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Purpose

The Paleozoic basins of eastern Canada are frontier basins that occur in close vicinity of densely populated areas in North America. Six Canadian provinces have their share of these Paleozoic lands and the Federal government is claiming responsibility for some of the offshore. The onshore parts of these Cambrian-Permian basins have been the subject of modern geological framework studies over the last decade (2 National Mapping and 3 Targeted Geoscience Initiative projects) with the recognition of hydrocarbon potential in all of these belts. The offshore extension of these belts has not been studied since the 1980s.

The Paleozoic successions can be assigned to distinct basins based on their age, tectonic history and proven hydrocarbon systems:

1- The Cambrian-Ordovician St. Lawrence shallow marine platform and coeval deep water facies (now preserved in the Taconian Humber and Dunnage zones)

2- The Silurian-Devonian shallow to deep marine Gaspé Belt

3- The Devonian-Permian mostly terrestrial Maritimes basin

Hydrocarbons are currently being produced in all of these domains.

On December 4 and 5, 2007, a workshop on the ‘Paleozoic Basins in Eastern Canada, Geological Setting and Petroleum Potential’, was held at GSC-Calgary. This workshop attracted twenty-nine participants from fourteen different oil and gas companies, the National Energy Board, Provincial Surveys and offshore petroleum boards. The workshop presented a review of the work done by the GSC in support of the project, ‘Hydrocarbon resource evaluation – Gulf of St. Lawrence and adjacent Paleozoic onshore’, as part of the Secure Canadian Energy Supply (SCES) Program. Presentations were made by GSC personnel from Calgary, Québec and Halifax, by our provincial project partners and from the offshore petroleum boards to cover their activities in New Brunswick, Nova Scotia, Newfoundland and Québec, as well as by one company on their recent drilling results in Prince Edward Island. Presentations focussed on all aspects of sedimentary basins and petroleum systems analysis. This Geological Survey of Canada Open File presents the communications made at this December 2007 workshop, together with some descriptive notes to accompany the visual presentations. Some presentations are unaltered from their initial release whereas some post-December 2007 material has been added to others.

In the following text, at the start of individual paragraph, the number refers to the slide in the accompanying presentation.

Presentation #1

History of hydrocarbon exploration in the Paleozoic basins of eastern Canada

(*D. Lavoie, N. Pinet and S. Castonguay; GSC-Québec*)

(#2) The search for energy in Canada goes back to the foundation of the Geological Survey of Canada in 1847. Its first director, Sir William Logan, was mandated to explore for coal to support the new metallurgical industry.

(#3) Some debate exists between Canadian and American as to whom was the first one to drill a hole in search for oil; Canadians are proud supporters of James Miller Williams who in 1856, drilled a hole at a locality later known as Petrolia in southern Ontario.

(#4) Based on the early geological reconnaissance mapping by Logan and his colleagues, the major geological domains in eastern Canada were recognized on the basis of paleontology, intensity of deformation and major depositional breaks or unconformities.

(#5) With extensive geological reconnaissance, localities with surface indications of hydrocarbons were recognized in all these newly defined geological domains.

(#6) In the Carboniferous succession of southern New Brunswick, a shaly rock that burn when ignited served as indictors for initial drilling in 1859. The oil and gas field of Stoney Creek was discovered in 1909 and is one of the oldest commercial fields in Canada. (#7-8) Almost simultaneously, drilling was initiated in slightly older rocks of the Gaspé Peninsula. The interest was based on reports of seeping oil out of Devonian rocks. The first wells were drilled in 1860 just west of Gaspé and for 75 years, periods of intense drilling activities were separated by sharp declines. Almost all of these shallow wells had indicators of hydrocarbons or produced variable volumes of oil. One company (Petroleum Occidental Trust) was so convinced of the potential of the area that they built a small oil refinery on the York River in 1904, only to dismantle it a few years later.

(#9-11) The presence of seeping oil out of Ordovician rocks in Western Newfoundland had been known for a long period of time around Parson’s Pond. From 1867 up to the 1930’s, individuals and companies drilled a significant number of shallow holes in the search for oil at many places along the west coast of Newfoundland. Again, if most of these holes yielded some oil, production was always sub-economic.

(#12) Oil seeps out of Carboniferous sandstone on Cape Breton Island was the incentive for initial exploration drilling along Lake Ainslie. As for the above localities, the presence of seeping oil was certainly not an indicator of immediate drilling success, as sub-surface geology for these areas was largely unknown.

(#13-14) In southern Québec, drilling for aquifers in the Trois-Rivières area resulted in the discovery of a significant volume of natural gas in 1887 and the first economic production of hydrocarbons in Québec. From 1905-1907, a pipeline carried gas from the Pointe-du-Lac field to the nearby town of Trois-Rivières. It is noteworthy that natural gas was produced out of an unconsolidated quaternary sand unit that overlies the fractured Ordovician black shales of the Utica Formation.

(#15) Since the advance of modern seismic reflexion surveys in the 1970's, exploration drilling became progressively successful and some significant discoveries were made in all these Paleozoic domains including the St. Flavien gas field (1972) in Lower Ordovician dolomite of southern Québec; the East Point gas field (1979) in upper Carboniferous sandstone offshore Prince Edward Island; the Galt gas field (1980) in Lower Devonian carbonate of Gaspé; the Garden Hill oil field (1995) in Lower Ordovician dolomite of western Newfoundland; the McCully gas field (2001) in Carboniferous sandstone of southern New Brunswick; the Haldimand oil field (2005) in Lower Devonian sandstone of Gaspé and the Gentilly gas field (2006) in Upper Ordovician dolomite of southern Québec. In April 2008, the Ordovician Utica Shale was at the forefront of the North American hydrocarbon world with the release of preliminary well and technical information suggesting major shale gas potential. In December 2007, almost all lands underlain by Paleozoic rocks with hydrocarbon potential were under exploration licenses in eastern Canada.

(#16) However, even if recent drilling successes support the hydrocarbon potential of these Paleozoic basins, these are still, from an exploration point of view, frontier basins. For example, for close to 150 years, barely 350 holes have been drilled in Québec (and most without any seismic data), this is less than 2% of the total wells drilled in Alberta in 2003.

(#17) The Geological Survey of Canada and the provincial surveys from all jurisdictions in eastern Canada initiated a series of geoscience projects in order to enhance our knowledge of the evolution and architecture of these geological domains and help local junior companies involved in the early stages of a renewed exploration phase. These projects were part of the Magdalen Basin NATional MAPping (NATMAP) project (1993-1998); the eastern Canada Bridge NATMAP project (1999-2004); the Targeted Geoscience Initiative (TGI-2; 2003-2005).

The abundant new information serves as the cornerstone of the actual project "Hydrocarbon Resource Evaluation of the Gulf of St. Lawrence and Adjacent Onshore", part of the "Secure Canadian Energy Supply" Program (2005-2009).

(#18-23) This last initiative comprises various acquisitions of new basic geological framework and hydrocarbon-related data including source rocks, thermal histories, seismic reprocessing of vintage data and acquisition of modern potential field information and new marine high-resolution seismic.

(#24) All these new datasets will be integrated and synthesized to provide the information needed to carry out the first independent resource evaluation of hydrocarbon plays in the Paleozoic basins of eastern Canada.

Presentation #2

Lower-Middle Paleozoic basins in eastern Canada: Overview of the geological framework

N. Pinet, D. Lavoie and S. Castonguay; GSC-Québec

(#2) The Paleozoic succession of eastern Canada was deposited during a complete Wilson cycle from supercontinent rifting (Rodinia in Ediacaran time) and ocean opening to a complex period of basin and ocean closures culminating in the formation of the next supercontinent (Pangea in Permian time). During that 320 Million years cycle, several regional to more local orogenic events served as markers for dividing the sedimentary succession into three major packages divided by two orogen-scale unconformities: the Ordovician Taconian and the Devonian Acadian unconformities.

(#3) Below the Taconian unconformity, the sedimentary succession corresponds to Lower Cambrian – Upper Ordovician rocks that are preserved in two major lithotectonic domains: (1) the St. Lawrence Platform of mixed carbonates and clastic units of initially shallow marine to ultimately deep marine settings and (2) the westernmost Appalachian domain known as the Humber zone which includes coeval deep marine slope and rise sediments. The following Upper Ordovician to Middle Devonian succession is topped by the Acadian unconformity. This succession consists predominantly of shallow to deep marine clastics and volcanics with local limestone platforms and reef complexes forming the Gaspé Belt. Finally, the uppermost Devonian to Lower Permian succession of the Maritimes Basin has been deformed during the Alleghenian Orogeny. This basin is predominantly a marginal marine to fluvial clastic succession with marine carbonates and evaporites near its base.

The Cambrian-Ordovician

(#4) The break-up of Rodinia in Ediacaran time (latest Neoproterozoic) resulted in the formation of Laurentia with a continental margin geometry characterized by reentrants and promontories. Such morphological heritage has played a critical role in the Tectono-sedimentary evolution of the margin during most of the Lower Paleozoic.

(#5-6) In Québec, significant Cambrian-Ordovician stratigraphic variations are recognized. They are related to the inherited margin morphology complicated by an uplift zone induced by a major magmatic intrusion at the junction (Anticosti basin) between the Québec Reentrant and St. Lawrence Promontory. A much more stratigraphically complete succession is present in western Newfoundland at the St. Lawrence Promontory.

(#7-10) Recent radiometric ages help to better constrain the history of the Rodinia rifting. Ages of dykes that cut through the Precambrian basement suggest that the rifting started in Ediacaran time (590 – 575 Ma). The break-up of Rodinia resulted in the formation of horsts and grabens and in the deposition of shallow (horst) and deep (graben) marine coarse clastics with local shallow marine carbonate banks on some highs.

(#11-14) As the newly formed Iapetus Ocean became progressively larger, the continental margin crust started to cool-off and the margin became tectonically passive. The drift history of that trailing margin started in Middle Cambrian with accumulation of carbonates on a narrow, high-energy platform which, in earliest Ordovician evolved into a wide, low energy platform as seawater invaded most of Laurentia. Adjacent to this shallow marine environment, the deep slope and rise are primarily characterized by deep marine muds with local coarser grained intervals that were the expression of significant erosional events of the shallow marine deposits.

(#15-18) Mountain building (Taconian orogeny) started in the Early Ordovician. The Cambrian-Lower Ordovician shallow marine platform was tectonically exhumed and significantly eroded whereas a foreland-basin was formed at the front of the incipient orogen. The shallow marine carbonates accumulated on fast subsiding carbonate ramps which were diachronically drowned from Middle Ordovician in western Newfoundland to Late Ordovician in southern Québec and Ontario. Deep marine anoxic basins accumulated organic matter rich muds rapidly diluted by northwesterly incoming thick flysch successions derived from the erosion of frontal zones of the encroaching Taconian thrust slices. The tectonically controlled sedimentation lasted from Middle to Late Ordovician with shorter-lived but multiple events at the St. Lawrence Promontory compared to one long-lasting event in the Québec Reentrant.

(#19-20) In the shallow marine foreland setting, tectonism is expressed in abundant synsedimentary normal to apparently (e.g., as recognized in the adjacent New York succession) transtensional faulting; whereas NW-directed thrust faulting dominates in the frontal part of the orogen.

The Silurian-Devonian

(#21-23) After the climax of Taconian deformation related to the obduction on Laurentia's deep continental margin of oceanic seafloor and associated volcanic arcs, sedimentation resumed on highly variable basements. On the shallow margin of Laurentia, northwest of the Taconian orogen, shallow marine carbonate sedimentation resumed without any significant break in latest Ordovician and extended up to the late Early Silurian (Anticosti and western Newfoundland). Further to the southwest, a complex basement of low relief and uplifted zones of oceanic (Dunnage Zone) and Laurentian (Humber Zone) material diachronically recorded (from south to north) the progressive onset of marine sedimentation in the Gaspé Belt "successor basin". Sedimentation lasted from the latest Ordovician to the Middle Devonian and was controlled by second-order transgressive-regressive events of both eustatic and tectonic controls.

(#24) The tectonic control on sedimentation became dominant in late Early Silurian time with the development of the Acadian-Salinic foreland basin. The climax of Acadian deformation is recorded in Early to earliest Middle Devonian in Gaspé and deformation, related to the accretion of Avalonia on the composite (Laurentia sensu stricto + Taconian volcanic arcs and ophiolites + Salinic Ganderia) margin of Laurentia.

(#25-27) The style of Acadian deformation changes across the Gaspé Belt and along-strike. The amount of shortening decreases to the NW and regional strike-slip faults predominate, especially in the eastern part of the Gaspé Peninsula. The effects of the Acadian deformation can even be observed in the far foreland succession of the Anticosti basin with the post-Taconian successions (Lower Silurian to Devonian?) being involved in large open folds in the St. Lawrence estuary.

(#28) The style of Acadian deformation was significantly different in western Newfoundland where some of the old Taconian normal faults in the foreland platform where reactivated as reverse fault in a thick-skinned tectonic scenario and a triangle-zoned was formed at the Acadian structural front. All of these have critical significance for the prospectivity of the area.

(#29) The Acadian Mountains represented certainly a significant topographic feature in eastern Canada as most of the Middle and Late Devonian time interval left no significant sedimentary record.

The Carboniferous - Permian

(#30-32) Roughly 20 Ma after the Acadian Orogeny that a new cycle of sedimentary accumulation started. Coarse to fine (and organic matter rich) clastics of alluvial plains to lacustrine settings accumulated in tectonic depressions or grabens during the earliest Carboniferous. It is only slightly later that a significant marine incursion resulted in the flooding of most of what is known as the Maritimes Basin. This major flooding event in the Viséan resulted in the accumulation of a thick succession of deep marine salt that later deformed as diapirs. After the retreat of the "Windsor" sea, the Maritimes Basin became largely a continental to marginally marine environment that lasted from the Late Carboniferous to the Early Permian, with a sedimentary succession that reaches its maximal thickness (roughly 12 km) to the south of the Magdalen Islands in salt diapirs dominated domain. The succession is marked by significant unconformities that are the testimony of the continental, fluvial dominated sedimentation. In this succession, thick coals accumulated in the Pennsylvanian succession. The last sediments to be preserved in the Maritimes basin are Lower Permian very porous eolian sands that crop out on the Magdalen Islands.

Presentation #3: No text provided

Some brief comments on hydrocarbon occurrences in Gulf of St. Lawrence area

Martin Fowler, GSC-Calgary

Presentation #4

The Lower Paleozoic St. Lawrence Platform in eastern Canada

(Cambrian to Late Ordovician) – Geological framework

D. Lavoie, N. Pinet and S. Castonguay; GSC-Québec

(#2) The St. Lawrence platform corresponds to the autochthonous sedimentary cover of the North American craton. The sediments of the St. Lawrence Platform were deposited on a shallow continental margin after the break-up of Rodinia in Ediacaran time up to the climax of Taconian orogeny in Upper Ordovician time when they were deposited in a foreland basin setting.

(#3) After the break-up of Rodinia, the newly formed Laurentia continent was in a sub-tropical setting where it stayed for a long period of time.

(#4) The paleosouthern margin of Laurentia was characterized by a rugged margin of horsts and grabens that formed major reentrants and promontories. The eastern Canada segment of the margin is formed by the Québec Reentrant and the St. Lawrence Promontory, two major features that have been interpreted by some authors to be divided by the St. Lawrence transform.

(#5) These major morphologic features have played a significant role in the diachronous tectonostratigraphic evolution of the St. Lawrence Platform.

(#6) Three areas will be examined in more details, southern Québec, Anticosti and western Newfoundland.

Southern Québec

(#7-8) Within the Québec Reentrant, significant stratigraphic variations are known. In southern Québec, the stratigraphic succession ranges from the Upper (?) Cambrian to the Upper Ordovician. The succession is divided in two major tectonostratigraphic packages, 1) the clastic to carbonate rift to drift succession and 2) the carbonate to clastics foreland basin succession.

(#9) The Upper(?) Cambrian Potsdam Group unconformably overlies the Grenvillian basement. The group is separated into two formations, the lower Covey Hill Formation made up of coarse conglomerates, impure sandstones and siltstones of fluviatile origin and the upper Cairnside Formation consisting of well sorted silica-cemented quartz arenite deposited in a marginal marine setting.

(#10) These basal clastics are developed along the entire continental margin of Laurentia although they include slightly younger rocks in Québec and eastern Ontario.

(#11) Little is known on the diagenetic evolution of the Potsdam, a significant sub-aerial unconformity has been recently documented between the Potsdam and the overlying Beekmantown groups.

(#12) The Beekmantown Group is a Lower Ordovician (Arenig) to lower Middle Ordovician succession. The Beekmantown is a tripartite unit with the lower Theresa Formation, the Middle Beauharnois Formation (with the Ogdensburg and Huntingdon members) and the upper Carillon Formation. The Theresa Formation carries conodont microfauna of Arenigian age and the entire Tremadocian stage is seemingly absent between the Cairnside and the Theresa. The Beekmantown Group is dominated by low energy, peritidal to shallow subtidal carbonates that commonly form meter-thick hemicycles; autocyclic and allocyclic processes have been put forward in the literature. The almost total lack of evaporites is significant and indicates that conditions were not very arid. The Carillon at the top of the group is characterized by finer-grained carbonate facies and regional considerations suggest that the Carillon was deposited in the first stages of the Taconian foreland basin.

(#13) Correlations (time and facies-wise) are well established with the succession in Ontario; conversely, the largely coeval St. George Group in western Newfoundland has some significant stratigraphic differences with the Beekmantown, having a much older base (a Tremadocian 3rd order cycle not present in the Beekmantown), major internal depositional break and a major sub-aerial unconformity topping it. Recent new fine-scale correlations with the succession in the Philipsburg Tectonic Slice at the Appalachian structural front in southern Québec have shed significant new lights on the overall evolution of the Lower Ordovician margin in eastern Canada.

(#14) The diagenetic evolution of the Beekmantown Group in southern Québec is poorly constrained. The presence of multiple dolomitization events, including late saddle dolomite, has been reported on a petrographic basis. The most detailed summary of the diagenetic evolution of the Beekmantown is from the St. Flavien gas field at the Appalachian structural front. Multiple carbonate (calcite and dolomite) cementation, dissolutions, fractures and brecciation events are documented and led to the eventual formation of the reservoir.

(#15) A slight time hiatus is recognized between the Carillon Formation and the overlying basal clastics of the Laval Formation (Chazy Group). This break is related to the passage of the peripheral bulge on the continental margin and marks the limit between the Sauk (passive or trailing margin) and the Tippecanoe (Taconian foreland basin) sequences.

(#16) The foreland basin carbonates consist of the Chazy, Black River and Trenton groups, which were deposited on a carbonate ramp that was subsiding at a much faster rate compared to the underlying Beekmantown platform. The Black River and Trenton groups are important units as they form major hydrocarbon reservoirs in nearby Ontario, New York and the

US Midwest. The Black River Group is a tripartite unit (Pamelia, Lowville, Leray formations) characterized by muddy carbonates with local small metazoan patch reefs and oolitic shoals. A slight eustatically-controlled unconformity separates the Black River from the Trenton. The Trenton Group is also a tripartite unit, for which only the middle unit (Deschambault Formation) has a uniformized nomenclature over southern Québec. A complex scenario of alteration of oceanic circulation in Late Ordovician time is recorded in the Deschambault Formation in Québec and in coeval units in the eastern USA. The Trenton is a rapidly deepening-upward succession with its uppermost beds heralding the overlying deep marine black shales. As shown by the overall lack of correlation between the eustatic sea level curve and the interpretation of relative sea level based on facies analysis, the main drive for the evolution of the Black River – Trenton interval is foreland basin tectonics, although locally, the eustatic signal can still be detected (Darriwilian – Caradocian limit). Besides a local diagenetic study in the Deschambault Formation, the diagenetic evolution of the Black River – Trenton groups in southern Québec is unknown. Very recent data will be discussed in the hydrocarbon presentation.

(#17-20) The rapid, tectonically-controlled, deepening upward event resulted in the eventual drowning of the carbonate ramp and the sedimentation of clastics in Late Ordovician. Three major assemblages are present, 1) the black calcareous shale of the Utica Shale, 2) southerly derived deep-marine flyschs (Lorraine Group and equivalent units) and 3) regressive shallowing upward post-orogenic coarse to fine-grained fluviatile to marginal marine clastics (Queenston Group). Some of the internal units present in the Utica Shale of New York are seemingly present in southern Québec although more work is needed to provide evidence for such correlations.

(#21-24) Recent reprocessing and reinterpretation of regional deep seismic lines in southern Québec has shed new lights on the structural framework of the St. Lawrence platform. The geometry of the base of the platform succession which is involved in half-grabens with few horsts is visible on all three seismic lines as well as an overall southeasterly thickening of stratigraphic units. Also worth mentioning, a sag is visible on M2003 line.

(#25) One major element of controversy is the presence or not of lateral displacement (inducing transtensional or wrench-faulting) along some of the rift-related normal faults visible in seismic and in the field. Very little is actually known on this issue. Noteworthy, previous interpretations of lateral motion based on horizontal striae along the Montmorency fault have been shown to represent intersection lineation (bedding on fault surface) and thus cannot be used as a kinematic indicator. In addition, the compilation of fault dips and striation pitches in the Charlevoix area, NE of Québec City, suggests that normal (dip slip) motions predominate.

(#26) The overall geometry of the St. Lawrence platform is relatively simple. However, recent studies enhance some possible structural complexities, all of which have significant impact on potential reservoir and trap developments.

(#27) The age of these extensional faults, and timing of multiple reactivation episodes are still imprecise: these were active at the break-up of Rodinia, reactivated during the Taconian foreland basin episode and recent AFT data indicate some Mesozoic movements. Moreover, recent multibeam bathymetry images from the St. Lawrence estuary show that the faults correspond to 300 m high escarpments with a very 'young' morphology including triangular faces which may suggest fairly recent movements.

(#28) Reinterpretation of marine seismic data has documented the presence of post-Taconian (Acadian?) folds in Lower Silurian or younger units in the St. Lawrence estuary and gulf.

(#29-30) At the contact with the Appalachian structural front, seismic (line M2002) and field (Nicolet River) data indicate the presence of major compressive deformation in the St. Lawrence Platform upper clastic units including a shallow triangle zone and deeper blind thrusts.

(#31) Finally, when the Appalachian structural front is close to the carbonate platform (e.g., Québec City for example), some relatively significant thrusting and folding are recorded in the carbonate units.

Anticosti basin

(#32-33) The onshore segment of the Anticosti basin is found on the north shore of the St. Lawrence Gulf and on nearby Mingan Islands where the Lower Ordovician Romaine Formation and the Middle Ordovician Mingan Formation are exposed, whereas on Anticosti Island Upper Ordovician (Vauréal Formation) to Lower Silurian (Anticosti Group) succession crop out. Potential reservoirs are documented in the Ordovician Romaine and Mingan formations as well as in the Lower Silurian Chicotte Formation.

(#34) The Lower Ordovician (Arenigian) Romaine Formation unconformably overlies the Grenvillian basement. The Romaine Formation, up to 400 m thick, is composed of 3rd cycles dominated either by subtidal or intertidal facies. Within these, numerous metre-thick shallowing upward cycles are developed and locally seemed to have controlled the intensity of dolomitization. The Romaine Formation is interpreted as a passive margin carbonate platform succession although some thickness anomalies would suggest that late stages of sedimentation are syn-tectonic.

(#35) The Middle Ordovician (Darriwilian) Mingan Formation (termed Trenton in some old exploration reports) is dominated by open marine carbonates without any significant peritidal facies. Evidence for active tectonism at time of sedimentation is used to support a foreland basin setting for that unit. In fact, the Sauk-Tippecanoe unconformity is visible at many places between the Romaine and the Mingan.

(#36-37) Recent high quality seismic data on Anticosti illustrates a significant number of extensional faults that affect the Romaine-Mingan succession. Most of these faults die out in the Upper Ordovician Macasty Formation suggesting a Taconian age. A major NW-SE extensional fault (the Jupiter fault) is documented on seismic and potential field data. This fault was active in the late stages of sedimentation of the Romaine Formation.

(#38) The Anticosti basin is largely an offshore domain that extends in the northern half of the Gulf of St. Lawrence and in the Estuary, where it has been investigated by seismic data of variable quality.

(#39) The compilation map of the top of Mingan Formation seismic marker shows that the platform is dipping towards the SW with a significant modification of the isochron pattern around Cap Chat in northern Gaspé.

(#40) Based on marine seismic information, a post-Lower Silurian succession is present in the Gulf of St. Lawrence between Anticosti Island and the northern Gaspé. The precise age and lithology of the sedimentary fill is unknown, however seismic data shows that the succession is involved in folds of large amplitudes.

(#41) In contrast, towards western Newfoundland, the normal fault-dissected platform is definitively involved in an offshore triangle zone with no preserved Silurian strata, all removed during the Salinic (Early - Late Silurian) tectonic exhumation of large segments of the Newfoundland Appalachians.

Western Newfoundland

(#42) One major element in the current round of hydrocarbon exploration in the Lower Paleozoic of eastern Canada was the discovery in 1995 of the Garden Hill oil field in dolomites of the Lower Ordovician St. George Group.

(#43) The Lower Paleozoic shallow marine sediments of western Newfoundland are found in two major domains, a parautochthonous domain mainly represented on the Port au Port Peninsula and an autochthonous domain in the northern half of the western peninsula. The preserved stratigraphic succession ranges from lowermost Cambrian to the Middle Ordovician. As the base of the stratigraphy is older along the St. Lawrence Promontory, the top of the platform must have been drowned significantly earlier than that of the Québec Reentrant.

(#44-46) The Lower Cambrian Labrador Group consists of coarse-grained clastics deposited at the onset of rifting; the rapid marine invasion of the area led to the local production of biogenic carbonates. These biological communities formed the oldest known Paleozoic reefs on the planet. These carbonate reefs were drowned under a blanket of nearshore clastics that prograded over the marine environment in latest Early Cambrian.

(#47-48) Sea level started to rise again in Middle Cambrian and resulted in a narrow, high energy carbonate platform with thrombolite (microbial) reefs or oolite shoals at the margin. This platform corresponds to the Port au Port Group and similar facies are recognized in the Percé area in Gaspésie as well as in the Philipsburg Tectonic Slice of southern Québec. The Middle to Upper Cambrian sedimentation of the Port au Port Group responded to major eustatic sea level cycles known as “Grand Cycles” which can be correlated all around Laurentia (from western Canada to southern USA to western Newfoundland).

