century. In the south, all permanent or semi-permanent infrastructure on or near shorelines will be impacted by this phemomenon. Be it roads, wharfs, homes, or business activities, decisions for location, design, construction and removal of new infrastructure on or near the sea should anticipate this eventuality.

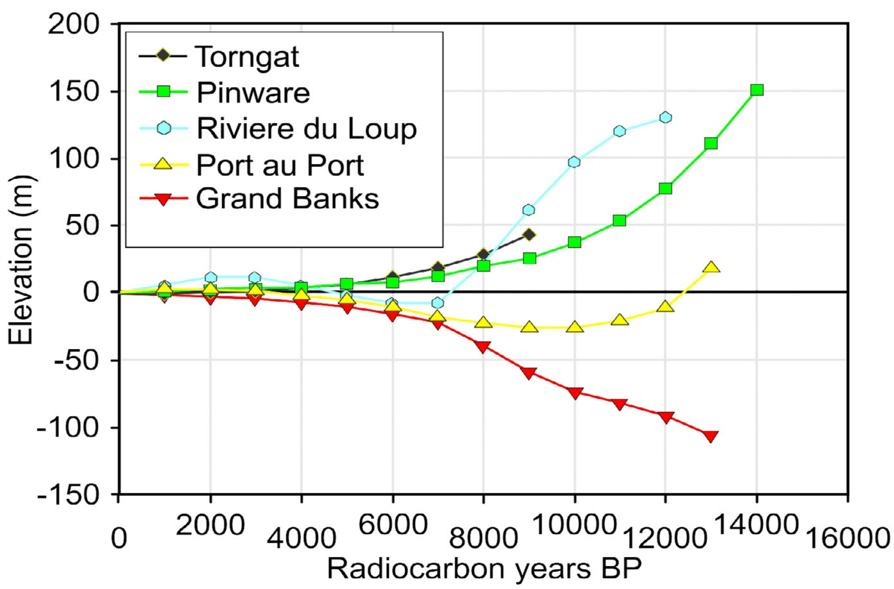

Figure 3. Graph showing relative position of sea level after glacial ice retreated from eastern Canada about 14,000 BP. At the edge of the Grand Banks, where there is little or no crustal rebound, sea level was more than 100 m lower at about 13,000 BP, and rising to today's position. In Pinware, on the Labrador coast, post-glacial crustal rebound of about 150 m has kept ahead of sea level rise. For Port au Port in western Newfoundland and Riviere du Loup in Quebec, modest crustal rebound has been outpaced by sea level rise and both areas are slowly becoming submerged. In the last 10,000 years sea level has climbed more than 20 m over the Port au Port area. Figure from Shaw et al. (2002).

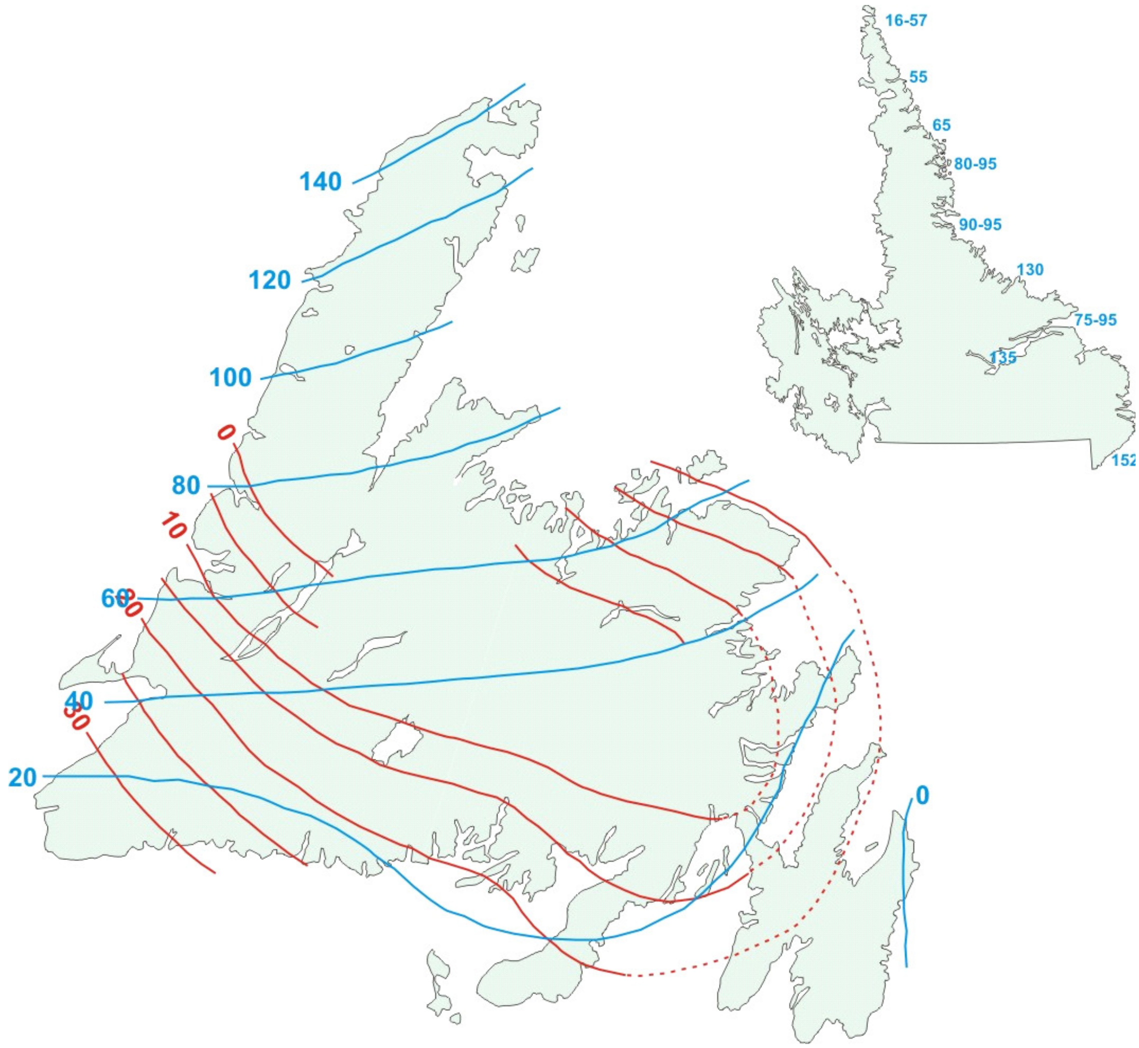

Figure 4. Isostatic rebound (blue lines) and sea level rise (red lines) across the island since the glaciers retreated from eastern Canada. Gains, blue lines, measured against losses, red lines, provide a crude indication of advancing or receding coastlines. Figure courtesy of Martin Batterson, (2015).

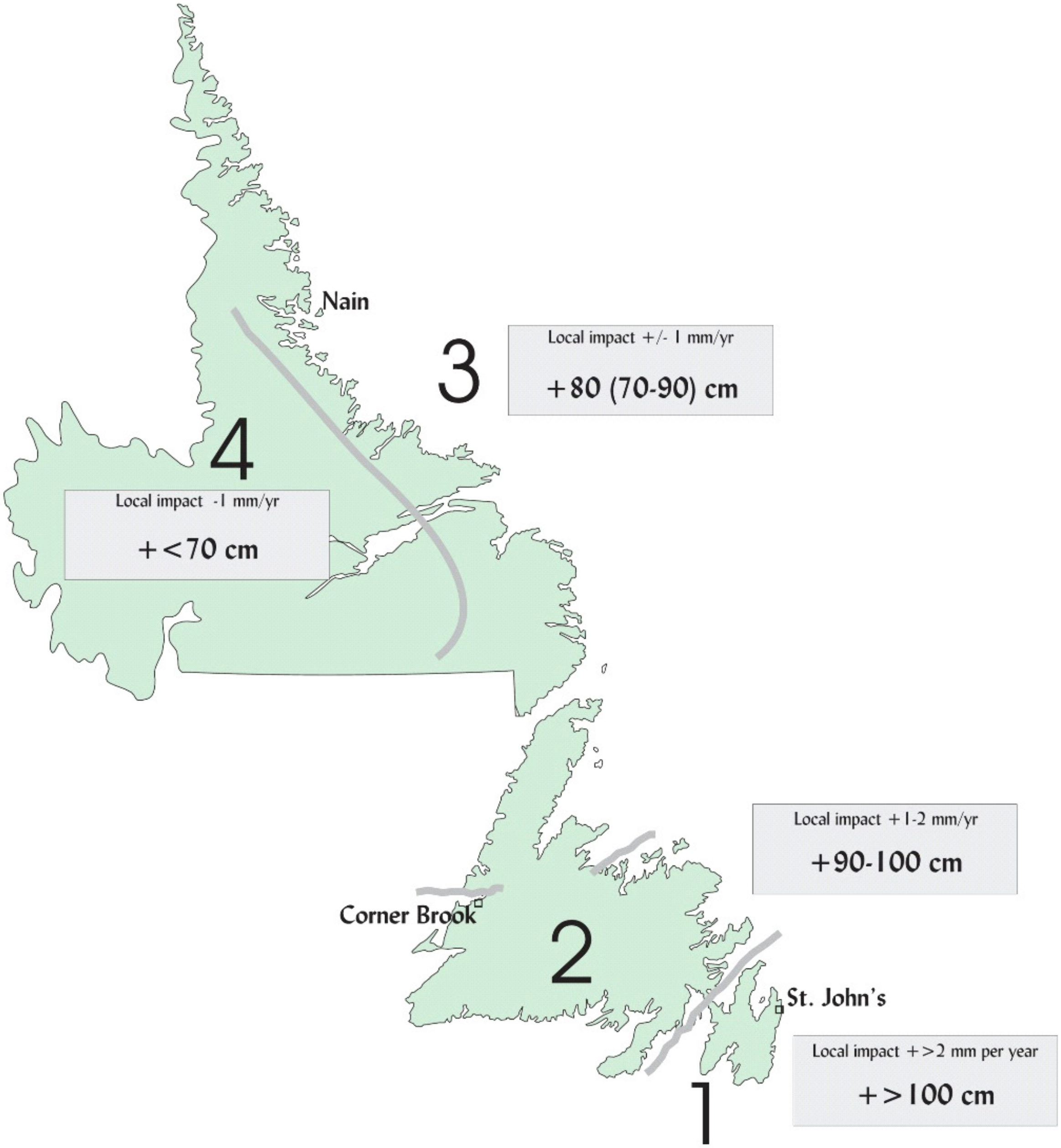

Figure 5. With global warming and predictions for glacial ice melting and seas warming, sea levels in Newfoundland and Labrador are predicted to exceed isostatic rebound rates by a wide margin and climb across the shores of Newfoundland by about a metre, and more in the southeast. Permanent and semi-permanent coastal infrastructure will have to be engineered for this eventuality. Figure from Batterson and Liverman, (2011).

Geomorphology

The physical evidence for earlier glacial activity is present throughout the province of Newfoundland and Labrador and including extensive deposits offshore. However, given the focus for this report, most descriptions and discussions will be limited to examples from the western regions of the island of Newfoundland. With well over 100 years of research into the glacial materials covering the island, we are fortunate to have a relatively robust body of literature and maps to basically and generally describe surface materials and properties. Three compilation maps by Liverman and Taylor (1990; 1990a), and generated by the Geological Survey of the Newfoundland and Labrador Department of Natural Resources, outline our surface materials. In recent years, and under direction of the Department of Environment and Conservation, consultants AMEC (2008; rev. 2013) and Jacques Whitford (2008) used or recompiled these maps to address future needs for agriculture and water. In this review for the Fracking Commission, the maps by Liverman and Taylor (1990a) are likewise simplified and reconfigured to show the distribution for 7 major types of surface material (Fig. 6). The strength and other mechanical properties of these surface materials and their ability to hold and transmit fluids can have a bearing upon urban, agricultural and industrial activities. For some deposits, and in some specific situations, additional background work to determine a subset of baseline conditions may become a recommendation of this Commission. Some of these areas will be identified, described and discussed elsewhere in this report.

In terms of distribution of surface materials, Newfoundland comes by the name “The Rock” honestly. For the most part, the island is thinly covered with soils and other loose materials of glacial and post-glacial origin. By far, the largest part of western Newfoundland is exposed or thinly covered “Bedrock” or a thin (less than 1.5 m) “Diamicton veneer” (Fig. 6). Diamicton is a descriptive name applied to poorly sorted sediment of mixed boulders, gravel, sand, silt and clay (fines). Interpreted, a widespread Diamicton veneer might be a thin, compacted Basal Till once laying at the contact between bedrock and glacial ice or less compacted Till left on a bedrock surface as stagnant glacial ice melted away. In regional extent, the largest exposures of bare rock with thin or no glacial deposits are found on the PreCambrian and early Paleozoic highlands of igneous and metamorphic rock, and not generally in any area where any hydrocarbons are anticipated to occur. The thin bedded character of this diamicton precludes any practical use as a groundwater source. In addition, with exposed bedrock, surface runoff will not be modified in any way before it enters the groundwater system.

Thick “Diamicton” (Fig. 6) tends to be found closer to the ancient glacial coastline of western Newfoundland and at other relatively lower elevations (e.g. the Deer Lake Sedimentary Basin and parts of the Bay St George Sedimentary Basin). Tending to be many metres to tens of metres thick, and visualized as thick sheets, hills and linear ridges these deposits are thought to be thick basal till filling depressions on an irregular bedrock surface and moraines formed on the sides and ends of glacial lobes. Offshore, on the Continental Shelf and in the Gulf of St. Lawrence, these ridges mark the full extent of continental and island glaciation. Onshore, they record pauses in the history of melting and retreat of glacial ice more than 10,000 years ago.

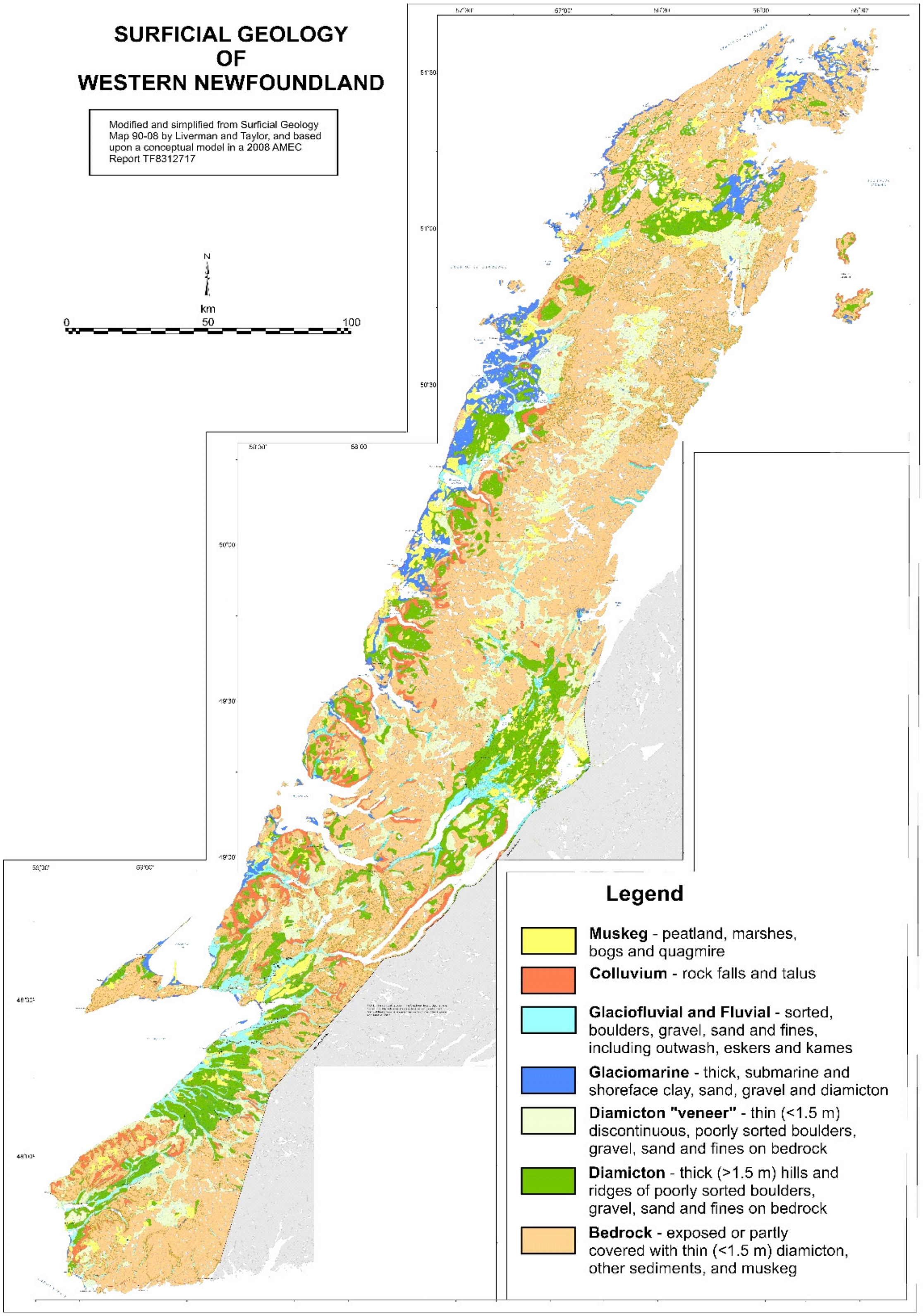

Figure 6. Surficial Geology Map for western Newfoundland generalized from compilation maps by Liverman and Taylor (1990). Areas where surface deposits are thick tend to be located upon rocks that may be petroliferous.

Onshore, these sediments can be a source for potable water and places where agriculture might be possible. So too, some of these deposits are located in the regions where hydrocarbon exploration is a possibility.

Thick beds of sorted and stratified glacial and post-glacial deposits (Fig. 6) are most often located in lower lying areas where glacial rivers once flowed or glacial and early post-glacial seas and lakes once covered the land. With few exceptions, and for example, the limestone barrens on the northern end of the Northern Peninsula (Fig. 7), nearly all of the flat, low lying coastal areas to as many as 150 m above present day sea level (depending upon the amount of post-glacial crustal rebound) have a thin or thick cover (tens of metres) of glacial marine and lake muds, and sands from glacial shorelines, beaches and rivers. Where conditions permit, these deposits are in large part the source for better drained and more readily tilled soils and as another possible source for potable groundwater. Sorted sand and gravel deposits from glacial beaches and rivers are also mined for road and building construction. In western Newfoundland, nearly all of these marine, lacustrine and glaciofluvial materials lay upon bedrock that holds some potential for hydrocarbons and other sedimentary mineral deposits.

Figure 7. Limestone Barrens at Cape Norman, Northern Peninsula. An elevated, washed, flat lying Cambrian carbonate platform with modern weathering opening joints and developing a karstic terrain with subterranean streams.

Once exposed by the ice or retreating seas, some particularly flat areas on both the highlands and lowlands, can develop as Muskeg. Used here, the map term “Muskeg” (Fig. 6) encompasses peatland, bogs, swamps, fens and quagmires. These deposits are persistently wet, not normally in areas that are inhabited, nor is the water commonly used for drinking. Muskeg water tends to be brown in colour and with taste and quality affected by organic humic acids and other modern naturally generated oils formed as by-products of plant decay. Muskeg is annually used for harvesting wild berries and more recently, in some places, for growing commercial crops (e.g. cranberries). Some Muskeg is located above areas where hydrocarbons may be discovered. In addition, there was at least one proposal submitted to the Provincial Government for review and explicitly for mining peat in the Stephenville area.

