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Upper Ordovician Stratigraphy and Oil Shales on Southampton Island

Field Trip Guidebook

S. Zhang

2010

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Zhang, S. 2010: Upper Ordovician Stratigraphy and Oil Shales on Southampton Island Field Trip Guidebook. Open File 6668, 42p.

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APPENDICIES

1. INTRODUCTION

The Hudson Bay platform crops out in parts of northern Manitoba, Ontario, Quebec and southeastern Nunavut, and it covers some 600,000 km^2 (Hamblin, 2008). More than half of the platform is covered by the water of Hudson Bay and James Bay.

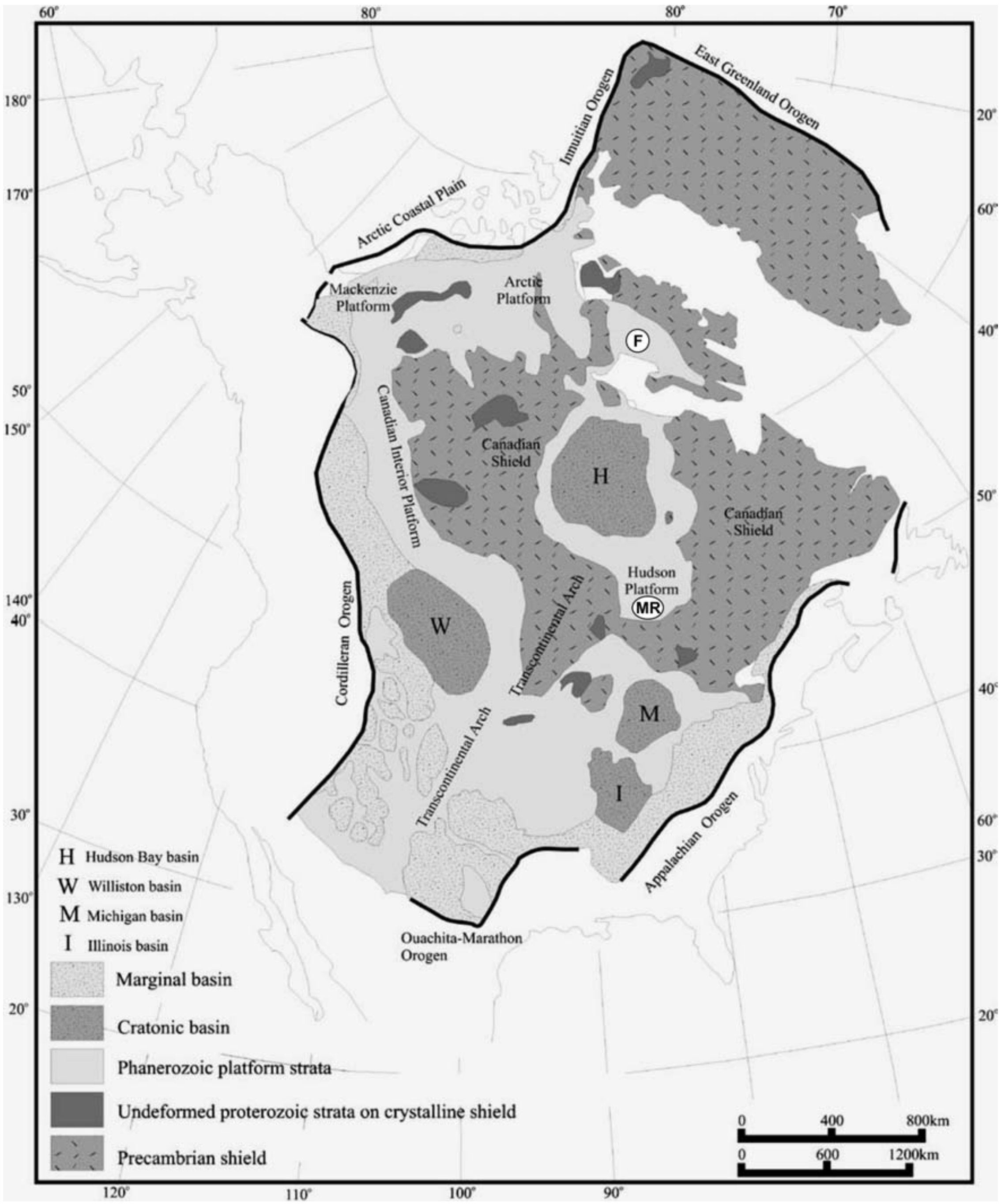

Fig. 1: Location of the Hudson Bay Basin on North America Craton (adopted from Burgess, 2008). F and MR in circles represent Foxe Basin and Moose River Basin, respectively.