(#49-50) In Western Newfoundland, the transition into the Ordovician was marked by a small sea level fall, but it did not result in a significant unconformity as in southern Québec, Ontario and New York. The ensuing small Tremadocian sea level rise resulted in the development of a 3rd order cycle of initial peritidal followed by subtidal and culminating in peritidal successions, which are part of the Watts Bight and Boat Harbour formations at the base of the St. George Group. A significant disconformity straddles the Tremadocian – Arenigian boundary and then sea level rose again and generated the second 3rd order cycle in the St. George Group formed by the upper Boat Harbour (peritidal), the Catoche (subtidal) and the Aguathuna (peritidal) formations. This Arenigian cycle can be correlated with the Romaine on Anticosti as well as with most of the Beekmantown in southern Québec. The St. George platform was tectonically uplifted as the Taconian peripheral bulge migrated on the continental margin, resulting in subaerial karstification and associated diagenesis of the unit which was a significant event for its later dolomitization.

(#51) After the passage of the bulge, the basin evolved as a tectonically active foreland basin and subtidal carbonates of the Table Head Group were deposited in a rapidly subsiding fault-dissected ramp, over a short period of time. In Middle Ordovician time, the carbonates were drowned and a black shale unit (Black Cover Formation) was deposited on top of the platform. Such an event would occur only a few million years later in the Québec Reentrant.

(#52) The ongoing tectonic activity resulted in significant movement along some faults and the exhumation of significant stratigraphic intervals, which were exposed to erosion and shedding of Cambrian to Ordovician limestone conglomerates in the deep foreland basin. This conglomerate unit is known as the Middle Ordovician Cap Cormorant Formation (the equivalent in southern Québec being the Upper Ordovician Lacolle Breccia). The Cap Cormorant is an important seismic marker as it is use to locate the position of ancient extensional faults in the basin that were inverted during the Acadian Orogeny. Porous dolomites of the St. George Group are almost invariably found in the hanging wall of these old extensional faults.

(#53-54) The structural style of the St. Lawrence platform is well illustrated in southwestern Newfoundland where a thick-skinned deformation has been documented on seismic and confirmed by drilling.

Presentation #5

Hydrocarbon systems in the Lower Paleozoic St. Lawrence Platform – hydrocarbon system data

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(#2) The St. Lawrence Platform in eastern Canada extends from western Newfoundland to Ontario. Age- and facies-correlative successions are also known in eastern USA where they are found in various mid-west basins (e.g., Michigan) and in the tectonically-deformed Appalachian basin to the east that extends from New York to Alabama and then turns west towards Texas. Examples of producing world-class hydrocarbon fields are, amongst others, the billion barrels of oil in the Lower Ordovician Ellenberger in Texas, the multimillion barrels in the Upper Ordovician Trenton in Michigan and Ohio, the multi-BCF of natural gas per well in the Black River in New York and the Trenton fields in Ontario that have been producing for a significant period of time. Recent drilling successes in the St. Lawrence platform in western Newfoundland

and in southern Québec suggest that the eastern Canada extension of that belt has significant potential not only in conventional reserves but also in unconventional gas play. Let's review the hydrocarbon system data that support such assertion

(#4) The St. Lawrence Platform with the coeval rocks of the Humber Zone (see further) forms the first tectonostratigraphic cycle of eastern Canada; all basic elements for a hydrocarbon system data are known in the Platform succession and will be discussed.

Source rocks and thermal zonation

(#5) From western Newfoundland to southern Québec / Ontario, thick successions of organic matter rich black shale are found on top of the drowned foreland basin carbonate ramp. The age of these black shales becomes progressively younger from the St. Lawrence Promontory (Middle Ordovician) towards the inner part of the Québec Reentrant (uppermost Ordovician) in the Lac St. Jean outlier. TOC ranges between 0.5 to 15.5% and HI between 7 and 633. The highest values are found in the immature (onset of oil window) Pointe Bleue Shale which might provide a hint at what could have been the maximum values for the slightly older and more mature shales. These shales are considered in eastern Canada and in eastern USA as excellent source rocks. However, it should be noted that the Middle Ordovician Black Cove Formation in western Newfoundland has been discarded as the source for the oil in the Garden Hill field (see the Humber section).

(#6) In detail, the Ashgillian-aged source rock (Pointe Bleue in the Lac St. Jean) have higher TOC compared to the Middle Caradocian (Macasty on Anticosti) and even slightly more than the Upper Caradocian (Utica in southern Québec).

(#7-8) The least mature samples correspond to Type I and II algal-dominated organic matter. All these potential source rocks have potential to generate oils and it is assumed that the natural gas in the St. Flavien Ordovician gas field is sourced from the Utica. In fact, when plotting the hydrocarbon yield potential of these source rocks versus their thermal maturation, a simple relationship is visible: the potential is high at low maturity and decreases with increasing thermal maturation. This relationship relates most likely to generation of hydrocarbons. A simple HI vs OI diagram also support the high source rock potential of these black shales with the less mature Pointe Bleue and Macasty being of Type I and II whereas the Utica, because of higher thermal degradation plots in the Type II and III fields.

Southern Québec

(#9-10) Let's now focus on the Utica Shale in southern Québec. The map of TOC values from outcrop samples suggest that, in first approximation, TOC values decrease from the NW towards the Appalachians in the SE. However, this map is based on a limited number of values and the GSC and the Québec Provincial survey are currently acquiring new data. (#11) The thermal maturation map of surface outcrops shows that Upper Ordovician successions, which form the core of the NE-trending Chambly-Fortierville syncline are the least mature units, being in the oil window. However, for older succession there is a SW increase of thermal maturation from the oil window in the Québec City area, to the dry gas zone in the Montréal area to even sterile near the US border. Note that the thermal effect of the Mesozoic Monteregian intrusives is very limited.

(#12) A similar conclusion can be reached when examining the thermal maturation of the Utica, from the oil window near Québec City to the dry gas zone in the Montréal area.

(#13-15) The evolution of the thermal maturation with depth is controlled in some wells. For example, the Nicolet #165 well was drilled through the entire succession in the Chambly-Fortierville syncline. Detailed TOC analyses have yielded good values (around 1% and over) in the lower beds of the Lorraine, in the Utica and the best value was found in the upper beds of the Trenton. The thermal maturation based on Ro indicates a depth normal increase relationship from condensate at surface to dry gas zone at the base of the stratigraphic pile. Interestingly, coke and anisotropic organic matter have been found in the Trenton and are indicative of alteration of organic matter by hydrothermal fluids. The burial history curve from that well indicates that sedimentary burial extended to the Devonian and that the Utica started to generate hydrocarbons after the Taconian Orogeny but before the Early Devonian.

Anticosti Island

(#16) The Macasty Formation on Anticosti Island is also an excellent hydrocarbon source rock, detailed mapping and Rock-Eval analyses of the unit indicate that the Macasty thickens in a southwesterly direction; however, even at the southwestern end of the island, the Macasty has still very high TOC values. Detailed analyses of the Macasty were done in the late 1980's and the distribution of TOC values indicates that the easternmost sector of the island is characterized by lower TOC values (and some anomalous stratigraphic units).

(#17) The southwesterly thickening of the Macasty Formation is also mirrored in an increase in thermal conditions from low mature (oil window) in the northeast to dry gas zone in the southwest.

(#18) The burial history based on the NACP well in central Anticosti suggests a fairly similar scenario as the one in southern Québec, sedimentary burial extended to the Early Devonian and hydrocarbon generation from the Macasty started sometime during the Silurian.

Newfoundland

(#19-21) The thermal history of the Port au Port Peninsula is based on multiple datasets (acritarchs and conodonts alteration index, reflectance values on organoclasts and bitumen, fluid inclusions data). The general conclusion indicates a rapid increase of surface thermal conditions in an easterly direction, from the oil window to the dry gas zone. For the subsurface, some wells behave normally (increase of maturation with depth) although some wells in the inverted fairway zone sometimes show lower thermal maturation at depth compared to structurally higher units. Further to the north, in the Parson's Pond area, the dataset suggests a southerly increase of surface maturation from oil window to the dry gas zone near the Humber Arm Allochthon. Finally still further to the north, in the Port au Choix area (the area with the exhumed oil field in the Lower Ordovician dolostones), surface maturation is higher and in the dry gas zone.

Potential and demonstrated reservoirs

(#22) Two major types of potential reservoirs are known, these are the Lower and Middle/Upper Ordovician (pre- and syn-foreland basin) dolomites, including hydrothermal dolomites and Cambrian rift and later Ordovician transgressive sandstones on the Grenvillian basement.

Dolomites

(#23-25) Ordovician hydrothermal (or not) dolomites are present in all three St. Lawrence Platform domains considered previously. The most complete dataset is from Anticosti Island where dolostones are found in both the Lower Ordovician Romaine Formation and in the Middle Ordovician Mingan Formation.

(#26-28) The detailed paragenetic succession recognized in the Romaine indicates an early dolomitization (possibly from reflux, see later) followed by burial pervasive dolomitization. A significant brecciation event occurred during the burial history generating significant secondary pore space that was initially coated by base metal (sphalerite) and significant saddle dolomite. Some hydrocarbons migrated in the open framework as testified by the presence of bitumen coating saddle dolomite and the presence of abundant oil inclusions in the following calcite cement. Finally, a late barite phase is recognized. The stable isotope analyses indicate a progressive depletion in ^{18}O from the early (RD1, early replacement) to late (PD2, saddle) dolomites. The homogenization temperatures of the fluid inclusions documents a progressive increase of homogenization temperature up to 155°C in saddle dolomite then a rapid decrease in the following cements. Interestingly, this suite of samples is from the LGCP well in northeastern Anticosti where thermal modelling based on Ro values indicate maximum burial temperature of 125°C. The high T_h values in the saddle dolomites and late replacement dolomite (RD3 and RD4) indicates an anomalous heat event that we associate with a flux of hydrothermal fluid in the succession. This is also supported by the fluid salinity information obtained from the fluid inclusions: the replacement and saddle dolomites are derived from saline fluids (typical but not equivocal indicators of hydrothermal fluids) whereas the post-dolomite calcite cements is derived by an even more saline fluid, so the lower T_h values for the calcite phase (<120°C) characterized the temperature of a deep burial saline fluids.

(#29-30) The Middle Ordovician Mingan Formation overlies the Sauk-Tippecanoe unconformity developed on top of the Romaine Formation. Our petrographic database is less complete than the one of the Romaine. The paragenetic succession indicates that burial calcite dominates the early events with rare replacement dolomite. As for the Romaine, the burial scenario was marked by a major dissolution and brecciation event that is associated with a replacement dolomite that is petrographically similar to RD3 and RD4 in the Romaine. This was followed by more burial fractures with various cement phases (calcite, silica, barite and sphalerite). Saddle dolomite was not observed in thin sections, although obvious fragments of that specific dolomite were observed in a preliminary examination of cuttings from a few wells. The T_h and salinity data for the Mingan fluid inclusions indicate that fluid responsible for the replacement dolomites (T-RD2 and T-RD3) were saline with temperatures again higher than the maximum burial temperature in the northern sector of Anticosti from where the samples originate (135 vs 115°C)

(#31) The paired T_h and $\delta^{18}O_{PDB}$ values from individual cement zones are used to evaluate the isotopic $\delta^{18}O_{SMOW}$ composition of the fluid responsible for the replacement or precipitated dolomite. It is noteworthy that the early dolomite in the Romaine Formation originated from a fluid that had $\delta^{18}O_{SMOW}$ values close to slightly enriched in ^{18}O compared to normal marine values for the Lower Ordovician (arrow lower right, -6 to -8‰). However, all other dolomites in the Romaine (RD3, PD1 and PD2) as well as those for the Mingan (M-RD1 and M-RD2) are derived from fluid(s) that is (are) significantly enriched in ^{18}O ($\delta^{18}O_{SMOW}$ of +2 to +7‰). The early dolomitization (at least in the Mingan) proceeded from a fluid that had no marine isotopic signature.

(#32-33) The $^{87}Sr/^{86}Sr$ ratios are useful to generate ideas about the rock-water ratios of the diagenetic system and the nature of the fluid that was present at the time of dolomitization. The Romaine late replacement dolomites and the Mingan early replacement dolomites are characterized by $^{87}Sr/^{86}Sr$ ratios that are significantly above that of their respective marine waters, so non-marine fluids were responsible for dolomitization. The lowest absolute Sr content in the Romaine dolomites indicate more intense diagenetic alteration for these whereas for both units, the near marine normal $\delta^{13}C_{PDB}$ values for the dolomites suggest that the HCO_3^- for dolomitization was locally derived from dissolved marine phases. It is noteworthy that when plotted against the $^{87}Sr/^{86}Sr$ seawater curve for the Ordovician and Phanerozoic, even the average $^{87}Sr/^{86}Sr$ values for the Romaine and Mingan dolomites cannot be derived from any marine waters. Dolomitization for both units (except for the early replacement dolomite in the Romaine Formation) originated from high temperature, saline and ^{18}O-enriched fluid that had major interactions with a Sr radiogenic unit (most probably the Grenvillian basement in the case of Anticosti). Such fluid that was also characterized by higher temperature than the maximum burial temperature can be qualified as hydrothermal.

(#34) A recent synthesis of all available rock petrophysical and well log data on Anticosti Island clearly supports the higher porosity and permeability for the Mingan and Romaine dolomites.

(#35) There has been little work on the diagenesis of the Ordovician dolomites in southern Québec. The recognition of saddle dolomite filling fractures cutting through outcrops of the Black River – Trenton groups is recent (2005) and no pervasively dolomitized interval for these foreland basin carbonates is known. Preliminary petrographic and geochemical data for the fracture filling dolomite (post December 2007 workshop) document the presence of saddle dolomite with slightly depleted $\delta^{18}O_{PDB}$ ratios (-7 to -8‰) compared to marine values. No fluid inclusion data is currently available to reconstruct the $\delta^{18}O_{SMOW}$ signature of the fluid responsible for dolomite precipitation. The $^{87}Sr/^{86}Sr$ ratios are similar to those found in Anticosti and are anomalously very radiogenic (0.711509), significantly above marine values. The diagenetic evolution of the autochthonous Beekmantown carbonates is largely unknown; a preliminary petrographic study of some samples from the Montréal area has documented the presence of multiple dolomitization events with a high temperature saddle dolomite as a final phase. Interestingly, methane-rich inclusions are present in the dolomite cement. However, no geochemical data is available, and information on the diagenetic evolution of the Beekmantown is available for the St Flavien gas field at the Appalachian structural front (see Humber section further).

(#36-37) The first detailed overview of the Lower Ordovician dolomites in western Newfoundland was done on a lead and zinc Mississippi-Valley Type (MVT) deposit (Daniel's Harbour mine). In 1995, an oil reservoir was drilled in the same dolomites in Port au Port Peninsula and as part of the current SCES program, a detailed research project on these dolomites was initiated. Dolomites are found in all units of the Lower Ordovician St. George Group, the oil field is hosted by dolomites of the Aguathuna Formation but porous dolomites were also found in the other three formations. Recent data are summarized in two papers and in a M.Sc. thesis.

(#38-39) The hydrocarbon reservoir in Port au Port, as well as exhumed oil fields at Port au Choix and at the "Arches", clearly indicates that oil accumulated in these porous dolomites. The highly porous cores from the Lower Ordovician in the Port au Port Peninsula and under the Carboniferous Deer Lake basin are mirror images to the very productive dolostone in New York.

(#40-42) We will here focus on the Lower Ordovician Aguathuna dolomites, which can be seen as time and facies correlative with the Romaine Formation on nearby Anticosti Island. The petrographic examination has revealed three types of dolomite that formed in shallow (micrite-sized replacive) to deep (saddle dolomite) burial, the earliest dolomite formed after the subaerial exposure and meteoric diagenesis (St. George Unconformity) of the Aguathuna Formation. The $\delta^{18}O_{PDB}$ and $\delta^{13}C_{PDB}$ ratios of the calcite phases indicate progressive burial. However, the values for the dolomites all plot in the heavier than marine Lower Ordovician carbonates. By plotting the T_h versus $\delta^{18}O_{PDB}$ of the three dolomites we can conclude that the early D1 dolomite originated from near normal $\delta^{18}O_{SMOW}$ marine fluid (similar to RD2 of the Romaine Formation) whereas the later D2 and saddle D3 phases originated from ^{18}O-enriched fluids with values close to those observed for the Anticosti dolomites.

(#43) The $^{87}Sr/^{86}Sr$ values for the Aguathuna dolomites are slightly different from those of the Romaine as they are closer to the marine values. Nonetheless, some enrichment is observed and indicates some interaction (even if less intense) with either a basal arkosic sandstone or the Grenvillian basement.

(#44) The model for the Aguathuna suggests some significant downward circulation of dolomitizing fluid for the early D1 and D2 phases, whereas D3 was introduced later in the system.

Sandstone

(#45) In the current round of exploration in the Cambrian-Ordovician sedimentary succession, sandstones are commonly considered as secondary targets. However, some have significant porosity and permeability and a few gas shows are known from Ordovician sandstones in Québec and Newfoundland.

(#46-48) In western Newfoundland, the Lower Cambrian early drift nearshore sandstone of the Hawke Bay Formation forms a distinctive sand blanket. The sandstone is locally well-sorted with abundant wave structures and evidence, such as desiccation polygons, to support a shallow marine depositional environment. In the Port au Port #1 well, the Hawke Bay sandstone is 64 m thick and has porosity up to 12.2% in the hanging wall of the Round Head thrust. The sandstone still has 5% porosity in the footwall. Not presented here, but some of the foreland sandstone flysch (Goose Tickle and American Tickle formations) in Western Newfoundland have generated some gas shows in recent exploration drilling in the Parson's Pond area.

(#49-50) In southern Québec, the Upper(?) Cambrian Potsdam drift sandstone deserves attention. The Covey Hill Formation is largely an impure sand and conglomerate unit. However, the overlying uppermost Cambrian Cairnside Formation consists of well-sorted, high-energy medium-sized quartzose sandstone deposited in a marginal marine setting. Some bitumen is locally present in the pore space and porosity (secondary from leaching of previous carbonate cement) can reach up to 9.2%. In the St. Lawrence platform, the basal unit on the Grenvillian basement is time transgressive from the SSW towards the NNE and these "Potsdam-like" sandstones are known everywhere, with highly variable thickness. A regionally distinctive, although quite variable in thickness, Middle Ordovician sandstone unit overlies the Sauk-Tippecanoe Unconformity. These shallow to near marginal marine sandstones and conglomerates are relatively poorly sorted and mineralogically quite immature. Porosities up to 7.4% have been measured in some outcrop samples. These sandstones are almost invariably gas-bearing in the subsurface.

(#51-52) With the exception of a thin (less than 50 cm thick) dolomitic sand to sandy dolomite interval overlying the Grenvillian basement, there is no documented basal sand on Anticosti Island. Similarly, a muddy limy sandy silt to silty sand is commonly developed on the Sauk-Tippecanoe unconformity. However, a very porous (Po up to 20%) Lower Silurian limestone unit is nicely exposed on the southwestern end of the Island. The Chicotte Formation is a shallow subtidal encrinite-dominated succession with local bioherms with multiple erosional surfaces indicating numerous high-frequency sea-level fluctuations and meteoric diagenesis (dissolution / cementation) in the limestone. High-resolution seismic profiles indicate that the southwesterly extension of the Chicotte in the St. Lawrence estuary is overlain by a 3 km thick succession. This 3 km of post-Lower Silurian strata is also supported by maturation values from Anticosti. However, the lithofacies nature of that succession is unknown. The Chicotte and other potentially porous sandstone or limestone units are stratigraphically overlying the high quality Upper Ordovician source rock of the Macasty Formation.

Traps

(#53) The St. Lawrence Platform is characterized by fault closures, broad anticlines (in the St. Lawrence estuary) and, at the Appalachian structural front, by the development of triangle zones in Québec and western Newfoundland. Moreover, diagenetic traps are to be expected for the hydrothermal dolomite play.

(#54) As exemplified here by a Lower Ordovician hydrothermal dolomite in New York, the fault-associated limestone dissolution / dolomitization laterally extends for some distance from the fluid circulation conduits. Away from the porous dolomite and leached limestone altered facies, well-cemented limestone provides the lateral seal. Current models indicate that the lateral dolomitization is significant only if upward movement of fluid was stopped by an unbreached seal (commonly the Utica Shale over the Trenton in eastern north-America). The fault movement, associated brecciation and locally the significant dissolution of limestone will ultimately result in a collapse of the fault-affected segment of the platform. This will generate a depression or sag that is commonly visible on seismic and offer a first-hand discrimination tool for the explorationist (however, not all sags are porous nor filled with hydrocarbons).

(#55-57) Based on close to 6000 km of available seismic lines, maps of top basement and top Trenton were constructed by the Québec Department of Natural Resources. These maps allow recognizing fundamental fractures in the basement and Paleozoic succession and these fractures are seen delimitating sag structures on the top of Trenton map. In the Lac St. Pierre area (central St. Lawrence Platform) these sags are of the same size to even larger than those of the famous Albion-Scipio fields in the Michigan basin. It is also critical to add that until three years ago, no sag was targeted for drilling as exploration was historically interested in structural highs. The successful Talisman Gentilly #1 was the second well that targeted such sags in southern Québec.

(#58-59) The seismic coverage on Anticosti Island is less dense compared to southern Québec. Two sectors have received more attention in the recent (1997+) exploration round on the island. This seismic line shows a sag that was drilled initially by Shell and partners in 2000 with follow up work by Hydro-Québec Oil and Gas, and Corridor later on. Porous dolomite was found in the Romaine Formation with small gas kicks whereas some dolomitized intervals in the Mingan Formation (Trenton-BR) were not tested in the first well. We will not go into the details of all the completion works and later re-entry, although it should be noted that some “sagging” is visible in the top Vauréal, which suggests that this specific sag might have a breached reservoir. Another sag is visible 2 km to the west of the Chaloupe well, the overlying Vauréal is not affected and the sag bounding faults are linked to structures in the Grenvillian basement.

(#60) When comparing the New York and Anticosti sag morphology, it is interesting to note that sometimes, the less obvious sags in New York (Glodes Corner for example) have proven the most prolific hydrocarbon wise. So it would seem that apparent offset does not matter that much!

(#61-62) Sags are abundant on Anticosti, most of them are affecting only the Romaine and Mingan (Trenton) units and as shown here, a large number of these are bounded by faults that connect to the Grenvillian basement. Such link has been described in the model for hydrothermal dolomite as potentially critical for the high temperature fluids and for the charge in ions and possibly Mg^{+2}. The area near the eastern tip of Anticosti Island has a dense, recent seismic coverage that allows mapping a significant number of NW-SE oriented sags, with many of them having size similar to the Albion-Scipio field.

(#63) In the parautochthonous domain on Port au Port Peninsula, the Garden Hill oil field is part of the inverted fairway with Acadian reverse reactivation of ancient Taconian extensional faults. So superimposed on diagenetic traps developed in the St. George Group (which should be a common phenomenon in the autochthonous domain), the inverted movement could have created structural highs sealed by the fault and have possibly compartmentalized reservoirs. There is however also the possibility that the late movement of the fault could have breached some reservoirs.

(#64) At the Appalachian structural front, the Acadian deformation (Silurian Clam Bank involved) has led to the formation of a triangle zone in the near offshore domain along the west coast. This triangle zone is still untested.

(#65-66) Still in the marine environment, but offshore Anticosti, the recent reinterpretation of historic and recently acquired seismic data as well as some new high resolution bathymetric surveys has shed new lights on the potential architecture of the St. Lawrence platform. The cartoon illustrates the recent model, a generally homoclinal, SW-dipping platform with some unknown post-Lower Silurian strata involved in a folded belt as it get closer to the Gaspé onshore. If reservoir candidates R1, R2 and R3 are known from outcrop and subsurface information on Anticosti Island, the Silurian-Devonian (?) sandstones (R4) and reefs (R5) are hypothetical. Such possible Devonian reef structure have been tentatively proposed on seismic data offshore Anticosti. Lochkovian and Pragian reefs have also been proposed by various authors on the basis of regional facies distribution and some boundstone fragments with marine cements preserved in the Lower Devonian outer shelf storm beds on Gaspé.

(#67-68) The folded nature of the succession near Gaspé is documented from high resolution seismic information and the hydrocarbon potential of these will be discussed later on. However, the nature of the contact between the succession beneath the St. Lawrence (Acadian foreland?) and the Cambrian-Ordovician units outcropping along the northern coast of Gaspé is currently unknown. This contact could be an unconformity, a normal fault or even a backthrust.

(#69-70) The presence of a significant hydrocarbon potential for the offshore extension of the St. Lawrence Platform has recently been documented from detailed high resolution seismic and bathymetric data. The basic element for such assertion is the presence of close to 2000 pockmarks in the sector between the mouth of the Saguenay River and Les Méchins / Pointe-des-Monts, 150 km downstream. Tens of these pockmarks were first identified on recent 2003-2004 seismic surveys and hundreds more were later confirmed with high-resolution bathymetry surveys.

(#71) On seismic, the pockmarks (from a few metres up to 700 m in diameter and up to 15 metres deep) are small depressions on the sea-floor almost invariably located on top of "seismic chimneys" with pull-downs of reflectors and lost of continuity. Over 90% of all the pockmarks are found over the area underlain by the St. Lawrence Platform and most of the seismic chimneys are rooted in this domain suggesting a thermogenic origin for the venting gas (see further). A few pockmarks, on the northern side of the St. Lawrence River, are found over the Grenvillian basement near the mouth of some of the major rivers flowing on the north shore. The escaping gas forming those last pockmarks is likely biogenic in origin. The mapping of these pockmarks based on high resolution bathymetric surveys, documents some obvious alignment for many of these structures, some of these alignments are multi-kilometres long and are clearly associated with structural features in the St. Lawrence platform (anticline, faults). We interpret these pockmarks as the result of gas escaping from breached hydrocarbon reservoirs in the St. Lawrence platform. In our interpretation, the pockmarks are methane cold seeps similar to those so abundant in the Gulf of Mexico and in the North Sea.