Colluvium is a geomorphic term used to describe modified glacial and post-glacial sediments and rocks on or adjacent to steep slopes. Mechanically unstable, colluvium is best recognised as talus, old and new rock falls and thin muddy slumps and debris flows. The surficial geology map (Fig. 6) show this material as linear deposits on the shores of fiords and finger lakes facing the Gulf of St Lawrence and as wide ramps of debris surrounding faulted and uplifted blocks of ancient crust. On steep hillsides colluvium may be forested or exposed as barren skree. However, once logged or burned, and exposed to runoff from rain and meltwater, some formerly forested colluvium can become unstable.

Surface and Groundwater

There are three sources of water available for consumption, agriculture and industrial use. These are surface water, phraetic water and formation water. As the name implies, surface water comes directly from precipitation, and flow into ponds and rivers. Groundwater recovered from wells is known as phraetic water – that is water that has slowly seeped into the substrate from precipitation. Formation water is water that is all but completely isolated from modern surface water, and held in rocks for millenia.

Surface waters from protected watersheds, and described in Government files and consulting reports www.env.gov.nl.ca/env/waterres/reports/index.html, are major sources for community water systems for drinking and for agriculture. Inasmuch as best practices for protection, collection and distribution are regulated targets, surface water may become contaminated by pathogens (bacteria and parasites) from nature (flooding and migrating animals) or from inappropriately applied practices from humans (nearby farming, sewage and other waste water disposal). Regularly issued public advisories and orders from Government www.env.gov.nl.ca/env/waterres/quality/drinkingwater/index.html, track the quality of the surface water and the upkeep and utilization of the provinces system of waterworks.

Surface water is significantly influenced by local soils, exposed bedrock, and organic compounds leaching from wetland drainage (AMEC 2013). In addition, surface waters will collect airborne particulate material (smoke, sea spray, and other chemicals) and exchange some gasses. Some aspects of water quality can be directly related to the nature and distance from urban and industrial sources. (Christopher et al., 1994; Robbins and Burden, 1996; Wadleigh et al., 2002). Turbidity, colour and taste are among the most frequently cited issues affecting the overall quality of surface and ground water. These parameters are often considered “aesthetic” and not necessarily a health or environment issue. Acidity, measured as pH is likewise a closely watched item. Low pH associated with acid rain, bog waters, boreal forests, and in some ponds and streams, will lead to corrosion of pipes. Neutral to slightly basic surface waters tend to be associated with exposed limestone terranes and other related calcareous sedimentary strata commonly found on the west coast of the island. In contrast, clastic, igneous, and metamorphic terranes have a tendency towards generating acidic waters. The minerals in these rocks may contain smaller quantities of available naturally occurring buffering agents.

Macro and trace element chemistry and other tests for colour, turbidity, and specific organic chemicals collectively address hardness or softness of the water, some aspects of taste, and the presence and quantity of certain dissolved nutrients and toxins. Toxic metals are occasionally found in water from some watersheds. A consulting report covering parts of this particular matter (Conestoga-Rovers, 2010) suggests that while on the one hand serious, the issue of toxic metals tends to be local and infrequent. Conestoga-Rovers (2010) suggested that the Province address these matters on a case by case basis.

The second major source of water, and namely phraetic water, is water that has seeped into the earth from above. Normally, it is fresh potable water, but can become contaminated with pathogens, and organic decay products, tanins, humic acids, natural biologic and geologic sourced methane and oil and significant quantities of naturally dissolved minerals. Private, shallow wells and sometimes called “dug wells” are also sites where water quality may be impacted by runoff and other effluent generated by seasonal weather (e.g. wet or dry summers and winters), larger floods (e.g. tropical storms), construction (e.g. new roads and other urban infrastructure) and improper sewage disposal. Several consultants reports (AMEC, 2008, 2013; Conestoga-Rovers, 2010; AECOM, 2013) and one university report (Sakar et al., 2012) specifically comment upon the growing problem of shallow wells contaminating potable water supplies and explicitly from (a) poor design, (b) poor construction, (c) no or limited servicing and (d) aging, unprotected infrastructure.

Deeper, phreatic water wells, also called "drilled wells" may be shallow, short holes and sampling seasonal infiltration, or deeper holes in the phreatic water aquifer and where water tends to be free of surface contaminants. As with surface waters, routine examinations for macro and trace element chemistry and other tests for colour, turbidity, and specific organic chemicals collectively provide guidance on the utility of any particular well and on recommended treatments for hardness or softness and for some aspects of taste, and toxicity.

Across Newfoundland and Labrador, the Provincial Government tests for basic water chemistry show that some rock units and including the glacial deposits derived from these rocks may carry specific suites of dissolved ions. In general, water from all carbonate rocks show elevated levels of dissolved calcium and bicarbonate ions. In contrast, siliciclastic rocks and igneous materials have higher levels of sodium and potassium ions. The Carboniferous strata of the Bay St George Sedimentary Basin south of Stephenville include sandstones and carbonates and may also contain salt and gypsum deposits that may taint the well water. Consequently, some wells in this region may be hard water with a high pH (basic) and contain elevated sulfate, bicarbonate, sodium and chloride values. Wells and springs with this composition are not necessarily potable and may have to be abandoned or sent for secondary treatments to reduce toxicity.

Much older carbonate and clastic rocks on the Port au Port Peninsula and along the west coast of the Northern Peninsula may also be hard calcium and bicarbonate enriched water and with neutral or basic pH . In reviewing the consultant's reports, it is not generally clear whether elevated sodium and chloride values encountered in some wells is sea water moving along fractures, ions coming from overlying glacial marine strata or ancient formation water leaking from other deeper bedrock sources. In addition, in this review of government files and other literature, I could not locate any groundwater reports that address whether there is a stratigraphy for water deposits in western Newfoundland.

The large igneous, metamorphic and clastic sediment terranes in western Newfoundland are largely associated with the faulted and folded strata of the older parts of the Appalachian mountains. Collectively, these rocks are also known as the Allochthons. Phreatic water from these rocks tends to be soft water with low pH (acidic) and no dominant metallic cations. Trace element chemistry is generally diagnostic of source terranes that lack carbonate minerals. Overall, this water is considered very good. That said, these particular rocks, and also the glacial sediments derived from these beds, have an increased tendency to contain dissolved toxins - and in particular arsenic. Regulations exist to cover due diligence and for reporting concerns about water quality.

The last and perhaps the largest source for groundwater is formation water. This may sometimes be accessed in deeply drilled water wells and it may be fresh potable water, but more often formation water is naturally loaded with elements and compounds derived from a long geological history of isolation from any surface water and from reactions of formation water with minerals. The highest and most obvious dissolved inorganic materials in formation waters are ions of sodium and chlorine rendering the water into saline brines and undrinkable. In other circumstances, naturally occurring formation water may be enriched with geologically produced hydrocarbons, sulfate, arsenic, lead, and uranium, to name but a few of many naturally occurring dissolved elements, ions and chemicals. Elsewhere, in Quebec, and at depth, these types of rock formations are included among other tightly sealed strata and to be used or proposed as sites for carbon dioxide and other fluid disposal (Ngoc et al., 2014).

Questions

(a) Risks associated with the disposition and nature of Quaternary and post-glacial sediments.

The upland regions, where bedrock with a thin veneer of diamicton is found, have few, if any, environmental risks from petroleum development. By far, the largest part of western Newfoundland is essentially bare Precambrian igneous and metamorphic rock and well outside any petroleum interests. The upland regions near Cape St George and at Cape Anguille, have been drilled for hydrocarbons. The Union Brinex Anguille H-98 well penetrated nearly 2.5 km of tight red sandstone before operations ended (Harris, 1973). The Port au Port #1 well, sits above a conventional exploration target laying more than 3.5 km down and beneath several hundred metres of granitic rock. In the last 20 years, the production of conventional hydrocarbons from that site has been erratic and small.

The thick Quaternary and post-glacial deposits, at low elevations and oftentimes in coastal settings, are more complicated than their glacial and post-glacial counterparts found at higher elevations. In some places (Fig. 7), little or no sediment remains on the wave washed glaciated surface. Here, the exposed surface of weathered and fractured bedrock hosts shallow subterranean streams, and fractures will contain groundwater that may be potable. The thickness, structure, porosity, permeability, and metamorphic grade for the rocks of the limestone barrens of the Northern Peninsula make them unlikely candidates for any hydrocarbon exploration.

Elsewhere, farther south on the Northern Peninsula and onward towards Port au Basques, many coastal areas may be covered with a thin to thick blanket of submarine till, submarine and terrestrial glacial moraines, outwash, raised beaches and other pro-glacial and post-glacial marine and non-marine sediment (e.g. Muskeg). The thickness, physical, mechanical and chemical properties of these unconsolidated sediments are varied and with some of the marine strata and muskeg easily changed to weak, soupy, thick fluids susceptible to sliding.

While infrequent, and spectacular, the repeated slides at Daniel's Harbour and over at least the last 10 years (Fig. 8) are not unique events. An adjacent, older, and now vegetated slide scar along that particular stretch of shoreline, and indeed across other parts of this region indicate that all low lying coastal and fluvial areas containing thick deposits of glacial marine strata regularly collapse by erosion from storms and floods (Fig. 9).

To be clear, slides are not at all frequent events and, beyond the obvious, certainly not easy to predict. In most places, forested, farmed, and exposed glacio-marine strata and other soils are very stable platforms and capable of supporting heavy loads encountered in many urban and industrial uses. Elsewhere, collapsed glacial beds along rivers, in tidal channels and sea cliffs, and in peat in marshes and fens, show, that when saturated, some landscapes are unstable, and unable to carry heavy loads. Reasons for specific collapse events can be complicated by natural and human activities (e.g. clear-cutting, urban and industrial pits and trenches, and disposal of septic waste and other fluids), but some general principles concerning slope stability may also be identified. Catto (2011) compiled and categorized the sensitivity of Newfoundland coastlines to erosion. Obviously, prudence, with appropriate background geology and site engineering, can be practical virtues before deciding if, how, and where new infrastructure can be installed near coasts and rivers. Should such developments happen, mechanisms are available for long term monitoring of land and foundation stability.

Figure 8. Shoreline collapse of glacial-marine sea cliffs at Daniel's Harbour Newfoundland. Photo from www.thetelegram.com/media/photos/unis/2013/12/06/2013-12-06-09-47-55-A11-Daniels-Hr-Land-slide-1286.jpg

Figure 9. Crabb Brook, north shore Bay of Islands, with slump and collapse of glacial-marine strata. Many low lying coastal areas share the same general style of sedimentation laying upon Cambrian and Ordovician sedimentary rocks.

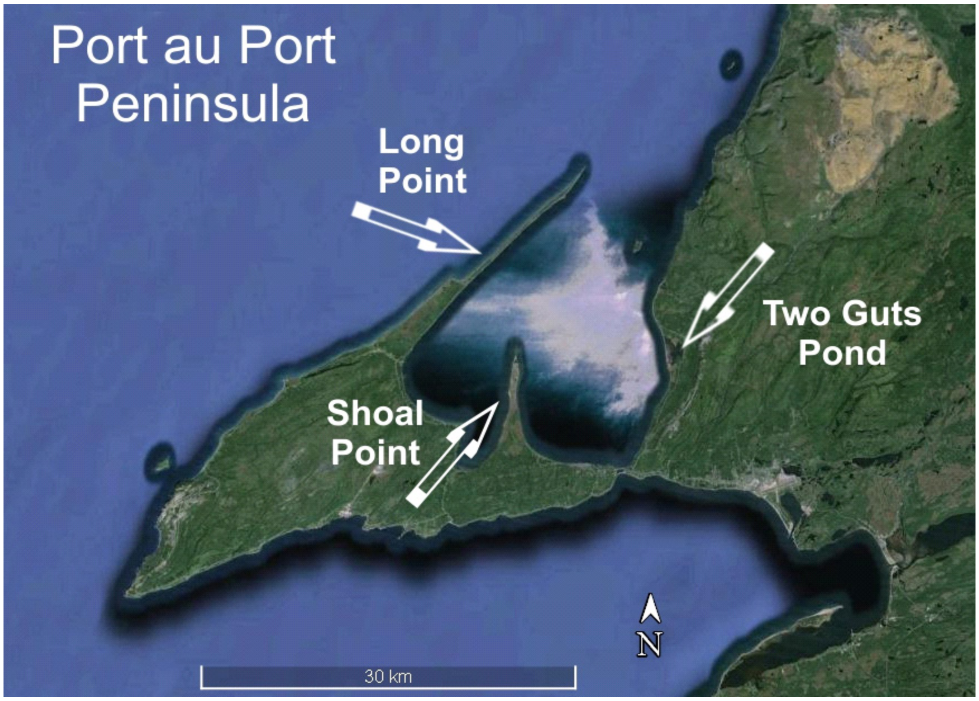

Figure 10. Google image of Port au Port Peninsula and adjacent Fox Island River area. Low lying peat bogs at Two Guts Pond and Shoal Point are eroding. Long Point is an elevated, rocky peninsula.

Figure 11. Peat bog, now eroding as higher sea levels undercut bog and its ancient buried forest.

In a contrast with the elevated sea cliffs of glaciomarine materials and diamicton, some other equally impressive coastal sites are the flat, extensive and well developed peat bogs on Shoal Point and around Two Guts Pond (Fig. 10). On these shallow coastal regions of Port au Port Bay, and where large blocks of peat are actively falling into the sea, these strata are 2 to 3 m of spongy peat laying upon a buried spruce and fir forest that is laying upon a bed of peaty soil and clean, well sorted marine sand (Fig. 11). On traversing inland from the cliff edge, and for as many as 30 m away from the beach, normal faults and other extensional fractures leave the peat as discrete broken and separated blocks, capped with distinctive dry or wet vegetation, and hosting small pools filled with water or simply drained, wet and drying mud (Fig. 12).

There is no reliable indication on when this rapid form of shoreface collapse started, and perhaps thousands of years ago, but faults appearing in the peat and many metres inland indicate that this style of erosion has not ended. Catto (2011) places coastal organic sediments - and in this instance raised peat beds, in a zone that is particularly sensitive to erosion.

Within the context of this report, a brief insight into the history of peatland erosion and of past and future impacts upon oil developments comes from an exploration report from Brown (1938) and indicating that then old oil wells, drilled into the Shoal Point bogs during the late nineteenth century, were already submerged and with oil leaking from a seep or an abandoned well. Today, the old Shoal Point #2 well (drilled by Golden Eagle – BRINEX in 1965 onshore and at ~2m above sea level and with a KB ~4.5m above sea level – see Golden Eagle, 1965; Fleming, 1970; AMEC, 2015), now appears at low tide as a tall pipe in several centimetres of water and several metres offshore. The top of the nearest peat is currently about 20 m east of this well (Fig. 13). Once the peat falls away, the sea rapidly expands across the now exposed strand plain.

Complicating this matter, and in 2015, as community and media reports attest, one of the remaining and exposed nineteenth century oil well casings was corroded, sheared by sea ice, and leaking small quantities of oil. The fragmentary nineteenth century records reported by Corkin (1965) and Fleming (1970) indicate all of the old holes were shallow (<300m) and some encountered small uneconomic quantities of oil at about 150m. In the nineteenth century, and without benefit of appropriate geology, geophysics and engineering, wildcatters would simply drill oil seeps with the expectation that the “pool” simply lay some distance below. Government has apparently assumed responsibility and costs for correcting the problems generated by this old, orphaned, broken and leaking well and are preparing plans for permanently sealing and burying this pipe (AMEC, 2015). Many other old, legacy wells are scattered across the west coast of Newfoundland.

The lesson from this particular style of coastal lowland, is that while 20th century coastal erosion is relatively rapid, and older small scale infrastructure is affected 50 or 100 years later, 21st century changes to coasts are predicted to occur at a much faster rate. Development plans for any coastal zone infrastructure, and construction, should include appropriate means and mechanisms for properly decommissioning, removing or sealing industrial sites after they have reached the end of their useful life.

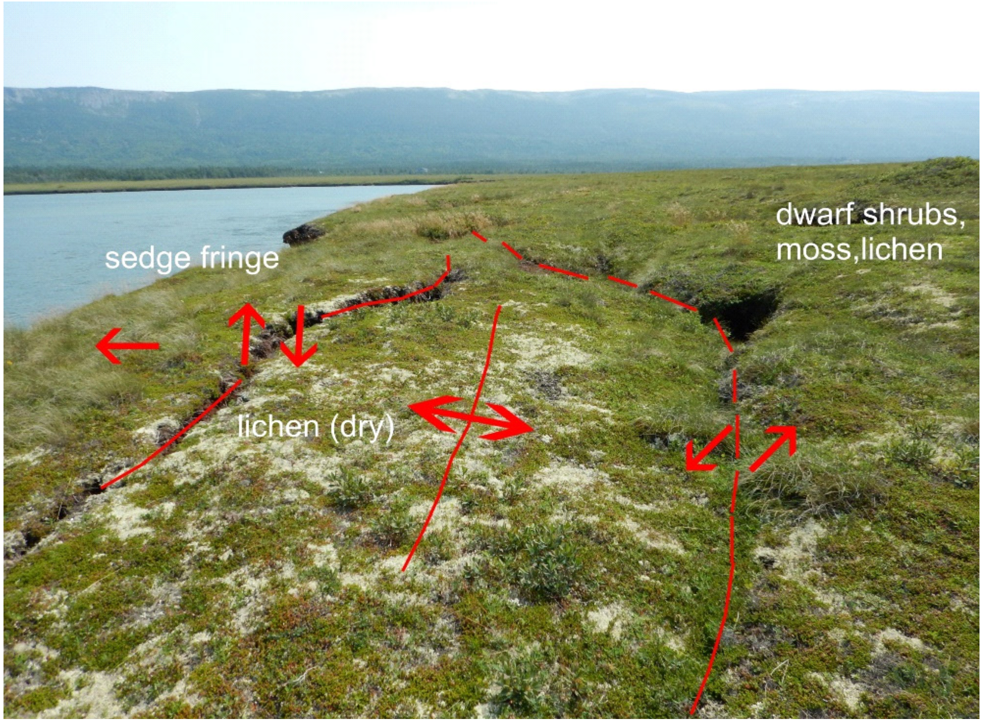

Figure 12. Peat bog with arcuate listric normal faults and roll-over anticline developed in fractured, undercut peat beds. The changed vegetation indicates that improved drainage has been an ongoing phenomenon.