Geologically, the Hudson Platform strata lie unconformably over the Precambrian basement and are surrounded by the rocks of the Canadian Shield to its north, west, south and east (Figs. 1 and 2). The platform consists of relatively undeformed Paleozoic rocks of Late Ordovician, Early and Late (?) Silurian and Devonian age and minor Mesozoic erosional remnants of Early Cretaceous age (Sanford and Grant, 1990). The Platform contains two sedimentary basins, namely Hudson Bay and Moose River basins (Figs. 1 and 2). The Hudson Bay Basin is separated from the southern Moose River Basin by a buried northeast-trending Precambrian basement high, the Cape Henrietta Maria Arch. To the north, the Hudson Bay Basin is separated from the Foxe Basin of the Arctic Platform by a buried northwest-trending Precambrian high, the Boothia-Bell Arch (Norris, 1993a,

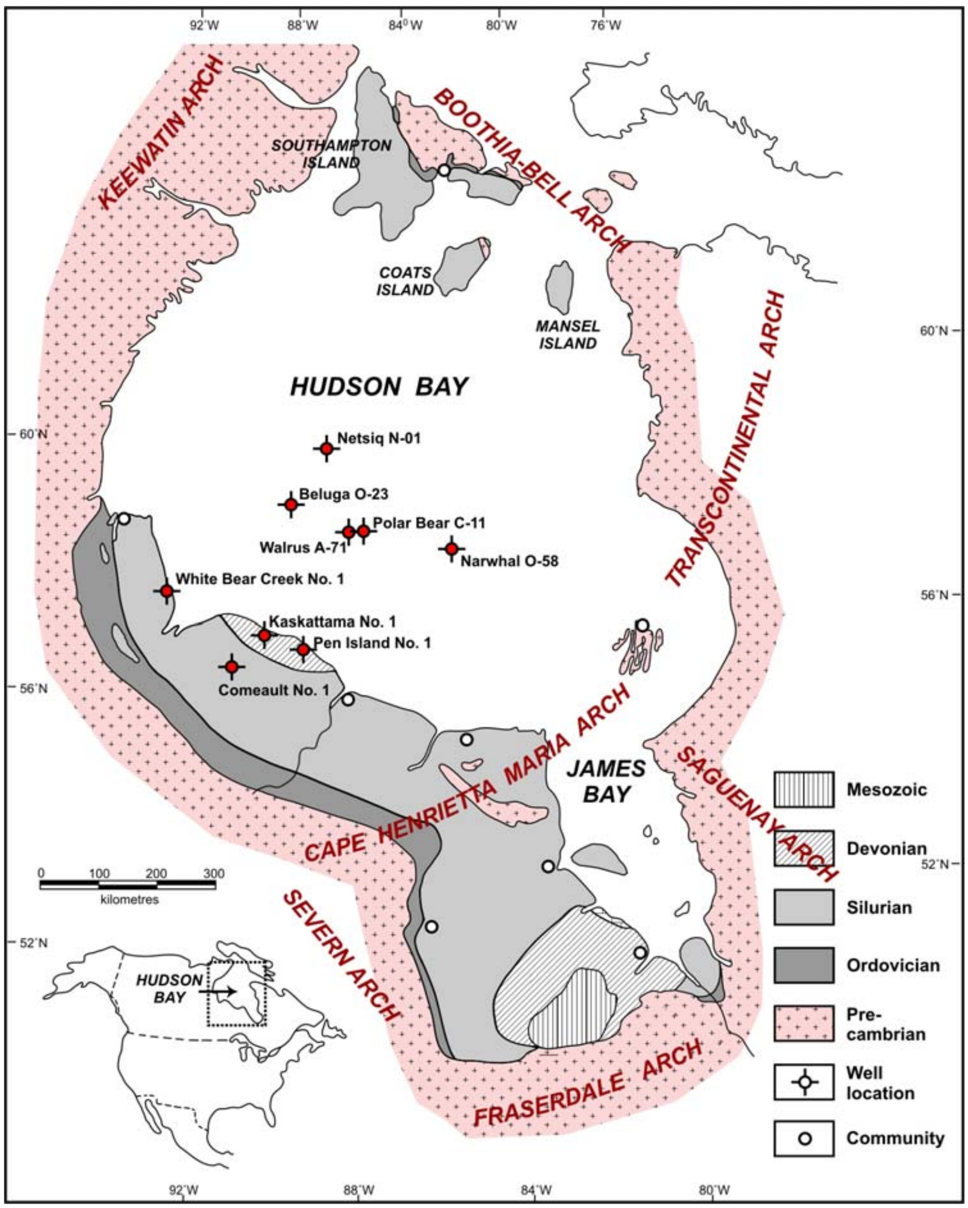

Fig. 2: Hudson Bay region showing onshore Phanerozoic domains, location of onshore and offshore wells and general geological setting (modified from Zhang and Barnes, 2007).

1993b). Paleozoic outcrops occur both on the northern islands (Southampton, Coats, and Mansel) and in the Hudson Bay Lowlands to the west and south (Fig. 2).