(#72) The venting of hydrocarbons was first indirectly supported by the presence of carbonate crusts in the vicinity of the pockmarks. Petrographic examination of these cement-rich crusts (post December workshop) has revealed the presence of abundant acicular aragonite cement with small ovoid micrite clots at the base of carbonate crystals. The aragonite cements are most likely by-product of bacterial CH_4-based chemosynthesis, an interpretation backed by stable isotope data from the cements (see the Gulf of St. Lawrence section). Video surveys of some pockmarks in the 2008 summer have documented spectacular microbial mats covering wide areas with slow- to high-rates escape of methane bubbles.

Conclusions

(#73) All the elements reviewed in this presentation are supportive of the hydrocarbon prospectivity of the St. Lawrence Platform in both the offshore and onshore domains. An excellent hydrocarbon source rock is recognized (Upper Ordovician Utica Shale and facies-correlative formations) and is known to have generated hydrocarbons. Down-dip on the continental slope, Lower Ordovician source rocks (see Humber section) should also be considered. Carbonate reservoirs (hydrothermal dolomites). They have been conceptually documented and recently discovered through drilling. However, the irregular distribution of the dolomite makes that play challenging to explore. Finally, the presence of gas-filled reservoirs in the onshore (Gentilly #1) and of former (now breached) reservoirs in the offshore, suggest that all timing constraints of the hydrocarbon system were satisfactorily met.

Presentation #6

The Lower Paleozoic Humber zone in eastern Canada
(latest Proterozoic (Ediacaran) to Late Ordovician) – Geological framework

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(#2-3) The sedimentary record preserved in the Appalachian Humber zone range in age from the Ediacaran (latest Neoproterozoic) to the Late Ordovician. These sediments are largely coeval with the Cambrian – Ordovician autochthonous St. Lawrence Platform. However, they were deposited on the Laurentia deep continental slope and rise and were first deformed during the Middle – Late Ordovician Taconian orogeny.

Regional setting

(#4) The Humber Zone is the westernmost tectonostratigraphic zone of the Canadian Appalachians; it extends from southern Québec (the zone has been recognized in the USA) to western Newfoundland and is likely present under the Estuary and Gulf of St. Lawrence.

(#5) The deep marine sediments preserved in the Humber Zone were deposited during and after the break-up of Rodinia and facies patterns and tectonostratigraphic history were, as for the marine sediments of the St. Lawrence Platform, also largely controlled by the inherited margin morphology.

(#6) Recent regional synthesis of the rift to drift succession facilitates correlations of the stratigraphy from Québec to western Newfoundland. The Cambrian Grand Cycles A, B and C are recognized in both areas, whereas a significant sea level lowstand at the Tremadoc – Arenig boundary in western Newfoundland occurred slightly later in Québec. This sea-level lowstand may be an effect of the first pulses of Taconian tectonic activity along the continental margin.

(#7) The Laurentian margin in southern Québec consists of a less deformed and metamorphosed external Humber Zone and a more deformed and metamorphosed internal Humber Zone, both zones share a similar stratigraphy although the internal zone consists of more distal strata for the Middle Cambrian to the Lower Ordovician. The internal Humber zone passes, eastward, to accreted rocks of the Lower Paleozoic oceanic domain known as the Dunnage Zone; some of the Dunnage rocks will be discussed in the hydrocarbon section.

(#8) Deformation in the Humber Zone of southern Québec is quite complex with Taconian (sensu stricto) syn-metamorphic NW-directed structures followed by Late Silurian – Early Devonian Salinic (?) SE-verging structures and SE-dipping normal faults. Finally, Middle Devonian (Acadian) reverse faulting is observed. Abundant $^{40}Ar/^{39}Ar$ and less abundant U/Pb and fossil ages provide time constrains on that tectonometamorphic history.

(#9) A similar tectonostratigraphic zonation is observed in northern Gaspé with external and internal Humber domains and slivers of oceanic material associated to the Dunnage Zone. Late Silurian (Salinic) normal faulting is recognized at many localities and the Acadian deformation climaxed with major dextral strike-slip faulting.

(#10) The Humber Zone in Québec consists of a large number of thrust sheets that have been emplaced during the Taconian Orogeny. Until recently, regional stratigraphic correlations of the rift to trailing margin succession in eastern Québec were complicated individual and separate stratigraphic nomenclatures of most thrust sheets. Based on detailed correlations of specific coarse-grained marker units and on palinspastic reconstructions, a unified framework is now available. In this new framework, rift – early drift and trailing (passive) margin successions are integrated, and the stratigraphic nomenclature of the foreland basin slope record has been simplified. The following description of the stratigraphic succession uses the coarse-grained units as markers for stratigraphic correlations as well as indicators of major events occurring along Laurentia.

Québec segment: Stratigraphy – sedimentology - paleoenvironments

(#11) The first coarse-grained unit of interest is termed informally the “Green Sandstone” unit. This unit is dated by means of trace fossils (*Oldhamia*), brachiopods and acritarchs as late Early Cambrian in age; chronostratigraphically, it correlates with the shallow marine sandstone of the Hawke Bay Formation in western Newfoundland. Potential correlation with the shallow marine Pinnacle Formation in southern Québec (internal domain of the Humber Zone) is currently envisaged. The “Green Sandstone” is a distinctive coarse arkosic and lithic sandstone and conglomerate that is known to occur from southern Québec to Gaspé (it is correlative, facies- and time-wise with the deep marine Irishtown Formation in western Newfoundland). The unit forms a relatively thick succession (+/- 600 m where documented) that is dominated by coarse-grained lithologies with subordinate green and red mudstone and fine sandstone. This unit (and correlatives) is interpreted to represent the end of the early drift episode (limit Sauk I and II) and marks a major depositional lowstand along the Laurentia margin.

(#12-13) The next major coarse-grained unit is the sandstone and conglomerate of the Saint-Damase Formation (and stratigraphic correlatives). The Saint-Damase is dated as early Late Cambrian from microfossils in interbedded mudstones. The base of that unit is sharply erosive in the underlying unit (km-thick mudstone of the Middle Cambrian Orignal Formation). The Saint-Damase is characterized by the cyclic deposition of channel-fill continental slope conglomerate with boulder-sized fragments of shallow marine Early to Late Cambrian limestones, nearshore coarse clastics, rift mafic volcanics and Grenvillian basement gneiss. This diversity in clasts is restricted to that unit and has been used to distinguish this conglomerate from others. The conglomerate is the expression of a major sea level lowstand of possible eustatic (end of Grand Cycle B and Sauk II – III limit) and local tectonothermal origin and was formed from major downcutting into the Cambrian platform and basement. The coarse-grained channel-fill unit is largely restricted to an area between Rivière-du-Loup and a hundred of km to the NE, along the south shore of the St. Lawrence estuary. Elsewhere, it is represented by a thinner and finer-grained (sandstone) succession. The Saint-Damase is likely correlative with the nearshore clastics of the Potsdam Group in southern Québec and with the Upper Cambrian platform-margin limestones of the Strites Pond Formation (southern Québec) and Corner-of-the-Beach Formation (Percé area, Gaspé Peninsula)

(#14) The next coarse-grained marker unit is the Kamouraska Formation. This unit is latest Cambrian – earliest Ordovician in age on the basis of limited scolecodonts and from the age of the better constrained underlying (Rivière-du-Loup Formation) and overlying (Rivière Ouelle Formation) units. The Kamouraska consists of a well sorted, massive, medium-grained very distinctive quartz arenite that fills channels downcutting into the muddy and silty continental slope deposits of the Rivière-du-Loup Formation. Here again, the Kamouraska is laterally highly variable and in places, not present. The Kamouraska Formation is time correlative with a significant sea level lowstand (end of Cambrian Grand Cycle C) and unconformity developed at the Cambrian-Ordovician boundary on the shallow marine margin of Laurentia (although poorly developed in western Newfoundland). The Kamouraska has been recently shown to be composed of reworked eolian sands that were shed on the continental slope; the sand is likely derived from the shallow marine Upper Cambrian Cairnside Formation that underlies the unconformity. The major quartz arenite slope deposits are unknown in western Newfoundland.

(#15-17) The following unit also has some coarse-grained conglomerate facies although its significance relies more on its potential as a hydrocarbon source rock (see Humber Zone hydrocarbon section). The Rivière-Ouelle Formation is an Early (Tremadocian) to earliest Middle (Darriwilian) Ordovician unit. It is a very heterogeneous unit that consists of variegated mudstone (with significant black mudstone intervals and early diagenetic carbonate concretions), with sandstone and various carbonates (calcarenite, calcilutite or ribbon limestone and limestone conglomerate). Locally, where the carbonate facies dominates, the succession is termed the Anse-du-Crapaud member. The limestone conglomerates are strikingly different from other conglomeratic levels being largely monogenic in composition (except in the immediate Québec City area, where is it called the Lévis Formation). Facies-wise, this unit extends in western Newfoundland where it is known as the proximal Cow Head – distal Northern Head units. In the shallow marine environment, the Tremadocian – Arenigian Rivière-Ouelle Formation correlates time-wise with the return to carbonate sedimentation documented in the Tremadocian-Arenigian succession in the Philipsburg thrust slice (Wallace Creek succession and younger) and in the Arenigian-earliest Chazian Beekmantown Group. The Rivière-Ouelle records some significant tectonic activity and its upper part was likely deposited during Taconian foreland basin sedimentation. In fact, the inception of the foreland basin is recognized in ultramafic-detritus rich flysch sandstone of the Tourelle Formation for which fossils suggest a maximum age as old as Arenigian.

(#18) The stratigraphy of the foreland basin succession in the deep marine environment is best exposed in the Gaspé Peninsula. Coeval successions in southern Québec are relatively poorly exposed (except in the immediate Quebec City area). The Gaspé succession consists of three fault-bounded formations: The Lower-Middle Ordovician Tourelle, the Middle Ordovician Deslandes and the Upper Ordovician Cloridorme. Laterally equivalent to the Rivière-Ouelle and Tourelle formations, the Cap Chat Mélange is a tectonic unit that has some source rock potential (see further).

(#19) The Tourelle Formation consists of a thick succession of cyclic flysch accumulations. The typical sandstone is greenish and immature as it contains some particles (chromite, spinels) derived from the erosion of ophiolitic thrust sheets. The sandstone can be very coarse grained and commonly shows evidence of turbidity current deposition. Similar (but slightly older) flyschs are known in western Newfoundland (Lower Head and Eagle Island formations). At the same time, foreland basin carbonates (Chazy and Black River groups) were accumulating on the shallow segment of the margin of Laurentia.

(#20) At the top of the foreland basin deep marine clastics, the Cloridorme Formation consists of alternating coarse-grained and finer-grained clastic members with a locally significant proportion of carbonate beds. The Cloridorme Formation is several kilometres thick (up to 5 km) and was deposited over a relatively short period of time suggesting extremely high sedimentation rates. Previous studies have proposed that the carbonates were exported from Anticosti Island (Caradocian Mingan / Trenton). The Cloridorme is the youngest deep marine Taconian foreland basin succession in Québec. In southern Gaspé and Western Newfoundland, the Caradocian was a time of post-Taconian (sensu stricto) sedimentation in either a Neo-Taconian foreland (Newfoundland, Long Point Group) or a successor basin (Gaspé Belt, Garin Formation).

Québec segment: structural framework

(#21) At or near the Appalachian structural front in southern Québec, thrust slices of detached shallow marine carbonate platform are intercalated within the structural stack of deep marine succession. Fifty of these slices have been interpreted to occur on the basis of seismic data between Québec City and the US border. Based on vintage seismic and recent data, more of these thrust slices have been identified to the NE, between Quebec City and Gaspé. The Saint-Flavien gas field is hosted by one of these tectonic thrust slices.

(#22-25) Some of these thrust slices are exposed in southern Québec and offers the opportunity to examine some of the more outboard / distal platform facies. From south to north, they are the Philipsburg, St. Dominique and Upton thrust slices. The most complete of these is the Philipsburg Tectonic Slice (PTS) for which the stratigraphy and tectonic histories have been recently investigated. The westerly-transported PTS offers a more complete shallow marine succession compared to the autochthonous St. Lawrence Platform, with platform margin carbonate facies that are as old as the Middle Cambrian and for which direct correlation with the more complete platform succession in western Newfoundland has been proposed. Major unconformities punctuate the succession and given the improved biostratigraphic framework, serve as correlation lines for widely dispersed areas.

(#26) As part of the Appalachian frontal domain, the units within the Humber zone have been significantly deformed through folding and faulting. The complex deformation, inducing locally steep dips, and the dominant fine-grained nature of the sedimentary pile render seismic acquisition, processing and later interpretation a difficult task.

(#27) Compared with classical fold and thrust belt, the Humber zone is characterized by a more complex geometry that may result of several tectonic processes, such as basement inherited structural style, out-of-sequence thrusting and polyphase deformation.

(#28) Also, a peculiar characteristic of the Humber Zone in Québec is the presence of steeply-dipping units at many places along the structural front. This contrasts strongly with more classical shallowly dipping frontal units of other structural fronts. The cause for such geometry is still uncertain but may be related to the back-stop effect induced by major fault-generated steps affecting the Precambrian basement at depth, and which forced the steepening of the main décollement and of its hanging wall.

(#29) Locally, in the Québec City area, the thrust slice at the top of the structural pile, the Rivière Chaudière Nappe, has been emplaced out-of-sequence with respect to the underlying thrust sheets. The timing of emplacement may be late Taconian or younger. Interestingly, the adjacent and structurally underlying Pointe-Aubin tectonic mélange (Middle to Late Ordovician in age, roughly coeval with the classical Taconian Orogeny) does not contain any fragments of the Cambrian-aged sediments from the Rivière Chaudière Nappe.

(#30) Post-Taconian reactivation of structures has been recently documented to have a critical role in the formation of the Middle Ordovician Cap Chat Mélange in Gaspé. Old Taconian thrusts have been reactivated as normal faults, likely during the Silurian Salinic Orogeny, and again reactivated (as reverse faults) during Acadian deformation.

(#31) Finally, recent K/Ar dating of fault gouges in eastern Québec has documented that some Taconian (or even older and more fundamental) faults were reactivated as inverse, thick-skinned faults, most likely during the Acadian Orogeny.

Newfoundland segment: stratigraphy – sedimentology - paleoenvironments

(#32) The Humber Zone was first defined in western Newfoundland by Harold Williams. In the type area, it primarily consists of Cambrian to Ordovician deep marine sediments that have been deposited on Laurentia continental slope along the St. Lawrence Promontory. The assemblage contains world-class source rocks and potential reservoirs (see further).

(#33) The deep marine succession can be separated into a more proximal and distal assemblage. The transition between the shallow and deep marine successions is found in the relatively less studied (relative to the other two domains) Penguin Cove and Reluctant Head formations. The proximal facies is known as the Cow Head Group which consists of the laterally equivalent Shallow Bay and Green Point formations (the latter being the source rock for oil in western Newfoundland). A total of seven members of coarse (sand to conglomerate) to fine-grained, clastic to carbonate-dominated facies are defined in both formations, the stacking of which reflects eustatic and, to some extent, tectonic sea level fluctuations affecting the shallow marine carbonate production zone. The age of the Cow Head is well constrained and ranges from the Middle Cambrian to the end of the Early Ordovician. The Cow Head Group records the deep marine accumulation during the passive or trailing margin stage of Laurentia at the St. Lawrence Promontory. Laterally equivalent and more distal to the Cow Head is the predominantly finer-grained Northern Head Group, which consists of the Middle Cambrian – Tremadocian Cooks Brook and the Tremadocian-Arenigian Middle Arm Point formations. The Northern Head Group overlies with a significant time hiatus the Ediacaran (?) – upper Early Cambrian Curling Group; coeval strata are unknown beneath the Cow Head Group. The transition between the rift-early drift succession (Curling Group) and the distal trailing margin assemblage (Northern Head Group) correlates with this time hiatus. The Curling Group is made up of two formations, the mudstone-dominated Summerside Formation and the mudstone-sandstone-conglomerate assemblage of the Irishtown Formation. Laterally to the Curling Group, and likely more proximal in nature, is the sandstone-rich unit of the earliest Cambrian Blow-me-Down-Brook Formation, which unconformably overlies rift-volcanics of the Wood Island lavas. The Northern Head and Curling groups with the Blow-me-down-Brook Formation are part of the Humber Arm Supergroup. Finally, both major assemblages (proximal Cow Head Group and distal Humber Arm Supergroup) are overlain by Taconian foreland basin flysch, the Middle Ordovician Lower Head and slightly older upper Lower Ordovician to Middle Ordovician Eagle Island formations.

(#34) When examining the subsidence history, the Taconian foreland (both the shallow Goose Tickle / Long Point formations and deep marine Lower Head and Eagle Island formations) is characterized by a significant increase in subsidence.

(#35) The combined inverted Apatite Fission Track and thermal maturation indicators techniques suggest that even if the Taconian foreland history resulted in significant burial of the Cambrian-Ordovician succession, most of the burial occurred during the Early-Middle Devonian Acadian foreland and also under a thick and more widespread than commonly assumed Carboniferous sedimentary basin.

(#36) Facies-wise, some correlations of the deep-marine succession along the entire Canadian segment of the laurentian margin can be recognized. The upper Lower Cambrian Irishtown Formation is a direct correlative of the “Green Sandstone” unit in the Québec Reentrant suggesting that this coarse-grained event was of continental scale.

(#37) The conglomerates in the Cow Head Group are largely time correlative with conglomerates of the Saint-Damase and Rivière-Ouelle Formation. A dominant eustatic control (late highstand progradation) for shedding of the clasts has been proposed. However, a significant tectonic signal is recognized for the Upper Cambrian conglomerates in the Québec Reentrant. In the more distal slope settings, possibly during 3^{rd} order maximum flooding events, thick accumulations of organic matter rich mudstones with great source rock potential are recognized in less thermally mature sections in western Newfoundland (Green Point Formation) and the same facies is present, even if of higher thermal maturity with accordingly reduced residual TOC, as the Rivière-Ouelle Formation in the Québec Reentrant. This orogen-scale correlation is a critical element to consider for exploration activities.

Newfoundland segment: structural framework

(#38) From a structural point of view, the Humber zone of western Newfoundland is quite complex. The most salient element, however, is the development of a triangle zone involving deep marine Humber rocks at the Appalachian structural front. The triangle zone is interpreted as a ‘late’ feature formed during the Acadian orogeny. That triangle zone has been seismically mapped in the nearshore from the northern limit of Port au Port Peninsula, north to roughly the Parson’s Pond area.

(#39) The Parson’s Pond area is not only well-known for its natural oil seeps, but it is also where the limit between the Humber Zone and the autochthonous platform is found. The transition and the subsurface structure are relatively well-imaged with potential field data (acquisition of new high resolution data was planned for 2008 by the provincial survey).

(#40) Available seismic helps to better constrained the Taconian and Acadian (?) deformation. In the platform sequence, large reverse faults are visible, which may or not be genetically linked with the inversion fairway to the south. Interestingly, the area covered by the seismic line is close to the old Daniel’s Harbour Pb-Zn mine, a Mississippi Valley-type (MVT) deposit hosted by hydrothermal dolostone of the St. George Group. MVT base metal deposits and hydrocarbon reservoirs in fault-controlled dolostone are both hosted by the same high temperature porous dolostone and dolomitic breccia, the only difference residing in the nature of the fluid that followed the dolomitization (base metal rich brines or hydrocarbons).

(#41) The next seismic line characterizes the geometry of the allochthon overlying the faulted (locally with pop-up) platform. The allochthons consists of large imbricated northwest-directed thrust slices, which are consistent with the overall deformation evolution of the Humber zone.

Presentation #7

The Lower Paleozoic Humber zone in eastern Canada

(latest Proterozoic (Ediacaran) to Late Ordovician) – Hydrocarbon system data

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(#2) The Humber Zone, which extends from southern Québec to western Newfoundland, consists primarily of a thick, pluri-kilometric fine-grained succession with subordinate coarser-grained (clastic and limestone) interbedded intervals.

(#3) The Humber (and Dunnage) Zone spans the same first tectono-stratigraphic cycle as the St. Lawrence Platform and given the dominant fine-grained nature, its main interest from an hydrocarbon point of view resides in its potential source rock intervals. Nonetheless, potential and demonstrated reservoirs will also be discussed.

Source rocks and thermal maturation

(#4) 2007 field and laboratory works have generated surprising TOC values for some units that previously had shown limited source rock potential. Of particular interest is the 3.7% TOC for the Lower Ordovician Pointe-de-la-Martinière Formation which is the highest TOC values that we have found for Lower Ordovician mudstones in the Québec Reentrant (see later discussion on the Upper Cambrian-Lower Ordovician Green Point Formation). Also, a TOC value of 2.9% in the Middle Cambrian Orignal Formation has confirmed some previous values for this unit in eastern Québec.

(#5) The Orignal is a km-thick mudstone succession deposited during an overall sea level rise – highstand. As such, this mudstone would deserve a much better/denser sampling program at least of its darker intervals and should eventually be considered in future exploration programs. The 2.9% TOC is the highest value of a fairly decent suite of samples that range between 0.5 to 2%, and although HI is low (25), the thermal maturation of this mudstone could be relatively high (lowest maturation between Quebec City and the mouth of the Saguenay River on the south shore of the St. Lawrence River).

(#6) The Lower Ordovician mudstones of the Humber Zone are demonstrated efficient hydrocarbon source rocks in western Newfoundland where the mudstones of the Green Point Formation have yielded TOC values well over 3% with a maximum of 10.4%. Hydrogen index can be as high as 759 and the organic matter has been demonstrated to be of Type I/II. The dark and OM-rich mudstones of the Green Point can form significant stratigraphic intervals and they were geochemically correlated (GC, GC-MS) with the oil seeps and produced oil at Garden Hill. Coeval shales in the Québec Reentrant (Rivière-Ouelle and Pointe-de-la-Martinière) have lower TOC values (0.5 to 3.7%) although they are of higher thermal maturity. Locally, bitumen-filled fractures are seen originating from the latter black mudstones. Hence, there is no fundamental reason to ignore these potential source rocks in the Québec Reentrant, as some up-dip migration of hydrocarbons produced from these Lower Ordovician shales could have filled some younger or even coeval reservoirs (clastics and/or HTD) well before the commonly assumed Upper Ordovician shales (Utica – Macasty) have started to generate hydrocarbons. This situation (timing of HTD and maturation of the Utica) has always been somewhat problematic in New York.

(#7) One of the major finding of recent work in eastern Canada has been the recognition of the source rock potential of Middle Ordovician black shales found in the oceanic domain known as the Dunnage Zone. Some high TOC values (over 10%) for samples in the oil window (southern Gaspé Peninsula) are backed by a larger number of analyses which yield values between 0.5 to 2%. Hydrogen Index is over 200 and the organic matter is of Type I. Comparison of GC-MS analyses of extracts from these shales and oils from recent wells suggest that these Middle Ordovician shales have contributed to the oil in place. These shales belong to deep marine, fore-arc facies of the Dubuc Formation of the Mictaw Group (part of the Mictaw Inlier of the Dunnage Zone) in southern Gaspé; they are also found in the Ruisseau Isabelle Mélange, a Dunnage inlier in northern Gaspé and they are also correlative (time and facie-wise) with the Popelogan Shales (Balmoral Group) in northern New Brunswick (also within an inlier of Dunnage rocks). These last two units are also characterized by TOC values higher than normal background (e.g., 1.5% for the now overmature Popelogan Shales). It is unknown if these occurrences are connected or not. However, the presence of the Dubuc shale has been recently interpreted, based on forward modelling of gravity data, to extend for some distance beneath the Silurian-Devonian Gaspé Belt in southern Gaspé.

(#8) In all these sequences (Middle Cambrian, Lower and Middle Ordovician), the black mudstone intervals are of significant stratigraphic thicknesses, a prerequisite for generation and efficient expulsion of hydrocarbons.

(#9-10) The plot of hydrocarbon yield versus thermal maturation is very informative: the samples with high yield values (Lower and Middle Ordovician) suggest that when these rocks were of lower maturity, they had major hydrocarbon production potential. Most of actual high maturity samples have a low remaining potential, they had an initial potential as good if not better, than the Upper Ordovician black shales. The potential of these Lower and Middle Ordovician mudstone is also nicely expressed by the HI vs OI diagram.

(#11) We are currently filling in the last remaining gaps in our knowledge of the thermal maturation of the Humber Zone in eastern Canada. As part of the SCES program, the evaluation of the thermal maturation and potential hydrocarbon source rocks of the Cambrian to Devonian successions between Québec City and the western end of the Gaspé Peninsula has been carried out. An open file report presenting the maturation maps and Rock Eval data should be released before the end of this project in March 2009.

(#12) The surface thermal maturity map of the Humber zone in southern Québec suggests that maturation increases from the NE towards the SW. Northwest of Logan's Line, the lowest thermal conditions are found near Québec City (end of the oil window) and the successions rapidly enter in the condensate to dry gas to overmature zones in southerly and easterly directions.

(#13) The Shell Saint-Simon well, located in the parautochthonous domain, west of Logan's Line but east of the Aston fault, and the Notre-Dame-du-Bon-Conseil well in the allochthonous domain, east of Logan's Line will be examined in detail.

(#14) In the Saint-Simon well, a stratigraphic repetition of St. Lawrence platform units through thrusting is documented. Early and late thrusting has been proposed and some repetitions of maturation trends suggest some post-maturation thrusting. As a whole, Ro ranges between 3.2 and 4.3% within the preservation window of dry gas. Coke is present and indicates early hydrothermal alteration in the Trenton Group.

(#15) The burial history plot for that well suggests that no sedimentation occurred after the Taconian orogeny. Tectonic burial and maturation were very rapid and hydrocarbons were generated from the Upper Ordovician source rock during the Taconian Orogeny.

(#16) The Notre-Dame-du-Bon-Conseil well has a complex stratigraphic log with multiple repetitions of carbonate units at the base and multiple repetitions of mudstone and flysch near the top of the well. Maturation is transported and reflectance profiles are repeated through thrusting. Thermal maturation is high, ranging from the dry gas zone to the greenschist metamorphic facies.

(#17) The burial history suggests that sedimentation ended at the Taconian orogeny. Thermal maturation was rapid due to tectonic burial and the generation of hydrocarbons occurred during the Ordovician tectonic stacking.