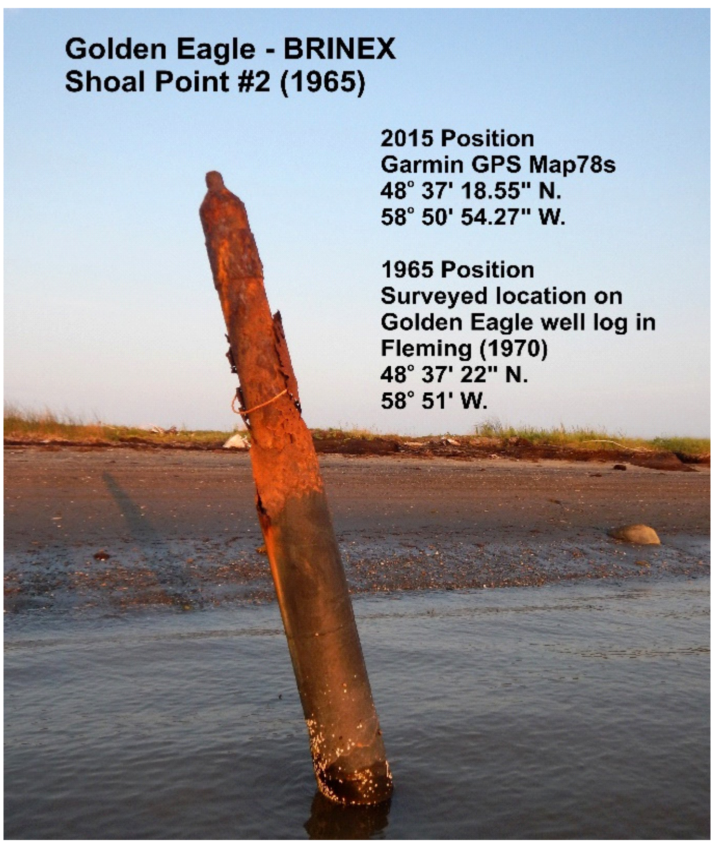

Figure 13. Golden Eagle – Brinex Shoal Point #2 was drilled onshore in 1965. Since that time coastal erosion has removed the beach and left the well head below the low tide mark.

The coarsest grained boulder rich diamictons, glaciofluvial deposits, and colluvium present two other risks in the construction phase of development. In many places, and particularly around the Allochthons south and north of Cornerbrook, highways and side roads are constructed across and below colluvium. Some of these sections of roadway are irregular surfaces and with asphalt that has become rutted and broken. In addition, in some of these same areas, barriers constructed for capturing a steady rain of small rocks falling from above are damaged and, with some larger boulders managing to cross onto the roadway (Fig. 14). A landslide risks assessment produced by Batterson et al (1999), and Liverman et al. (2003) shows clusters of events and numerous fatalities in this part of Newfoundland.

Figure 14. Stone and wire mesh barrier near York Harbour is damaged from falling debris and including with boulders that leap this barrier and cross the highway.

Finally, in reviewing early exploration practices in western Newfoundland (Burden et al, 2014), a significant number of the old holes failed when drilling equipment was unable to penetrate the unstable rock and soil and became stuck in the hole. Today, we are well aware of the fact that the fine- and coarse-grained rocks above and in target strata are significantly broken and fractured from multiple episodes of tectonism. Creating a "glory hole" and drilling boulder till to reach and to drill broken bedrock is a practical engineering matter requiring a properly powered rig, and with appropriate casing and seals.

(b) Risks associated with the hydrological and hydrogeological disposition of potable or useful surface and subsurface water, including the presence of known brine springs and oil seeps.

At the global scale, the impact of human exploitation, and developed infrastructure on the quality and quantity of potable water are well known from our long history of farming, mining, urbanization and industrialization. The idea of protecting and effectively managing our surface and groundwater supplies is a much newer concept.

Today, in Canada, there exists a common set of specific National guidelines and legislation to cover water quality and quantity for consumption for people, agriculture and industry. In Newfoundland and Labrador these matters are covered under the Provincial Water Resources Act (House of Assembly, 2002). This body of legislation instructs government to establish agencies and protocols for monitoring and enforcing issues concerning water quantity, quality, disposal and pollution.

In application, some of the nationally regulated rules and guidelines for water, are targets for aesthetic purposes; other regulations are critical matters specifically for human and agriculture safety (e.g. levels for toxicity) and protection of infrastructure (e.g. corrosion). Unless specifically authorized by the Minister, the Newfoundland and Labrador Water Resources Act does not contain provisions for conducting new research to keep on top of the science or to be in front of changing technology and need.

The Provincial Government Department of Environment and Conservation is one of two government portfolios responsible for administering the Act. Their staff routinely collect data and manage sampling, analyses and other records for basic water quality and distribution protocols (e.g. boil water orders). Periodically they commission independent consulting reports to compile and interpret data and to address and make recommendations on improving regional water quality and distribution issues. Much of this material is available on-line.

In recent years, three consultant's reports (AMEC, 2008; rev 2013; Jacques Whitford, 2008; CBCL 2012) addressed a number of significant aspects concerning the potable water in western Newfoundland. Another report (AECOM, 2013) examined infrastructures to determine whether they are appropriately sealed and safe from contamination at the source. These large, and yet limited compilations of some chemistry, physical properties and infrastructures provide a very basic starting point upon which future changes to water quality and distribution are being be measured. In addition to government and industry surveys, citizen scientists (e.g. ACAP, 2015) and university faculty (Sarkar et al., 2012) collect and report upon their own analyses. Unless explicitly stated in these independent reports, there is no guarantee that any outside samples are properly collected by trained and certified hydrologists following appropriate protocols, and analysed in ISO approved labs.

Among the consultant's compilations, some of the key findings are outlined here. Statistically, across Newfoundland and parts of Labrador, the CBCL (2012) compilation of government files shows more than 18,000 drilling records that may or may not contain complete sets of numerical data collected by drillers (Fig. 15). Categorized, and in statistical summaries, well depths for the Province are generally between 31 and 76 m, and with bedrock tending to lay between 2.1 and 6.7 m (CBCL, 2012). The mean value for static water level is 6.1 m. The mean production rate is 25 L/min at a depth of 57 m. The median production rate (the most likely outcome from a drilled well) is 9 L/min at a depth of 49 m.

	Depth to Bedrock (m)	Well Depth (m)	Static Water Level (m)	Airlift Yield (L/min)
# Records	5247	18 503	4151	16 825
Mean	5.7	57	6.1	25
Variance	48	1126	76	4352
Standard Deviation	7	34	8.7	66
Minimum	0	2.0	0	0
First Quartile	2.1	31	3.0	2.0
Median	4.0	49	5.0	9.0
Third Quartile	6.7	76	6.0	23
Maximum	110	400	304	2250

Figure 15. Summary statistics from AMEC water well survey (2008; rev 2013). The mean depth 57 m and yield 25 L/min belies the fact that the median well depth is 49 m and with a yield of 9 L/min. A long tail of poor yields is balanced by a small number of wells with high yields.

Shallow wells sampling surficial materials in western Newfoundland (Fig. 16) tend to be situated upon glaciofluvial and (sandy)glaciomarine strata where permeability is high. The CBCL (2012) report notes that, inasmuch as glaciofluvial deposits carry "favourable" properties respecting fluid transmission and yield, overdevelopment for agriculture and other purposes may cause a decline in the hydraulic head. Away from these areas and where bedrock is shallow or exposed (e.g. north of Deer Lake), there are relatively few records for any surface wells. This might be a function of limited records generated from private "dug" wells or overall poor quality (e.g. colour, taste, bacteria, etc.) and, consequently, no official reports on or about the general use of these shallow reservoirs.

In an effort to gain some insight into the scope of reporting and in the quality of records, Sarkar et al. (2012) and AECOM (2013) collected data from wells and examined well records from a slightly different perspective, and basically to address procedural matters and human error. In their work, Sarkar et al. (2012) examined the placement of wells and sampled the chemistry and biology of private wells from a small number of small communities between Bay St George and Bonne Bay. AECOM (2013) likewise reported upon surface waters and other contaminants leaking into many of our provincial public water well systems. Both studies confirm unacceptable levels of chemical and biological agents entering too many wells and with human error in design and neglect in protecting and servicing among the leading factors contributing to low standards for water quality.

In deeper wells and where water is kept separate from surface contaminants, correlating bedrock in outcrop with bedrock in drilled wells simply confirms the obvious – and namely that typical bedrock wells are shallow and do not necessarily pass into another rock formation (Fig. 17). Summarized well records for southwestern Newfoundland (Fig. 18 and 19) indicate that within the Codroy Valley, there are generally favourable groundwater conditions for depth (20-50m) and yield (> 20 L/min). Yields are apparently a little more erratic on the Port au Port Peninsula and in the Humber Valley, and where some wells can be 150 m deep. Nevertheless, some wells in this area are producing more than 500 L/min. These variations can likely be attributed to basic differences in the geology and structure of the Bay St George Subbasin set against the more deformed Anticosti Basin and Allochthon farther north.

For some of the deeper wells and historically from anecdotal evidence of springs and shallow wells, some well water is unacceptably salty or smells of sulfate or sulfide. In the Bay St George Basin, an area where ancient evaporitic salt, potash, gypsum and anhydrite deposits are known to occur, there is no general guarantee that well water will be free from naturally dissolved salts and other materials or to later become contaminated from overuse. Likewise, in coastal settings, where gypsum and salt deposits are not present, excessive use of freshwater will cause seawater to move inland and destroy the reservoir.

With respect to the concerns and intent of this commission and to reporting on hydrocarbon risks, the sampling of water for petroleum hydrocarbons in not routinely practised in Newfoundland and Labrador. This is a serious oversight if any progress is to happen with respect to our understanding the quality and quantity of groundwater resources.

In nature, methane and other light hydrocarbons evaporate quickly. In addition, other naturally occurring oils tend to become biologically degraded and are not normally observed in surface waters. A more common phenomenon, and observation is with modern organically generated oils as ephemeral stains seen in some standing water in bogs.

Natural, thermogenic petroleum seeps, seen in some places – and normally along the ocean coasts, are all very small. Their discovery over the last 200 years is as much by chance as it is by purposeful investigation. Hicks and Owens (2015) have specifically compiled a list of these features. None of these identified seeps apparently affect any potable water supplies.

In my own experience measuring and mapping strata on and around the allochthons of western Newfoundland, I have not seen any petroleum hydrocarbon leaking into freshwater – too much of the landscape is covered. In coastal marine settings, some petroleum seeps are seen at the top of sandstone successions where darkened beds of bedrock contain traces of live petroleum seeping from pores. By and large, these features are simply residual trapped, physically and biologically degraded hydrocarbons slowly being released from the rock matrix as erosion gradually takes the rock (Fig. 20). Apparently larger seeps occur on jointed and otherwise fractured rock surfaces.

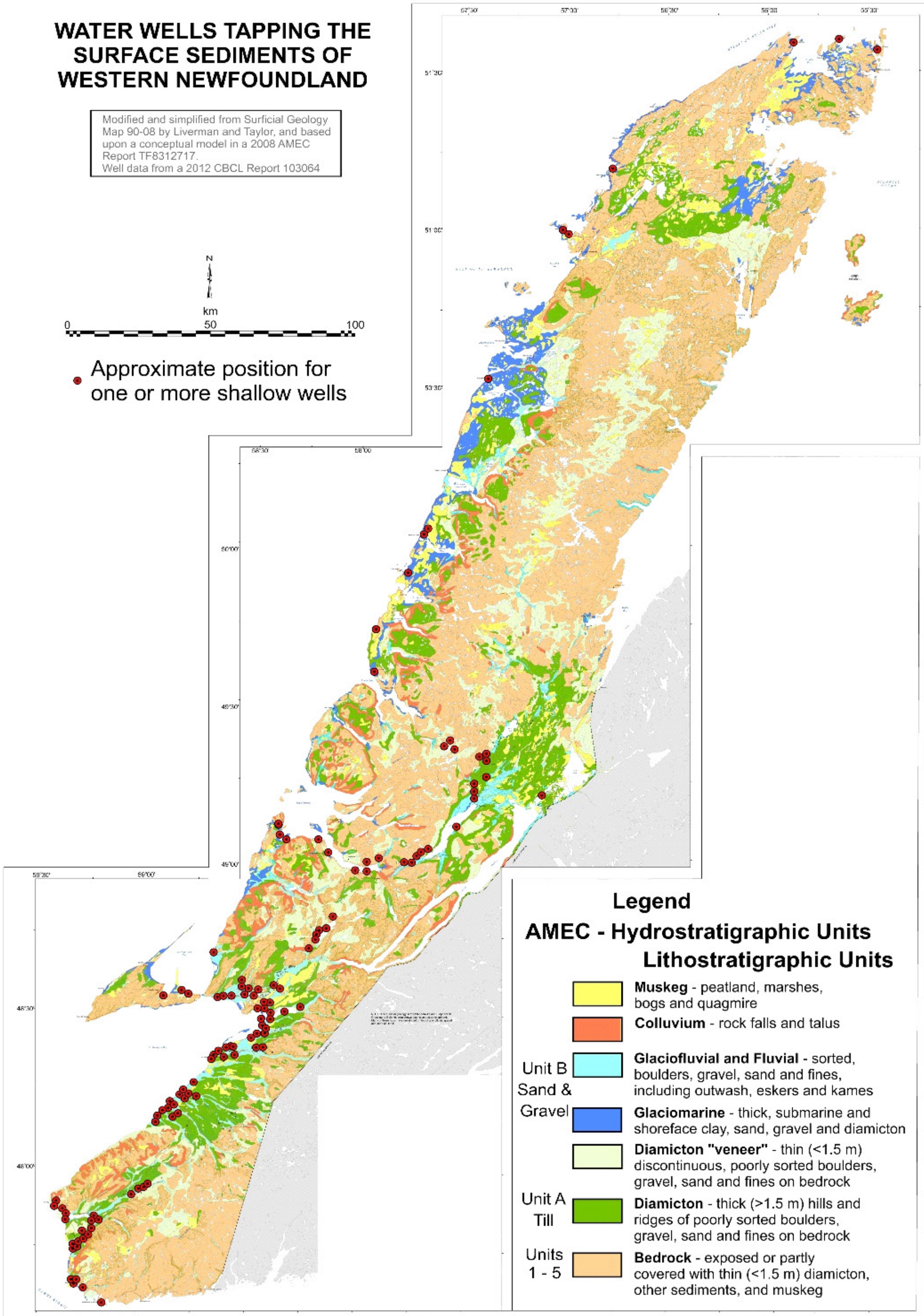

Figure 16. Sample of surface sediment water wells identified in the AMEC report (AMEC 2008; rev 2012). The concentrations of these surface sediment water wells around St George's Bay and the Deer Lake areas is thought to be related to favourable sedimentary geology and structure and sandy glacial deposits.

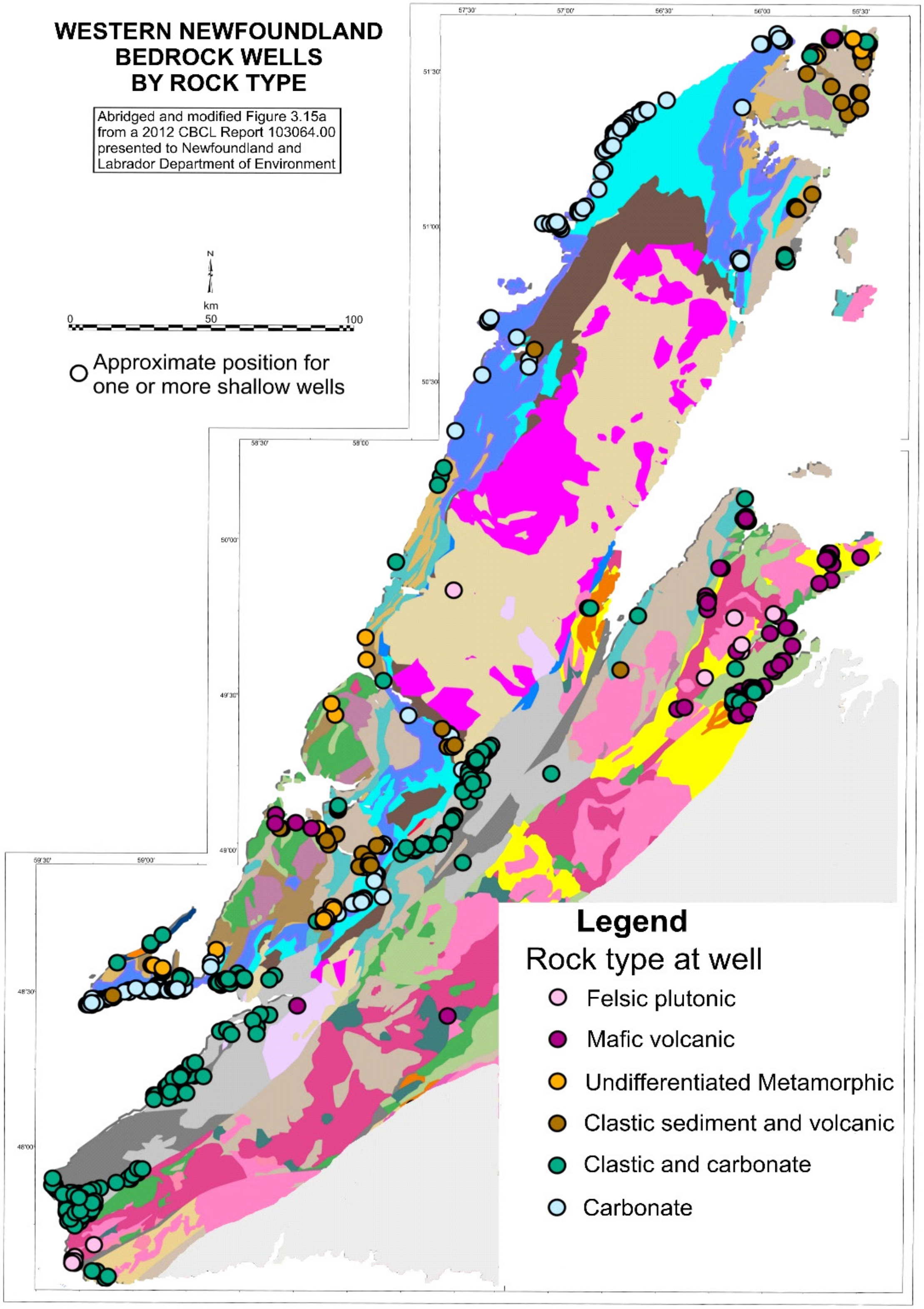

Figure 17. Rock types at the well head generally correspond with formations at the bottom of the wells. AMEC (2008: rev 2013) and CBCL (2012) show that rock types at the well head offer some guidance on the basic types of water that may be found in the well.