The Hudson Bay Basin is larger than the Moose River Basin in the Hudson Platform. The basin concept for the offshore regions of Hudson Bay, inferred from marine-magnetometer profiles, was first proposed by Hood (1964). Refraction seismic data indicate that roughly 2000 m of Phanerozoic strata are present in the centre of Hudson Bay Basin (Hobson, 1964a, 1964b).

Geological research in the Hudson Bay Basin is still in an early stage. Current geoscience knowledge about the area is largely based on reconnaissance mapping, geophysical survey and 4 onshore and 5 offshore wells (Fig. 2; Appendix 1) drilled in the late 1960s to early 1980s; this state-of-knowledge has been, over the years, summarised by Sanford (1987), Sanford et al. (1993), Sanford and Grant (1990, 1998), Norris (1993a, 1993b) and Hamblin (2008). The first round of hydrocarbon exploration did not result in any discovery, and petroleum exploration in the region has ceased.

2. Geological Setting of the Hudson Bay Basin

(1) Tectonic setting

The Hudson Bay region includes three major overlapping tectonic elements; the Paleozoic–Mesozoic Hudson Bay Basin, the Proterozoic Tans-Hudson orogen, and a thick lithospheric mantle root that underlies much of this region (Eaton and Darbyshire, 2010). Various hypotheses for the tectonic assemblage of the diverse Precambrian terranes beneath Hudson Bay Basin are presented in Eaton and Darbyshire (2010). The model they proposed suggests that the basement of the younger Hudson Bay Basin resulted from the collision between the Superior and Western Churchill (Rae and Hearne domains in Fig. 3) cratons. The proposed scenario is similar in scale and tectonic style to the modern Himalayan-Karakorum orogen. The Western Churchill craton formed the upper plate of the 2.0-1.9 Ga Thelon-Taltson orogen to the west and that of the 1.9–1.8 Tran-Hudson orogen to the south and east whereas the Superior Craton formed the lower plate (Fig. 3). Based on potential field and teleseismic data, the central part of the Hudson Bay itself was interpreted to mark a major SW-NE suture zone between various Precambrian terranes (Eaton and Darbyshire, 2010) (Fig. 3).

The Hudson Bay Basin is one of the four Phanerozoic intracratonic sedimentary basins (Michigan, Illinois, Williston and Hudson Bay) on the North America Craton (Fig. 1). Evolution of the Michigan, Illinois and Williston basins as discrete elements in Late Cambrian time suggests that they may be somewhat associated with the break up of supercontinent Rodinia in Late Precambrian (Burgess, 2008). In contrast, the oldest preserved sedimentary record in the Hudson Bay Basin is Upper Ordovician; any link with Rodinia break up is more difficult to define (Burgess, 2008).

First-order evolution of the intracratonic basins is primarily controlled by two important processes: 1) eustatic sea-level changes, and 2) tectonic uplift and subsidence (Sloss, 1963; Burgess, 2008). However, significant stratigraphic differences exist amongst the four intracratonic sedimentary basins on North America Craton; albeit dominated by Paleozoic shallow-water carbonate and evaporites, the cratonic depositional sequences (Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni and Tejas; Sloss,

1963) significantly vary in thickness and facies (Fig. 4). It can be concluded from the cross sections in Fig. 4 that the four intracratonic basins did not experience similar tectonic uplift and burial history; instead they followed their own individual subsidence patterns (rates and timing) with accelerated subsidence occurring at different times (Bally, 1989). The notable exception being the Ordovician-Silurian boundary, characterized by a common major unconformity, is likely controlled by a global end-Ordovician glacio-eustatic regression. The Hudson Bay Basin has the shortest preserved Paleozoic sedimentary history among the intracratonic sedimentary basins on North America Craton; the sedimentation did not start until Late Ordovician (Edenian), and ceased in the Late Devonian, representing parts of Tippecanoe and Kaskaskia sequences. The Absaroka strata might be deposited in the Hudson Bay Basin (Tillement et al., 1976), but it is strongly questioned (Hamblin, 2008). The preserved Paleozoic section of the Hudson Bay platform is marked by numbers of more or less pronounced unconformities and the overall thickness of eroded sediments is totally unknown. The Mesozoic sedimentary record of the Hudson Bay Basin (Figs. 4 and 6) consists of erosional remnants of Cretaceous strata (Zuni Sequence) preserved in the central parts of Hudson