(#18) Here are some preliminary thermal maturation surface data along a couple of cross-sections in the zone of newly acquired data in eastern Québec. The cross-sections are based on 2006 field work and cover two sectors with Cambrian to Devonian rock units (Humber + Gaspe Belt). The structural framework is a complex pattern of NW-verging tight folds and thrust planes in the Humber Zone, with possible positive flower structures. The structural style of the Gaspé belt is characterized by open folds, with local overturned limbs of synclines neighbouring reverse faults. The stratigraphic section along the Sainte-Blandine section covers the Middle Ordovician to the Lower Devonian, except for the Devonian limestones which lie in the condensate zone; the remaining stratigraphy is within the dry gas zone. The second section (Saint-Guy) consists of Lower/Middle Cambrian to Upper Silurian strata; besides the stratigraphically higher bed at the high end of the dry gas zone, the entire section is within the overmature domain. However, the information is based on limited data point and new information gathered since the construction of these figures will likely improve the overall picture.

(#19) The thermal maturation for western Newfoundland is presented and discussed in the St. Lawrence platform section. Between the Port au Port (to the SW) and the Parson’s Pond (to the NE) areas, the Humber Arm area has been preliminary covered (for thermal maturation) during the last NATMAP and TGI 2 projects. No coherent maps could be produced as the complex superimposed Taconian and Devonian structural frameworks resulted in the juxtaposition of samples with lower oil window values (commonly deep marine slope units) against overmature units (commonly platform tectonic slices).

Reservoirs

(#20) Multiple type of hydrocarbon reservoirs are known in the Humber Zone, including *in situ*, slope-related coarse-grained clastics as well as exotic imbricated thrust slices of shallow marine carbonate platforms.

(#21-22) A recently documented hydrothermal dolomite locality in the Humber Zone of northern Gaspé has critical importance for the potential of the area. HTD have been found in the ribbon limestone facies of the Lower Ordovician Rivière-Ouelle Formation (primarily considered as a source rock in the basin). At this locality, many elements characteristics of classical HTD are present: transpressional dextral fault plane, pervasive dolomitization away from the fault, brecciation and boxwork texture along the fault plane and late silica. However, given the muddy nature of the carbonate facies and the abundant shaly interbeds, it is doubtful that significant volume of dolomite would have been created. Recent (post-December 07 workshop) petrography, stable isotopes and radiogenic strontium isotopes have been carried out on samples from this locality. Saddle dolomite has not been observed, but small sized planar-S dolomite crystals are present, the $\delta^{18}O_{PDB}$ values (3 analyses) range from -9.6 to -9.9‰ and $\delta^{13}C_{PDB}$ range between -2.8 and -3.0‰. Of great interest are the $^{87}Sr/^{86}Sr$ ratios, these are strongly radiogenic (0.713096 and 0.713224). The dolomitization is associated with the Rivière-Madeleine Fault, which belongs to a structural corridor that obliquely cuts the Humber zone and Gaspé Belt from northern Gaspé to northern New Brunswick. A Lower Devonian West Point pinnacle reef has been intensely dolomitized along the same fault a few kilometres to the SW (see section on the Gaspé Belt). $^{87}Sr/^{86}Sr$ are drastically different for the pinnacle reefs (0.708383 to 0.709216), which indicates that we are dealing with multiple HTD events with very different sources of fluids.

(#23) The coarse-grained clastic conglomerate and turbidite facies share similitude in the overall depositional facies and thickness of potential pay zones with some of the giant Cenozoic West African deep offshore fields of Angola and Nigeria. Of course, the old Paleozoic successions of Eastern Canada are now fairly well cemented, but evidence for hydrocarbons charge is locally well displayed.

(#24) In southern Québec, in the Chaudière River Nappe, significant amount of low maturity bitumen and impsonite (extracts for GC-MS and IRMS were made) are found in highly mature Lower Cambrian sandstones, the late charge likely post-dating the out-of-sequence emplacement of the nappe over the Pointe-Aubin Mélange (with identified source rock within the oil window).

(#25) In eastern Québec, in an area where the maturation level is largely unknown, exploration drilling of these Lower Cambrian sandstones at Parke has revealed the presence of porous and permeable (secondary dissolution and fractures) intervals over a significant thickness.

(#26) In western Newfoundland, coeval (?) rift related coarse-grained sandstone of the Blow-Me-Down-Brook Formation occurs in zone of fairly intense deformation (folding and faulting). At a well exposed seashore locality, the Lower Cambrian sandstone is structurally overlying Lower Ordovician ribbon limestone and OM-rich shale of the Cooks Brook Formation. Along the entire exposed section, the sandstone is totally impregnated with bitumen and live oil.

(#27) Higher up in the stratigraphy, the clean quartz arenite of the Kamouraska Formation has a significant reservoir potential. In eastern Québec, shallow drilling for groundwater has resulted in some short term gas escapes when drilling into the Kamouraska sandstones. From outcrops, the Kamouraska is characterized by open fractures which are lined by quartz crystals with nicely formed tips and bitumen coating on the quartz. The Kamouraska is locally interbedded with intervals of OM-rich black mudstone (TOC up to 2%) which could have provided a nearby source of hydrocarbons although other sources (Lower Ordovician Rivière-Ouelle and Middle Cambrian Orignal) are also hypothetically viable hypotheses in this structurally complex area.

(#28) These potential clastic reservoirs are involved in multiple structural traps, including folds, duplexes and thrust slices. Because they are commonly surrounded by thick mudstone successions, potential seals are abundant. However, because of the complex tectonic history, integrity of these reservoirs and seals is uncertain.

(#29) Documented hydrocarbon reservoirs consist of tectonic slices of the shallow marine platform that were detached from the autochthonous platform and incorporated in the orogenic wedge at the Appalachian structural front presumably during the later stages of Taconian Orogeny. The St. Flavien gas field which is hosted by Lower Ordovician dolostones of the Beekmantown Group represents such a reservoir.

(#30) The seismic line M2001 extends over the St. Flavien field. This 1.5 km deep field is located on a fault anticline in the hanging wall of the Aston fault and structurally under Logan's Line. The field (5 Bcf) was discovered by Shell Canada in 1972 and put into production in the 1980's by SOQUIP. After depletion, it was turned into an underground natural gas storage facility. A compilation study of seismic data from the Appalachian structural front of southern

Québec has identified a large number of these tectonic slices, of various sizes, and locally imbricated and stacked one over the other (e.g., previously shown Saint-Simon well). Only a few of these have been drilled and some returned good gas shows (Shell Saint-Simon). Northeast of Quebec City, available seismic data is of lesser general quality and coverage is sparse, however, some of these platform slices have been tentatively identified.

(#31) The platform slice consists of units of the Potsdam, Beekmantown, “Trenton” and Utica, transported over autochthonous Upper Ordovician Lorraine and Utica which is the most likely source of the hydrocarbons.

(#32) A 3D seismic survey of the St-Flavien field clearly outlined a domal structure affected by a large number of fractures that were shown to be critical for reservoir connectivity and permeability. The dolomitized reservoir was formed after a complex history of shallow burial to syn-tectonic deformation (see further). The pay zone averages 3.5 m with a 6% average porosity and permeability of 2-6 mD (average).

(#33) The details of reservoir formation are schematically illustrated, with an initial reflux-type shallow burial dolomitization in Early Ordovician with burial stopped during a short emergence and limited karstification in early Middle Ordovician. Meteoric calcite cementation and renewed burial in Middle to Upper Ordovician resulted in the rapid calcite cementation of karst pore space, some burial cementation and most likely some geothermal dolomitization. Horizontal stylolites were developed. Near maximum burial in Late Ordovician, vertical fractures with pore-filling and replacement saddle dolomite indicate the presence of high temperature fluids. The onset of significant compression in Late Ordovician removed a slab of the platform and incorporated it in the tectonic wedge. This was accompanied by vertical stylolites and near horizontal fractures where high temperature fluids circulated resulting in small secondary pore space. Finally, near final emplacement at shallower depth, a cooler fluid resulted in improved final porosity and permeability. The field is not a classical HTD field as observed in the New York Appalachians and Michigan basin. However, the reservoir formation resulted from fault-controlled fluid circulation and associated dolomitization and dissolution.

Traps

(#34) As shown from seismic lines M2002 and M2003, sizable fault anticlines with platform slabs are common along the Appalachian structural front, only a few have been properly tested.

(#35-37) Tectonic slices of platform rocks are also an on-going target of exploration drilling in the Humber Zone of western Newfoundland. The tectonic style is quite different as platform rocks are involved in inverse, locally thick-skinned (basement involved) faulting. Displacement of platform units is locally significant. The successful Hunt et al (1995) Port au Port #1 drilled through platform, then through a thick interval of Precambrian basement in the hanging wall of the Round Head Thrust, and then intercepted porous dolomite rocks of the Lower Ordovician St. George Group.

(#38-39) The detailed history of the St. George dolomite reservoir is different from that of the Beekmantown fractured-dolomite in southern Québec. Initial steps were fairly similar, initial reflux dolomitization, exhumation and karstification, followed by rapid tectonic subsidence resulting in fairly intense downward dolomitization as recently documented through a detailed study. Later fracturing-faulting (late Taconian and / or Salinic; e.g. during the Late Ordovician to Early Devonian), possibly inherited from early foreland basin normal faults, allowed the circulation of high pressure and temperature, hydrothermal fluids that has resulted in intense local brecciation and massive dolomitization of the St. George Platform, preferably in the hanging wall of extensional faults. It has been assumed that the early karstification of the platform was a critical element for later hydrothermal fluid circulation. The relationship between extensional (transtensional?) faulting with high pressure and high temperature fluid circulation renders the situation similar to the classical Middle – Upper Ordovician HTD (and with nearby Anticosti). If this late event generated significant fracture and dissolution porosity, a significant amount of dolomite was also formed earlier from reflux and geothermal processes. Finally, in Middle Devonian, the Acadian Orogeny was responsible for inverse reactivation of the extensional HTD fault / feeders and possibly resulted in significant reservoir compartmentalization. Hydrocarbon charge likely occurred before the formation of the inverse faulting.

(#40) In conclusion, excellent source rocks are recognized in the Lower and Middle Ordovician deep marine shale and fair source rock potential has been recently documented in the Middle Cambrian. Geochemical links with oils are presented in the Gaspé Belt section. Thermal maturation is complex and relates to both sedimentary and tectonic burial of the successions. In Québec, the lowest surface thermal maturation is between Quebec City and for 100 km to the northeast (oil to condensate zones). Elsewhere, dry gas to overmature conditions is observed. In the subsurface, overmature conditions are rapidly reached east of the Logan's Line in southern

Quebec where the prospective area is largely restricted to the parautochthonous domain. The lack of subsurface information northeast of Quebec City prevents us from proposing any conclusions. Thermal maturation is also highly variable in western Newfoundland, in particular for the inverted fairway (parautochthonous domain) where the footwall of some of the reverse faults was shown to be less mature than the shallower hanging wall. In the true allochthonous zone, complex stacking of high maturity (overmature detached platform slices) and low maturity (oil window slope and rise successions) makes subsurface prediction hazardous. Both clastics and carbonates (HTD-like) reservoirs have been potentially demonstrated (oil charge) or in production.

Presentation #8

Middle Paleozoic Gaspé Belt (Late Ordovician to Middle Devonian) – Geological framework

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(#2-3) The term Gaspé Belt is used to designate the stratigraphic package of sedimentary and volcanic units that were deposited after the main Taconian event (late Ordovician) and before the sub-aerial unconformity that relates to the climax of the Acadian Orogeny (Middle Devonian). Within that interval, a locally significant orogenic pulse (Salinic Orogeny) left its mark at various localities.

(# 4) During the interval herein considered, the Gaspé Belt depositional basin was located near the paleosouthern outboard margin of Laurentia and was well within the southern hemisphere tropical belt. During the Silurian-Devonian interval, Laurentia experienced a slight anti-clockwise rotation. From a largely cool and humid climatic situation after the waning of major ice sheets on Gondwana from latest Ordovician to Early Silurian, the climatic situation then became more arid and hot in Late Silurian to Early Devonian.

Regional setting

(#5) In eastern Canada, rocks assigned to the Gaspé Belt are recognized from southern Québec (and they extend in New England) to Gaspé / Northern New Brunswick and reach as far north as western Newfoundland. They are likely present beneath the Gulf of St. Lawrence although the nature of the succession is largely unknown. The southern Québec succession has been shown to be thermally overmature and will not be discussed any further

(#6) This simplified geological map (at the group level) of eastern Québec and northern New Brunswick shows the three major tectonostratigraphic domains forming the Gaspé Belt, 1) the Connecticut Valley – Gaspé synclinorium (CVGS) to the north made up of Upper Ordovician to Middle Devonian units, 2) the Aroostook-Percé anticlinorium (APA) in southern Gaspé which consists of Upper Ordovician to Lower Silurian units and 3) the Chaleurs Bay synclinorium (CBS) that encompasses Upper Ordovician to lowermost Devonian units. The contact between the CVGS and the Taconian allochthons is either a fault or a major unconformity. The contact between the CVGS – APA and between APA – CBS is usually faulted whereas a major unconformity marks the contact between the three tectonostratigraphic domains of the Gaspé Belt and Carboniferous rock units.

(#7) As represented in this schematic stratigraphic chart, the nature (age and lithologies) of the succession that underlies the Gaspé Belt is highly variable and interpretative. From mixed Humber and Dunnage zones basement in the northern end, to Dunnage Zone volcano-sedimentary units in central and southern Gaspé to possibly Gander zone successions at the extreme southern end in northern New Brunswick. The base of the preserved Gaspé Belt succession is as old as early Late Ordovician in central – southern Gaspé and is as young as latest Silurian at some localities in northern Gaspé where merged Taconian and Salinic unconformities can be mapped.

(#8) The Gaspé Belt is unconformably overlain by red siliciclastic units assigned to the poorly constrained Bonaventure Formation. Correlation with other units of the Maritimes basin to the south has led previous workers to assign a general Carboniferous age for this largely fluvial succession.

Stratigraphy – sedimentology - paleoenvironments

(#9) As a whole, the stratigraphic succession of the Gaspé Belt was deposited in response to major, second-order, transgressive-regressive relative sea level fluctuations. Three major regressive events (R1 to R3) are documented and are separated by two major transgressive (relative) episodes (T1 and T2). These major phases are used to divide the succession into three major stratigraphic packages. The R1 succession is followed by the T1 – R2 package and an upper T2 – R3 stratigraphic interval. The first of the large scale stratigraphic assemblage formed during the R1 event and covers the Late Ordovician to the late Early Silurian.

(#10) The base of the first assemblage is highly variable and is represented by a significant angular unconformity (Lower Silurian over pre-Upper Ordovician units) in northern Gaspé to a slight time hiatus (one or two graptolite zones) between deep marine units in southern Gaspé.

(#11) The R1 is a large-scale regressive succession that, where complete, starts with deep marine clastic facies of the Honorat Group (and equivalent Grog Brook Group in New Brunswick and Cabano Group in the Témiscouata region). These are overlain by deep (below wave base) outer shelf to slope limestones of the Matapédia Group in Gaspé and New Brunswick (with the laterally equivalent Sources and Awantjish formations in northern Gaspé). The Ordovician-Silurian limit is within the Matapédia Group and the major Late Ordovician glaciation is recorded in a clastic mudstone succession within a predominant limestone interval. The regressive event resulted in significant shallowing during the Early Silurian and is recorded in the lower units of the Chaleurs Group. The succession consists of lower Silurian shallowing upward offshore to nearshore clastics of the Clemville, Weir and Anse Cascon formations in southern Gaspé and the nearshore Val Brillant – Robitaille formations in the northern Gaspé / Témiscouata area.

(#12) The first regressive event culminated in the establishment of peritidal carbonate ramp sedimentation of the La Vieille (southern Gaspé – New Brunswick) and Sayabec (northern Gaspé – Témiscouata) formations. The shallowing event recorded in northern and southern Gaspé, and northeastern New Brunswick did not affect the areas of central Gaspé (Burnt Jam Brook and Laforce formations) and northwestern New Brunswick (Gounamitz Lake Formation), where deeper marine successions are developed.

(#13) The La Vieille and Sayabec formations mark the oldest shallow marine carbonate sedimentation in the Gaspé Belt. The depositional setting is a laterally well-zoned carbonate ramp dominated by a wide peritidal flat flanked by a shallow subtidal narrow knob reef belt and a well sorted above fair-weather wave base limestone sand belt. Offshore mixed clastic and limy muds mark the transition with deep slope (e.g., the Limestone Point and Gounamitz Lake formations in New Brunswick and the Laforce Formation in central Gaspé).

(#14) The carbonate ramp was built at the time when extensional faults were active possibly as a result of the establishment of the Salinic-Acadian foreland basin.

(#15) The paleogeographic reconstruction of the Gaspé Belt is based on a retro-deformation of the basin achieved by removing the major Acadian dextral strike-slip movement and the significant shortening through regional folding and internal deformation. The resulting map is characterized by an overall shallower marine setting that follows the general geometry of the St. Lawrence Promontory / Québec Reentrant (still prominent elements) and a deeper marine basin to the south and west.

(#16) The previously described R1 event is summarized in these 4 time slice maps with initially Upper Ordovician deep marine clastics going into lowermost Silurian slope limestones; in the first two time slice maps, a significant link existed between the deep marine Gaspé depositional basin and the Anticosti shallow marine platform. This link seemed to have ceased in Early Silurian time when the shallowing resulted in nearshore clastics in northern and southern Gaspé with a deeper marine mud basin preserved between the latter two areas. At that time, Anticosti was the locus of significant shallow marine carbonate ramp sedimentation (Chicotte Formation). Finally, the nearshore clastics were replaced at the end of Llandoverian time by the Wenlockian peritidal carbonate ramp. Here again, northern and southern Gaspé recorded shallow marine sedimentation whereas in between, deeper marine mud and limestone sand and gravel (Laforce Formation) were accumulating. Even if seismic information in the St. Lawrence estuary and thermal maturation synthesis clearly indicates post-Chicotte sedimentation on Anticosti, the nature of such sediments is currently unknown.

(#17) The next stratigraphic package consists of the uppermost Lower Silurian to the mid-Pridolian interval recorded by the upper part of the Chaleurs Group; this succession was deposited during the second-order T1-R2 phase. The red boxes refer to non-deposition or erosion whereas Re are for reef facies of the West Point Formation.

(#18) The T1 –R2 cycle was initiated in the late phase of sedimentation of the Sayabec-La Vieille formations carbonate ramps. The upper most beds of these units consist of offshore mixed carbonate and clastic muds that are largely devoid of macrofauna. The rapid increase in clastic mud content is interpreted to result from a significant increase in tectonic subsidence related to the rapid collapse of far foreland extensional faults. Significant thickness variations in the overlying deep marine clastics testify for tectonic blocks with varying subsidence rates. These overlying, lower Upper Silurian (Ludlovian) deep marine greenish silt and mud (below storm wave base; interpreted as outer shelf clastics and pro-delta muds) form thick succession for which a complex nomenclature exists. Where the Upper Silurian (late Ludlovian – Pridolian) reef facies of the West Point Formation are present, the pre-West Point fine-grained Ludlovian clastics are designated as the Gascons Formation whereas the West Point laterally equivalent and overlying fine-grained clastics are part of the Pridolian-Lochkovian Indian Point Formation. In the absence of the West Point reefs, the fine-grained clastic succession of the Saint-Léon Formation goes uninterrupted from the Ludlovian to the Early Devonian (Lochkovian).

(#19) Overlying and laterally equivalent to the below wave base clastics are the famous Silurian West Point reef complexes and carbonate platforms. The Upper Silurian West Point Formation has been divided in three major reef complexes; the lower two are part of the T1-R2 interval whereas the upper reef complex belongs to the overlying large-scale cycle. Between these two, a major unconformity (Salinic Unconformity) testifies to sub-aerial exposure at the end of the R2 event in mid-Pridolian time.

(#20) The lower reef complex of the West Point Formation was established in a deep marine environment, below the photic zone. The seafloor started to be colonized by deep marine stromatoporoids, corals and sponges, an ecological association that ultimately grew into large red mud mounds (Gros Morne Member) with the enigmatic “stromatactis” structure that is currently interpreted to be the early calcified relict of a sponge network that was connected to the seafloor allowing significant marine cementation in the open decay cavities.

(#21) As sea level was regressing (eustatic with a potential tectonic imprint in southern Gaspé), the seafloor eventually reached the photic zone and the deep marine mud mounds were environmentally and ecologically replaced by microbial and metazoan very shallow marine cement-dominated reefs (Anse-à-la-Barbe Member). These microbial reefs had some synoptic relief on the seafloor as testified by the size of large reef block shed in the fore-reef setting. The deep marine mud mounds and the shallow microbial reefs internal facies architecture responded to two major (4^{th} order) shallowing upward “sequences” and form what is informally designated as the Lower reef complex of the West Point Formation.

(#22) The overlying Middle reef complex (Anse McInnes Member) is a thin, highly cyclic succession that consists of up to 60 m-thick shallowing upward “sequences” of shallow marine crinoidal banks that culminated in near shore stromatoporoid rubbles and clastics. The offshore extension of that belt is characterized by major debris flow units. The Middle reef complex was formed at the time of major lowstand in the depositional basin and evidence for episodic and more or less prolonged sub-aerial exposures are found in that interval as well as in the underlying successions.

(#23) The Late Silurian sub-aerial exposure event in the Gaspé depositional basin is related to the combined global sea level low and Silurian Salinic Orogeny (accretion of Ganderia along the composite margin of Laurentia) and the physical expression of the resulting lowstand is referred to as the Salinic Unconformity. The expression of the Salinic Unconformity is quite variable in the basin with southern localities (southern Gaspé and northern New Brunswick) showing a ubiquitous and major Late Silurian sub-aerial event. In central and northern Gaspé, the unconformity is only developed in areas that were paleotopographic highs at the margin of tectonic blocks although it has been shown through detailed mapping that the Salinic downcutting event could be severe with the Late Silurian Salinic Unconformity merging with the Late Ordovician Taconian Unconformity in northeastern Gaspé.

(#24) There is little to no angular relationship visible in outcrops to suggest the presence of this unconformity, although some 1: 50 000 mapping patterns locally suggest angular relationships. Most of the evidence are found as meteoric karst features present in carbonate units and locally associated with the angular map pattern, for example for the Lower Silurian La Vieille and Sayabec formations; this subaerial event is a critical time element in the evaluation of hydrothermal dolomitization and hydrocarbon charge (see further).

(#25) Similar solution features related to the Salinic Unconformity are documented in the Lower reef complex of the West Point Formation, primarily as outcrop solution pipes and as meteoric calcite cements in the secondary pore space.

(#26) The last stratigraphic package was deposited during latest Pridolian to the early Middle Devonian during the T2 – R3 cycle. The succession consists of the upper units of the Chaleurs Group, the Upper Gaspé Limestones and the Gaspé Sandstones (and laterally equivalent units as shown on the stratigraphic chart).

(#27 - 29) The base of the last cycle was initiated as sea level started to rise again after the Late Silurian lowstand. As sea level rose, a laterally well-zoned carbonate platform was established in the Gaspé Belt; its spectacular development can be seen in southern Gaspé outcrops although specific outcrops and seismic information suggest that this platform also developed in northern Gaspé, Témiscouata, southern Québec and northern New York, thus forming a 1000 km long reef tract in Late Silurian time. The Pridolian upper reef complex consists of a laterally well zoned platform with fore-reef (included in the Indian Point Formation), reef margin, lagoonal or back-reef and a supratidal coastal plain. Such facies architecture is similar to that of the famous Middle Devonian reef platforms in the Western Canadian Sedimentary Basin. The fact that the reef margin reaches total vertical thickness of over 600 metres during a short time interval during the Pridolian (the entire Pridolian is 2.7 Ma) is a strong indication of significant tectonic subsidence for creation of the needed accommodation space. In detail, the initial (post Salinic Unconformity) sea level rise was of moderate pace allowing for initial progradation of the platform (1^{st} cycle within the upper reef complex) and then the pace accelerated significantly and the platform aggraded vertically (upper three shallowing upward cycles). Let's have a closer look at the facies, from the deeper fore-reef to the coastal plain.

(#30) The reef margin was predominantly built by encrusting stromatoporoids, corals and some significant microbial material that help to produce a structure strong enough to resist significant wave energy. The continuous sea water pumping in the construction growth spaces resulted in significant marine cementation, as for modern fringing reef margins. Within the reef margin itself, individual cycles are recognized and result in a succession of facies indicative of progressive shallowing and increase in wave energy. The reef margin was likely steep and the fore-reef environment received significant carbonate detritus (small fragments up to decametre-sized blocks derived from the reef front) to mix with a clastic background sedimentation.

(#31) A large, shallow and low-energy subtidal back-reef or lagoon existed behind the reef margin that acted as breaker for wave swells. The facies are mixed, consisting of peritidal clastics derived from the erosion of some unknown adjacent relief near the marine environment and of in situ produced carbonate material in the tropical sea with abundant small corals and stromatopores patch reefs that were colonizing the sea floor. The shallowing upward cycles resulted in initial subtidal carbonate-dominated facies passing to nearshore clastic-dominated beds.

(#32) Laterally, the nearshore clastics are part of a wide intertidal to supratidal red bed coastal plain. The dominant facies are mudcracked mudstones with desiccation polygons and locally abundant sulphate pseudomorphs nodules (now calcite) with the typical sabhka-associated chicken-wire structure. All these elements are indicative of a Late Silurian hot and arid climate in the Gaspé Belt.

(#33) The overall evolution of the Late Silurian West Point reef complexes is summarized in the following slides. The West Point started as deep marine, sponge-dominated reefs that grew up below the photic zone in the early stages of the R2 event. It is uncertain if the extensional faults, responsible for the drowning of the Lower Silurian carbonate ramps, were still active in the Late Silurian.

(#34) As sea level was decreasing, near the end of the R2 event, shallow water microbial-cement reefs were constructed at the shelf margin. Here again, movement along reactivated extensional faults is equivocal.

(#35) The crinoidal-stromatoporoids banks of the middle reef complex were formed during multiple 3rd order sea level fluctuations along the shelf break during the major 2nd order sea level lowstand in the Gaspé Belt. At that time, major erosion, solution and downcutting resulted in the formation of the Salinic Unconformity.