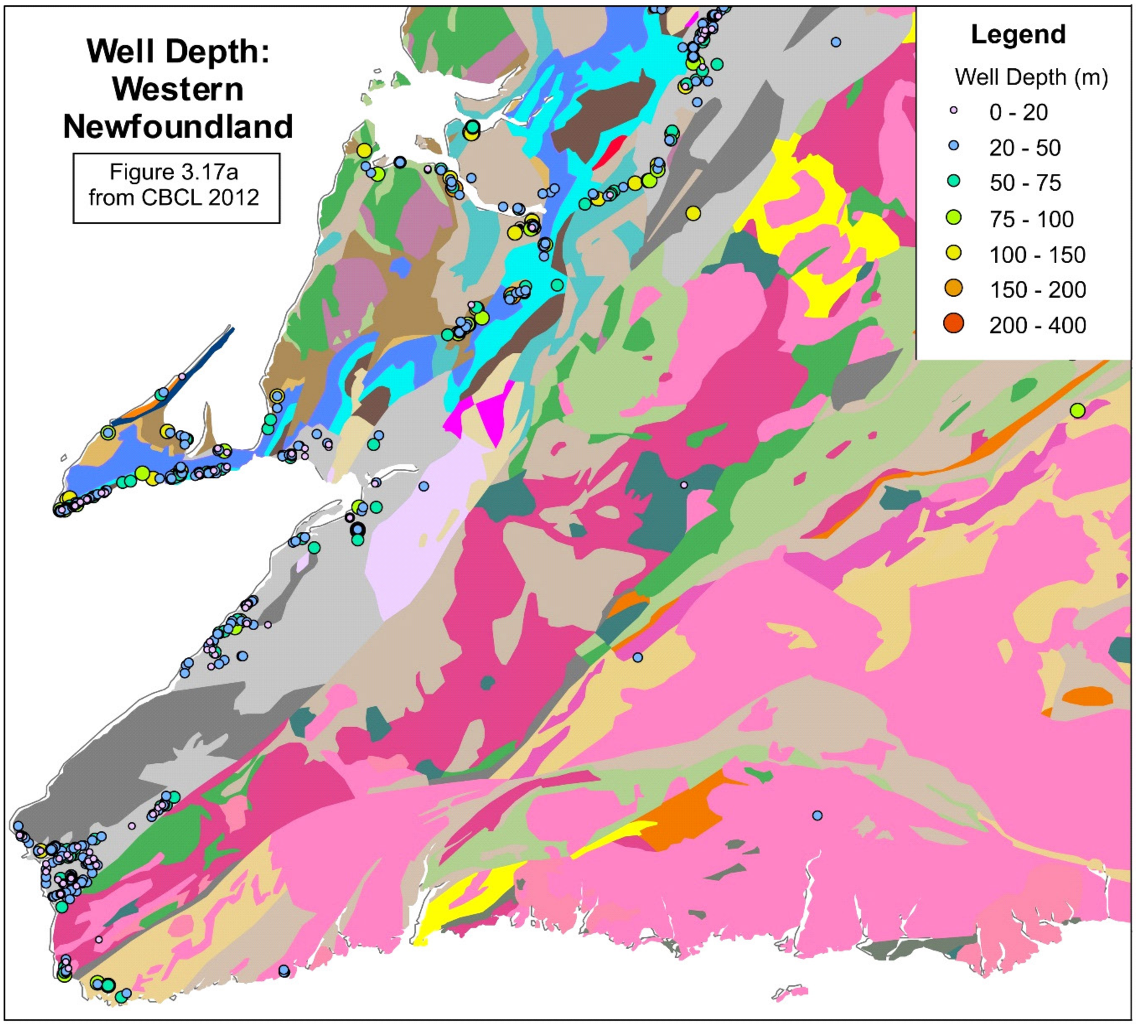

Figure 18. Well depth tends to be slightly shallower in rocks from the Bay St George Basin. The CBCL report (2012) suggests that the deepest wells tend to be located in the allochthon.

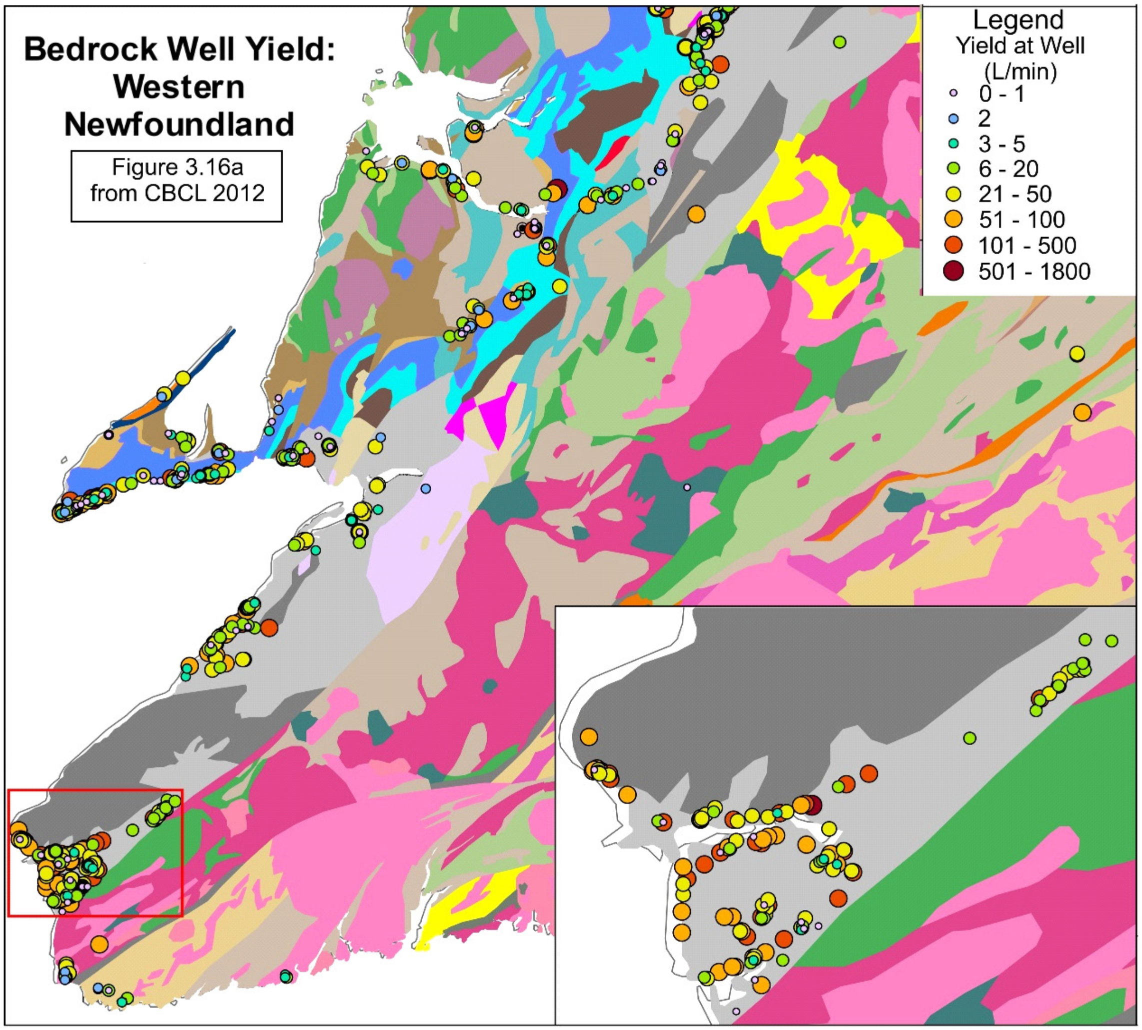

Figure 19. Wells from the Bay St George Basin tend to be very productive. Farther north on the carbonate platform and in the allochthon, the well production values become more erratic and less predictable. Some of the largest water wells are located in or under the allochthon.

On warm days, these broken rocks begin to leak drops of dark, thick, oil (Fig. 21). Beneath the bedrock surface, microorganisms, cooler temperatures, higher fluid viscosity, tight fractures, and lower rock permeability are all checks against maintaining a steady continuous flow.

Inasmuch as this basic information demonstrates the widespread occurrence of petroleum leaking from the ground, it does little to address the questions of where and how much natural hydrocarbon is to be found and tolerated in the groundwater resource.

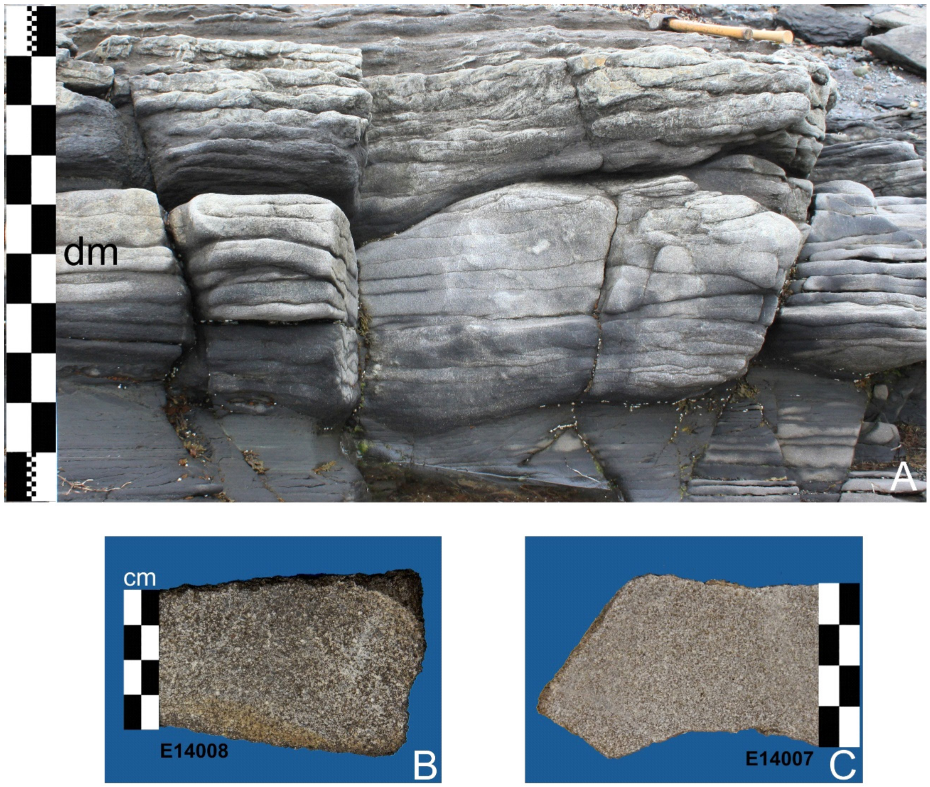

Figure 20. (A) Hydrocarbon stained outcrop from locality E14007 on a shoreline beach at Two Guts Pond. Dark, and coarser sediments from E14008 (B), a nearby and slightly higher outcrop are saturated with dead oil. In locality E14007, the strata are slightly finer grained and not nearly as dark in colour (C).

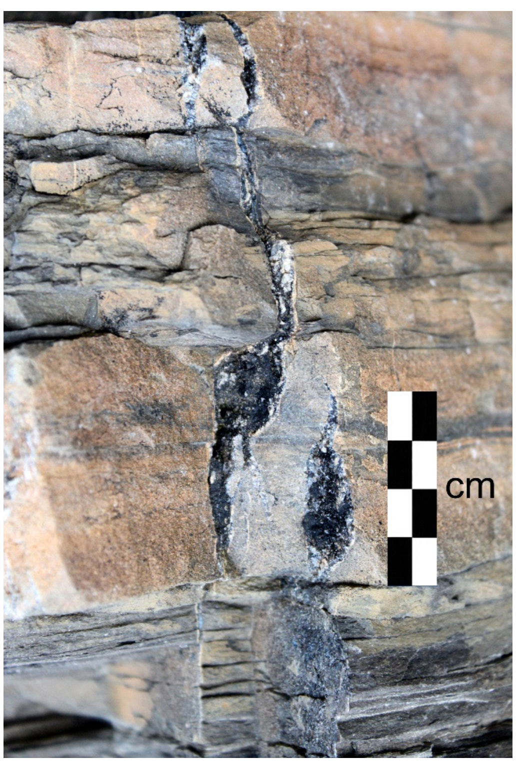

Figure 21. Pale pink and brown weathering dolomitic fine sandstone and siltstone with heavy, degraded oil leaking from fractures on warm days (Conche, NL). Strata in this area are slightly deformed Carboniferous lake and delta deposits formed in a transtensional basin on the edge of the offshore St Anthony Basin.

For comparison, in Quebec, beneath the St Lawrence Lowlands and on Anticosti Island, the level of Federal and Provincial government supported research and reporting is far more advanced than that found anywhere in Newfoundland and Labrador. In particular, in Quebec, several years of targeted research into carbon sequestration, and other unconventional hydrocarbon exploration and disposal programmes has led to the identification of specific layers of water in the phraetic zone and for direct measures for source and quantity of naturally occurring petroleum hydrocarbons seeping from bedrock and into phraetic water. For example, on the carbonate platform on Anticosti Island, Peel et al. (2014) show a shift away from carbonate ion (Ca+) enrichment in the surface waters and into sodium (Na+) and potassium (K+) in the deeper wells where deep phraetic water is essentially isolated from exchange with surface water. In that region of Quebec, and elsewhere across the St Lawrence Lowlands (e.g. Savard, 2013), the basic chemistry of deep phraetic water is becoming determined by the physical, chemical and structural properties of the bedrock. In another recent paper Moritz et al. (2015) established baseline concentrations for methane in shallow aquifers of the St Lawrence Lowlands, and used carbon isotope signatures to differentiate modern biogenic methane from naturally occurring thermogenic methane in groundwater. While admittedly speculative on their part, Moritz et al (2015) suggest that faults may be a conduit for thermogenic methane migrating into groundwater. Provided with this level of detail and understanding, it starts to become possible to establish realistic benchmarks on water quality, on separating natural and manmade disturbances (fracking) to water chemistry and for generating guidelines respecting developments in the proximity of major faults. Apparently, none of this type of data presently exists in Newfoundland and Labrador. No tests have been conducted or numerical models constructed to address the physical integrity of strata and faults before any fluids are injected into the allochthon and hydrocarbons are removed. Without appropriate baseline data, we have no way of knowing what, if any problem, exists.

(c) Geomorphological risks related to siting of multi-well development sites.

No development plans have come to my attention, and this matter is largely hypothetical in nature. Developed industrial sites with infrastructures are modest in size and need not appear disconnected from the rural setting. In some places (and notably, California and the Netherlands), where the landscape may have a particular scenic value, pump jacks and other infrastructure are sometimes covered or made to appear as part of the traditional landscape (e.g. barns and small treed islands).

The process for physically constructing commercial hydrocarbon production sites is a larger enterprise. In localities where there is little glacial and post-glacial soil laying upon bedrock and also where they are well above sea level, the impacts of future sea level change are negligible. For rocky locations, practical matters include levelling land and stationing a drill and other development infrastructure. Fundamentally, these are expected engineering questions, and not necessarily outside normal site design and operating conditions.

Conditions and risks related to siting of multi-well developments on shorelines and other unstable soils are not nearly as clear. On visiting the now mostly abandoned Shoal Point K39 well site, and aside from the fenced in and protected well head, there is very little of the original infrastructure remaining on this location (Fig. 22). For storm surges and ice, rip-rap of very large boulders, and perhaps as much as 2 m high, lies along the shorelines adjacent to the site. The actual drill site is surrounded with a rock and soil berm at least a metre high. Inside the berm, the land is level and still holds some equipment and empty shipping containers. There is plenty of room for a large drill and associated buildings and trailers. Four very large metal pylons, well anchored to the ground, and arranged as the corners of a square on the inside edges of the berm, were likely used for support cables to help keep the drill erect during storms. Bedrock is not visible at this site. Bedrock is present a little more than a kilometre south along the west shore of Shoal Point. By extension, and beneath the Shoal Point well, bedrock should be laying close to the surface and upon a thin layer of glaciomarine sand and peat. Groundwater in this low coastal area is likely to be saline (and corrosive to steel pipes).

Adjacent to and on the north side of the well head there is a large and thick concrete pad, probably used to support heavy machinery. On inspection, it is split by an east-west oriented crack and with a second shorter north-south break in the southern half of this block (that is closer to the well head). The cause for these cracks is unclear. An August 28, 2015 conference call with Mark Jarvis and Jock MacCracken of Shoal Point Energy indicated that this pad may have been constructed for one of the smaller service rigs used by another operator and not needed by the much larger Nabors rig used during their work. Whatever the origins are for this concrete pad, it is clear that any infrastructure proposed for this headland will require proper foundations able to support specific loads for many years and appropriately protected from the rising sea.

Figure 22. Shoal Point K-39 well site at the tip of Shoal Point in Port au Port Bay (A) with a berm surrounding the site and covered with boulder rip-rap (B). The thick concrete pad adjacent to the north side of the fenced well head is cracked (C).

Recommendations regarding Surface Materials and Water

Recommendation 1: Design and engineering of infrastructures on coastlines and other unstable ground should include additional provisions for properly constructing and decommissioning sites in a timely manner and in particular, for places that will one day be at or below sea level.

Recommendation 2: Government agencies tasked with looking after our groundwater resources should become more actively involved in gathering and interpreting the quantity, quality and availability of this valuable resource. This should include systematic regional studies of the stratigraphy of water, the influences of formation water chemistry (e.g. As, salts, and hydrocarbons) on potable water, and better data on sustainable production of groundwater.

Recommendation 3: Appropriate, statistically relevant, groundwater analysis should be completed by a third party before any fracking is started. In particular, baseline conditions regarding the quantity of hydrocarbons in the local water will become a standard to be used as a decision making tool.

Bedrock Geology – Strata, Structures and Fluids

Bedrock Geology Questions to Be Addressed in This Report

(a) Risk associated with known faults such as their potential as pathways for fluid migration, of fluid migration during multi-stage hydraulic fracturing, for interfering with the productivity of wells through excessive fluid influx, and other widely understood risks of a geological and fluid flow nature.

(b) Risks associated with the presence of currently unidentified faults that could impact drilling and development activity that could lead to enviro-economic risks.

(c) Risks associated with the nature of the cap rock or formation seal integrity with respect to the multi-stage hydraulic fracture stimulation process.

(d) Risks associated with the presence of swelling clays or exceptionally high differential earth stresses which may cause issues of borehole stability and attendant risk to drilling activity.

(e) Risks associated with the presence and trajectories of legacy well bores.

(f) Risks of encountering unexpected overpressures that could impact safety and operations

(g) Risks related to the possible presence of hydrogen sulfide and carbon dioxide.

Background Geology – Origins for Conventional and Unconventional Source Rock Reservoirs in Western Newfoundland

Under any proposed development programme, the present practical debate about fracking onshore hydrocarbon deposits is fundamentally a western Newfoundland based matter. If there are to be any commercial deposits of onshore hydrocarbons identified, they will come from western Newfoundland. For all of the rest of the island and Labrador, the onshore rocks are not considered to be petroliferous.

The largest part of the region being considered extends from south of the community of Daniel's Harbour to about Tompkins in the Codroy Valley. This area is underlain by two sedimentary basins - that is places where the Earth's crust has warped and sagged into a depression that is filled with thousands of metres of sediment. The older, Cambrian and lower Ordovician (~550-470 million years) Anticosti Basin, was formed as a Passive Margin Basin (see Coleman and Cahan, (2012) for definitions for basin types). A hundred million years later an upper Devonian and Carboniferous (~370-310 million years) Borderland Basin – the Magdalen Basin, developed upon and adjacent to the much older and now deformed Anticosti Basin strata and structures (Fig. 23).

Strata of the Anticosti Basin are deposited upon and adjacent to the trailing edge of a passive continental margin of Laurentia – the ancient core of what is now North America (Fig. 24 A and B). The thickest part of the Anticosti Basin, and perhaps as much as 8 km thick, covers a large part of the present Gulf of St Lawrence. The thinner edges for the basin extend northeast across part of northwestern Newfoundland and southwest along what is now the St Lawrence estuary In the west, on the coast of northern Newfoundland, southern Labrador and the Quebec "North Shore", the rocks are thin (< 1 km) flat-lying deposits of mostly shallow water carbonates laying upon the Precambrian rocks of the Canadian Shield. In drill holes beneath Anticosti Island and in outcrop on the west coast of Newfoundland, these parts of the Anticosti Basin may contain more than 2 km of gently dipping mostly shallow water shelf carbonate rocks, with some older, shallow water quartzose sandstone and shale. Farther east, the shelf deposits merge into a succession of deeper water marine slope carbonate conglomerate, with carbonate mudstone, organic shale (source rock) and lithic sandstone.