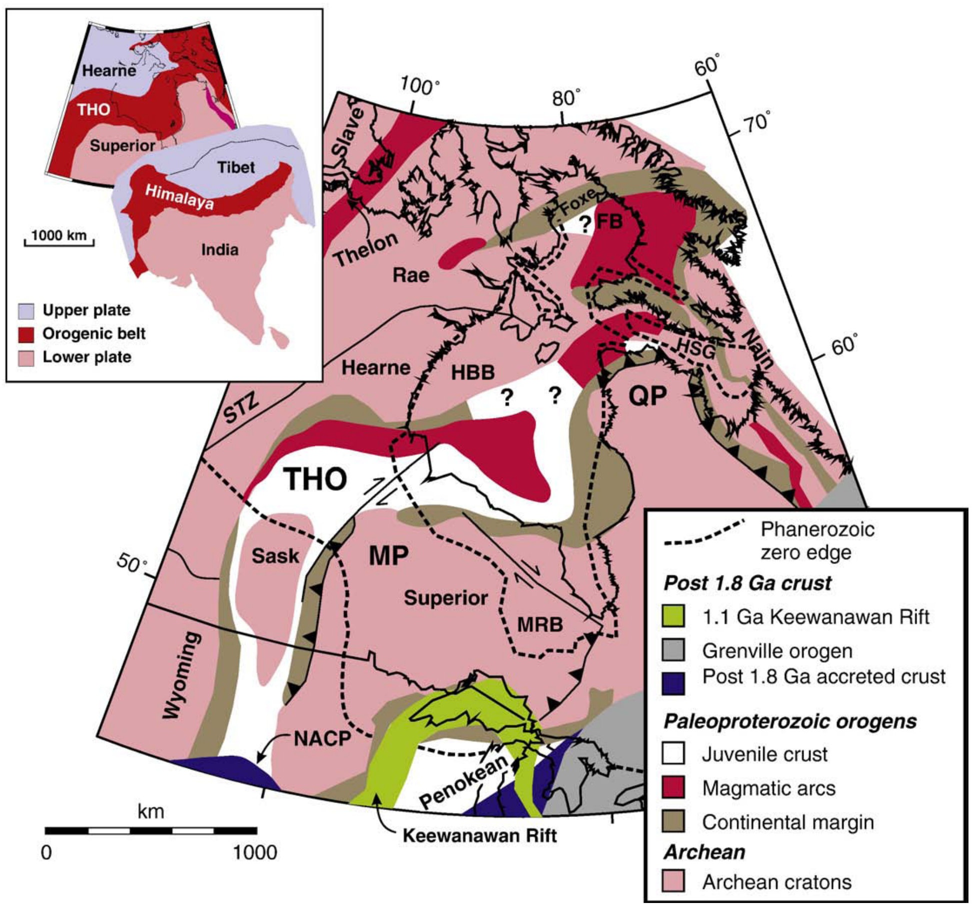

Fig. 3: Simplified tectonic map showing crustal subdivisions of Hudson Bay and adjacent regions of the Canadian Shield (adopted from Eaton and Darbyshire, 2010). Abbreviations: THO, Trans-Hudson orogen; MP, Manitoba promontory; QP, Quebec promontory (Ungava Peninsula); HBB, Hudson Bay Basin; HSG, Hudson Strait graben; FB, Foxe Basin; MRB, Moose River Basin; NACP, North American Central Plains orogen; STZ, Snowbird Tectonic Zone. Upper left inset compares the shape and extent of the THO with the modern Himalayan orogen.

Bay and Hudson Strait (Sanford and Grant, 1990) and at some localities in the Hudson Bay Lowlands in northern Ontario and in the Moose River Basin (Norris, 1993b; Ziegler and Rowley, 1994).