(#36) At the onset of renewed relative sea level rise (T2 event, combined eustatic and accelerated tectonic subsidence), the laterally well zoned upper reef complex of the Late Silurian West Point started to prograde offshore, but then aggraded vertically as pace of relative (tectonically-controlled) sea level rise became too fast to allow for lateral progradation.

(#37) In Early Devonian time, tectonically-driven sea level rise was so rapid that most of the carbonate platform was unable to keep pace. But, the biologically-constructed reef margin was able to keep pace for some time. This resulted in the formation of largely isolated pinnacle reefs, surrounded by fine-grained clastic sediments, similar to the Upper Devonian Leduc-like pinnacles in the Western Canadian Sedimentary Basin. These pinnacles grew on top of paleotopographic highs left after the Salinic erosion and on top of the Late Silurian West Point reefs.

(#38) These pinnacle structures are visible on seismic but also in the field, such as the famous Madeleine River Pinnacles that have vertical relief of close to 300 metres and km-sized bases.

(#39) The internal architecture of these individual structures is complex with stromatopores-corals-microbial bioconstructed zones with irregularly distributed areas made up of reworked bioclastic detritus. In most of the accessible pinnacles, a conglomeratic fore-reef detritus belt is developed around individual construction.

(#40) Based on our current understanding of seismic and field data, the pinnacle reefs grew on top of uplifted margins of fast subsiding fault-bounded blocks. Pinnacles are seen over the Salinic Unconformity or over the Late Silurian West Point reef margin. Eventually, in

Lochkovian time, the pinnacles were buried under deep marine fine-grained clastic of the Indian Point Formation.

(#41) The deep-marine Indian Point Formation consists of various members of below wave base clastics and fine-grained impure limestones. In late Lochkovian – Pragian time, at the maximum of T2 second-order event, carbonate production was efficiently re-establish and led to the sedimentation of the Upper Gaspé Limestones. This unit is a tripartite group with, from base to top, the Forillon, the Shiphead and the Indian Cove formations. The lithostratigraphic formation limits are also coincident with 3rd order relative sea level rises of most likely tectonic control and the overlying succession in each of these three 3rd order cycles is a shallowing upward of initially deep, below storm wave base sediments progressively culminating in slightly above fair weather wave base sediments.

(#42) The facies architecture of these Lower Devonian limestones in Gaspé allows recognizing southwesterly deepening marine conditions. Associated with the deepening, the succession also becomes significantly thicker (500 m to 2000 m) and more homogenous (facies-wise); the older two-fold stratigraphic nomenclature (Cap Bon Ami = Forillon and Shiphead; Grande-Grève = Indian Cove) is locally still in use. In central and western Gaspé, the carbonate dominated succession passes to a coeval deep marine clastic turbidites and associated lithofacies of the Fortin Group and Témiscouata Formation. The shallow marine production zone for the Upper Gaspé Limestones was clearly located north – northeastward of Gaspé Peninsula, but it is presently unclear if it is still present under the St. Lawrence Estuary / Gulf.

(#43) The last of the 3rd order sea level fall (Indian Cove Formation) marks the onset of the R3 event and the mid-shelf carbonates that top the Indian Cove are overlain either by a thin limestone-sandstone transition zone (York Lake Formation) or rapidly by sandstones (York River Formation). These two units mark the base of the regressive, Emsian to Eifelian Gaspé Sandstones. The Gaspé Sandstones Group occupies roughly the northern half of the Gaspé Belt; to the south, it is replaced by the Fortin succession. The Gaspé Sandstones sedimentation patterns were controlled by the ongoing Acadian oblique accretion of Avalonia along the composite continental margin of Laurentia-Ganderia. The overall succession can be very thick (locally up to 5 km) and accumulated over a short period of time that testifies for the presence of significant relief to be eroded for continuous supply of sediments. The Gaspé Sandstones are a coarsening-upward succession with a fluvial-marginal marine sandstone base (York Lake and York River formations), going into a sequence (Battery Point Formation) of conglomeratic sandstone, medium to coarse-grained sandstone, and minor siltstone and mudstone overlain by a redbed unit of sandstone, siltstone and mudstone and culminating in an upper sequence (Malbaie Formation) of thick-bedded conglomerate composed of pebbles and cobbles of limestone, siliciclastic and volcanic fragments derived from the older Matapedia and Chaleurs groups, and interbedded with medium to coarse-grained red sandstone. The Malbaie Formation is unconformably overlain by Carboniferous rocks.

(#44) The Gaspé Sandstones Group therefore corresponds to an abrupt shoaling event, from shallow marine facies to terrestrial facies. The transition from the deep water facies of the Upper Gaspé Limestones to the shallow water sands of the Gaspé Sandstones is gradational (York Lake), except in the Forillon-Percé area, where it is abrupt (York River). The overlying Battery Point Formation contains a lower, distal, braided stream deposit and interbedded marine deposits, and an overlying meandering river system associated with playa or ephemeral lake deposits. The overlying Malbaie is interpreted as a proximal braided plain deposit.

(#45) From Emsian to Eifelian, the regressive sedimentation patterns recorded in the Gaspé Belt were largely controlled by the westward (modern-day coordinates) displacement of the Acadian orogenic wedge along some of the major Acadian dextral strike-slip faults. Following the Middle Devonian Acadian deformation, sedimentation resumed in Late Devonian time in some marginal marine embayments; these successions are known in southern Gaspé (Miguasha Group, famous exquisite preservation of vertebrate fossils documenting part of the evolution from fish to amphibians) and Témiscouata (Touladi Formation). These were later gently deformed by possibly the Late Devonian Neo-Acadian or later by the Alleghenian orogenies.

(#46) A significant part of the Gaspé Belt stratigraphy consists of various volcanic units that range in age from the Early Silurian to the Early Devonian. A dominant sub-alkaline to alkaline within-plate tholeite geochemical affinity has been recognized at many localities that form a roughly NE-SW alignment from eastern Gaspé to northwestern New Brunswick. A different suite of older volcanics with a tholeitic to calc-alkaline geochemical affinity is recognized in the Témiscouata area, near the base of the Gaspé Belt succession.

Structural framework

(#47) The aim of the second part of this presentation is to review the geometry of the Gaspé belt in the Gaspé Peninsula using both surface and sub-surface data. On this geological map, the change in strike of lithotectonic units from a NE trend to the SW to a nearly E-W trend in the eastern part of the Gaspé Peninsula is conspicuous. This change in strike correlates with a change in the kinematic of major structures: thrusting toward the NE predominates in southern Québec and in the Témiscouata area, whereas right-lateral strike-slip faulting predominates to the east. Most of the deformation in the Gaspé Peninsula is attributed to the Acadian Orogeny. However, a polyphase history has been documented for several structures and pre-Acadian normal faulting is recorded along several faults.

(#48) Potential field maps give another view of the overall geometry of the Gaspé Belt. Gravity data define two- sub-basins and enhance the importance of a NE-trending structural corridor that crosscut the entire Gaspé Peninsula from the New Brunswick to the St. Lawrence shore. In both sub-basins, the lowest Bouguer anomaly values correlate with the distribution of youngest rock units.

(#49) Magnetic long-wavelength anomalies show an overall correlation with gravity data and also define two sub-basins on both the eastern and western side of the structural corridor.

(#50) High-resolution aeromagnetic data are also a useful tool for mapping purposes. For that, several methods that enhance short-wavelength anomalies have been used.

(#51) This map shows the main potential field mapping results. New faults are indicated by dashed lines. It should be noted that in several cases, the apparent offset of faults can be quantified by the offset of magnetic markers. The most important result of this analysis is that structures trending obliquely compared with the main structural grain have been underestimated by previous geological studies. Also, this map illustrates the different map pattern of the two sub-basins. NE-trending faults are found predominantly in the western sub-basin, whereas NW-trending faults are mainly located in the eastern sub-basin.

(#52) At the outcrop scale, the deformation of Silurian-Devonian rocks is generally relatively simple. Folds are commonly broad and open and the fault zones exhibit brittle deformation and their kinematics is often recorded by slickenlined surfaces.

(#53) This composite geological cross-section shows the geometry of the Gaspé belt at a more regional scale. Open folds are often cut by steeply dipping faults that commonly exhibit predominant strike-slip motion.

(#54) Recent seismic data acquired by the Québec government also contribute to a better understanding of the geometry of the Gaspé belt. We will look at several seismic lines, starting in the western part of the Gaspé Peninsula.

(#55) The first transect is around 40 km long and is a composite of 4 seismic lines. The quality of this dataset is good and several seismic packages are clearly identified on the line drawing and on the interpreted cross-section.

(#56) Near the NW end of this transect, the Shickshock Sud fault clearly divides two rock packages: on the NW of the fault a thin, sub-horizontal Silurian-Devonian cover forms the Matapédia syncline. On the SE of the fault, the sedimentary succession is thicker and is involved in broad open folds. The dip of the Shickshock Sud fault imaged on seismic is in agreement with drill hole and gravity data.

(#57) The seismic characters of the sedimentary succession of the Gaspé Belt are nicely summarized in this image from the central segment of the seismic line. The Taconian unconformity is relatively well-defined and is overlain by seismic unit 1 which is almost transparent and characterized by few small amplitude reflectors. The overlying seismic unit 2 includes high amplitude reflectors and is correlated with the lower part of the Chaleurs Group (e.g, the Val Brillant – Sayabec formations). These seismic characteristics of the lower part of the Chaleurs Group are found in most of the seismic lines. In this particular example, several triple points are visible and could be tentatively interpreted as clinoforms. Units 3 and 4 correspond to the upper part of the Chaleurs Group and include a lower, almost transparent seismic unit characterized by few small amplitude reflectors and an upper unit characterized by well-defined parallel reflectors. Finally, the seismic unit 5 corresponds to the Upper Gaspé Limestones.

(#58) A slight angular unconformity is locally present between seismic units 3 and 4 and is interpreted as the Salinic Unconformity.

(#59) In detail, the geometry of the Siluro-Devonian succession may be locally complex such as in the area of the Amqui anticline, which is affected by both NW- and SE-dipping faults.

(#60) In other cases, the geometry mimics positive flower structure such as in the area of the Lac Humqui anticline. Detailed observation also shows that a flat spot is imaged in the hinge zone of the fold in the lower part of the Chaleurs Group.

(#61) This slide illustrates another profile located in the central part of the Gaspé Peninsula. The main structural feature on this part of the profile corresponds to the Mont Berry syncline. In this case, a complete Siluro-Devonian succession is imaged. As in the previous seismic transect, the lower part of the Chaleurs Group exhibits a clear seismic signature. Three points are of particular interest on this profile: (1) the variable thickness of the seismic package 1, which is almost absent in the central part of the syncline; (2) several faults do not cross the entire succession and do not affect the uppermost part of the Chaleurs Group; (3) from seismic unit thickness, the depocenter migrates toward the NW as expected in a foreland setting.

(#62) The gravity model linked to the previous seismic section is shown and despite the low density of the rocks found in the core of the Mont-Berry syncline, the latter is characterized by a positive residual gravity anomaly. This may suggest the presence of high density volcanic rocks below the syncline. These rocks may be correlated with the Late Neoproterozoic to Cambrian mafic volcanic rocks of the Shickshock Group that crop out to the NW.

(#63) The next seismic profile is located in the eastern part of the Gaspé Peninsula. The most prominent structural feature is the Rivière Saint-Jean anticline which is bounded to the south by the Rivière Saint-Jean fault and by an unnamed fault to the north. The former fault dips toward the N in agreement with field and gravity data. This profile also illustrates a thickness increase toward the south of rock units predating the Chaleurs group (black arrows). A similar southward thickness increase is also imaged for younger rock units corresponding to the Chaleurs Group and Upper Gaspé Limestones (blue arrows).

(#64) In the same area, gravity data shows a long wavelength positive anomaly located in the eastern part of the Gaspé Peninsula. Forward modeling along a section parallel to the previous seismic line indicates that mafic volcanic rocks are probably present below the Rivière Saint-Jean anticline.

(#65) The geometry of the Gaspé belt in the Chaleurs Bay area is more elusive. The three maps on the right-hand slide correspond to the Bouguer anomaly map, the shaded relief of the residual magnetic field and the geologic interpretation. All these maps show a complex map pattern that includes faults of various orientations with complex cross-cutting relationships. Moreover, this area is characterized by significant volume of volcanic rocks that are well-imaged on the magnetic map (e.g, the Restigouche Syncline and northwestern part of New-Brunswick, image b) and by significant changes in the thickness of the sedimentary pile.

(#66) This complexity makes the interpretation of seismic data even more difficult. However, a broad open fold involving the lower part of the Chaleurs Group (seismic unit 2) has been imaged by recent profiles.

(#67) At the regional scale, the Gaspé Peninsula exhibits structures of various orientations with different kinematics. As noted previously, NE-directed thrusting predominates in southern Québec and in the Témiscouata area, whereas right-lateral strike-slip faulting predominates in the east. This geometry looks like younger orogens like the eastern Alps, which result from the indentation of a rigid crustal block into a softer geological domain.

(#68) For the Québec-New Brunswick Appalachians, the indenter may correspond to parts of the Brunswick Complex of northern New Brunswick, which is characterized by a different magnetic grain.

(#69) The regional analysis of geological and geophysical data leads us to propose an indentation model which includes three stages. The first stage is characterized by the folding and by faulting, exhibiting a significant thrust component. During the second stage, major strike-slip faults such as the Shickshock Sud fault and Grand Pabos fault accommodated most of the deformation. Finally the third stage is characterized by dextral strike-slip faulting in the eastern part of the Gaspé Peninsula (Bassin Nord-Ouest and Troisième Lac faults) and allows the eastward translation (or escape) of tectonic blocks.

Presentation #9

Middle Paleozoic Gaspé Belt (Late Ordovician to Middle Devonian) – Hydrocarbon system data

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(#2) As shown in the previous presentation, the Gaspé belt consists of sedimentary and volcanic units that range in age from the Late Ordovician to the earliest Middle Devonian. The succession is limited at its base and top by the Taconian and Acadian unconformities, respectively. Another significant unconformity (the Salinic Unconformity) is documented and separates pre-Pridolian and post-Pridolian (Upper Silurian) rock units.

(#3) On this schematic stratigraphic column of the Gaspé Belt, the sedimentary succession has been divided into shallow to deep marine carbonates (brick patterns), shallow marine – nearshore – fluvial sandstones and conglomerates (yellow) and fine-grained clastics (green). The overall Gaspé Belt succession is the result of second order relative sea level changes (see previous presentation) with shallow marine carbonates developed at the end of the first and second regressive phases. Elements pertinent to hydrocarbon systems are also illustrated. The best source rocks are Ordovician with some fair potential in Lower Devonian units. Units with reservoir potential are shown with the green stars and include both clastics and carbonates (HTD being circled). Finally, producing units (oil and gas) are shown by the blue stars.

Source rocks and thermal maturation

(#4) The presence of fair-quality potential hydrocarbon source rocks within the Silurian-Devonian succession remains to be demonstrated. These HI versus Ro or Tmax diagrams from various sectors in the Gaspé Belt indicate that some of the Lower – Middle Devonian samples have some undeniable genetic potential (oil); these are (thin) coal seams in the York River Formation in easternmost Gaspé and in the Val D'Amour and Campbellton formations in northern New Brunswick, and limy shales of the Upper Gaspé Limestones (Forillon and Shiphead formations). The same Forillon Formation has a limited potential in central Gaspé. However, higher thermal conditions in western Gaspé might mask the original potential of the Forillon in this area. The Silurian-Devonian succession in southern Gaspé has a negligible source rock potential, however, at few localities in the Upper Ordovician Garin Formation has yielded some TOC values above regional background (over 0.5%) and the coeval Upper Ordovician units in northern New Brunswick (Grog Brook Group, see later) locally have a fair source rock potential. Some higher values in southern Gaspé are found in the largely immature lacustrine – marginal marine mudstones of the Upper Devonian Escuminac Group.

(#5) Of greater interest for source rocks are the various outliers of Ordovician deep marine shales that are observed at various localities surrounding the Gaspé Belt. In northern Gaspé, the Ruisseau Isabelle Mélange is a tectonized assemblage of Lower to Upper Ordovician rock units that belongs to the Dunnage Zone, a domain that has been seismically traced for some distance under the Gaspé Belt. In that mélange, Lower to Upper Ordovician black shales have yielded TOC values between 0.1 to 3%. An excellent source rock has been recently identified in southern Gaspé. This is the Middle Ordovician Dubuc Formation (Mictaw Group) which also belongs to the Dunnage Zone. TOC values range between 0.1 and 10.7% (see next slide). The Popelogan Shales in northern New Brunswick is another Middle Ordovician black shale succession interpreted from the Dunnage Zone. A few analyses of this poorly exposed shale has revealed that it is thermally very mature (end of the dry gas zone) but still yielded TOC up to 1.8%. The Mictaw and Popelogan shales are both coeval (with the inherent uncertainty of the available biostratigraphic data) and interpreted to belong to the same major Taconian tectono-stratigraphic domain. It is unknown if they are part of a single continuous belt in the subsurface or if they occur in two different basins. This has profound implication for the prospectivity of the entire Chaleurs Bay Synclinorium. In detail, the TOC values for the Middle Ordovician black shales define two major assemblages; a first one with lower (more gas prone) TOC values (0.5 to 2%) and a second oil-prone assemblage with TOC values ranging from 8 to 10.7%. HI is up to 266 and the material is algal-derived.

(#6) A major question on the hydrocarbon potential of the Gaspé Belt has always been the source of the hydrocarbons found in seeps and in wells, with all the oil being found in Devonian hosts (Upper Gaspé Limestones and Gaspé Sandstones). M/Z 217 fragmentograms from potential source rocks extracts are shown in grey (Upper Ordovician Macasty, Ordovician Ruisseau Isabelle, Devonian coals and Devonian deep marine shaly limestones). This slide also shows fragmentograms for 2 oil samples from Gaspé wells (Galt #1 and POT#16) and one oil seep sample from Ordovician host in western Newfoundland. The fragmentograms for the Newfoundland and Gaspé oils are very similar even if samples are from different age hosts. The best match between the oils and potential source rocks seems to be with the Ordovician-aged source. However, in other samples, biodegradation and higher thermal conditions make the correlation tenuous and Devonian-aged source rocks cannot be discarded.

(#7) If we examine cross-plots of various organic components and ratios (upper part of the slide) for Middle Ordovician (Mictaw) and Upper Ordovician (Macasty) source rock extracts (blue squares), one can see that both plots are in very distinct fields (although only one analysis for the Mictaw is available). The same ratios are plotted for oils (yellow squares) in Gaspé (Galt #3 and Haldimand #1 wells – Devonian hosts). Some of these ratios might suggest a relationship between the Haldimand and the Upper Ordovician source rock (Macasty). Conversely, the Galt #3 oil seems to share some characteristics with the Middle Ordovician source rock (Mictaw). Obviously, more analyses are needed to elaborate on precise contributions of potential source rocks to known accumulations (with implications for migration pathways). The lower half of the slide presents some GC-IRMS results for Upper Ordovician (Macasty) and Devonian (Upper Gaspé Limestones and Gaspé Sandstones coal) source rocks. If the coal samples are less depleted in ^{13}C, the Ordovician and Devonian marine shales are isotopically similar and no obvious distinction can be made with the oils.

(#8) Our understanding of the thermal history of the Gaspé Belt has been recently improved with the release (post-December workshop) of regional thermal maturation map as part of a recent Ph.D. thesis at INRS. This new map integrates datasets and upgrades the information that was available in eastern Gaspé (EG: oil and gas windows), western and part of central Gaspé (WCG: mostly gas window and spatially-restricted oil window zones). The new data in southern Gaspé (Chaleurs Bay Synclinorium (CBS) and Restigouche Syncline (RS)) indicates high thermal conditions for the Chaleurs Bay synclinorium with large dry gas zones and restricted zones within the oil and condensate windows whereas the Restigouche syncline in southwestern Gaspé is mostly characterized by oil window conditions. The new information suggests that the Aroostook-Percé Anticlinorium (APA: Upper Ordovician to Lower Silurian rock units) is thermally overmature. It is worth mentioning is that the Lower Devonian Fortin Group (Fo) of the central part of the Connecticut Valley – Gaspé synclinorium is also overmature.

(#9) In eastern Gaspé, the successions of the northern limb of the Connecticut Valley – Gaspé synclinorium are amongst the thermally least mature in the Gaspé Belt with some Devonian clastic units in the heart of synclines being only at the threshold of the oil window. Two cross-sections based on field outcrops and well info (A-A') suggest that the iso-reflectance value lines are folded and thus that the maturation was largely acquired prior to Acadian folding and faulting.

(#10) In the same area, the Ro evolution with depth is highly variable. In some wells (e.g. Gaspé Nord), a significant maturation jump is observed between the pre-Gaspé Belt units and the Silurian-Devonian succession which indicates erosion prior to sedimentation of the Gaspé Belt. Conversely, in other wells (e.g. Gaspé Sud; south of the Bassin Nord-Ouest fault), the Ro increases steadily with depth with no indication of a thermal jump. However, in the latter case, some have speculated that the Ro values of the Québec Supergroup are from subsequently introduced (remobilized) bitumen. Note that the petrophysical analyses of these two wells are, amongst others, available in GSC Open File 5485.

(#11) 2D and 3D basin and thermal modelling is currently under progress in collaboration with INRS and the Institut Français du Pétrole (Ph.D. project). This slide presents the result of a preliminary 1D model for the Sunny Bank #1 well. Two potential Lower Devonian source rocks are modelled here; no attempt has been made to consider a more probable Ordovician source. Depending on the sulphur content, a lowermost Devonian source rock (fair to poor potential - Indian Point Formation) entered the oil window in late Early to early Middle Devonian, just before maximum burial. Oil to gas cracking was initiated at maximum burial of this potential source rock. Lower Devonian rocks (coal in the York River) only entered the oil window during burial if the organic matter is of type IIA and IIB; type IIC and D organic matter remained immature and no gas generation is expected.

(#12) In western Gaspé, a detailed study of Ro evolution with depth in three wells indicates a normal Ro increase with depth. Available information for the two wells in the northern part of this area suggests that the succession is still within the prospective domain (both in the condensate zone), whereas for the well in the central domain, overmature conditions are reached within the first 500 metres.

(#13) In northern New Brunswick, detailed maturation and source rock studies were carried out during the 2003-2005 TGI 2 program. Surface Ro values are concordant with the Restigouche syncline (see a few slides above) and a large domain of the Gaspé Belt in northern New Brunswick is within the oil window. This domain is encircled by an even larger zone where surface conditions indicate condensate and dry gas zones. Sterile conditions are found to the south-east (in an inlier of the Middle Ordovician Popelogan shales, see source rock discussion above) and towards the west and south-west, where entering the Aroostook-Percé anticlinorium. The two cross-sections are highly speculative as there is no seismic data available in this area and very few mining wells are available, unfortunately without thermal maturation evaluation. Finally, the HI vs Tmax diagram summarizes the available information on potential source rock in this area, the Popelogan shale excluded given their high thermal maturation and near zero residual HI. Best potential local source rocks are coals in the Lower – Middle Devonian Campbellton and Val d’Amours formations whereas some fair to poor potential has been ascribed to the Upper Ordovician Boland Brook Formation of the Grog Brook Group.

Reservoir rocks

(#14) A wide spectrum of clastic and carbonate units with reservoir potential has been documented through research and from actual hydrocarbon production (stars with reddish outline on the slide). These include nearshore to fluvial clastics, carbonate reefs and associated facies and hydrothermal dolomites. These types of potential reservoir are known all over Gaspé Peninsula and northern New Brunswick.

(#15) These potential reservoir units are also stratigraphically dispersed over the entire Silurian-Devonian time interval covered by the Gaspé Belt.

(#16) Starting with the clastic units, the Lower Silurian nearshore to platform sands of the Weir/Anse Cascon formations (southern Gaspé and northern New Brunswick) and the Val Brillant Formation (northern and western Gaspé) are distinctive units that are well imaged on seismic (see further).

(#17) These predominantly sandstone units occur stratigraphically near the end of the first major regressive event for the Gaspé Belt (R1). As a whole, the Weir/Anse Cascon are shallow subtidal to nearshore sands, locally relatively impure (abundant feldspars and lithic fragments in the Weir sandstones) with only fair granulometric sorting (better in the Anse Cascon). Average porosity of field samples ranges between 3.4% (Weir, dissolution) and 1.8% (Anse Cascon, dissolution); permeability is relatively low (0.03md). The Val Brillant Formation is a nearshore to shoreface quartz arenite with less than 5% feldspars; sorting is excellent. A few field samples yielded an average porosity of 2% and an average permeability of 0.02 md.

(#18) The Lower Silurian sandstones are characterized by locally significant dissolution of feldspars and even quartz that results in a significant secondary porosity. This dissolution of metastable alumino-silicates is not a superficial event as the pore space is locally filled by bitumen and highly fluorescent residual oil. In some well-cemented pore space under shallow burial (Th of fluid inclusion less than 85°C), some quartz cements are carrying liquid oil inclusions. This is an important element to support the potential critical importance of Ordovician hydrocarbon source rock under the Gaspé Belt.

(#19) The following and recently documented reservoir within clastic units is the Lower Devonian Gaspé Sandstones.

(#20) The reservoir unit consists of high energy, marginal marine to fluvial sandstone that locally fills channels. Large scale migrating sand bars are locally highly porous (grab samples: average of 6.3% for York River Formation; 9.4% for the coarser grained Battery Point). Similar to even slightly higher values are reported from the eastern Gaspé petrophysic well study. The Gaspé Sandstones are a common host for many of the 80+ known hydrocarbon seeps in eastern Gaspé alone.

(#21) In 2006, the successful drilling of the Haldimand #1 well was reported. A 22 m thick pay zone in the York River Formation was tested over a 15 days period with a stabilized 34 barrels of oil at 45°API. Delineation wells and new seismic are planned for 2008.

(#22) As for carbonates, the most promising reservoir targets are hydrothermal dolomites (HTD). HTD in the Lower Devonian Upper Gaspé Limestones are a sub-economic oil and gas producer near Gaspé (Galt #1 and 3 wells). HTD are found in all carbonate-dominated units of the Gaspé Belt, with the exception of the offshore lime muds of the upper Ordovician-Lower Silurian White Head Formation.