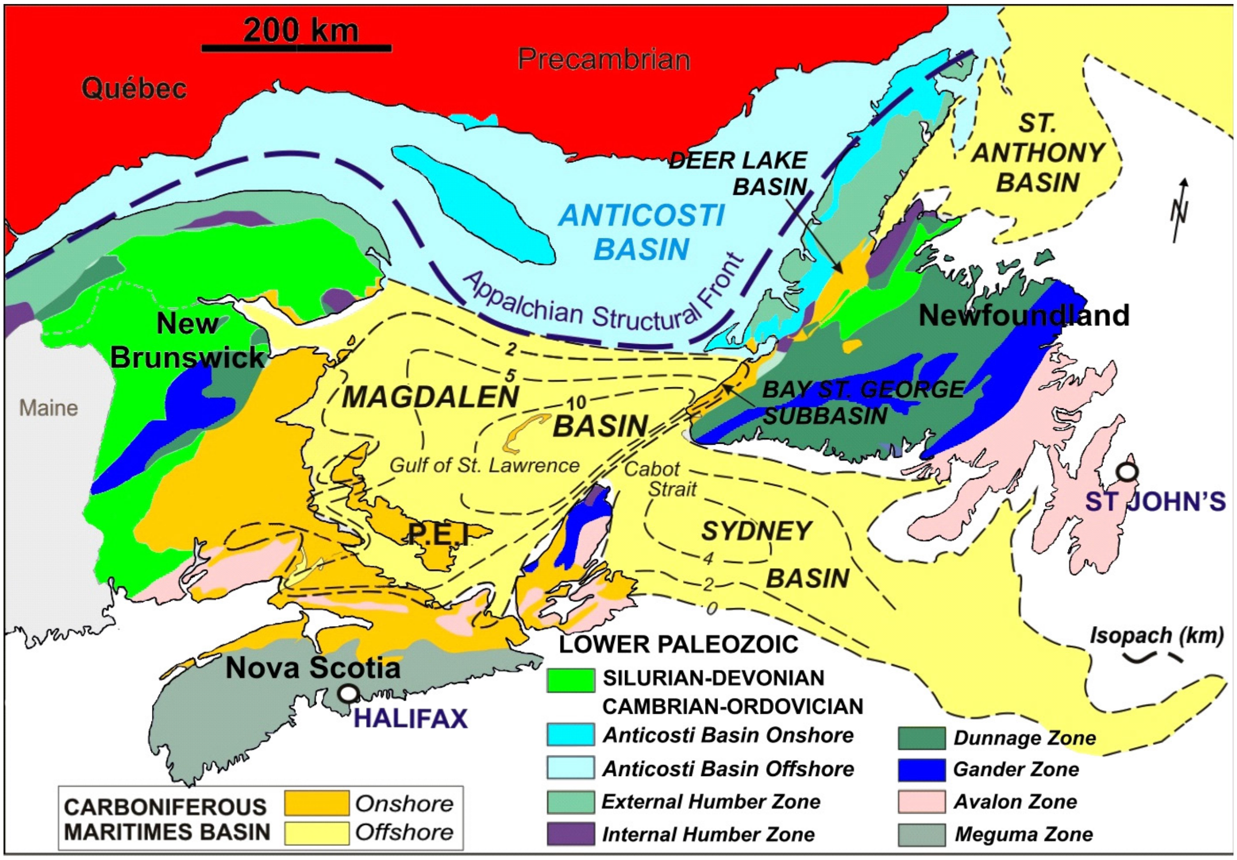

Figure 23. Regional outlines for major tectonostratigraphic features that form the Paleozoic basins of Atlantic Canada. Their shape fill and structure are determined from plate tectonics. Map generated as a modification/compilation from a number of Geological Survey of Canada reports and mostly authored or co-authored by Lavoie et al.

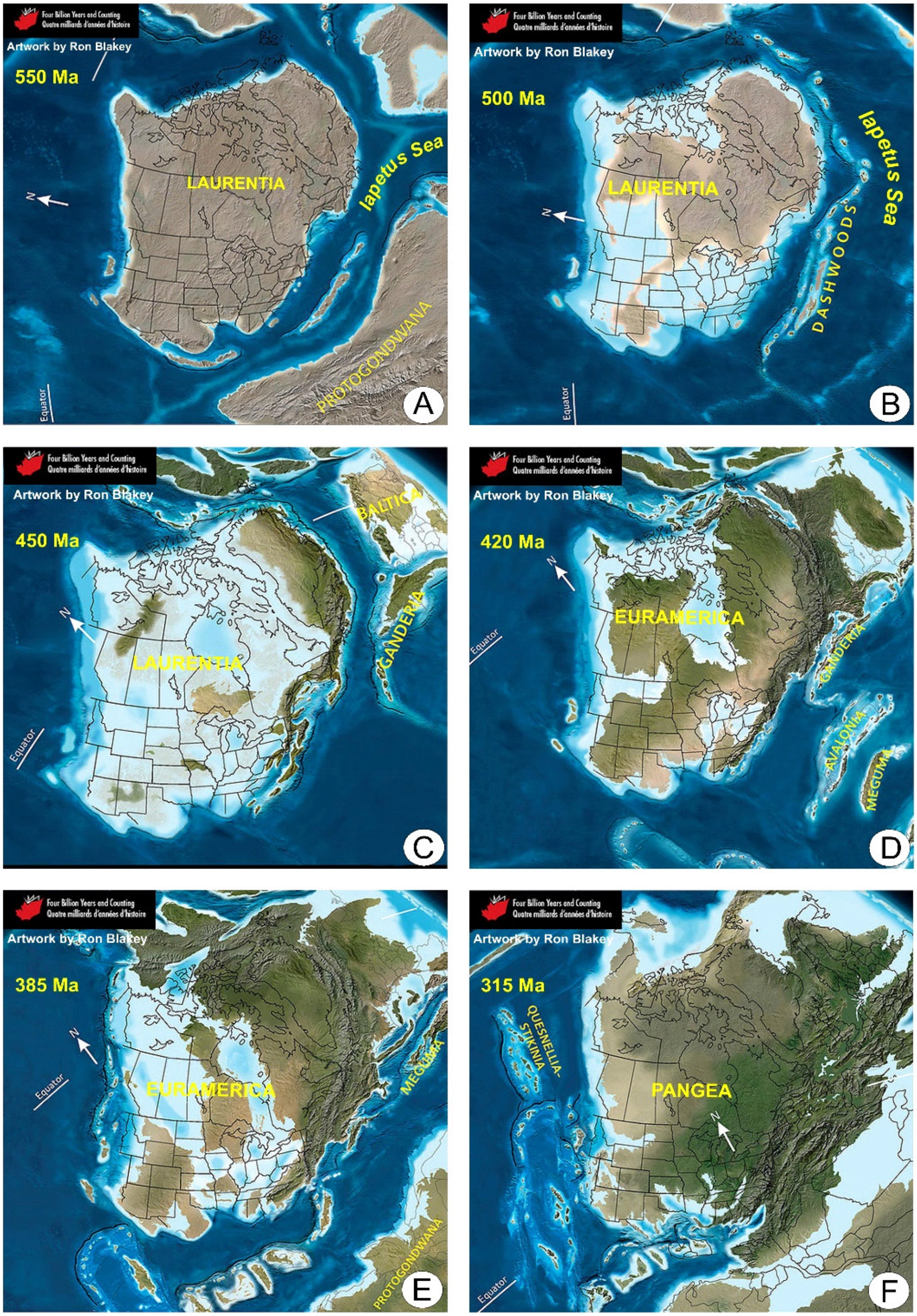

Figure 24. Composite images tracking the opening of Iapetus 550 Ma (A) through the final suturing of Protogondwana onto Euramerica to create the supercontinent Pangea (F). Images from Fensome et al (2014).

Shallow water rocks include marine clastics and carbonates of the Labrador Group, the Port au Port Group, and the St. George Group. Deep water marine deposits are found in rocks of the Cow Head Group north of Bonne Bay and the Northern Head Group, Curling Group and Blow Me Down Brook formation, south of Bonne Bay (Fig. 25). In the southern part of this area of Newfoundland, there are significant differences in thickness of the deep marine strata, and including distinctive, and different members and formations. In addition, in the south, there are small, well dated late Precambrian granitic plutons that are to some degree coeval with nearby rift volcanics in the adjacent allochthon. Collected, these data suggest some fundamental change in the shape and structure of the ancient Laurentian coastline somewhere south of Bonne Bay.

In some regional assessments (Thomas, 1977; Allen et al. 2009) the complex geology and irregular shape of the Laurentian margin in an area known as the St Lawrence Promontory, is schematically explained as a zone of transfer faulting (also sometimes called transform faults) generated during the Precambrian stretching and rifting of Laurentia more than 550 million years ago (Fig. 26). While visualized in their conceptual diagram as a sharp and well defined region of brittle listric growth faults, the boundaries drawn across southwestern Newfoundland and the Gulf of St Lawrence are nevertheless schematic illustrations, for a complex style of breakup that may involve brittle behaviour of the upper crust and plastic behaviour and sagging of the lower crust (see Graham et al, 2014 Pindell et al, 2014 and Lundin et al, 2014). In this circumstance, hyperextension, beneath what is now the Anticosti Basin, should leave some tell-tale signatures, such as the major NW trending basement fault identified in aeromagnetic surveys illustrated in Hinchey et al (2015) and generate some igneous melts, granitic and ultramafic intrusions, dikes and rift volcanics – lithologies we also see within and on attenuated Precambrian crust in Newfoundland and Labrador and Quebec (McCausland and Hodych, 1998; Allen et al., 2009).

For some, this structural and stratigraphic complexity is simply a detail around which Cow Head Group formations (e.g. Green Point Shale) are simply extended across transfer faults and with the expectation that there exists a common style of deep marine sedimentation and source rock along the entire ancient Laurentian margin. Whether right or wrong, the choice of words is in fact a risk in basic reasoning that can influence ones view of the shape for this basin, the generation, quality and quantity of petroleum source rocks, the migration pathways (fairways), and the overall architecture of possible petroleum systems.

A basic part of our science wrestles with appropriately describing and naming rock units. This is an ongoing exercise aimed at achieving the best interpretation from the data at hand. Hinchey et al (2015) also raise this as an interpretive matter they too considered in their report. In this review, the strata of the Cow Head Group are retained as separate rock units, and maintained as distinctive and yet correlative intervals from the thicker Northern Head Group strata of the Bay of Islands and farther south. As more details emerge to describe primary deposition structures, provenance, geochemistry, reservoir properties and metamorphic overprint, researchers will be in a better position to consolidate western Newfoundland rock formations from a sound scientific basis or to keep and modify existing monikers.

Beginning about 467 Ma, pulses of orogenic tectonism rippled across what is now eastern North America and eventually building the Taconic, Acadian and Alleghenian mountains of the greater Appalachian mountain system. Repeated episodes of folding and faulting with additional igneous and metamorphic activity pushed and elevated mountain systems from the ancient Iapetus Ocean and crust (Fig. 24 c-f). By the late Ordovician, and as a consequence of this first episode of Appalachian mountain building, smaller, thinner, shorter lived, foreland basins and reactivated hybrid basins were created landward of the emerging mountains. These basins are variously named after a locality or a rock formation and include the petroliferous Utica and Marcellus basins, and farther west, hybrid, and reactivated intracratonic rift basins, the Michigan, Illinois, Arkoma and, Anadarko basins (Coleman and Cahan, 2012). In these basins, the quality and quantity of basin fill is related to crustal subsidence and to the type and quantity of clastic materials eroded and transported from mountains rising in the east. These variables affect source rock chemistry, thermal maturation, porosity, permeability, cements and down hole pressure. Fundamentally, the younger basins farther west of the Appalachian mountains have little in common with the source rocks and strata of the older and now deformed Anticosti basin.

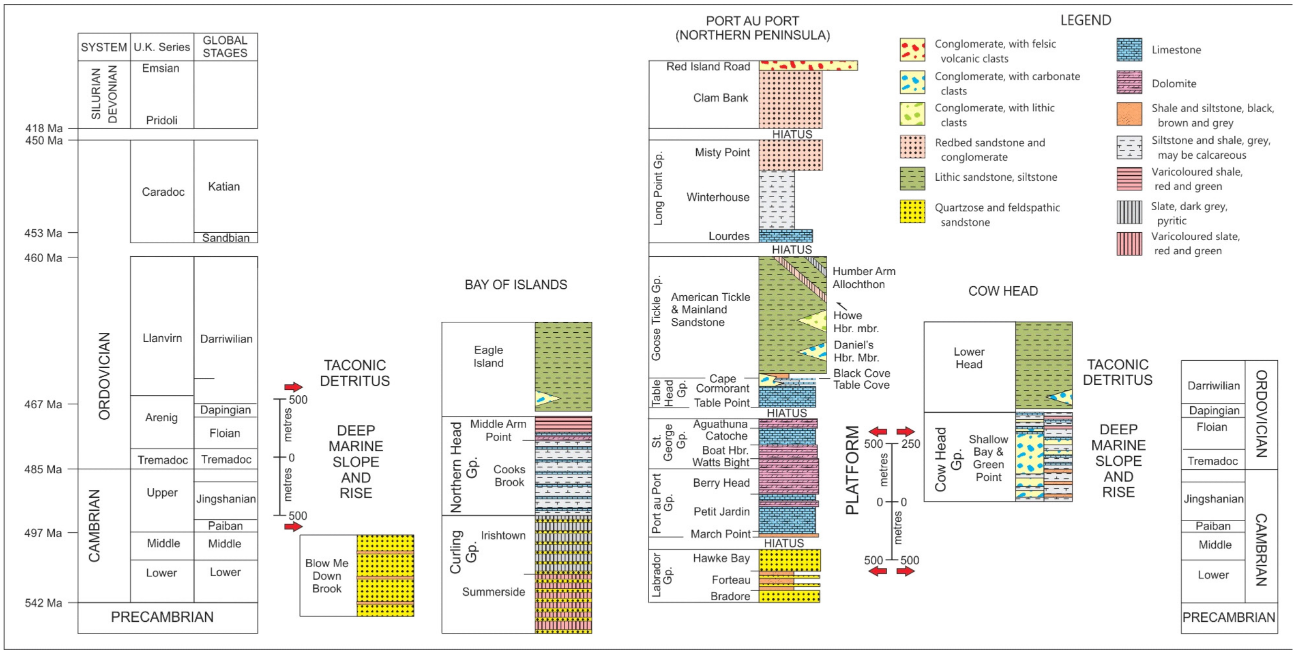

Figure 25. Stratigraphic correlation of Cow Head and Bay of Islands allochthons with the Port au Port autochthon rock.

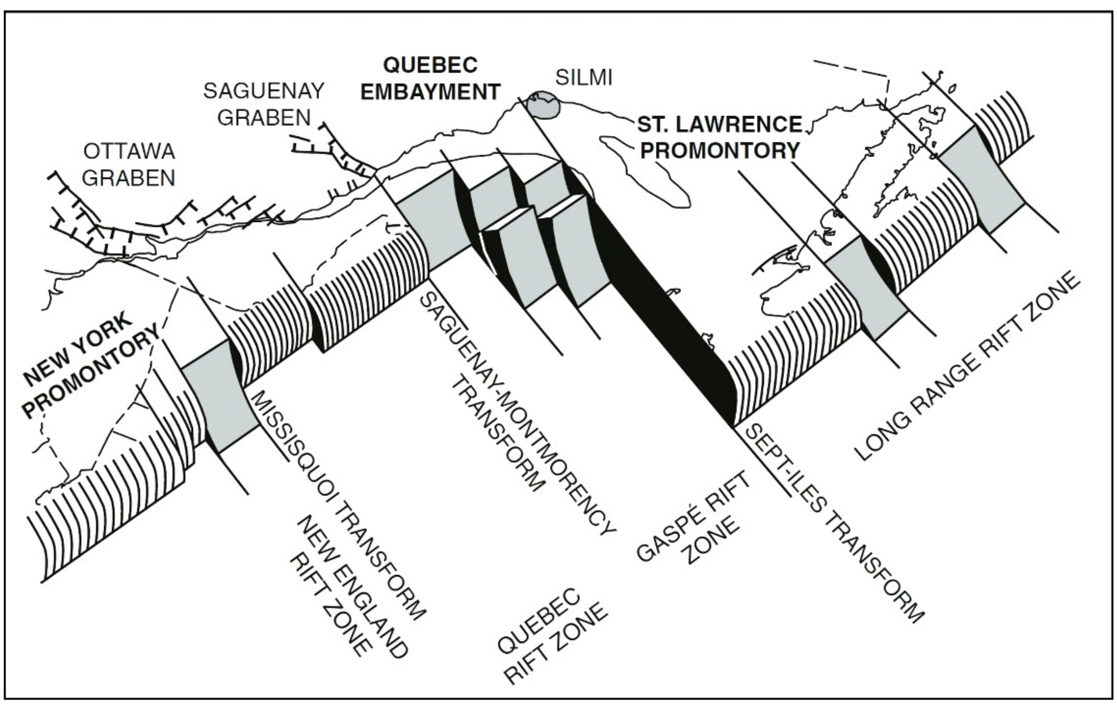

Figure 26. Schematic model for architecture for the base of the Anticosti Basin on the St Lawrence Promontory from Allen et al. (2009). SILMI is Sept Iles Layered Mafic Intrusion. Elsewhere on the Precambrian crust on this promontory there are small, very late Precambrian granitic intrusions and mafic dikes.

As a specific and important translation event in the Taconic Orogeny, parts of western Newfoundland, and indeed parts of what is now the entire east coast of North America, were moved from their deep water setting and onto the shallow water carbonate platform. Collectively, these pieces of uplifted and deformed deep marine strata, ocean crust and mantle are known as the Allochthon. The shallow water, essentially undeformed rocks are known as the Autochthon.

Following the Taconic orogenic event, a second significant mountain building episode, the Acadian Orogeny (~400 million years ago), featured the suturing of what is now Europe with North America (Fig. 24 D and E). Some structural deformation is recorded on regional maps of western Newfoundland (Williams and Cawood, 1989; Williams, 1995) but the larger part of the Acadian Orogeny is recorded in the deposits of Silurian and Devonian igneous, sedimentary and metamorphic rocks of central Newfoundland, New Brunswick and Gaspé, Quebec, and the regional deformation of Precambrian, Cambrian and Ordovician rocks from eastern Newfoundland, and Nova Scotia.

The last regional tectonic event, the Alleghenian Orogeny (~300 million years ago) is linked to the suturing of Africa to North America. During that time, rocks across much of Atlantic Canada were stretched and sheared into a Transtensional Basin and creating space for up to 10 km of mostly fluvial and lacustrine clastic sediment and coal, with some salt and gypsum evaporite deposits and limestone. In Canada, these transtensional basin deposits and structures are collectively known as the Maritime Basin Tectonostratigraphic Zone. This includes the Sydney Basin, Magdalen Basin, St Anthony Basin, Deer Lake Basin and Bay St. George Subbasin. An artistic map of the Carboniferous world from Great Britain through Ireland, Portugal, Newfoundland and south along the American seaboard, shows an equatorial great lakes system (Fig. 27) where tropical strata are significantly enriched with organic material (coal and other source rock).