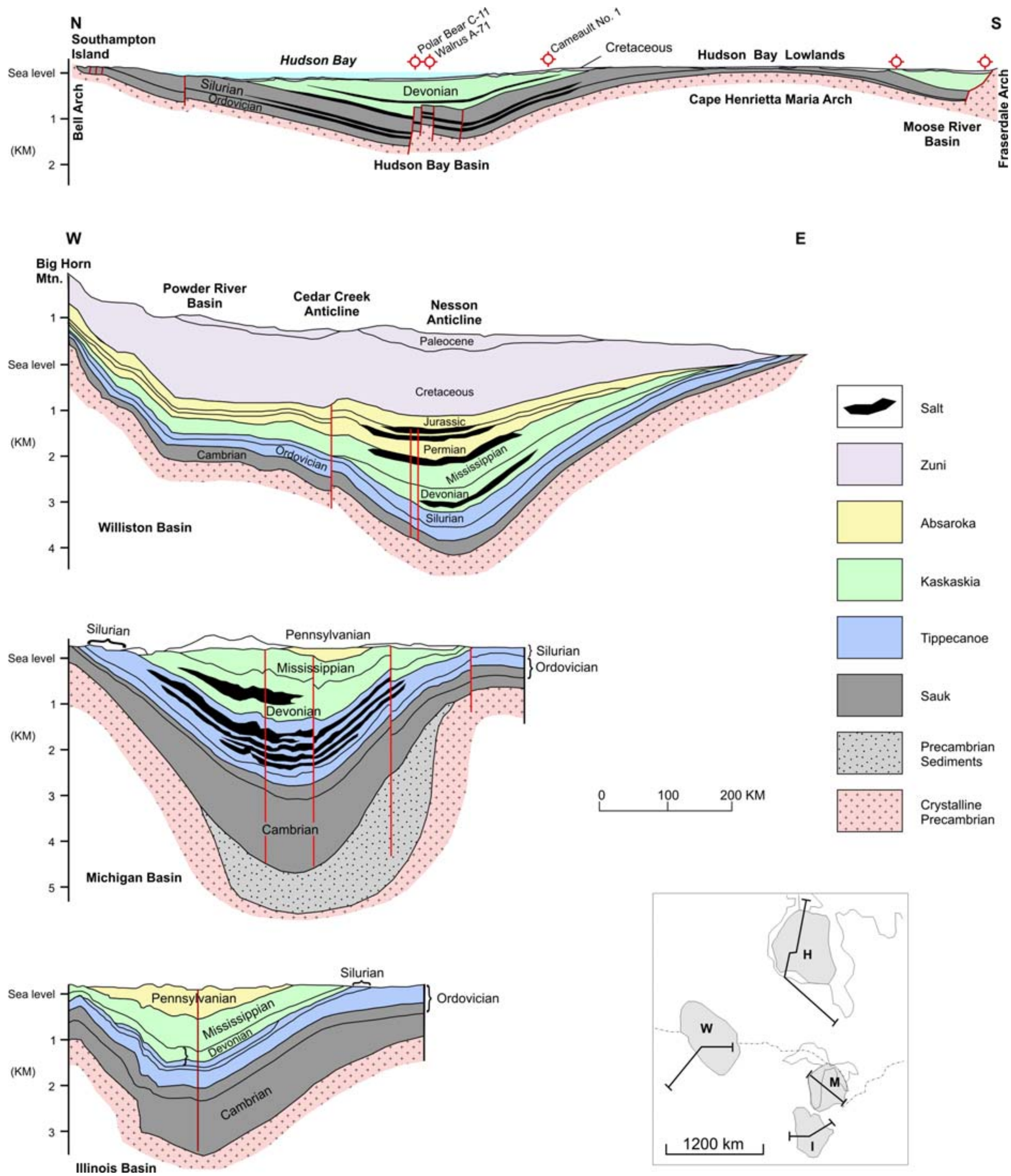

Fig. 4: Schematic cross sections across the four intracratonic basins on North America Craton. The sequences of Sloss (1963) are coded by different colors. Cross section of Hudson Bay Basin (north-south direction) is modified from Norris (1993a), and those of Williston, Michigan and Illinois basins (west-east direction) are modified from Bally (1989), Leighton and Kolata (1990) and Burgess (2008).

The Hudson Bay Basin is limited by the Boothia-Bell and Keewatin arches on the northeast and northwest, respectively, and by the Cape Henrietta Maria Arch that separates it from Moose River Basin to the south (Fig. 2). Seismic profiles acquired in Hudson Bay during the 1970s and 1980s reveal a series of normal faults with a NNW-strike direction bounding a horst-like uplift that divides the basin into two nearly symmetrical sub-basins from Late (?) Silurian to Early Devonian (Sanford and Grant, 1990) (Fig. 5).