(#23) HTD are found all over Gaspé Peninsula and in northern New Brunswick and a simple examination of the regional geological map allows recognizing a clear link between major faults and occurrence of HTD.

(#24) The best locality to examine the Lower Silurian HTD is certainly at the Saint-Cléophas quarry on the southern flank of the Lac Matapédia syncline. A massive dolomitic breccia body of 3 m (high) x 6 m (wide) x 7 m (long) that belongs to the lower member of the Sayabec Formation, is nicely exposed offering a 3D view of the breccias, irregularly surrounded by massive dolostone. The brecciated beds are seen as injecting into the massive dolostone. Both the breccia and dolostone units are porous (Po average of 5.5%, up to 25% in grab samples).

(#25) The complex dolomitization – brecciation events (see further) were followed by a local to regional (?) hydrocarbon charge as seen by abundant bitumen filling in pore space in the dolostone and in the breccia.

(#26) The coeval La Vieille Formation of southern Gaspé and northern New Brunswick also offers HTD. The best exposed locality is along the shore of Chaleurs Bay between Petit Rocher and Culligan. There, pervasive dolomitization with well defined fronts away from a central feeder is nicely exposed. Also, intense brecciation resulting in outcrop scale sags is visible as well as major dissolution cavities and fractures filled with alternating high temperature saddle dolomite and calcite cements.

(#27) The petrographic study of the Lower Silurian HTD in Gaspé – New Brunswick has documented significant large-scale similarities with some local fine-scale distinctions. Details can be found in the pertinent literature cited below. The general theme indicates that initial burial with calcite and minor dolomite was rapidly and abruptly stopped by a major fracture and brecciation event that resulted in the formation of secondary porosity. High temperature and saline fluids used this plumbing system to pervasively replace the host limestone (planar and non-planar dolomites) and to precipitate non-planar saddle dolomite in the voids. Afterwards, hydrocarbons migrated in the open framework as testified by the abundant bitumen filling small (mm-sized) to large (cm-sized) voids. Post-dolomitization burial is documented by the presence of some dull-luminescent calcite crystals that are developed on top of the dolomite crystals. This burial cement is then corroded and micro-scalloped with the dissolved "cement unconformity" being overlain by a strongly zoned (under cathodoluminescence) calcite cement that is interpreted (with geochemical arguments) as a meteoric cement. This interpretation has major significance for the timing of hydrothermal dolomitization and likely hydrocarbon charge. Everywhere in the Gaspé Belt, the sub-aerial exposure and meteoric diagenesis affecting the Lower Silurian carbonates is associated with the global eustatic (and tectonically enhanced (Salinic Orogeny) in the Gaspé Belt) sea level lowstand in mid-Pridolian (Late Silurian). It follows that high temperature dolomitization of the Lower Silurian carbonates occurred after the end of carbonate ramp sedimentation (late Early Silurian) but before the sub-aerial exposure in Middle to Late Silurian. Assumed burial depth of the carbonates to be dolomitized is definitively less than 1 km.

(#28) The stable isotopes and fluid inclusions microthermometry support the above scenario, with the dolomites being of high temperature and from very saline fluids whereas the late CL-zoned (meteoric) calcite cement offers the typical "inverted-J" stable isotope distribution of values as well as low salinity, liquid-only, monophase fluid inclusions.

(#29) The nature of the dolomitizing fluid, using its $\delta^{18}O_{SMOW}$ signature as proxy, can be evaluated by plotting paired T_h and $\delta^{18}O_{PDB}$ of a single cement crystal. Lower Silurian seawater had $\delta^{18}O_{SMOW}$ that ranged between -3 to -6‰. The dolomites from the Lower Silurian rocks were derived from a non-marine fluid that had $\delta^{18}O_{SMOW}$ ratios between +8 to +10‰. Interpreted hydrothermal dolomites are commonly derived from isotopically heavy fluids, although only a very few cases from the western Canadian sedimentary basins have values as heavy as those from the Gaspe Belt. Magmatic fluids are likely involved.

(#30) The understanding of the dolomitization system is improved with the help of radiogenic strontium isotope ratios $^{87}Sr/^{86}Sr$ in the hydrothermal dolomites (new research results since the December 2007 workshop). In almost all known cases of HTD, the $^{87}Sr/^{86}Sr$ ratios of the dolomites are significantly enriched in radiogenic isotopes (^{87}Sr); this results from more or less profound interactions with a lower clastic interval (a common carrier bed for fluid) or with a "basement" rich in feldspars. The inset in the lower left corner presents the global $^{87}Sr/^{86}Sr$ curve for the Phanerozoic oceans and the Ordovician Anticosti case (blue star) as one example to illustrate the enrichment in ^{87}Sr. Results from two hydrothermally-altered Lower Silurian sections are illustrated. The Lac Matapédia section shows the higher than marine radiogenic ratios (although the enrichment is rather small) whereas the Ruisseau Isabelle section is characterized by seemingly lower than marine radiogenic values. We believe that the dolomitizing fluids had profound and major interactions with the ultramafic units of the Dunnage zone that form the basement of the Lower Silurian ramps in northern Gaspé.

(#31) The simple plotting of known Lower Silurian HTD localities on a geological map allows to recognize a first order correlation between hydrothermally altered localities and the presence of Ordovician oceanic (Dunnage zone) mafic volcanics (Elmtree Inlier) and ultramafic units (La Rédemption and Mont Albert complexes). The only exception is the coastal section of the La Vieille Formation in southern Gaspé.

(#32) Moreover, when these localities are plotted on the residual total magnetic field map, a nice correlation is visible between major magnetic positive anomalies and the location of Lower Silurian HTD and that even for the La Vieille in southern Gaspé which is adjacent to a series of magnetic positive anomalies in Chaleurs Bay.

(#33) A similar relationship can be documented between the Lower Silurian HTD and the Bouguer anomaly. The HTD are spatially associated with positive gravity anomalies that are related to the massive and dense volcanic and ultramafic units. We think that, for the Lower Silurian carbonates, a clear link can be made between a dense and magnetic "basement" (volcanic and ultramafic) and occurrence of HTD. These Mg-rich basements could have provided the Mg^{+2} needed for dolomitization and work in progress involves Mg isotopes studies in order to link the occurrence of dolomites with specific sources of Mg.

(#34) Recognition of HTD in the Upper Silurian to lowermost Devonian carbonates and reefs of the West Point Formation is very recent (2006). In central Gaspé, at the Montagne Blanche, a fault-bounded block of the microbial-reef facies of the Anse-à-la-Barbe Member (lower reef complex) is characterized by some dolomitic breccia and fractures filled by saddle dolomite and calcite cements. An in-depth study of this locality has yet to be initiated.

(#35) The lowermost (Lochkovian) pinnacle reefs of the West Point Formation preferentially developed on paleotopographic highs in the basin, some of which being the faulted margin of tectonic blocks. In northern Gaspé, at the junction between the major Shickshock Sud and Rivière Madeleine dextral strike slip faults, one of these pinnacles is characterized by significant outcrop scale dolomitization. There, a ca. 35 m large zone is intensely dolomitized with razor sharp margins with non-dolomitized units.

(#36) The dolomitization is commonly massive. However, in some areas, the dolomite is localized, filling slickenlined fractures that exhibit dextral strike-slip kinematic indicators and which are associated with the formation of small (cm-sized) “pull apart”.

(#37) Under the microscope, the altered facies consists of large crystals of replacive saddle dolomite (D2) with large void-filling saddle dolomite (D3) crystals. Both dolomites are ferroan and largely non-luminescent under cathodoluminescence. These two dolomite phases are cut by late fractures filled by strongly luminescent calcite cement.

(#38) This succession of carbonate phases is summarized in the paragenetic diagram. Although, timing relationships remain relative, the dolomitization is apparently linked with the strike slip movement of Acadian faults, and is thus most likely Middle Devonian in age.

(#39) The stable isotope ratios of the pervasive and pore-filling dolomites as well as that of the late calcite cements are characterized by strongly negative $\delta^{18}O_{PDB}$ ratios (average between -16 and -20‰) but also by some significant depletion in ^{13}C for these carbonates ($\delta^{13}C_{PDB}$ between -1 to -8‰).

(#40) Critical information for the understanding of the dolomitization is deduced from the fluid inclusion microthermometry of these carbonate phases (post-December 2007 workshop). The pervasive dolomites are characterized by fluid inclusions with very high entrapment temperature (average of 350°) from a relatively saline fluid (13.4 wt% $NaCl_{equiv.}$). The following pore-filling dolomite and fracture-filling calcite cements are characterized by a significant decrease in homogenization temperatures (164 and 115°C) and a more subtle one for salinity.

(#41) The paired $\delta^{18}O_{PDB}$ and Th values for an individual phase led to the recognition of non-marine fluids as responsible for the dolomitization of the West Point pinnacle reefs. The very high Th as well as the ^{18}O-enriched signature of the dolomitizing fluid suggests the involvement of magmatic waters.

(#42) The $^{87}Sr/^{86}Sr$ ratios from the replacive dolomites are more radiogenic than those of the Lower – Middle Devonian seawater, again suggesting some significant interactions between the dolomitizing fluid with some underlying clastic units before altering the West Point pinnacle reef.

(#43) In the Gaspé Belt, the model of emplacement of the Lower Devonian pinnacle reefs at the faulted margin of tilted tectonic blocks has major implications for the potential of hydrothermal dolomitization of these units. The main movement of these block-bounding faults is dextral strike-slip during the late Acadian Orogeny, although these faults have been shown to be initially extensional faults genetically associated with the advancing Acadian foreland basin (late Early Silurian to Devonian). These fault zones, and most importantly their associated subsidiary splays, are likely preferential conduits for high temperature fluids and possibly hydrocarbons.

(#44) The tectono-sedimentary model based on multiple field evidence has recently being substantiates by modern reprocessing of vintage seismic data that resulted in the interpretation of reef masses at the margin of faulted block.

(#45) The Lower Devonian Upper Gaspé Limestones is the uppermost limestone interval in the Acadian Gaspé Belt. In northern Gaspé, the group was deposited during the early highstand phase of the 2nd order sequence that was initiated during the earliest Devonian. The Upper Gaspé Limestones consists of three formations (from the base; Forillon, Shiphead and Indian Cove) which represent 3rd order shallowing-upward sequences with a deep marine (outer shelf limestone; below storm wave base) base capped by mid to inner shelf (above fair-weather wave base) facies. Each of these sequences is 100 – 150 metre-thick. To the south and southwest, facies homogenize and a rather monotonous, below storm wave base impure fine-grained limestone succession prevails, and is designated as the Cap-Bon-Ami (=Forillon + Shiphead) and Grande Grève (= Indian Cove) formations.

(#46) The shallowest preserved facies on Gaspé Peninsula is found in the northeastern most tip of the peninsula and consists of a mid-ramp bioclastic limestone. The facies architecture and the thickness of the unit are controlled by the extensional faults in eastern Gaspé and deep marine (toe-of-slope) facies are present in central Gaspé where the unit becomes interlayered with the Fortin Group.

(#47) Within that predominantly fine-grained and muddy facies, abundant evidence for fault-controlled, high-energy fluid pulses are recognized in the Percé area. The faults are abundant and served as conduits for alteration. Brecciated dolomitic limestone is invariably associated with some of the major and secondary fractures. The "boxwork" texture is a good indicator of high energy fluid pulses along fault planes.

(#48) In eastern Gaspé, in the vicinity of the Troisième Lac fault (Acadian dextral strike-slip fault), the small oil and gas Galt fields are hosted by hydrothermally altered carbonate breccia with saddle dolomite cement. The breccia illustrated on the slide is strikingly similar to dolomite breccia in the Middle Ordovician Black River in New York, a unit that hosts some of the largest and most prolific recent onshore US gas discoveries. The stable isotope ratios for burial calcite cements and interpreted hydrothermal dolomites are illustrated with the saddle dolomite being characterized by very negative $\delta^{18}O_{PDB}$ values (-16 to -19‰) whereas the negative $\delta^{13}C_{PDB}$ ratios are indicative of biogenic HCO_3^- in the diagenetic fluid. No fluid inclusion data or radiogenic strontium ratios are currently available for the Upper Gaspé Limestones.

(#49) A petrophysical analysis of all digital log information for wells in the Lower Paleozoic (Cambrian to Devonian) in eastern Québec (and including the Gaspé Belt) has recently been released. It is however important to note that if the information for the clastics is an accurate up-dated evaluation of their reservoir potential, the carbonate data are plagued by the fact that the high profile HTD potential reservoirs have not been encountered in those Gaspé wells.

(#50) In Paleozoic rocks, primary pore space is rarely preserved and a significant part of the porosity in demonstrated and producing reservoirs is from the combination of various types (and origins) of secondary porosity. Fractures are an important factor not only for the overall volume of pore space but more importantly for generating efficient porosity and permeability. Fractures are abundant in the Gaspé Belt and their orientations and kinematics are highly variable.

Traps

(#51) If fractures are important for efficient porosity and permeability, and as the preferred migration pathways for circulation of fluids and eventually hydrocarbons, they are also involved in a large number of structural traps in the Gaspé Belt, for example, this faulted anticline crest in eastern Gaspé.

(#52) The faulted anticline is a common exploration target in eastern Gaspé and the Lower Devonian Galt field is hosted in such a structure with a series of stacked reservoirs from near surface heavy oil in Lower Devonian sandstones to light oil and eventually dry gas in deeper intervals.

(#53) These structural targets are also observed in deeper stratigraphic intervals, as on this profile in western Gaspé where the Lower Silurian seismo-stratigraphic succession is involved in a broad anticline. This anticline is interpreted as bounded by opposite dipping fault planes forming a positive flower structure. In that structure, a "flat spot" has been identified although the nature of this feature is currently unknown (true two fluids contact or diagenetic front).

(#54) Further to the west, near the Témiscouata region, anticlines become asymmetric with faulted forelimbs that are seemingly associated with fairly steep reverse faults.

(#55) In conclusion, the Gaspé Belt contains few *in situ* potential source rocks, which have a marginal potential. However, outliers of Middle and Upper Ordovician black shales with high TOC and HI are found to the north and south of the Gaspé Belt; GC-MS and GC-IRMS analysis of source rock extracts and oils are supporting the critical input of these Ordovician rocks. Thermal modelling of these old source rocks has yet to be done. Thermal maturation data are now available over most of the Gaspé Belt; potential for oil and gas preservation is preserved in eastern Gaspé whereas, in western Gaspé, higher thermal conditions are more indicative of gas potential. Finally, the Chaleurs Bay synclinorium in southern Gaspé is more prone to gas preservation although the western extension of the belt, in the Restigouche syncline and in northern New Brunswick, is characterized by a large domain with potential for oil preservation. Demonstrated reservoirs are found in the hydrothermal dolomite breccia of the Lower Devonian Upper Gaspé Limestone as well as in the Lower Devonian Gaspé Sandstones. In both cases, traps are, in part, structurally-controlled. Other potential reservoirs consist of Lower Silurian nearshore sands as well as significant Lower Silurian, Upper Silurian and lowermost Devonian HTD, all of which offer evidence for hydrocarbon migration / charge.

Presentation #10: no text provided

The Maritimes Basin – mute witness to continental collision and Carboniferous to Permian polar glaciation

Peter Giles; GSC-A

Presentation #11

Geological Setting and Petroleum Systems of the Carboniferous Magdalen Basin, Gulf of St Lawrence, Eastern Canada

J.R. Dietrich; GSC-C

The Carboniferous Magdalen Basin underlies the southern Gulf of St. Lawrence and adjacent onshore areas of Prince Edward Island, southwest Newfoundland, northern Nova Scotia, southeast New Brunswick, and eastern Québec (Gaspe Peninsula) (Figure 2). The basin encompasses an area of about 200,000 km^2, with about 60% of the basin located offshore. The Magdalen Basin is part of the broader Maritimes Basin that includes the Sydney and St. Anthony basins. The Maritimes Basin is a late Paleozoic (post-Acadian orogeny) successor basin, overlying a collage of lower Paleozoic continental margin basins and Appalachian orogenic tectonic zones. The Carboniferous basins developed in intracontinental strike-slip and foreland basin tectonic settings, prior to and during the Alleghenian Orogeny.

Stratigraphy

The Magdalen Basin contains up to 12 kilometres of Carboniferous-Early Permian continental and shallow marine strata (Figure 3), deposited in three main tectono-stratigraphic packages (Figure 3): an early Carboniferous (Tournaisian) succession of alluvial and lacustrine clastics and volcanic rocks in deep, fault-bounded sub-basins (Horton Group); a widespread early Carboniferous (Viséan) succession of marine carbonates and evaporites and non-marine clastics (Windsor Group); and a thick middle Carboniferous to early Permian succession of alluvial, fluvial and estuarine clastics (Mabou, Cumberland, and Pictou groups). Coal-bearing sections ("coal measures") are abundant in the Namurian-Westphalian Cumberland and Pictou groups (Figure 2). Cumberland Group strata occur in fault sub-basins in southern parts of the Magdalen Basin. The more widespread Mabou and Pictou groups have a combined thickness of up to 9000 m in the offshore central part of the basin (Figure 4). Basin structures are associated with rift faulting, strike-slip related inversion tectonics (multiple phases), and salt diapirism (Figures 5 to 7). Significant local variations in basin stratigraphy are associated with syndepositional faulting and salt diapirism.

Petroleum Systems

The Magdalen Basin contains the key petroleum-system elements for a substantial petroleum resource potential (Figure 8), including widespread reservoir rocks (Figures 9 to 11), thick shale and salt sections (seals), large volumes of thermally mature source rocks (Type I organic matter in Horton Group lacustrine shales, and Type II-III organic matter in Upper Carboniferous coal measures; Figures 12 to 17), and abundant and diverse trap types (Figure 18). The gas-prone Upper Carboniferous coal measures are the most widespread and thickest source rocks in the basin.

The primary exploration plays in the basin involve Horton Group sandstones or conglomerates in combined structural-stratigraphic traps (Figures 18 and 19), Windsor Group carbonate reefs (Figure 20), and Upper Carboniferous fluviatile sandstones in fault block traps (Figure 21) and salt structure traps (salt withdrawal anticlines, salt pillows, salt-flank onlap and sub-salt traps (Figures 22 to 25). The sub-salt play includes potential Horton Group reservoir strata (Figure 26). The Upper Carboniferous salt-structure play contains the largest number of known prospects in the basin (Figures 27 and 28).

Exploration Risks

The main exploration risks in the Magdalen Basin are associated with reservoir quality and trap preservation (Figure 8). Carboniferous sandstones in the basin have generally low porosity and permeability in the depth range most commonly explored for oil or gas traps (1000-4000m) (Figure 10). However, good quality reservoirs (porosity of 10% or more) are present in all stratigraphic units over a wide range of basin depths. The best quality sandstone reservoirs occur in the Upper Carboniferous Pictou Group in the northern Magdalen Basin (Figures 10 and 11). Detailed reviews of porosity and permeability trends in Carboniferous sandstones in the basin have been presented by Bibby and Shimeld (2000), Chi and others (2003), and Hu and Dietrich (2008).

The trap preservation risk is related to the timing of hydrocarbon generation and late-stage basin exhumation and erosion (Figure 17). The peak period of hydrocarbon generation for source rocks in many parts of the basin occurred in the late Carboniferous to early Permian, prior to (Mesozoic) uplift and erosion of upper parts of the basin fill. Long-term preservation or sealing of early-charged hydrocarbon traps may be problematic. Nonetheless, the known presence of several hydrocarbon accumulations in the basin attests to the local effectiveness of trap sealing.

Known or Indicated Hydrocarbon Resources

Two onshore oil and gas fields have been discovered and developed in the Moncton Subbasin, New Brunswick (Stoney Creek and McCully; Figures 29 to 31). Other onshore gas discoveries (Green Gables in Prince Edward Island and West Stoney in New Brunswick; Figure 30) continue to be evaluated. The offshore East Point gas field (Figure 32) was discovered in 1974, but development of the field was deemed uneconomic after a step-out well was unsuccessful.

Several onshore wells have recovered natural gas in drill-stem tests, albeit at low reported flow rates (Figure 29). Numerous other exploration wells have encountered mud-log or wireline-log indications of hydrocarbons (Figure 33 and 34). Possible seismic hydrocarbon indicators (reflection amplitude anomalies, flat spots) are apparent in many seismic profiles in the basin (e.g. Figure 35).

Petroleum Resource Potential

Based on the identified petroleum-system elements (and risks) and known or indicated hydrocarbon resources, the Magdalen Basin is considered to have low-to-moderate oil potential and high natural gas potential (Figure 36). Further exploration in the basin will likely result in more gas discoveries, with the potential for several large (Tcf +) gas fields. Although not evaluated in this review, there is also significant potential for unconventional hydrocarbon resources in the basin, including coal bed methane, tight gas, shale gas, and basin-centre gas.

Presentation #12

The Gulf of St. Lawrence: significant potential at an early stage of evaluation

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(#2) The aim of this presentation is to briefly review the available geoscience framework for the offshore segments of the Lower and Middle Paleozoic domains present in the St. Lawrence estuary and gulf and to present data to support their hydrocarbon prospectivity. This presentation is mainly based on recent data collected by the GSC. In several cases, the interpretation of these recent datasets is only preliminary and more work or modelling will be done in the future.

Lower Paleozoic geological framework – the status of knowledge

(#3) This map illustrates the hydrocarbon-targeted industrial marine seismic lines acquired over the last 40 years. Over 40 000 linear km of seismic data was acquired mostly in the 1970-1980 period using various airgun systems. Looking at this map, we can have the impression that a lot of data are available for both the Anticosti and Maritimes basins.

(#4) However, this is partly true if we only consider the quantity of data, but this is clearly wrong if we consider their quality. In fact, most seismic lines are of poor to very poor quality due to 1) an inappropriate acquisition system, 2) the strong reflection of the sea bottom and 3) the related problem of multiples.

(#5) Another source of information is the high-resolution seismic data acquired by the Geological Survey of Canada with a 40 cubic inches airgun system (1980's data) or more recently (2003-2004; the thin lines in the dashed outline area) with a sparker source. These datasets image the Quaternary succession and the top of Paleozoic rocks.

(#6) Despite their low penetration, these high-resolution seismic datasets (here an airgun profile) are useful to map the extension of the Platform domain which is characterized either by a homoclinal geometry or by broad open folds such as in this seismic and potential field analogue.

(#7) Although most of the older industry seismic is of low quality, detailed reprocessing of the better lines and integration with the lower penetration but higher quality GSC seismic has allowed us to present a new offshore geological interpretation which locate 1) the Appalachian structural front, 2) the Magdalen basin margin, 3) an offshore fold belt between the Humber Zone and the Anticosti platform and 4) the interpreted extension of Lower Devonian foreland strata that unconformably overstep the Humber and Anticosti platform.

(#8) This schematic cross-section with a strong vertical exaggeration illustrates the geometry of the Platform domain between Anticosti Island and the Gaspé Peninsula. The sedimentary succession consists of Ordovician to Lower Silurian carbonate rocks outcropping on Anticosti Island overlain by a 2.5 to 3 km thick package that is folded near the Gaspé Peninsula. The post-Lower Silurian offshore succession is virtually unknown and the occurrence of Devonian rocks is still hypothetical. Moreover, a transition from near-shore to shallow subtidal carbonates on Anticosti Island to deeper water rocks in the estuary / gulf is probable but not documented. The lower section illustrates (at one to one scale) that the thickness of the offshore succession is grossly similar to the thickness of the eroded sedimentary pile on Anticosti, suggesting a late tilting of the platform domain, in agreement with maturation data. Finally, the schematic cross-section also illustrates that the Ordovician structural front that corresponds to the boundary between the platform domain and the Humber zone is probably located offshore and is overlain, either unconformably or structurally, by Middle Paleozoic rocks.

(#9) This conclusion is also supported by forward modelling of gravity data. On the Bouguer anomaly map, a prominent positive anomaly is located both onshore and offshore. We interpret this anomaly to relate to late Proterozoic to early Paleozoic rift volcanics of the Humber zone. If true, Appalachian-related units extend up to the offshore boundary of the gravity anomaly or even northward. Three possibilities exist for the nature of the Platform-Appalachians boundary. It could correspond to a N-directed thrust that overrides Lower Silurian rocks, but if so, it cannot be related to the Ordovician Taconian orogeny. The contact could also correspond to a S-directed thrust, also post-Early Silurian in age or to an unconformity that could be Taconian-related.

(#10) Considering the poor quality of seismic data, the potential field data may help to constrain the geometry of the offshore part of the Paleozoic basins. Despite the fact that the aeromagnetic and gravity coverage is old and imperfect, two studies, one in the northern and one in the southern segments of the Gulf of St. Lawrence, show that these datasets are still useful.

(#11) First, in the northern part of the Gulf, in an area limited by the north shore (Grenvillian rocks), the eastern tip of Anticosti (Platform rocks) and the western coast of Newfoundland (Humber and platform domains), the integrated analysis allowed to locate NE-SW oriented extensional faults rooted in the Grenvillian basement as well as other major faults at high angle with these. The same data set served to identify possible NE-SW, S-dipping (?) thrust planes.

(#12) The second example is from the southern part of the Gulf of St. Lawrence, between Cap-Breton Island and the eastern tip of Prince-Edouard Island.

(#13) In this recently published study, the modelling of both gravity and magnetic data suggests that the East Point Magnetic anomaly is related to three Devonian plutons which are possibly located over the boundary of several Paleozoic terranes and interpreted to stitch these domains. It is noteworthy, that the East Point HB-49 discovery well (5 MMcf/d) is right over that potential field anomaly.

(#14) Potential field data and especially gravity data can be also used to map terrane boundaries below the thick Carboniferous Magdalen basin. This theoretical model has been built to represent an area of 1000 by 1000 km that is characterized by a sedimentary cover varying in thickness from 6 to 15 km. This sedimentary cover overlies two terranes with slightly different density. The corresponding hypothetical Bouguer anomaly map indicates that the basement boundary is imaged even in the thickest part of the basin.