Strata, Structures and Fluids

In total, the mechanics of rifting, spreading and later, mountain building provide all of the necessities for several discrete petroleum systems to operate in the Paleozoic strata of eastern Canada. In one of many Federal Government compilation studies of the geology and petroleum potential of the Paleozoic strata of eastern Canada and completed in the last 25 years or so, Lavoie et al (2009) illustrated the geology for 15 conventional petroleum plays and three unconventional gas plays in strata spanning an area from Montreal to the edge of the continental shelf. In addition, their report also includes a detailed statistical analysis for six of the plays that have sufficient data to formulate a full quantitative assessment for the size distribution of the potential resources.

Moving from a potential resource to a proven resource and later a reserve requires some very specific proofs backed up with quantifiable data. For unconventional resource plays this story is also as much about the technology required for recovery as it is about quantifying a volume of fluid in the ground. Given the fact that a large number of the conventional and all of the unconventional plays identified by Lavoie et al (2009) cannot be quantitatively assessed, the total conventional potential resource they present is by their own admission a minimum potential and an acknowledgement that there is some evidence for other hydrocarbon charges in most of the other qualitatively assessed plays.

Figure 27. Paleogeography of the Appalachian Mountain system as Africa was sutured to North America and Europe to create the supercontinent Pangea. The equatorial intermontaine lake system in transtensional basins that formed at this time contain thick deposits of fluvial and lacustrine sediments and including rich hydrocarbon source rocks. Artwork modified slightly from a base map by Ron Blakey in Fensome et al. (2014).

The plays of the eastern Canada Paleozoic basins that do contain appropriate analytical data have a potential resource calculation showing a cumulative median (P50%) in-place potential for 1170 x10^9 m^3 (41 Tcf) of natural gas and 403x10^6 m^3 (2.5 Bbbl) of oil (Lavoie et al., 2009).

Examined for play type, it is the Carboniferous Maritimes Basin play (Fig. 23) that accounts for about 95% of the potential gas and 60% of the total potential oil resource for onshore Atlantic Canada, Québec and the Gulf of St Lawrence (Lavoie et al., 2009). To be clear, in-place potential is simply suggesting a resource that may be in the ground and not confirming and determining a recoverable reserve. Once found, recovery of a reserve is dictated by technology and market demand. Recovery rates for conventional oil are typically around 20-30% of a reserve.
St Lawrence Platform carbonate deposits extending from Montreal to Cape Norman (Fig. 28), and notably the hydrothermal dolomite plays in this body of rock, are thought to have a potential (P50%) to hold about 40x10^9 m^3 (1.4 Tcf) of natural gas and 127x10^6 m^3(799 MMbbl) oil. The range of probabilities for this platform carbonate play type show 90% certainty for 54.5x10^6 m^3 (343 MMbbl) and a highly speculative 10% certainty of 207x10^6 m^3 (1303 MMbbl) oil (Lavoie et al., 2009).

One of the very telling aspects of the Lavoie et al. (2009) analysis rests with their assessment of the number of fields that may be expected from the Ordovician hydrothermal dolomite play and a ranking for field size. Lavoie et al. (2009) indicate that the Ordovician St Lawrence Platform platform carbonates may hide 217 gas fields and 131 oil fields. Statistically (P50%), the largest field may be 6.5x10^6 m^3 (41 MMbbl) oil in place, and with a much larger number of fields being much smaller than 1.0x10^6 m^3 (6 MMbbl) oil in-place. For a developed onshore petroleum province where pipelines and other infrastructure are nearby, it may be possible to install infrastructure and produce from small fields. Where no infrastructure exists, and where manylarge and small exploration targets lie offshore, smaller structures and discoveries will be identified as stranded, or subeconomic, or undeveloped resources.

In the last few decades several major advances in drilling and development technology have allowed petroleum exploration and development companies to precisely steer a drill bit horizontally and vertically through kilometres of rock to penetrate a specific horizon, and where significant volumes of hydrocarbons can be produced from natural reservoir pressure or from stimulation. Older fields may have additional reserves identified and undeveloped and undiscovered potential resources may become booked reserves.

In western Newfoundland and beneath the Gulf of St Lawrence there are a number of localities and rock formations where, with new technology and research, conventional and unconventional exploration may become commercially successful. To try to make some sense of this, and for more than 20 years, several Federal Government research programmes have been conducted in partnership with the Provinces and Universities. So too, and in the last 6 years, the Newfoundland and Labrador Government has directly supported petroleum exploration and research through NALCOR and the Petroleum Exploration Enhancement Programme (PEEP).

Our practical knowledge of the geology of western Newfoundland changed dramatically in 1995 when oil was reported at Cape St George on the Port au Port Peninsula, and in a well identified as Hunt-Pan Canadian Port au Port #1 (Cooper et al., 2001). Top on this list of accomplishments is proof of concept in demonstrating that reserves of conventional hydrocarbons may be found in this area and an active petroleum system once existed here. In addition, this well, and others drilled since the 1990's, demonstrate that other reservoirs exist in the subsurface and some source rocks may also be viewed as an unconventional resource.

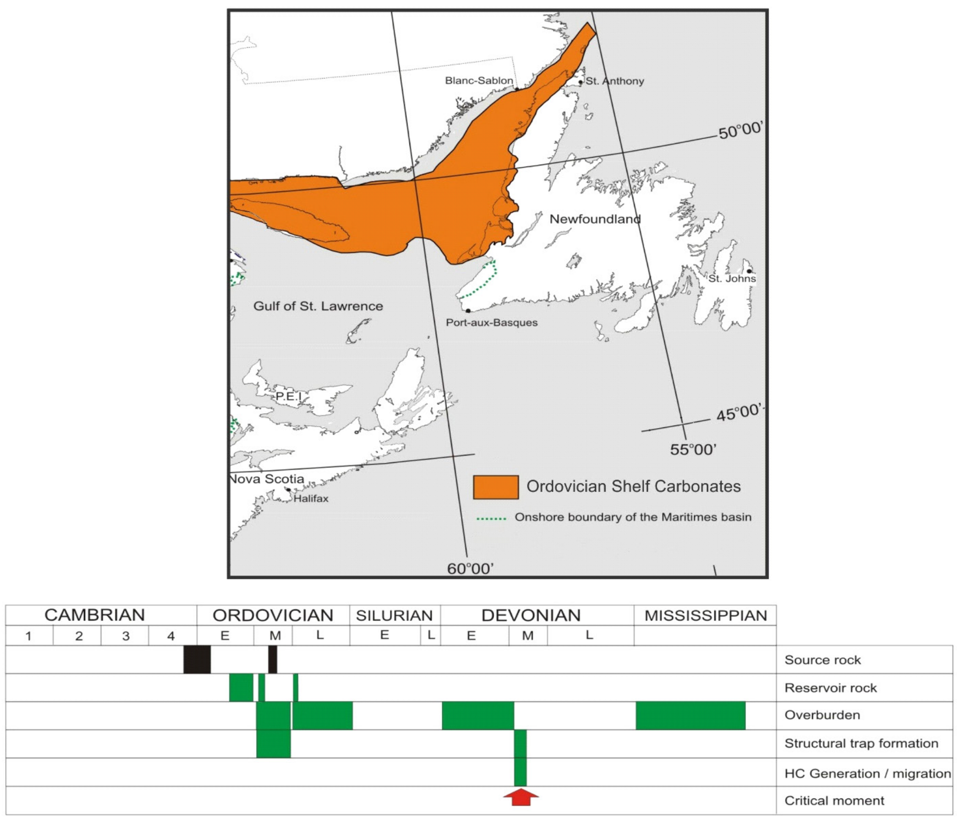

Figure 28. Map of Late Cambrian and Ordovician carbonate platform distribution across Atlantic Canada, and a play chart to show the timing for each of the system parts to develop (from Lavoie et al., 2009). The critical moment in the middle Devonian in the Acadian Orogeny unites all of the parts into a reservoir. Statistical assessment of these rocks may be taken to suggest these rocks have a potential (P50%) to hold about $40x10^9$ m^3 (1.4 Tcf) of natural gas and $127x10^6$ m^3(799 MMbbl) oil.

For Port au Port #1, sustaining pressure and flow for production has been an ongoing challenge. Identifying the causes for this pattern of fluid recovery, and (if possible) creating a practical solution for establishing a commercially successful enterprise, cannot be completed without additional subsurface tests. Discovery of a practical solution to achieve success from this conventional well and field may have a direct bearing on a strategy for recovery of unconventional hydrocarbons that are believed to lie beneath Port au Port Bay.

With additional drilling across the St Lawrence Lowlands and on into the Anticosti and Maritimes Basins, the last 20 years of new field work, laboratory and other petroleum studies (e.g. Fowler et al, 1995; Hamblin et al, 1995; Cooper et al., 2001; Waldron et al., 2003; Burden et al., 2006) is complimented by at least 250 other large and small geology and geophysics studies tied to the petroleum systems of this Atlantic region (see database associated with Burden et al. (2014) for a list of published references and additional statistics). In addition to the Cambrian and Ordovician Platform carbonates (Fig. 28), Lavoie et al (2009) have outlined and defined potential petroleum exploration areas to include Cambrian clastic rocks in rift successions (Fig. 29), Silurian and Devonian foreland basins (in Gaspé – not illustrated here) and Carboniferous transtensional basins with ancient rivers and deltas laying above Carboniferous salt diapirs (Fig. 30 and 31).

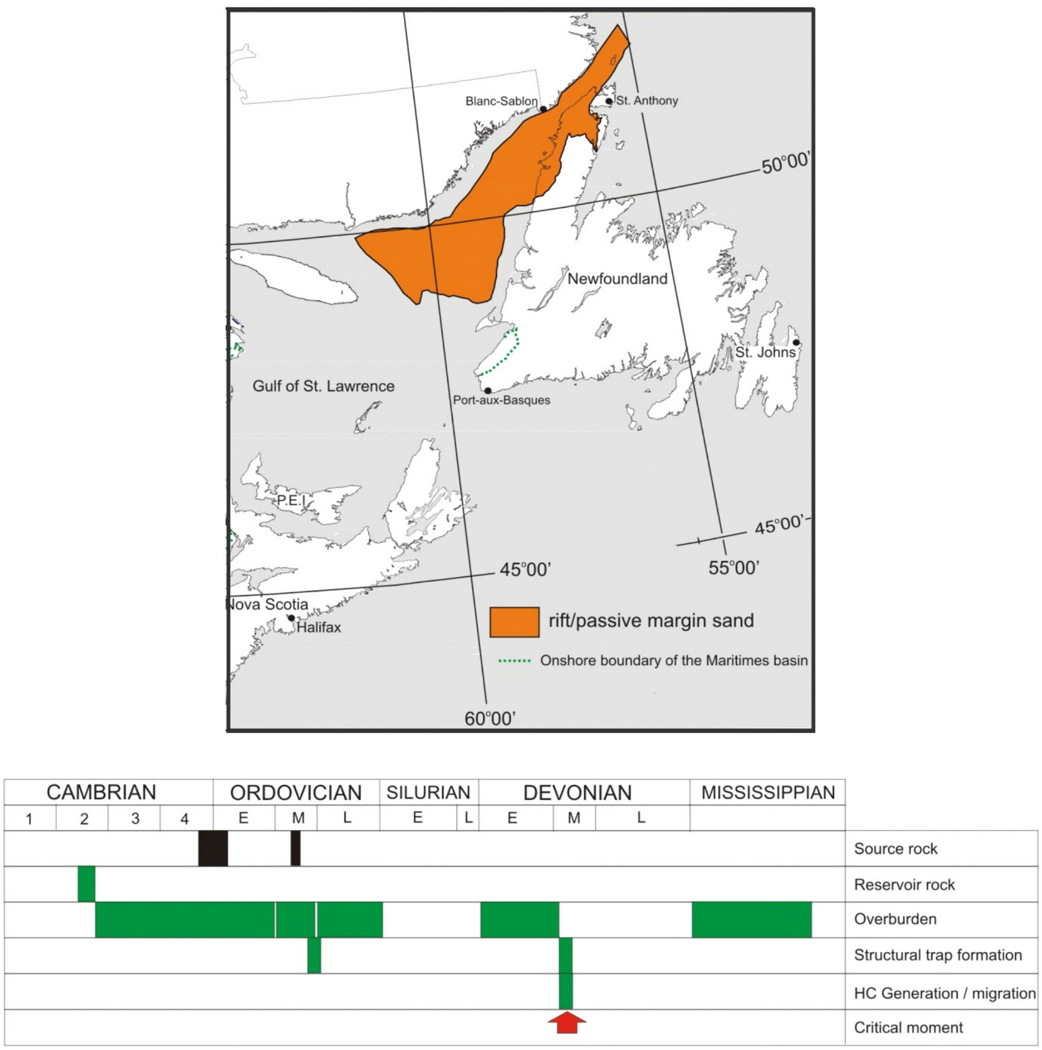

Figure 29. Map of Early and Middle Cambrian clastic successions formed during the early rifting events across Atlantic Canada, and a play chart to show the timing for each of the system parts to develop (from Lavoie et al., 2009).

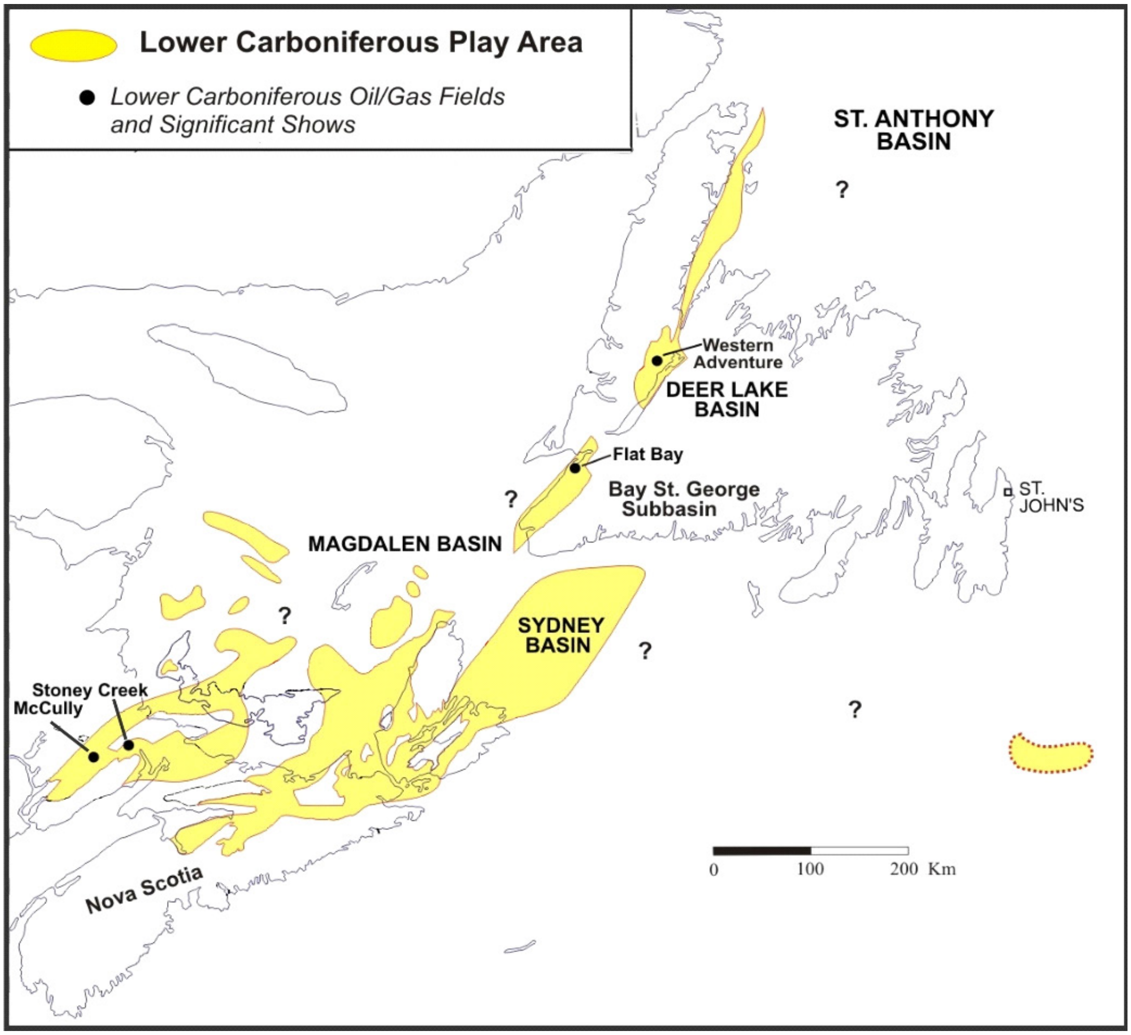

Figure 30. Conventional Lower Carboniferous plays may involve clastic and carbonate deposits. Unconventional plays are organically rich lacustrine source rocks. Lower Carboniferous evaporates are a major part of many Upper Carboniferous plays (Lavoie et al., 2009).

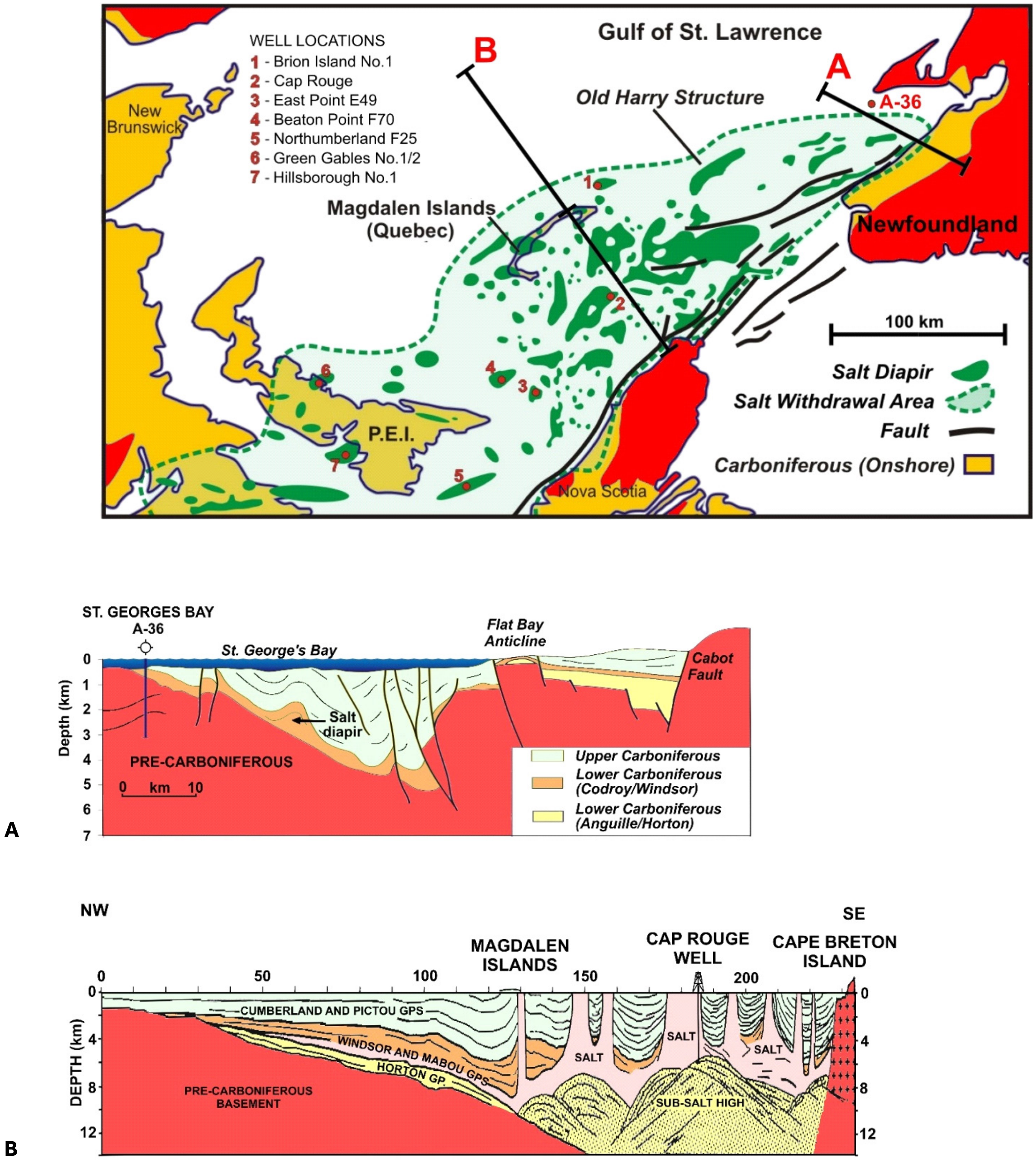

Figure 31. Lower Carboniferous evaporates are diapirs intruding into and deforming Upper Carboniferous strata and forming massive structures laying beneath the Gulf of St Lawrence. These have significant potential for large oil and gas deposits. Note change in vertical scale between A and B. Images from Durling and Mareillier (1994) and Dietrich (2009).