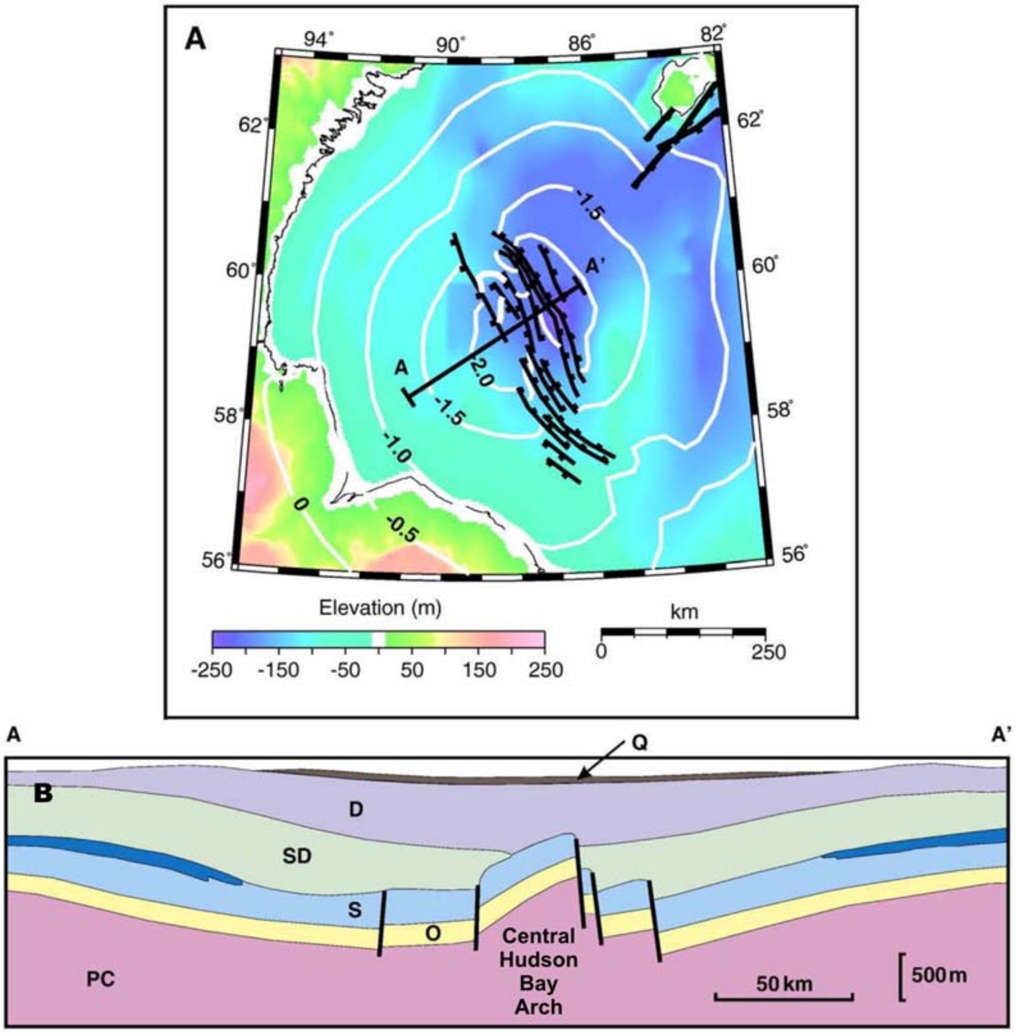

Fig. 5: A. Faults and total sediment isopach contours in km; B. Cross-section A–A' across the centre of the Hudson Bay Basin (modified from Easton and Darbyshire, 2010). PC, O, S, SD, D and Q denote Precambrian, Ordovician, Silurian, Silurian-Devonian, Devonian and Quaternary, respectively.

(2) Phanerozoic history of the basin

During the Cambrian, much of the central segment of the Canadian Shield remained emergent. The transgression recorded in Sauk strata in almost all the intracratonic basins (Michigan, Illinois, and Williston) on Laurentia (Bally, 1989; Leighton and Kolata, 1990; Burgess, 2008) and across much of the paleo-southern and -northern Laurentia margin (Lavoie et al., in press; Dewing and Nowlan, in press) had left no unequivocal preserved record in the Hudson Bay area. Sanford (1987) reported Sauk-aged strata consisting of approximately 60 m of orthoquartzite sandstones and conglomerates overlain by sandy and stromatolic dolostones in small areas in the south-east of the basin, but without fossil evidence for the Cambrian age assignment.

The earliest significant development of Hudson Bay Basin as an intracratonic tectonostratigraphic element started in Edenian (early Late Ordovician) as demonstrated by the fossil record (Zhang and Barnes, 2007; Zhang, submitted). This widespread occurrence of Edenian strata demonstrates that the marine transgression was pronounced; a thin craton-derived basal clastic rock interval that directly unconformably overlies the Precambrian basement is followed by a thick succession of shallow subtidal to intertidal-supratidal carbonate facies with subordinate but locally important evaporites and local nearshore clastics. The preserved succession belongs to the parts of Tippecanoe and Kaskaskia sequences.

The Late Ordovician Tippecanoe I sub-sequence (Sloss, 1988) in Hudson Bay Basin is represented by three lithostratigraphic units of the Upper Ordovician; in ascendant order, they are 1) Edenian–Maysvillian Bad Cache Rapids Group of intertidal to shallow subtidal bioclastic limestone with basal orthoquartzitic sandstone; 2) lower Richmondian Churchill River Group that consists of open marine platform argillaceous bioclastic limestone; and 3) upper Richmondian Red Head Rapids Formation that comprises supratidal biohermal algal dolostones, brecciated dolostone and limestone, minor evaporite and thin black shales (Fig. 6). The Upper Ordovician stratigraphic assemblage is bounded by two unconformities, the Precambrian-Phanerozoic one at the bottom and the Ordovician-Silurian contact at the top; facies-wise, this Ordovician assemblage records a complete Edenian-Richmondian (middle–late Katian) T-R cycle (Zhang, submitted). They have been deposited within the time framework of the Taconic Tectophase of the Taconian Orogeny (Ettensohn, 2008). The initiation of the earliest significant transgression in Hudson Bay Basin is coeval with a widening of the Appalachian foreland basin (Zhang, in preparation) after plate convergence, subduction and eventual collision with island-arc terranes during the Taconic Tectophase (Ettensohn, 2008). The end-Ordovician regression that resulted in sub-aerial exposure and erosion is most likely associated with the latest Ordovician Gondwanan glaciation (Brenchley et al, 1994; Zhang and Barnes, 2007). The petroleum source rocks in the Red Head Rapids Formation were deposited during the short sea level bounce in the early stage of the regression (Zhang and Hefter, 2009).