(#15) We have started to analyse the deep structural trends in the Gulf of St. Lawrence by computing the maxima of the horizontal derivative of the Bouguer anomaly for different values of upward continuation. These maxima or worms are located above density contrast boundaries at different depths. We can recognize the Gaspé Peninsula to the left and Newfoundland to the right. In between, some clear gravity lineaments are imaged and their interpretation is in progress.

(#16) The understandings of the deep structure of the Gulf of St. Lawrence will also beneficiate from the recent acquisition of teleseismic data, with ten new seismograms being deployed around the gulf.

(#17) In this kind of study, natural earthquakes are used as seismic source and recorded at several locations. Powerful distant earthquakes such as this 2006 California event recorded at one of our station can be used as well as more local but less energetic ones; eastern Canada being an active seismic zone, a large number of seismic events have been recorded. S and P waves travel at various speeds depending on the lithology and variations of these arrival times are used to map various discontinuities such as the Moho or the contact between different sedimentary basins.

(#18) Preliminary results from several recorded events at several locations allow recognizing velocity contrast boundaries that corresponding to the Moho or to other crustal features. Significant variations in the depth of the Moho have been recognized for the first time and will have major implications on the origin of the various sedimentary basins as well as having repercussion on thermal modelling. Moreover, this information will provide the general boundary conditions for the potential field forward modelling exercise.

The St. Lawrence Estuary – Documenting a hydrocarbon system

(#19) In the second part of this presentation we will focus on shallow features recently documented in the St. Lawrence estuary on the basis of 3000 km of high-resolution seismic data acquired in 2003-2004 (sparker source), this initial work served as a cornerstone for high-resolution bathymetric survey and backscatter coverage with acquisition of very high-resolution seismic (see later slides)

(#20) A 160 km-long longitudinal section in the central segment of the St. Lawrence estuary outline the topography of the basement.

(#21) On this line, the thickness of Quaternary deposits varies from less than 20 m at the northeastern end to more than 450 m at the southwestern end. Seven seismic units have been distinguished in the Quaternary succession and 3D model showing the architecture of quaternary sediments are now available. The contact between the Quaternary and pre-Quaternary basement is easily picked on this line as well as on all the other ones. The seismic data image some superficial features in the bedrock that have been used to distinguish and map boundaries between the Grenvillian basement, the very slightly folded and faulted Lower Paleozoic St. Lawrence Platform and the faulted and folded Lower Paleozoic Humber zone of the Appalachians.

(#22) If seismic provides a subsurface 2D image, complementary information is provided by multibeam bathymetry data which generate a detailed image of the seafloor. This slide illustrates the multibeam data presently available. The coverage will be increased in the coming years. The warm colours are indicative of shallow waters whereas the cooler ones indicate deeper conditions. The resolution of the multibeam bathymetry is around a metre.

(#23) The integrated analysis of high-resolution seismic and multibeam datasets resulted in the documentation of various gas escape features in the Quaternary pile. Among the spectacular features is the mapping of pockmarks, which correspond to crater-like depression on the seafloor. Presently more than 1900 pockmarks have been documented in the St. Lawrence estuary.

(#24) Amongst the numerous evidence for the presence of gas in the Quaternary pile is the common seismic blanking and the enhancement of some reflectors visible on seismic lines, both indicated by the white arrows

(#25) The spectral decomposition of the seismic data confirms that the seismic enhancement of reflectors is related to the presence of gas. The analysis of seismic data in the frequency domain indicates that the reflector enhancement (e.g., 20 Hz) disappears at higher frequency (e.g., 60 Hz), which is typical of gas.

(#26) This slide illustrates the seismic signature below gas seepages or pockmarks. On this profile, as well as others located over the St. Lawrence platform domain, a well-imaged gas chimney (indicated by the arrows) is rooted in the Lower Paleozoic rocks. Seismic blanking is obvious at the top of bedrock substratum (arrows). Reflector pull-downs are visible at many places along the margin of the chimney. Arrows in the bedrock indicate various reflectors in the St. Lawrence platform domain which define synclinal and anticlinal structures.

(#27) In some case, as in this example, gas related features (arrows) are restricted in the lower part of the Quaternary succession and do not reach the surface. Arrows point to well define bedrock markers.

(#28) On multibeam images, pockmarks may form individual features ranging from 100 to 700 metres in diameter and have an average depth of 5 metres

(#29) Pockmarks may also form linear alignments that may extend for tens of kilometres; these linear trends are made up of single structures but also by coalescing small and large-scale individual features.

(#30) In most cases these alignments of pockmarks are found in the relatively flat St. Lawrence deep marine channel far from biogenic input coming from the major rivers flowing on the north shore. Some pockmarks are found in areas over the Grenvillian basement near the discharge of these major southerly flowing rivers; these pockmarks are NOT rooted in the basement and the gas forming the pockmark is most likely of biogenic origin.

(#31) This slide illustrates another one of these pockmarks trains. In this case, a regular grid of high resolution seismic data with 5 km spacing allows documenting the spatial relationship with the Lower Paleozoic bedrock.

(#32) For this specific case and because of the quality of the available seismic, the alignment of pockmarks is parallel to a bedrock ridge which is probably associated with the presence of a more competent sedimentary unit within the St. Lawrence Platform or with a structure within that platform. Seismic chimneys are rooted in that “ridge” from which thermogenic gas is escaping from potential reservoir(s) in the St. Lawrence Platform.

(#33) A significant number of the gas seepage structures documented in the St. Lawrence estuary are recent features. Such a conclusion is substantiated by the fact that high Quaternary sedimentation rate, up to 7 cm per year, would rapidly attenuate these bathymetric features. Despite these high sedimentation rates, backscatter data shows highly indurate sea floor in some pockmarks and sidescan sonar data image active venting.

(#34) Sampling of Quaternary sediments in and around the pockmarks surprisingly recovered solid crusts, which resulted in some damage of the sampling equipment.

(#35) Indurated carbonate crusts have been found irregularly scattered within the dominant unconsolidated mud and silt succession. These samples are massive and consist of a mixture of carbonate cement crusts (yellow and white carbonates) with mollusc shell more or less well preserved and micrite- to silt-sized darkish amorphous carbonates. Quartz and clays are embedded in the carbonate dominated concretions.

(#36) Since the December 2007 workshop, petrographic and geochemical data were acquired and support the hypothesis put forward at that time that these cement crusts and carbonate concretions are the product of bacterial chemosynthesis based on cold methane venting. The most spectacular petrographic result is the recognition of carbonate fibres/needles forming individual fans that coalesce to form isopachous cement crusts. Aragonite, a common tropical shallow marine cement for high energy reef margin, is the only common carbonate to form needles or fibres and its presence at such depth and in cool, largely stagnant waters (4°C) cannot be explained without biotic control. The aragonite fibres are commonly over small micrite ovoids that are interpreted to be calcitized bacterial remains. Besides these cements, the concretions are made up of aragonite molluscs shell material which is commonly encrusted by the micrite ovoids; nowhere do the aragonite cement crust directly overlie the shell material. Finally, small micrite peloids are dispersed in the material and are commonly forming subtle concentric layers likely the result of sediment burrowing by locally abundant polychaetes worms. Pyrite was not observed in the two concretions that were studied.

(#37) The biotic control on the precipitation of the aragonite cement is unequivocally supported by the oxygen and carbon stable isotope ratios of the carbonates. Aragonite crusts yielded $\delta^{18}O_{PDB}$ ratios of +2.6 and +3.0‰ and $\delta^{13}C_{PDB}$ ratios of −32.7 and −33.5‰. The mollusc aragonitic shell yielded $\delta^{18}O_{PDB}$ ratios of +3.3 to +3.6‰ and $\delta^{13}C_{PDB}$ ratios of −9.9 and −29.1‰. Finally, the peloidal micrite yielded $\delta^{18}O_{PDB}$ ratios of +2.9 and +3.0‰ and $\delta^{13}C_{PDB}$ ratios of −26.3 and −27.0‰. The +3‰ average $\delta^{18}O_{PDB}$ ratios for cements and molluscs is in agreement with precipitation in isotopic equilibrium with cool seawater. However, the strongly negative $\delta^{13}C_{PDB}$ ratios clearly indicate that normal marine carbon (±0‰) was not used in the cement precipitation process or in the shell formation. Bacterial oxidation of methane (or chemosynthesis) is responsible for the introduction of isotopically strongly negative HCO_3^- in the pore fluid to be incorporated in the precipitating aragonite, the precipitation of which is favoured under the high alkalinity of that diagenetic system. The range of $\delta^{13}C_{PDB}$ ratios of the carbonates is more consistent with a thermogenic methane source; significantly more depleted values would be expected if methane was of biogenic origin.

(#38) In our opinion, all the elements associated with the seismic chimneys – pockmarks are supportive arguments to the hydrocarbon prospectivity of the onshore and offshore St. Lawrence Platform domain. Gas seepages root in the Lower Paleozoic St. Lawrence Platform and often exhibit a clear linear distribution mimicking bedrock ridge / structures clearly suggesting that the gas is thermogenic. This interpretation is supported by the methane chemosynthesis around pockmarks. Recent video recording of the sampled and other pockmarks, have produced the first footage of microbial mats on the St. Lawrence seafloor as well as spectacular active escape of methane (?) bubbles from the seafloor in areas colonized by the microbial mats. It is noteworthy that at the regional scale, the distribution of pockmarks is highly variable. If close to 2000 of these structures are present in the upstream sector of the St. Lawrence Estuary, they are virtually absent downstream between Anticosti and northern Gaspé Peninsula. So if some Lower Paleozoic reservoirs are likely breached upstream, an efficient seal seem to be present downstream the St. Lawrence Estuary. Future multibeam bathymetry data in the area between Gaspé and Anticosti as well as very high resolution seismic data might test this interpretation.

(#39) In the southern part of the Gulf of St. Lawrence, a 1D thermal modelling exercise using Petromod was attempted for some of the wells.

(#40) The Beaton Point F70 well is shown here as an example. The modelling result suggests a significant thermal anomaly at roughly 150 Ma, coincident with the opening of the Atlantic, which has resulted in a significant upward deflection of thermal isograds. This interpretation which has been corroborated by other wells has significant implications for hydrocarbon generation in relationship with structural traps development.

(#41) A detailed petrophysical study of six wells in the southern part of the Gulf of St. Lawrence has been recently completed and will be released as GSC Open File 5899, although the results of this study are already incorporated in the on-going resource evaluation exercise.

(#42) An integrated onshore and offshore geoscience database for the Magdalen islands will be released shortly. This database will incorporate maps and punctual geological information for this area.

(#43) Finally, all the information presented in this Open File will serve as basic geoscience and hydrocarbon system data that will be integrated and analysed in order to provide the first quantitative and qualitative (when information is not sufficient) hydrocarbon resource evaluation for the major plays in the Paleozoic basins of eastern Canada.

Présentation #13

Current Exploration Activities and Hydrocarbon Plays in Québec

Robert Thériault and Jean-Yves Laliberté

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(#2 to 7) Oil and gas companies have been exploring for hydrocarbons in Québec for nearly 150 years, with limited success. This explains why the province remains a relatively unexplored frontier region, as demonstrated by its meagre 800 oil and gas wells done since 1860, compared to the 20,000 - 30,000 wells done yearly in the Western Canada Sedimentary Basin. While very few hydrocarbon producing fields have been found in Québec, this may be about to change and we could be on the verge of very significant discoveries, considering that the land presently under permit reached 7.3 million hectares in 2007, an all time high. In fact, this number is now well above 8 million hectares, and over 90% of the known exploration zones within the sedimentary basins of Québec have already been claimed. This has been sparked by the recent announcements made by Forest Oil and Talisman Energy concerning preliminary results of their Utica / Lorraine shale gas play in the St. Lawrence Lowlands, which created a boom in exploration.

The geological context of Québec's sedimentary basins is the same as the one which characterizes the ancient continental margin of eastern North America, where very prolific hydrocarbon fields are being found and exploited. In this perspective, an overview of the main hydrocarbon plays presently being investigated in Québec are presented, with analogies being made to known oil and gas fields found elsewhere in eastern North America.

The prospective areas for hydrocarbon exploration in Québec are located within Palaeozoic sedimentary basins of the St. Lawrence Platform (including the St. Lawrence Lowlands and Anticosti basins), the Gaspé Belt and the Magdalen Basin. Hydrocarbons are also found within Quaternary sediments along the axis of the St. Lawrence River and Estuary. In this framework, the main hydrocarbon plays are the following:

(# 8 to 89**) 1- St. Lawrence Platform (Cambro-Ordovician)**

a) karstic dolomites of the Beekmantown (St. Lawrence Lowlands) and Romaine (Anticosti) groups

b) hydrothermal dolomites (HTD) associated with the Trenton / Black River (St. Lawrence Lowlands) and Mingan groups (Anticosti)

c) shales and siltstones of the Utica and Lorraine groups (St. Lawrence Lowlands)

d) thrusted tectonic slices of the St. Lawrence platform rocks (St. Lawrence Lowlands)

(#90 to 111) **2- Gaspé Belt (Siluro-Devonian)**

a) Silurian reefs of the West Point Formation

b) hydrothermal dolomites (HTD) associated with the La Vieille / Sayabec, West Point and Indian Cove / Forillon formations

c) Devonian sandstones of the Grès de Gaspé Group (York River and Battery Point formations)

(#112 – 119) **3- Magdalen Basin (Carboniferous)**

a) sandstones of the Pictou and Cumberland groups associated with salt diapirs

(# 120 – 136) **4- Quaternary deposits**

a) unconsolidated sands in the areas of Lac St. Pierre (Pointe-du-Lac) and the St. Lawrence Estuary

Particular attention is placed on the two fairly recent exploration concepts which are now in vogue in Québec, which are the hydrothermal dolomite and shale gas plays. Having as of recently an unsuspected potential, these new play types have revealed themselves as being highly promising, based on recent major discoveries of natural gas within hydrothermal dolomite reservoirs in the southern New York State area, and unconventional shale gas in the Barnett field in Texas.

Présentation #14

Geology and hydrocarbon potential of the Paleozoic Basins of Eastern Canada: Maritimes Basin exploration, and production in New Brunswick

Clint St. Peter and Steve Hinds (New Brunswick Department of Natural Resources)

(#3) At present, the known hydrocarbon resources in New Brunswick occur in the Carboniferous Maritimes Basin (in yellow on slide 3). Oil and gas exploration in New Brunswick has been mostly confined to the Upper Paleozoic (“Carboniferous”) Maritimes Basin. The basin has a surface area of about 60,000 square miles and underlies eastern New Brunswick, northern Nova Scotia, Prince Edward Island, the Gulf of St. Lawrence and parts of southwestern Newfoundland. The Maritimes Basin, in a simplified sense, comprises an early rift phase and a later sag phase. The early rift phase includes a series of Mississippian sub-basins that are filled by thick sequences of coarse terrestrial beds and lesser marine strata. The two producing fields are the older Stoney Creek Oil and Gas Field and the recently discovered McCully Gas Field. Both fields have Carboniferous source and reservoir rocks. There is active exploration in the Ordovician to Silurian stratigraphy (in blue on slide 3) of northern New Brunswick. The northern exploration could reveal a southern extension of the hydrocarbon bearing rocks of the Galt Field in the Gaspe Peninsula.

(#4) The Carboniferous sub-basins of southern New Brunswick formed as a result of intermittent extensional tectonics during the late Devonian to early Carboniferous. The areas in red (Slide 4) are exposed crystalline basement uplifts or "highs" and the green areas represent the surface and subsurface distribution of deep Carboniferous sub-basins. The areas in yellow (Slide 4) are younger uneconomic Carboniferous rocks that form a thin depositional sheet above the basement. During the Late Devonian Acadian Orogeny, strike-slip or transpressional tectonics caused crustal subsidence of southern New Brunswick and surrounding areas which resulted with the initiation of Carboniferous sediment deposition within the present day Maritimes basin. Within southern New Brunswick and northern Nova Scotia, the lower Carboniferous portion of the Maritimes basin is separated into the Moncton, Sackville, and Cumberland sub-basins (in green). Each sub-basin is bounded by faults which are theorized to be periodically re-activated throughout the Carboniferous by mostly a combination of compressional and transpressional tectonics. In southern New Brunswick, the Moncton Sub-basin is bounded by three near surface to surface basement highlands termed the Caledonia Uplift to the south, the Westmoreland Uplift to the east, and the New Brunswick Platform to the north. The Moncton Sub-basin is host to the McCully and Stoney Creek fields. At present, hydrocarbon exploration is being conducted on the unproven Sackville and western Cocagne sub-basins.

(#5) The Carboniferous stratigraphy of southern New Brunswick is represented by six major depositional sequences often separated by unconformities (Slide 5). These unconformities represent periods of compressional and extensional tectonism that resulted in erosion of the older sequences and deposition of the younger sequences. The overall depositional environment of the Carboniferous is intercontinental lacustrine in a desert-like climate. The Windsor Group limestones and evaporites represent the only incursion of marine conditions in southern New Brunswick. In the Moncton Sub-basin, the Horton Group comprises a lower red conglomeratic unit (Memramcook and Mcquade Brook formations), a middle grey shale and sandstone unit (Albert Formation) and an upper red clastic unit (Bloomfield Formation). Its thickness ranges from approximately 250 m to more than 1 km in the central portions of the Moncton Sub-basin. The Horton strata rest unconformably on the basement complex and are unconformably overlain by the Sussex Group. The age of the Horton Group in New Brunswick ranges from Late Devonian (Famennian) to Mississippian (Tournaisian).

(#5) The Albert Formation is subdivided into three members: a lower conglomerate and sandstone unit (Dawson Settlement Member), a middle organic-rich mudstone and shale unit (Frederick Brook Member) and an upper sandstone and shale unit (Hiram Brook Member). Type sections for these three members are located in, and south of, the Stoney Creek Field. The Albert Formation ranges in thickness from 100 m to 150 m at the sub-basin margin to more than 1 km at the McCully Field. The lower facies of the Dawson Settlement Member is dominantly polymictic conglomerate and interbedded sandstone, whereas the upper facies consists of fine to coarse sandstone and lesser siltstone and mudstone. Exposed sections can consist of medium to coarse, poorly sorted sandstone containing about 40% quartz. Bitumen is present in pores of some of these sand beds, and calcite was observed locally as a cementing agent.

(#5) The Frederick Brook Member is at least 800 m thick throughout most of the Moncton sub-basin as determined from seismic and borehole intersections. The Frederick Brook Member has the largest quantity of organic matter and is interpreted to be the primary source rock for the hydrocarbons found in the McCully and Stoney Creek fields. This member could also be the host for significantly large shale gas reservoirs. Dark brown to grayish brown, kerogen-rich, dolomitic, laminated mudstone and shale are characteristic of the unit. Siltstone, sandstone, and limestone beds are present as minor components.

(#5) The Hiram Brook Member comprises an interbedded sequence of grey shale, siltstone, and sandstone with lesser beds of kerogenous mudstone and conglomerate. The finer grained clastics are usually comprised of light brown, parallel-bedded sandstone interbedded with swaley-trough, cross-stratified and ripple-laminated sandstone. Thicknesses can exceed 500 metres for this member throughout the Moncton Sub-basin. The presence of swaley cross-bedding and wave-ripple-laminated sandstone interstratified with kerogenous, laminated mudrock suggests that the Hiram Brook Member was in large part deposited in a shallow lacustrine environment. However, fining-upward sandstone sequences identified in well records at the McCully Field show that at least some of the sand bodies represent fluvial deposits.

(#6) This diagram portrays some of the complex tectonic relationships of the southern Moncton Sub-basin margin. In general, the various fault structures are often re-activated throughout the Carboniferous during different phases of extensional and compressional tectonism. The maps often portray a juxtaposition of extensional and compressional fault structures and research is continuing in order to compile a more comprehensive tectonic history.

(#7 to 30) New Brunswick has had a long and colorful history of oil and gas exploration and production. The first indication that oil occurred in the province was recorded in 1849 when a vein of solid bitumen, given the local name Albertite, was found cutting very organic-rich oil shales of the Albert Formation at Albert Mines south of Moncton. The Albertite was mined and shipped to eastern U.S. cities where it was distilled for street lamp oil. In 1859, one of the first oil exploration wells in North America was drilled in the Dover area, about 10 miles southeast of Moncton. This well and adjacent wells drilled at that time produced a few barrels of oil from shallow Albert Formation sandstones. In 1909, the Stoney Creek Field was discovered immediately west of the Dover area. Over its long productive history from 1910 to 1991, the field yielded 30 billion cubic feet of sweet gas and about 800,000 barrels of paraffinic oil.

(#30) The McCully Natural Gas Field is located approximately 10 km east of Sussex in the southwestern part of the Moncton Sub-basin of the Maritimes Basin. The McCully A-67 discovery well was drilled in 2000 by Corridor Resources Inc. and Potash Corporation of Saskatchewan Inc. (PCS) with two objectives: 1) Corridor's natural gas exploration of the Upper Devonian–Mississippian Horton Group, and 2) PCS's search for a water disposal well for their potash operations. The McCully Field reservoir lies at a depth of approximately 2.5 km in tight sandstone intervals of the Carboniferous (Tournaisian) Albert Formation (Horton Group). These sand bodies are separated by interbedded siltstones, shales and organic-bearing shales. The trap is a gentle anticline, partly eroded, and unconformably capped by continental clastics of the Sussex Group.

(#31 and 32) The New Brunswick Department of Natural Resources has an extensive digital database of 2D and 3D seismic plus boreholes for both onshore and offshore New Brunswick (Slide 32). This dataset is a powerful tool for research that will result in a better understanding of the structural and stratigraphic relationships of southern New Brunswick.

(#33 and 34) The Department of Natural Resources has the digital geology/drilling reports for each borehole. We also have the digital files for all boreholes that recorded electric log surveys.

(#35 to 37) Interest for shale gas is also increasing in New Brunswick with the Frederick Brook Member being actively chased.

(#38 and 39) This is one of the McCully wells that has detected the presence of gas horizons within the shales of the Frederick Brook Member.

(#40 to 43) Stoney Creek was one of the first economic hydrocarbon discovery in North America. Slide 43 is a simplified geologic cross section across the Stoney Creek Field. The historic Stoney Creek Field is shallow, under 1500 metres in depth. The trap is both stratigraphic and structural. Several “drilling sand” intervals have been intersected and produced in the Hiram Brook and Frederick Brook (?) members. The correlations of some of these sand units are currently being revised.

(#44) To aid their interpretations, Contact Exploration has produced a standardized digital version of the old lithology logs and can now create digital lithological cross sections across the field.

(#45-46) Based on new well data, some digital cross sections are created. As seen, the old lithology logs are correlated with new gamma ray logs obtained from re-entering the old boreholes. Correlation of the new gamma ray logs results in a more detailed description of the sediment unit interval.

(#47-49) From these correlations, detailed 3D grids of unit thicknesses and depths can be produced. This, in combination with seismic interpretation, provides better confidence in determining future exploration targets.

(#53) A typical drilling/production pad in the McCully Field; up to four wells can be directionally drilled from this one pad, which saves the environment and reduces rig transfer times. Above is a simultaneous drilling and fracturing operation.

(#54) There is a considerable digital dataset of boreholes and seismic in the McCully Field area. Detailed 3D grids are produced of the different sandstone units within the Hiram Brook Member and its upper and lower boundaries.

(#55) A generalized cross section across the McCully Field which shows the structural and stratigraphic traps for the Hiram Brook Member natural gas. The Horton Group beds are folded into an anticline structure which truncates against the impermeable fine grained red beds of the overlying Sussex Group. As seen in the southern portion of the cross section, there is no seal for the Horton Group, which explains the dry Kerr-McGee Urney #1 well.

(#56) A detailed cross section of the major sand units within the Hiram Brook Member; estimates of OGIP is close to 1 Tcf with 183 Bcf of proven and probable reserves.

(#57 to 62) The characteristics of the various producing sands are presented, the sands are characterized by fair porosity but low permeability, massive fraccing has been demonstrated to significantly increase the gas production.

Presentation #15

Onshore Exploration - WESTERN NEWFOUNDLAND
(Past, Present & Future)

Larry G. Hicks, P. Geo.
Department of Natural Resources – Energy Branch
Government of Newfoundland and Labrador

(# 1 and 2) The aim of this presentation is threefold: 1) to outline past petroleum activity for western Newfoundland, 2) give an overview of current exploration activity as well as highlight major components of the geology and petroleum system for each onshore basin and 3) relate known or anticipated future activity for the region.

(#3 and 4) For onshore western Newfoundland, the period between 1867 and 1989 is generally regarded as the historical era for petroleum exploration. The first petroleum well was drilled on the Northern Peninsula in 1867 and subsequent wells up to the last in 1973 (southern Bay St. George area) were all drilled without the benefit of seismic, being sited mainly on the basis of hydrocarbon seeps and favourable surface geology. Interestingly enough, over half of these wells (60?) contained oil and/or gas in some quantity. The current round of exploration activity began after 1989, following release of geological reports favourable to hydrocarbon exploration in the region, announcement by the Newfoundland and Labrador Government of a new onshore Royalty regime and shortly thereafter in 1995, by the discovery of oil and gas by Hunt / PanCanadian in their Garden Hill well on the Port au Port Peninsula. This discovery well was the first to be drilled in western Newfoundland with the benefit of seismic information.

The 1867 date for the first petroleum well in Newfoundland is roughly on par with drilling activity taking place elsewhere in the Atlantic region and within Ontario (1858) and the US (1859).

(# 5) Petroleum Drilling, Western Newfoundland

Historically, five regions have been targeted in western Newfoundland for petroleum exploration / drilling. The first was at Parson's Pond in 1867 (John Silver well) and then later in 1895 by Colonial Newfoundland interests. Immediately to the south at St. Paul's Inlet, drilling efforts commenced in 1896 and still further to the south on the Port au Port Peninsula (Shoal Point) in 1898. It is unclear as to the exact year drilling took place in the Deer Lake Basin, but newspaper records suggest two wells may have been drilled in 1913 by British interests. Petroleum potential in the Bay St. George Basin was not recognized until 1956, when delineation drilling undertaken by the Government Mines Department at the Flat Bay Gypsum deposit encountered separate oil and gas shows within two drill holes.