Furthermore, unconventional exploration plays in Newfoundland and Labrador are not simply "Green Point" shale in the Allochthon (Fig. 32). While quantifiable large volumes of rock with favourable organic geochemistry continue to remain elusive, there is no particular geologic reason to summarily exclude all of the dark mudstone deposits of the Forteau and Irishtown formations (Fig. 29) as either source rocks or source rock reservoirs formed during the early Cambrian rifting of the Anticosti Basin (see Coleman, 2014 for his review of Cambrian platform rocks in America). Likewise, in the Late Ordovician foreland basin laying upon and adjacent to the edge of the Anticosti Basin the "Utica Shale" source rock play is an important resource beneath the St Lawrence lowlands east of Montreal, on Anticosti Island, and therein extending beneath the Gulf of St Lawrence towards Newfoundland. Onshore, in Newfoundland, on Long Point, on the Port au Port Peninsula, "Utica" rocks are known as Winterhouse Formation – and another rock that smells bitumenous and contains oil shows (Hinchey et al, 2015). In Carboniferous, Alleghenian transpressional basins, ancient lake deposits in Newfoundland and New Brunswick are well known as essentially undeformed, high grade source rocks (Fig. 33). In New Brunswick, in the past, and before extraction technology changed, these beds were considered a mineable resource.

In the last 20 years, and with significant indications for conventional hydrocarbons in western Newfoundland, the intensity of basic practical research in, geology, petroleum geology and exploration of the Anticosti Basin region has been moving in the right direction. That said, the overall level of research into the practical geology and resource potential of conventional targets and unconventional resource plays on or adjacent to the island is, at best, very modest – that is about 6 papers per year that say something about one or more parts of any Anticosti Basin petroleum system (Burden et al. 2014). For the other Paleozoic basins on or around Newfoundland and Labrador's coasts, the quantity of any petroleum system geology research published in any given year is practically zero (Burden et al., 2014).

Within the Anticosti Basin, the most glaring weakness in petroleum system research rests with improving our understanding conventional and unconventional reservoir seals (Burden et al., 2014). Gathering a practical knowledge and developing expertise in physical and chemical properties of the rocks in this area is needed for successful outcomes for resource discovery and exploitation. If progress in this direction is to happen, some of this new information will have to come from carefully designed drilling, coring and down hole testing.

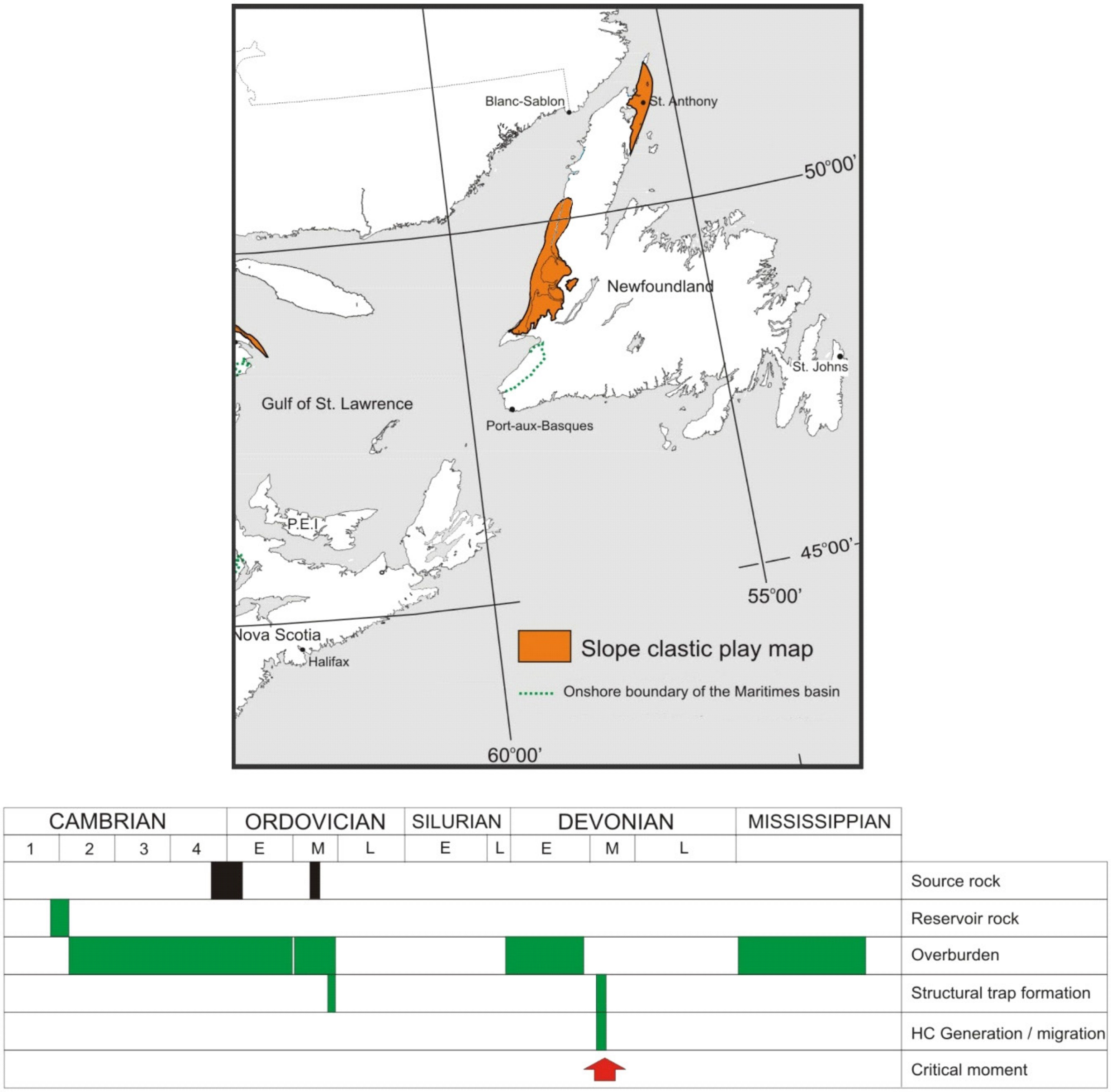

Figure 32. Map of transported Cambrian and Ordovician clastic and carbonate shelf and slope deposits formed during the early stages of rifting and sea floor spreading and later transported onto the Carbonate platform. The Critical Moment in the Acadian Orogeny has to be tempered with the fact that the younger Alleghenian Orogeny stretched the crust across this region creating the Maritimes Basin Tectonostratigraphic Province in some places and crustal inversion and significant uplift in other places. Play chart from Lavoie et al. (2009).

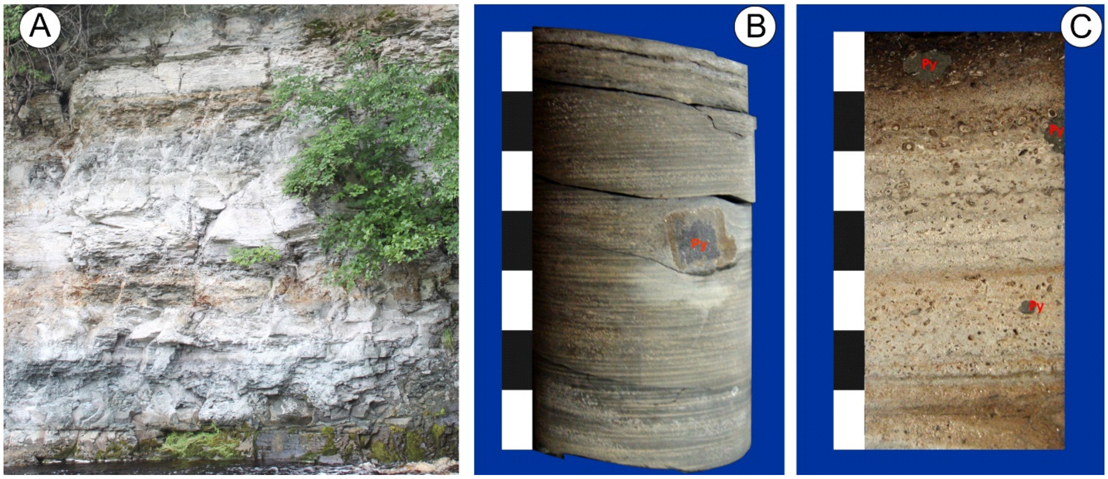

Figure 33. (A) Five metre outcrop section of essentially flat lying Rocky Brook Formation (Carboniferous) organic mudstones with thin carbonate beds are ancient lake deposits. (B) Core (scale 7 cm) from this interval tends to be dark in colour, laminated, friable and pyritic. (C) Carbonate bands are graded beds of coated clasts, oncolites and pyrite indicating deposition of organic material in lakes with low levels of dissolved oxygen. Illustrations from Kelly and Burden (2011).

Questions

(a) Risk associated with known faults such as their potential as pathways for fluid migration, of fluid migration during multi-stage hydraulic fracturing, for interfering with the productivity of wells through excessive fluid influx, and other widely understood risks of a geological and fluid flow nature

(b) Risks associated with the presence of currently unidentified faults that could impact drilling and development activity that could lead to enviro-economic risks

Outcrops of the Allochthon mapped from Bonne Bay to the shores of the Port au Port Peninsula are everywhere folded and faulted from the superposition of multiple tectonic events and including out of sequence thrusts and back thrusts. During the first round of mapping with the Plate Tectonic paradigm as a model, and essentially encompassing the work effort completed from the 1960's and on into the 1990's, large parts of what is still arguably the best regional map of the Allochthon (Williams and Cawood, 1989) were simply called "mélange", a term used to describe chaotic and broken beds with mixed origins.

Newer 1:50000 maps by Waldron et al (2004) and Burden et al (2005) for the central part of the sedimentary successions of the Allochthon have endeavoured to create records for some of the larger folds, faults and other prominent lineaments that are traceable for several kilometres – and namely to identify possible analog features about the same size as some of the small subsurface structures that may contain hydrocarbons. The word "mélange" may be finding less use on newer maps, but the concept of a broken formation remains.

Figs. (34-36) offer some visual examples of the many scales of folding and faulting present in the sedimentary strata of the Allochthon. The two dimensional image of complex geology generated from close mapping of coastlines offers little comfort that the buried sedimentary strata of the allochthon are any less folded and faulted. At the microscopic scale, and in source rock and adjacent strata, the movement of hydrocarbons into and out of fracture networks shows a variety of early and late fractures, flow and pooling. For instance, in essentially undeformed strata in some Carboniferous beds on the Northern Peninsula, hydrocarbons seem to be flowing from diffuse areas, merging into small (primary) fractures, gathering along bedding planes and later moving and diffusing into other porous and permeable strata (Fig. 37). In strata of the Allochthon, the fracture networks are apparently larger, much more extensive and show structural damage to the bedding (Fig. 38). This level of structural complexity and the multitude of scales required for practical resource measurements and management is barely addressed in any of our present surface mapping. In small research exercises within the mapping programmes and theses, Burden et al. (2005), Gillis (2006) and Burden et al. (2010) produced simple models of folds and fractures to try to explain, in the context of petroleum, some of the possibilities for hydrocarbon flow and trapping. Likewise, Waldron and his students continue to explore some of these matters in other formations in the area.

For a successful outcome in this unconventional hydrocarbon development, there needs to be some proof that the complex geology we see on the surface disappears at depth, or that the multitude of the faults and fractures we see on the surface can be successfully modelled and engineered under appropriate underground pressure and temperature to achieve safe, and commercially sustained hydrocarbon flow. If unconventional hydrocarbon projects are to happen, at some point, subsurface testing of the integrity (leakiness) and interconnectedness of small and large faults will be required.

Figure 34. (A) Section of about 250 m of coastline south of Serpentine River and showing part of a complex of refolded folds and faults extending as a continuous coastal outcrop for at least 3 km along that shore. (B) One of many refolded folds examined along this section of shore. The person for scale (~1.5 m) is standing upon the F2 fold axis and beneath parasitic folds and faults that may have been generated by the F2 event.

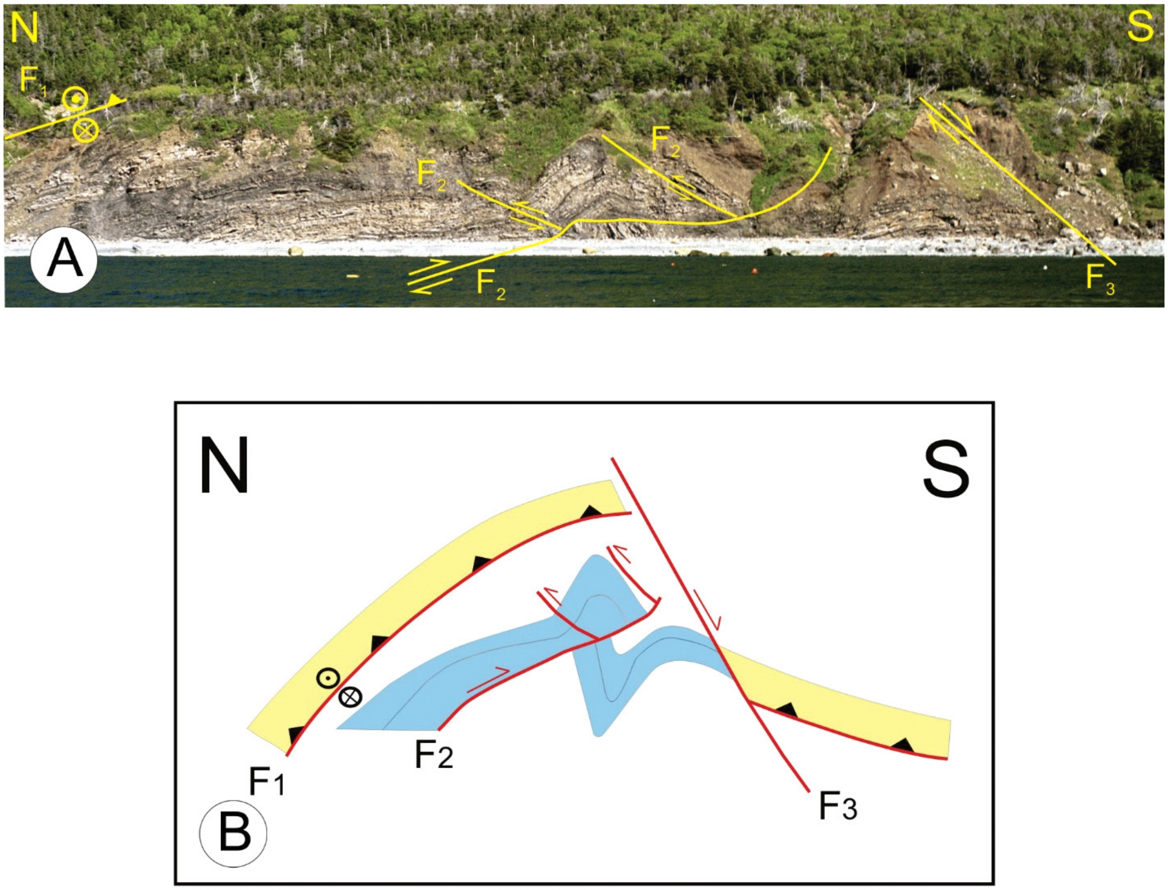

Figure 35. (A) Panorama of about 250 m of coastline at Sluice Brook, north of Fox Island River. Image shows the crest for a feature that may be cover rock for as many as 500 m of coastline. Blow Me Down Brook formation sandstones are thrust upon Cooks Brook Formation source rocks. (B) Schematic reconstruction outlining a proposed sequence of events wherein Blow Me Down Brook sandstone is thrust upon (already deformed?) Cooks Brook Formation source rocks (F1) and later folded and internally thrust faulted (F2). Late stage NE striking normal faulting (F3) splits this antiformal structure (Burden et al., 2005).