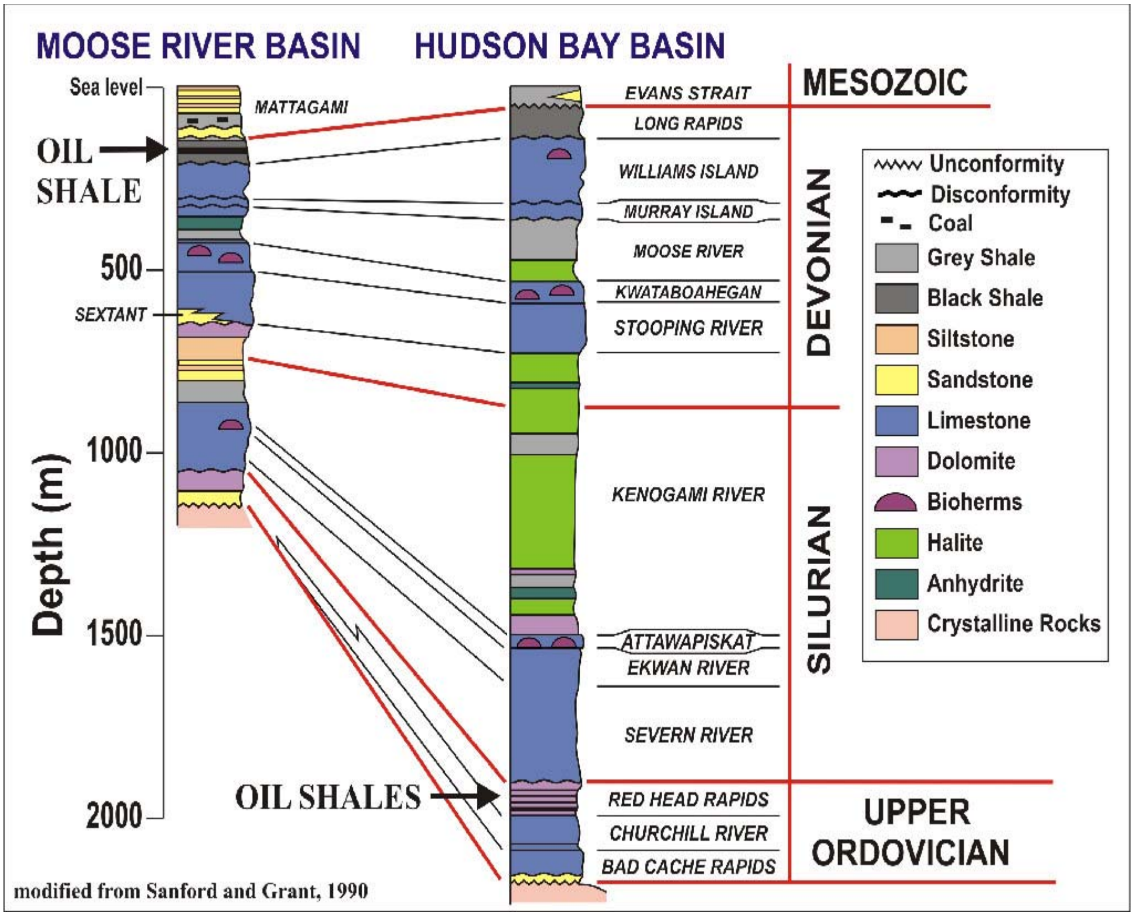

Fig. 6: Lithostratigraphic framework of Paleozoic and Mesozoic in Hudson Platform (adopted from Dietrich et al., 2009 and Lavoie et al., 2010) that was modified from Sanford and Grant (1990)

A disconformity between the Upper Ordovician Red Head Rapids Formation and the overlying Lower Silurian Severn River Formation separates the Tippecanoe I from the Tippecanoe II sub-sequence. This disconformity represents a depositional hiatus during the Gamachian (Hirnantian) or part of it (Zhang, submitted). Sedimentation resumed in the Early Silurian, which may correspond to craton-wide Early Silurian rejuvenation of transgression (Sloss, 1988; Lavoie, 2008; Ettensohn, 2008). Four major lithostratigraphic units were deposited during the early Rhuddanian–late Telychian of the Llandovery (Early Silurian) (Zhang and Barnes, 2007); in ascendant order, they are 1) the Rhuddanian–lowest Telychian Severn River Formation made up of intertidal-shallow subtidal fossiliferous limestone and some dolostone; 2) the lower Telychian Ekwan River Formation that consists of subtidal skeletal and pelletoidal limestone and fine-grained dolostone with upper part passing laterally into 3) the Attawapiskat Formation characterized by various sized metazoan-algal bioherms and shallow subtidal limestones; and 4) middle–upper Telychian Kenogami River Formation dominated by supratidal evaporites and dolostone (Fig. 6). The development of Attawapiskat Formation reef system may have been aided in part by reactivation of the various structural arches underlying the central portion of the basin (Sanford, 1987; Suchy and Stearn, 1993). The reactivation caused uplift, initially shoaling in the central basin area, and finally generating an emergent arch, the Central Hudson Bay Arch (Sanford and Grant, 1990), facilitating reef growth, and dividing the basin into eastern and western sub-basins (Fig. 5) (Roksandic, 1987; Burgess, 2008). This second deepening-shallowing succession (intertidal-shallow subtidal to subtidal, then to supratidal) represents lower part of Sloss' (1988) Tippecanoe II sub-sequence in Hudson Bay Basin.