(#6) Parson's Pond Oil History

The presence of hydrocarbons has been recognized for almost two centuries or possibly earlier by both French and English fishermen who frequently plied their trade along the shores of western Newfoundland. As early as 1812, it is reported that a Mr. Parsons skimmed oil from surface waters and along the shores of Parsons Pond and used this substance as a cure for rheumatism.

This substance remained a source of curiosity and rumour for another 55 years until John Silver, a sawmill operator from Nova Scotia who upon hearing these rumours came to the area in 1867 and used a steam powered drill to put down a 213 m hole along the south shore of the pond. The hole encountered "some oil and gas shows", but further drilling was not pursued and it is believed Mr. Silver departed the area shortly thereafter.

(#7-8) Parson's Pond Oil History

In the early 1890's, two prospectors staked a 2 square mile area around the old Silver drill hole, then applied and received a mining license for the area. This license after a series of work commitments was subsequently upgraded to a mining lease. At about the same time, the Newfoundland Oil Company was formed in 1893 by a group of local St. John's businessmen and politicians, who in short order through legal transfer by the prospectors' acquired all the rights, title and interest in the mining lease.

The Newfoundland Oil Company was the first of at least five companies incorporated in St. John's between 1894 to 1909 (Colonial Newfoundland Era) with a mandate to drill for oil at Parson's Pond. After demise of the Newfoundland Oil Company (by 1898), the combined efforts of the four other Newfoundland incorporated companies also met with little success and by 1910 the last of these companies, the Newfoundland Oil Development Co., incorporated in 1909 went bankrupt. This last bankruptcy ended the colonial Newfoundland petroleum exploration era at Parsons Pond. In retrospect, overall production according to records and local eyewitness accounts appears to have been less than 2000 barrels for the entire 15 year period. Approximately 800 to 900 barrels of this total was sold to the Gas Light Co. in St. John's and most of the remainder was utilized by fishermen or home owners around the Parsons Pond area.

Between 1910 and possibly up to 1926, records indicate at least three British incorporated companies (British Era) conducted petroleum exploration at Parsons Pond. These records are very incomplete and no particulars are given for holes drilled or production results. Based on eyewitness accounts and newspaper articles from the day, it is known that General Oilfields Limited had in 1922 at least four wells producing, three in the process of being drilled and an operating refinery capable of processing three tons of oil per week to produce gas and kerosene. Production was mostly consumed by the Gas Light Co. in St. John's and by local residents along the coast.

The next round of exploration was undertaken by John Fox (American entrepreneur) interests, who drilled at least two holes at Parsons Pond between the years 1952 and 1953 (American Era). No logs exist for these wells, but it is known they were drilled to depths of 838.4 m and 457.3 m, with oil bearing zones being penetrated in both wells.

(#9) Parson's Pond Oil History

Historically, the last well to be drilled at Parsons Pond was in 1965 by Newfoundland and Labrador Corporation Ltd. (NALCO) (Canadian Era). The NALCO I - 65 well was targeted for a depth of 1524 m but had to be abandoned at 1302 m when considerable caving was encountered and the drill stem broken. Gas was present throughout the well, with the best shows and highest pressures encountered at the 1302 m depth. According to eyewitness accounts, "gas belching could be heard 9 to 12 m from the well and this activity continued for one month" (Fleming, 1970). The well penetrated at least ten minor oil bearing zones over a combined 35 m interval. Testing indicated a "sweet oil" of 43.4^0 API gravity.

(#10) St. Paul’s Inlet Oil History

Petroleum drilling in the St. Paul’s Inlet area was first reported by Colonial Newfoundland government geologist James P. Howley who visited the site in 1896 while on the return leg of a visit to the Newfoundland Oil Company operations at Parsons Pond. According to newspaper records, this well was being drilled by the Canadian – Newfoundland Oil Co. (Noseworthy well) and was located approximately 0.8 km south of the narrows along the western shore of the pond. The well was completed in 1897 to a depth of 518.3 m, with oil being encountered in black and red shale beds at 294 m, 303 m and 314 m depths (Henry, 1910). The well also penetrated several gas bearing zones. There are no records of any further work taking place at this site.

Over the period from 1952 to 1953, the American John Fox drilled at least three holes in the area. Drilling records exist for only the first well and they indicate it was drilled to a depth of 608 m with oil shows being encountered within four different zones. These zones range in thickness from 1.5 m to 13.5 m.

There are no other records to indicate further petroleum related activity in the area, but petroleum has been observed many times while putting down water wells for local residents. As recent as 1977, four shallow water wells (approximately 30 m deep) drilled near the old John Fox penetrations encountered oil and had to be abandoned from their original intent.

(#11) Shoal Point Oil History

Oil seeps from along the west side of Shoal Point on the Port au Port Peninsula were first noted in 1874 by government geologist James P. Howley while conducting geological reconnaissance surveys throughout the region (Howley, 1875). First drilling took place in 1898 when the Western Oil Company Ltd. drilled four holes to depths ranging from 51 m to 200 m, with total production from these wells said to have been anywhere in the range from 10 to 20 barrels per day. Further drilling activity after this time is uncertain, but government reports (Baker) indicate that by 1928 at least eleven wells had been drilled in the area.

There is no further recorded activity until 1964, when British Newfoundland Exploration Limited (Brinex) and Golden Eagle Oil and Gas Limited undertook a joint exploration program throughout the Port au Port Peninsula. A detailed geological examination was made later in the same year by H. Corkin and based on his suggestions, two wells were drilled at Shoal Point in 1965 in order to obtain stratigraphic and structural information. The first well, Shoal Point #1 encountered only minor to trace indications of oil staining or zones of porosity development (Golden Eagle, 1965a). In contrast, sandstone and limestone cuttings from the Shoal Point #2 well frequently exhibited trace to fair, live or dead oil staining and bright lemon-yellow fluorescence in association with local zones of intergranular (sandstone) and intercrystalline, pinpoint or vuggy (limestone) porosity. Both wells were subsequently plugged and abandoned.

(#12) Deer Lake Basin

Petroleum activity in the Deer Lake Basin is reported to have commenced around the turn of the last century where stories persist that "solid bitumen" was mined close to the shoreline of Deer Lake at Nicholsville. Actual drilling is believed to have taken place prior to World War 1, where it is rumoured that a local syndicate sank two wells, each to a depth of 244 m. These wells were not sited on the basis of geological structure and no favourable results were obtained from the drilling efforts.

During the period 1919 to 1921, T. Landell-Mills representing the Colonial Oil Shale and Chemical Co. drilled three holes near the town of Nicholsville in order to evaluate the oil shale potential of the Rocky Brook Formation. Regrettably, only a portion of the Mills #1 well log is known to have survived to the present time. This partial log records 230.8 m of drilling, although people involved with this drilling report that the well was sunk to 290.5 m. According to Landell-Mills, small amounts of gas were blown out intermittently while drilling, but strongest gas pressures were encountered at 118.6 m and 230.8 m. At the 118.6 m depth, "the shot was blown out of the hole"; at 230.8 m, "eruption of gas, violence thereof severely damaged drilling plant. Eruption continued for several days in varying intensity". The amount of gas given off is not known but Landell-Mills reports, "I examined this well twelve months after drilling had been shut down and gas was still being briskly given off".

The area received no further petroleum interest for 35 years, until Claybar Uranium and Oil Limited and Newkirk Mining Company began an extensive joint exploration program in the basin in 1954. A detailed geological examination was undertaken by H. J. Werner in 1954/55 and based on his observations a drill program was initiated over promising geological structures. Claybar #1 was spudded in late 1955 and it targeted the Big Falls-Little Falls anticline. The well was drilled to 473.8 m. Minor gas shows were encountered in upper Rocky Brook shales and gas under considerable pressure was recorded over a 1.6 m interval, between 346.9 m to 348.5 m within fine grained sandstones of the North Brook Formation. Werner reports that, "the gas caught fire and caused the drillers to abandon operations for at least three days". Unfortunately, due to the lack of field equipment, there was no way to measure gas pressures or perform gas analysis at the drill site. The well terminated in andesite after passing through approximately 68 m of platform carbonates. The second Claybar hole situated approximately 19 km to the south of Claybar #1 was drilled to test the proposed extension of the anticlinal structure. The hole however was terminated at 847.6 m before reaching its target objective. Claybar #3 was located approximately 4 km southeast of the first Claybar well and drilled to a depth of 730.5 m. The hole encountered only minor amounts of gas in Rocky Brook shales. The final Claybar hole was located 5.6 km northeast of Little Falls on the Humber River and drilled down to 152.4 m before being terminated without reaching its target objective. There were no hydrocarbon shows in this well.

(#13) Bay St. George Basin

Hydrocarbons were first noted in the Bay St. George basin by government geologists during the mid 1950's while in the process of conducting delineation drilling for the Flat Bay gypsum deposit. One hole (24N0E) drilled to a depth of 33.5 m encountered natural gas at a depth of 31.4 m within anhydrites of the lower Codroy Group. A second hole (28N4W) drilled to penetrate the evaporites and investigate deeper lithologies encountered petroleum bearing conglomerate at 107.3 m. The hole was terminated at 120.4 m after penetrating 13.1 m of oil stained rock. According to McKillop (1957), "petroleum was present in the conglomerate to the extent that droplets oozed from the core along its total length. After a few days the droplets became diffused to cover most of the surface of the core coloring it dark brown". The conglomerate forms part of the Fischells Brook Member of the Spout Falls Formation (Anguille Group).

No further petroleum related exploration took place until 1973, when Union Brinex spudded the Anguille H-98 well in the southern part of the basin. This well was drilled in a highly structured zone to a depth of 2311 m and encountered only trace percentages of poorly developed porosity.

(#14) What went Wrong

The reasons for the failure of an oil industry to develop in western Newfoundland (between 1867 – 1973) are numerous and for most of those listed on Slide 14, are self explanatory and were applicable to all companies operating in the regions. The main exceptions would be Spotswood's death which only affected the Newfoundland Oil Co. (1894 – 1898). Spotswood was supposedly the oil expert and when he died in 1896 there was no one with expertise to take over the drilling operation at Parson's Pond. The French Shore issue would only have affected companies working along the coast, namely at Parson's Pond, St. Paul's Inlet and Shoal Point. Under various treaties between the French and English, France had been given control of the Newfoundland coastline from Cape Ray in the southwest to Cape St. John on the Baie Verte Peninsula (became known as the French Shore). These treaties prevented English citizens / companies from establishing fixed dwellings along this stretch of coast and those who did risked military intervention by French naval squadrons. This continued risk of French military action severely curtailed or completely thwarted many economic ventures in western Newfoundland, including oil exploration. It was not until 1904 when the latest French / English treaty was abrogated that English citizens / companies could settle along the coast without the fear of French intervention.

(#15) Current Activity

The current round of exploration activity began after 1989, following release of geological reports favourable to hydrocarbon exploration in the region, announcement by the Newfoundland and Labrador Government of a new onshore Royalty regime and shortly thereafter in 1995, by the discovery of oil and gas by Hunt / PanCanadian in their Garden Hill well on the Port au Port Peninsula. This discovery well was the first to be drilled in western Newfoundland with the benefit of seismic information.

(#16) Onshore / Offshore Basins

Three Paleozoic aged sedimentary basins – Anticosti, Bay St. George and Deer Lake (approximately 1,762,000 ha. in area), make up the onshore portion of western Newfoundland, with the Anticosti and Bay St. George basins extending out under the Gulf of St. Lawrence. The Bay St. George basin is a sub-basin to the larger Maritimes Basin. The Anticosti Basin (onshore) is three times larger (1,307,000 ha.) than the other two and contains rock sequences ranging in age from Upper Precambrian / Lower Cambrian to Devonian. Both the Deer Lake and Bay St. George basins contain mostly Lower Carboniferous and minor volumes of Upper Carboniferous aged sediments.

(#17) Onshore Hydrocarbon Shows

Onshore oil and gas seeps and/or shows have been noted since 1812, but over the ensuing years these for the most part have not been systematically documented. The Department of Natural Resources of Newfoundland and Labrador is currently in the process of compiling an up to date hydrocarbon shows database with information being gathered from field visits, government files, university research and mineral exploration assessment files. Once complete this database will be uploaded to the Department of Natural Resources website.

(#18) Onshore Seismic

There has been approximately 1050 line km of onshore 2-D seismic acquired to date over western Newfoundland. Most of this is concentrated in areas of distinct (historic) hydrocarbon prospectivity; however survey lines do exist in other areas of western Newfoundland. Exclusive seismic data is kept confidential for a period of five years whereas non-exclusive is confidential for fifteen years. At present, most of the onshore seismic data is open filed and available as paper copy, although all lines have been scanned as pdf files. Paper copies can be obtained through the Department of Natural Resources.

In the offshore region of western Newfoundland (Gulf of St. Lawrence), approximately 12,000 line km of 2-D seismic data has been acquired.

(#19) Petroleum Rights & Exploratory Drilling

There are ten exploration permits and one production lease (regulated under the Petroleum and Natural Gas Act) active for onshore western Newfoundland. These total approximately 280,390 ha. Onshore permits can have a maximum size of 40,000 ha. Eight offshore exploration parcels (regulated under the Canada-Newfoundland Atlantic Accord Implementation Acts), totalling 1,079,230 ha. are presently under license in the Gulf region. Offshore licenses can have a maximum size of 80,000 ha.

*<u>Note</u>: Since this slide presentation was prepared, one onshore exploration permit and one offshore license has expired, thus giving a current total of nine onshore permits (3 on the Northern Peninsula in the Anticosti basin; 3 in the Deer Lake basin and 3 in the Bay St. George basin). Seven licenses are active in the offshore sector.

There have been eighteen onshore exploration (Anticosti basin - 6; Deer Lake basin – 2 and Bay St. George basin – 10) and two stratigraphic test (Anticosti basin – 1 and Bay St. George basin – 1) wells drilled since 1994. In addition, four onshore to offshore wells (Anticosti basin – Port au Port Peninsula) and one offshore well (St. George’s Bay A-36) have been drilled.

(#20) Anticosti Basin

The Anticosti Basin proper includes most of the Humber Zone (Williams, 1979) and extends offshore over to the coast of Labrador / Québec. The Humber Zone consists of five distinct lithological associations: 1) Precambrian crystalline basement (Long Range Inlier, Indian Head Complex and Steel Mountain Anorthosite); 2) Cambro-Ordovician non-transported (autochthonous) succession of shallow marine sedimentary rocks, termed in ascending age, the Labrador, Port au Port, St. George and Table Head Groups. These are overlain by the Goose Tickle Group, representative of autochthonous, easterly derived, flysch sedimentation; 3) Cambro-Ordovician transported (allochthonous) complex of deep water sedimentary, igneous and metamorphic rocks, collectively referred to as the Curling and Cow Head Groups, Lower Head Formation, Maiden Point Formation and Ophiolite Complexes; 4) A localized upper Middle Ordovician and Silurian to Devonian non-transported (neo-autochthonous) foreland basin fill of clastics and carbonates (Long Point Group, Clam Bank and Red Island Road formations) in structural contact with the allochthon and resting unconformably on Cambro-Ordovician platform rocks (west of the triangle zone); 5) Late Devonian to Carboniferous aged sedimentary rocks occurring in two separate areas (Bay St. George Sub-basin and Deer Lake Basin).

(#21) Port au Port Peninsula

Since 1994, there have been five exploration (Hunt / PanCanadian PAP #1, Hunt / PanCanadian Long Point M-16, Talisman et al. Long Range A-05, Inglewood Man O'War I-42 and PanCanadian et al. Shoal Point K-39) and two delineation (CIVC Sidetrack #1 and CIVC Sidetrack #2) wells drilled on the Port au Port Peninsula. Four of the exploration wells (M-16, A-05, I-42 and K-39) were drilled onshore to offshore. The lone offshore well (not depicted on the slide), St. George's Bay A-36 is located approximately six kilometres to the southwest of the southwest end of the Port au Port Peninsula. The St. George's Bay structure is along strike with the onshore Garden Hill (PAP #1) structure.

The modern round of petroleum drilling commenced on the Port au Port Peninsula during the mid 1990's, when Hunt / PanCanadian spudded the Port au Port #1 Garden Hill well in September of 1994. This well immediately attracted the attention of the Province and petroleum industry in the spring of 1995 when a flare from the well lit up the sky along the southwestern part of the Port au Port Peninsula. The well encountered several reservoirs, one of which is hydrocarbon bearing. Two intervals within the hydrocarbon bearing zone flowed at 1528 and

1742 barrels per day of high quality (51^0 API) oil and 2.6 and 2.3 million cubic feet per day of natural gas, respectively, plus associated water. An extended test on one of the intervals flowed a total of 5,012 barrels of oil over a nine day period. After the drilling of Port au Port #1, Hunt / Pan Canadian spudded the Long Point M-16 well at the tip of Long Point in September/95 and followed this up in May/96 with an offshore well (St. George's Bay A-36) approximately six km southwest of Cape St. George. There were no shows in the Long Point well, but minor live oil and numerous bitumen occurrences in the St. George's Bay well. This well also had good porosity development in the Watts Bight and Hawke Bay formations. Sandwiched between the above wells, Talisman *et al*. spudded the Long Range A-09 well in February/96 approximately 3 km south of the Port au Port #1 well. This well was subsequently plugged and abandoned. Inglewood Resources started the Man O'War I-42 well near Campbell's Creek on the southern Port au Port Peninsula in Nov/98, but were unable to finish due to drilling related problems. PanCanadian Petroleum and partners Hunt Oil, Mobil and Encal Energy spudded the Shoal Point K-39 well on February 8, 1999. This was the 14th (historic and modern) well to be drilled at Shoal Point. The well was directionally drilled to a depth of 3035 m to test a large structure located beneath Port au Port Bay. On May 26, 1999, PanCanadian announced that the well had tested water and would be abandoned. In the fall of 2000, Memorial University's Earth Science Department acquired additional seismic data in the Shoal Point area that suggests the well may have missed the target.

On August 17/2001, Canadian Imperial Venture Corp. (CIVC) spudded Port au Port #1 sidetrack #1 in order to earn their farm-in with Hunt/PanCanadian. The original PAP #1 well was re-entered and at about 2300 m the well was kicked off in a northwesterly direction in order to penetrate the Garden Hill reservoir further updip in the oil bearing zone. Unfortunately, the upper Aguathuna Formation which was dolomitized and possibly karsted in the original well was tight and mostly limestone in the sidetrack. Minor oil shows were present in dolostones of the lower Aguathuna Formation. Also within this timeframe, CIVC submitted a development plan for the original PAP #1 well. On April 3, 2002, a lease was granted to allow production to proceed. CIVC drilled a second sidetrack well during the summer of 2002 and announced that this well flowed at 195 bopd, with 1.2 million cubic feet per day of natural gas. They also announced that there was no produced water with the test and the pressures were constant during the test.

The onshore production lease was originally issued to CIVC, but through a series of legal transactions the lease is now operated by PDI Production Inc.

(#22) Structural Elements

Upper left on slide – Section C – C" southwestern end of Port au Port Peninsula shows an anticlinal trap developed above the footwall shortcut fault; Upper right on slide – Section B – B" triangle zone geometry developed along the northern portion of the Port au Port Peninsula (Long Point area); Bottom center on slide – Section A – A" imbricate thrust slices of Cow Head Group / Lower Head Fm. strata above autochthonous platform sequences at Parsons Pond, Northern Peninsula

(#23) Deer Lake Basin

The Deer Lake Basin is positioned along strike to the northeast of the Bay St. George sub-basin, with both basins sharing a similar geologic and tectonic history related to extensional movements along the Cabot Fault system. Sediments range in age from early Mississippian (Tournaisian) to mid Pennsylvanian (Wesphalian) and they are entirely non-marine in nature. The basin exhibits a central flower structure cored by tilted Anguille Group sediments and flanked to the left and right, respectively, by the Cormack and Howley lateral basins. Sediment thicknesses in both basins may have been in the order of four kilometres or greater.

(#24) Bay St. George Basin

The Bay St. George basin (sub-basin) forms the northeast extension of the larger Maritimes Basin and contains approximately 10 km of sediments ranging in age from Late Devonian to Late Carboniferous. The strata are divided into three groups: Anguille (Famennian – Tournaisian age), Codroy (Visean age) and Barachois (Namurian – Westphalian age). All three groups are mostly nonmarine terrigenous clastic sediments with marine strata only within the Codroy Group. The sub-basin formed as a pull-apart adjacent to, and west of, the northeasterly trending Long Range fault, a major strike-slip structure that is part of the Cabot Fault system in western Newfoundland (after Knight, 1983)

(#25) Future Activity

This slide is a lead in to Slide 26 - anticipated exploration activity for 2008 and beyond (eg., drilling, seismic or other exploration surveys).

(#26) Future Activity – Drilling and Seismic

On the drilling front, for 2008 it is anticipated that Tekoil & Gas Ltd. will drill their Glori #1 onshore to offshore well at Little Port which is located immediately to the south of the Bay of Islands. Shoal Point Energy and partner(s) plan to drill an onshore to offshore well at Shoal Point on the Port au Port Peninsula. This well will target the original Aguathuna Fm. reservoir section which was not penetrated in the original PanCanadian et al. Shoal Point K-39 well. PDI Production Inc. plans to re-enter and deepen the original PAP #1 Sidetrack #2 well prior to drilling a horizontal well into the Aguathuna Formation at Garden Hill.

*Note: Since this slide presentation was prepared, Tekoil has experienced financial difficulties and are unable to proceed with the Glori #1 well at Little Port. Towards the south, Shoal Point Energy has completed the Shoal Point 2K-39 well and according to their partner CIVC, "we drilled the well and it came up dry" (The Telegram, July 22/08). In the meantime based on drilling results CIVC has begun an analysis of a potential Green Point shale gas play in the area. Elsewhere on the Port au Port Peninsula, PDI Production Inc. re-entered the PAP #1 Sidetrack #2 and after careful evaluation of all data decided against deepening the hole (Batten-Hender, Oil & Gas Symposium, Sept. 14/08) and will concentrate their efforts on re-entering the original wellbore and deviating outwards laterally into the oil-bearing Aguathuna Formation.

There are three seismic surveys planned for the Port au Port area in the near future, two of these will be 3-D (one onshore, one offshore) and one 2-D survey.

*Note: Since this slide presentation was prepared, Tekoil has experienced financial difficulties and will be unable to undertake their 3-D offshore survey extending from Little Port down to the Port au Port Peninsula. PDI Production Inc. are moving forward with the 2-D survey on the western side of the Peninsula, lines have been cut and they anticipate a late fall 2008 to early 2009 start date. There still has been no activity on the PDI Production Inc. 3-D survey at Garden Hill South.

(#27) Energy Plan

On Sept. 11/07, the province unveiled its new Energy Plan. As part of the Energy Plan, funds have been allocated into two separate programs: 1) the Petroleum Exploration Enhancement Program (PEEP) – A $5 million fund to be administered by the newly created (government) Energy Corp. in order to reprocess old or acquire and assess new seismic data as well as other geoscientific information which then can be accessed by academic institutions / industry or used by government to be potentially utilized in consideration for an equity interest in onshore projects. Initial funding for the PEEP program is 2 years. 2) A $20 million offshore fund administered by the Energy Corp. to be used to purchase existing proprietary seismic data for re-evaluation and to acquire new seismic data. This data may also be potentially utilized in consideration for an equity interest in offshore projects. Initial funding for the offshore project is 3 years.

Slide 28 – Concluding Remarks

As per slide.

Presentation #16

Offshore Exploration Activity - Western Newfoundland and Labrador,

Harold J. Klassen,
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(#2) The Canada-Newfoundland and Labrador Offshore Petroleum Board (CNLOPB) situated in St. John's, NL, interprets and applies the provisions of the Atlantic Accord and the Atlantic Accord Implementation Act to all activities of operators in the Newfoundland and Labrador offshore area.

(#3 to 6) Currently there are 37 exploration, 49 significant discovery and six production licenses in the Newfoundland and Labrador offshore area. During the period 1964 to 2006, approximately 2 million kilometres of seismic have been acquired. Over 330 wells have been drilled in the offshore area between 1966 and 2006.

(#9-14) In the western offshore area of Newfoundland and Labrador, 12203 km of 2D seismic have been recorded. The data can be viewed at the CNLOPB. There is no 3D seismic. Around the Port au Port Peninsula, one offshore and four onshore to offshore wells have been drilled, all during the 1990's. The purely offshore well, St. George's Bay A-36, was drilled using the jackup rig, Rowan Gorilla IV. Currently, there are eight offshore exploration licenses on the west coast. A Call for Bids ended successfully in 2007-11-30. Corridor Resources Inc. purchased EL1105 for a work commitment bid of $1,521,000 for the parcel, which totals 51,780 ha.

(#16) Two exploration wells are planned to be drilled in 2008. Tekoil & Gas Corporation will evaluate EL1069 with an onshore to offshore well called Glori E-67 while Shoal Point Energy Ltd. will drill into the offshore EL 1070 with an onshore location called Shoal Point 2K-

39. The status of geophysical programs planned for the offshore in 2008 may be found on the CNLOPB website.

(#17-24) A current lithostratigraphic chart displays the possible platform carbonate and clastic reservoirs in the potential Cambro-Ordovician section. Excellent source rocks are present in the Green Point Formation. Two prospective structural fairways exist in the offshore, namely the inversion and the extensional plays. A large number of structural leads have been mapped for the offshore area. Examples of these structural leads are presented in A- A' (St. George's Bay A-36), B-B' (Shoal Point K-39) and C-C' (extensional leads). In addition to the Cambro-Ordovician leads in the St. George's Bay area, there are also prospects involving Carboniferous rocks. Consequently, the offshore area of the west coast possesses all the basic attributes of an effective hydrocarbon system.

(#25-27) The Hopedale Basin of the offshore Labrador Shelf contains both Mesozoic and Paleozoic gas discoveries. Examples of Paleozoic discoveries are the Gudrid and South Hopedale wells. Eastcan et al. Gudrid H-55 has 64 m of net gas pay with an average 10% porosity from a Paleozoic age (probably Ordovician) carbonate. An east - west seismic line shows a Precambrian fault block capped with carbonate. Estimated resources for the feature are 26 x $10^9 m^3$ (924 BCF).

Call for Bids NL07-2 on the Labrador Shelf closes 2008-08-01 and features four parcels for sale, totaling almost 1 million hectares. One parcel surrounds the Gudrid H-55 Significant Discovery License.

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