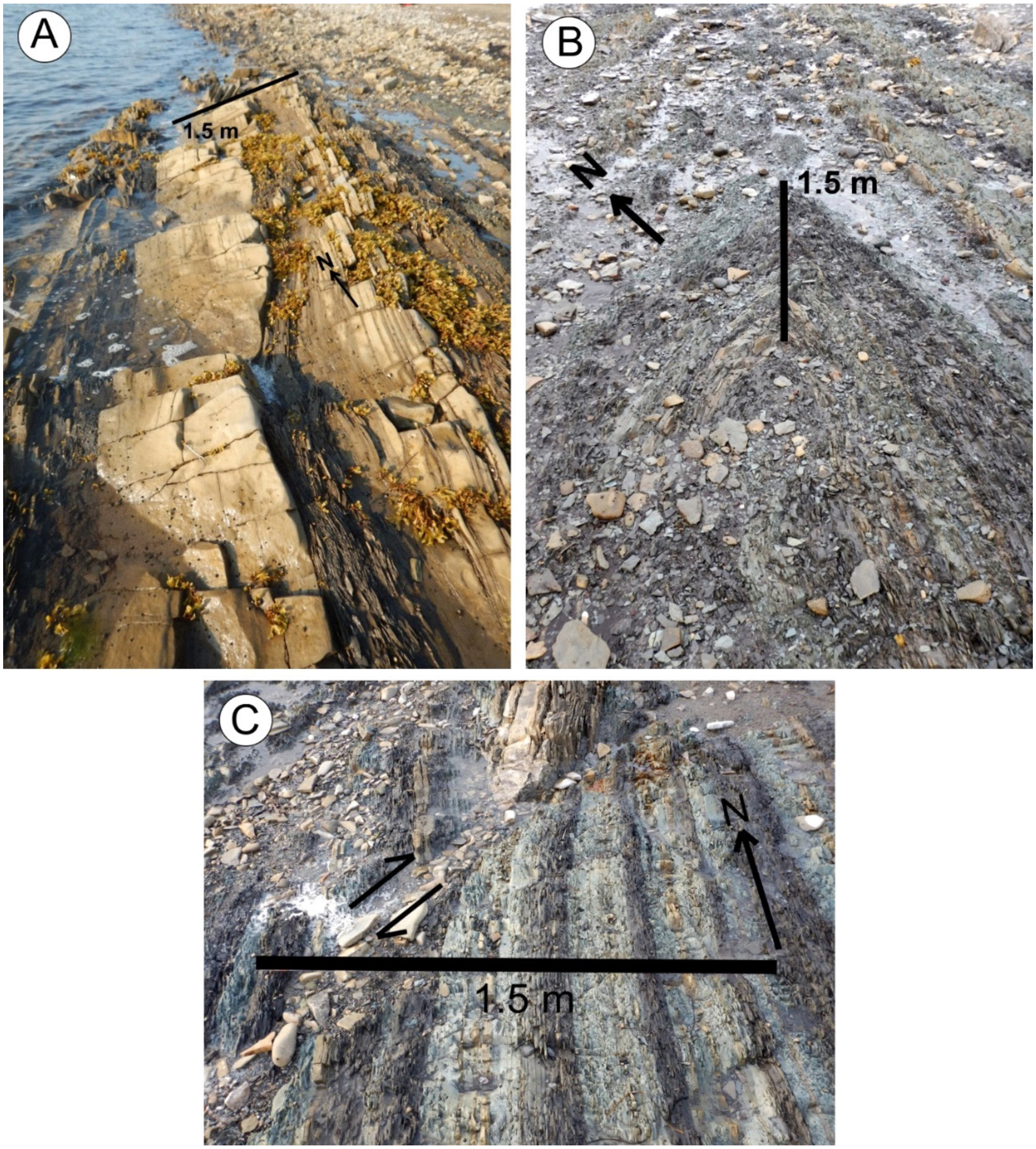

Figure 36. Structurally deformed outcrops near Shoal Point K-39. (A) Steeply dipping, lensoid, thick-bedded calcarenite, in fining- and thinning- upward successions. Prominent west striking and steeply north dipping joint sets are distinctive parts of these thick bedded, coarse-grained limestones. (B) Friable, thin-bedded, grey and black calcareous siltstones and carbonaceous mudstones; tightly folded, with multiple fracture sets (approaching phacoidal cleavage). (C) Friable, thin-bedded, grey and black calcareous siltstones and carbonaceous mudstones with "apparent" dextral strike-slip faults spaced at 10-20 m intervals and striking in a NE direction.

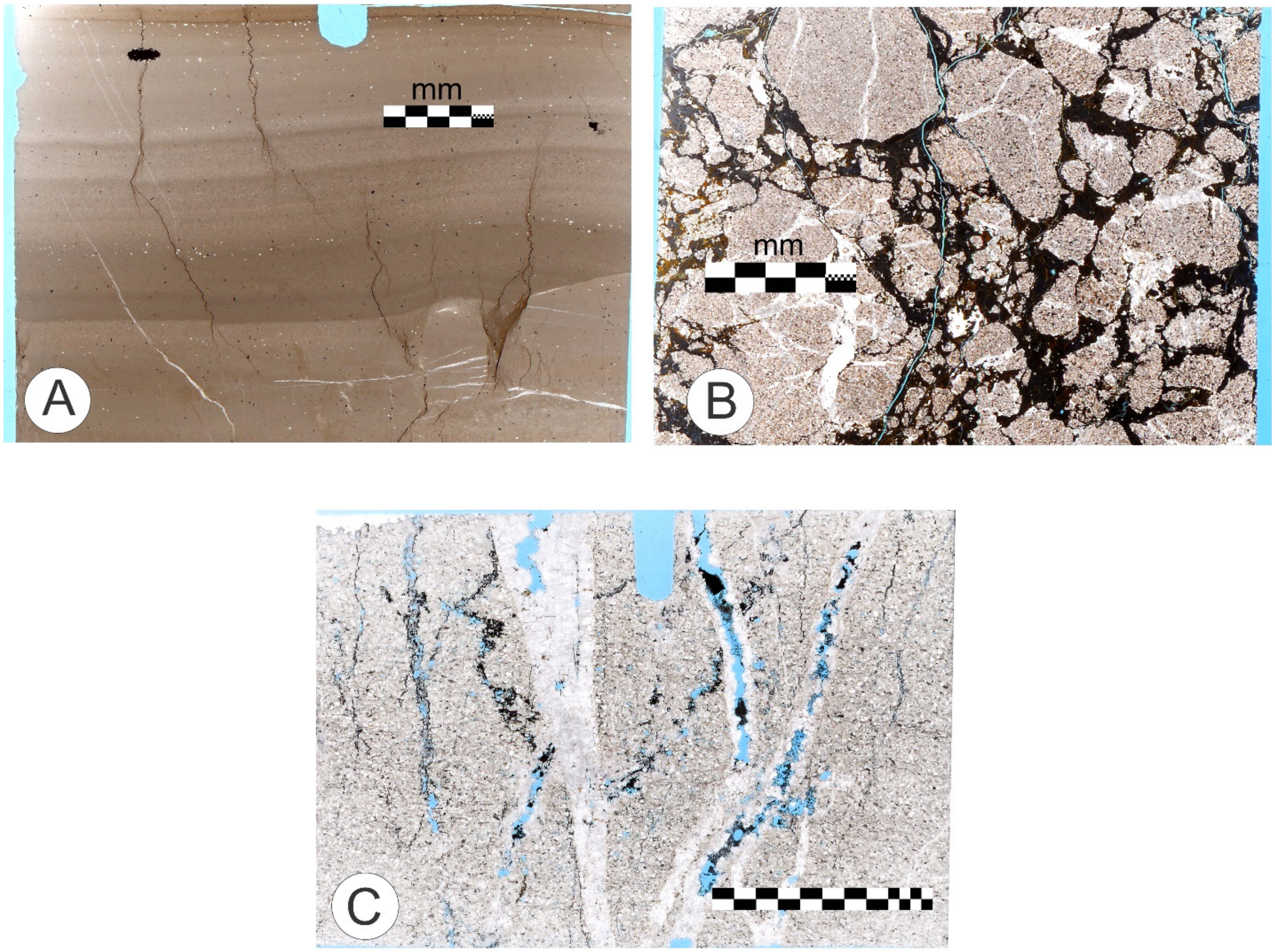

Figure 37. Hydrocarbon migration through strata from western Newfoundland. (A) Early migration of hydrocarbons from a probable Carboniferous source rock at Conche, Northern Peninsula. Thin wispy veinlets grow, amalgamate and disperse along bedding planes as they migrate upward through permeable paths. (B) Cataclastite in a large normal fault at Conche. Dark material is thought to be degraded pyrobitumen and fine-grained minerals. (C) Pyrobitumen in pores and tectonic, quartz-lined extensional fractures – Allochthon east of Trout River Pond. Note: blue is open pore spaces and the U-shaped notch indicates top.

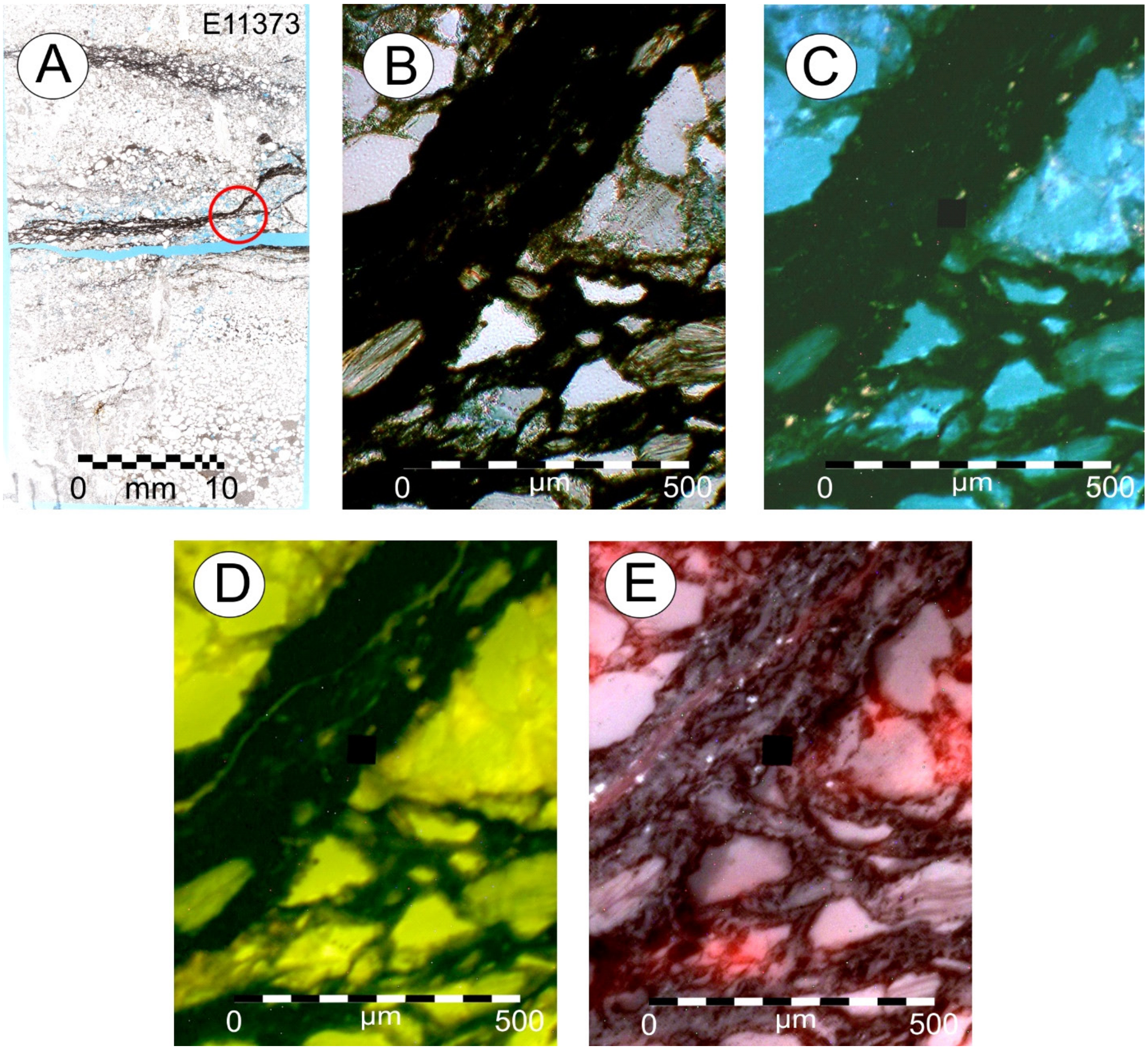

Figure 38. Interbedded, cleaved, tightly folded, dark grey mudstone with thin-bedded, stretched and broken, carbonate cemented quartzose sandstone and siltstone, southeast of Trout River Pond. (A) Thin-section of thick laminae of graded, quartzose, carbonate cemented sandstone with some (dead-) oil saturated laminae. (B) Transmitted-light enlargement of circled area in (A) and showing hydrocarbons along bedding plane with a cut-off breaking up section and across a cemented horizon. (C), (D) and (E) are fluorescent light images of broken quartz grains and carbonate cements, a late stage fracture along the hydrocarbon vein in (D), and "frozen" flow textures of hydrocarbons in the lamina and the cross-cutting fracture in (E).

(c) Risks associated with the nature of the cap rock or formation seal integrity with respect to the multi-stage hydraulic fracture stimulation process.

Source rock reservoirs tend to be very different from conventional hydrocarbon pools and the definition and need for a cap rock may be a moot point. Williams (2013) outlined three distinct types of petroleum systems.

Type 1 is a traditional conventional system of source, seal, reservoir, trap and timing, with petroleum migration determined by density differences in oil, gas, and water contained in a porous and permeable water wet environment (Williams, 2013). This may be similar to the conventional target known as Port au Port #1.

Type 2 is known as a continuous basin centred accumulation (Williams, 2013). This system traps migrating hydrocarbons in relatively impermeable water wet strata – the seal and the trap are one in the same (Williams, 2013) Younger rocks and strata with good seals may be overpressured and gaseous Type 2 systems. In contrast, Type 2 systems in older rocks and strata with imperfect seals may be underpressured.

Williams' Type 3 source rock system is a very different end-member formed as very fine-grained (organically enriched), perhaps also tightly cemented, oil and gas wet (preferentially carbonate) rocks (Williams, 2013). In its strictest interpretation, Williams (2013) considers this system to be a gas generating environment. Interbedded strata carrying Type 3 rock suites with other fine-grained, (calcareous) sandstones and siltstones carrying Type 1 and Type 2 characteristics are considered Type 3 composites that can produce both oil and gas (Williams, 2013).

The faulted structure outlined in Burden et al. (2005) and the strata encountered in the Shoal Point well may be similar to a Type 2 or a composite Type 3 petroleum system. The physical presence of a seal rock is not a prerequisite if the hydrostatic seal is not damaged.

A recently published review paper by Hao et al (2015) and explaining petroleum accumulation and leakage in overpressured reservoirs lists forced top seal fracturing of domes and anticlines, frictional failure along faults and other fractures and capillary leakage as the major mechanisms for petroleum loss from conventional reservoirs. Surface mapping as illustrated in figures 34 to 38 show the allochthon as a region where many of these conditions once existed.

At this point, we have no real way to determine whether tectonism and diagenesis of the allochthon have completely compromised the integrity of the hydrostatic seal. This ancient structural damage to the strata may become an issue if, by fracking, the older faults and fractures are opened in an unacceptable manner and fluids are delivered to the surface. This is a matter for measurement and careful consideration by lease holders, site engineers and government regulators.

(d) Risks associated with the presence of swelling clays or exceptionally high differential earth stresses which may cause issues of borehole stability and attendant risk to drilling activity

Rocks from western Newfoundland have been through hundreds of millions of years of burial and diagenesis. Swelling clays associated with the weathering of volcanic materials are not expected to pose any problems. Many of the rocks in this area do not originate from volcanic sources and have chlorite indices that indicate a significant burial history and diagenesis of clay minerals.

Complex faulting and associated joints and cleavage have rendered many of these beds as friable, easily broken and eroded strata. Historically, there are reports for cavings, spalling into open, uncased holes, trapping drillstems and ultimately ending a project (Fig 39). Today, this problem is understood, casing and cementing a hole is a normal practice, and drills are larger and much more powerful.

(e) Risks associated with the presence and trajectories of legacy well bores

Almost all of the very old wells are apparently shallow (less than 300 m) and nearly vertical in orientation. In the early days of exploration, more than 100 years ago, basic geology was virtually unknown and wildcat drillers would drill on or about oil seeps leaking from near vertical fractures and along bedding planes, and with the expectation that the pool simply lay a short distance down. It is unlikely that any of the old legacy wells are located in stratigraphic horizons or in places where trajectories of old wells will interfere with new targets. In addition, today's targets are apparently located offshore, and beyond the reach of the older wells.

Without any real appreciation of fluid flow in the subsurface or any sense of reservoir shape, structure, permeability and pressure, many of these legacy wells, and including wells drilled 50 years ago, were simply abandoned by the inadequacies of the science, the drilling technology, and the financial management.

Today, companies are much better informed about their corporate responsibilities to government, communities and to the environment. The examples from legacy wells should serve as a reminder for government and industry of what not to do in decommissioning a well and abandoning a site.

Figure 39. An abandoned legacy well from the Parsons Pond area. In the early part of the 20th century the drill stem became trapped in the hole. Photo courtesy of L. Hicks.

(f) Risks of encountering unexpected overpressures that could impact safety and operations

Information I have seen and reviewed from some of the released engineering reports for Port au Port wells drilled in the last 20 years do not seem to show any extraordinary down hole pressures (see Government web site for reports). For instance, data presented in Hinchey et al (2015) and describing reservoir pressure at 1251.5 m on the order of "about10,000 kilopascals" for Shoal Point K-39 is simply a confirmation that downhole pressures are recording normal hydrostatic pressure. Furthermore, and within the Port au Port #1 well, a conventional well drilled into essentially undeformed platform carbonates, the engineering reports for pressure tests on a reservoir buried more than 3 km show the well failed to sustain significant oil and gas flow. After a short time, pressures dropped below the bubble point for gas. Flow and build-up tests between 3354 and 3391 m and conducted over a 4 month period in 1995 record a drop from about 37,000 kPa at 55°C to 27,500 kPa at 54°C.

(g) Risks related to the possible presence of hydrogen sulfide and carbon dioxide

I am unable to make any clear statement beyond the fact that no significant information has been discovered in a coded background search of all the literature compiled for these rocks (see Burden et al., 2014).

Recommendations regarding Bedrock Geology – Strata, Structures and Fluids

Recommendation 4: Government efforts towards building greater industrial capacity in this part of Newfoundland and Labrador should include work with industry to understand these natural resources and to help define appropriate and safe recovery strategies. Logically, this should include better measures of (1) the size, shape, quality and quantity of this potential resource, and (2) measures to confirm recovery is possible in rocks with complex structures and without compromising the surface and groundwater environments.

On a go forward basis, there are two significant matters that need to be resolved, and namely, (1) safe recovery of hydrocarbons and (2) safe disposal of waste fluids. Very little of this basic discovery process can happen in a laboratory. Field experiments to identify and to quantify a commercially recoverable reserve are required.
On this first point, field experiments with microseismic monitoring may provide a solution to determining length, direction and connectivity of large and small fractures. At depth, the shattered, weathered and broken rocks we see on the surface are under significant load pressure and the fractures are tightly closed. Opening these fractures under controlled experimental conditions will provide valuable data on rock strength and behaviour, on the length and development of interconnections of fracture networks that may transmit fluids, pressure gradients associated with fracture networks, and to determine whether any sustainable pressures exist to allow the transmission of commercial quantities of petroleum back to the well bore (see Baig et al., 2015; Billingsley et al. 2015; Crowley et al., 2015; Urbancic et al., 2015).

Fluids used for fracking operations are controversial. Collection and disposal of these fluids is certainly an important consideration in development of unconventional reservoirs. A report by Council of Canadian Academies (2014) indicates suitable sites in Alberta and British Columbia may be found in saline aquifers laying between 0.5 and 1.5 km depth. The Council of Canadian Academies (2014) review suggests that Quebec and the Maritimes may not have strata suited for deep aqueous disposal. At least part of their statement is at odds with a report by Ngoc et al (2014) and indicating some strata of the St Lawrence Lowlands are significantly isolated from overlying aquifers and able to accept carbon dioxide. For Newfoundland and Labrador, the Council of Canadian Academies Report (2014) is almost completely silent.

In Newfoundland and Labrador, beneath the Grand Banks, there are conventional oil reservoirs that are apparently becoming depleted and being flooded with water. On the Port au Port Peninsula, the Port au Port #1 well is underpressured and unable to sustain flow. To my knowledge, no one has asked whether an apparently naturally depleted and underpressured conventional hydrocarbon reservoir, 3500 m beneath the surface in western

Newfoundland, is able to accept expended fracking fluids. On this matter, and simply from a very basic scientific position, the chemistry of fracking compounds and water-rock interactions on deeply buried carbonate rocks under reservoir conditions needs to be addressed.

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