Kaskaskia strata are separated from underlying Tippecanoe strata by an Early Devonian unconformity surface (Roksandic, 1987, Sanford and Grant, 1990). Based on conodonts, the middle member of Kenogami River Formation was correlated to the upper Telychian stage of the Llandovery (Zhang and Barnes, 2007); however, the upper member of the formation to the Gedinnian (Lochkovian) stage of the Lower Devonian (Norris, 1993b), but it is lacking fossil evidence to support this age assignment. Therefore, the upper member of the Kenogami Formation could range anywhere from the uppermost Llandovery to the lowermost Devonian. The unconformity that possibly separates the Kenogami Formation from the Stooping River Formation (Sanford, 1987; Sanford and Grant, 1990; Norris, 1993b) could be temporally correlative with the Late Silurian Salinic unconformity that is present in eastern Canada (Waldron et al., 1998; van Staal, 2005, Lavoie, 2008). This unconformity was developed from continental margin uplift at the time of accretion of Ganderia along the composite paleosouthern margin of Laurentia (van Staal, 2005); however, such correlation is highly speculative for now.

The Devonian strata in the Hudson Bay Basin are represented by a succession of Lower, Middle and Upper Devonian marine limestone, evaporites and mudstone (Fig. 6). Four Lower and Middle Devonian lithostratigraphic units were deposited in the two Hudson Bay sub-basins; in ascendant order, they are 1) the Emsian (Lower Devonian) Stooping River Formation formed by subtidal limestone; 2) the uppermost Emsian (Lower Devonian)–lowest Eifelian (lower Middle Devonian) Kwataboahegan Formation that consists of biohermal limestone; 3) the lower Eifelian Moose River Formation dominated by evaporites and shale and 4) the upper Eifelian Murray Island Formation of subtidal limestone (Sanford and Norris, 1975; Norris, 1993b). The two Hudson Bay sub-basins ceased to evolve as separate tectonic entities and merged into a single tectonic element in the late Middle Devonian and for the rest of the Devonian, as well as during the Cretaceous (Sanford and Grant, 1990). Locally, the Givetian (upper Middle Devonian) William Island Formation of biohermal limestone and dolostone overlapped the central tectonic high in the Hudson Bay sub-basins and unconformably rests over the Lower Silurian strata (Fig. 5) (Sanford and Grant, 1990). The upper Frasnian–lowest Famennian (Upper Devonian) Long Rapids Formation is the youngest undisputed Paleozoic rock unit in Hudson Bay Basin. It is composed of black shale, sandstone, carbonate and evaporite interbeds. The terrigenous detritus of the regions was obviously derived from a local provenance (Sanford, 1987), most likely from the numerous tectonic arches surrounding the basin (Fig. 2); however, no detailed provenance studies are available. If one assumed that no Carboniferous sediments have ever been deposited in Hudson Bay Basin, then the Kaskaskia Sequence was terminated by marine regression, and the Hudson Bay Platform was subjected to extensive erosion throughout the rest of Paleozoic time.

The palynological studies from the Narwhal O-58 suggest the presence of close to 170 m of Westphalian (Pennsylvanian) clastics and evaporites (Tillement et al., 1976). However, the conclusions of this report were largely ignored by the geoscience community (e.g., Hamblin, 2008). It is unclear if any and how much Absaroka strata

(Lower Carboniferous–Middle Jurassic, ~90 Ma) might have been deposited and subsequently eroded (Hamblin, 2008). If the uplift in the basin occurred in Mesozoic, it may have been due to uplift of eastern North America over a dynamic topographic high developed by Pangean mantle insulation (Burgess et al., 1997; Burgess, 2008).

The Zuni II sub-sequence in Hudson Bay Basin is represented by the Lower Cretaceous (?) Evans Strait Formation marine clastic rocks (Fig. 6) (Grant and Sanford, 1988). The thickness of Evans Strait Formation in the center of Hudson Bay Basin is unclear, but an interval (625–580 m) above the Long Rapids Formation in Beluga O-23 well (Fig. 2) is dark green fine grain clastic rocks based on well cuttings. The Evans Strait Formation is interpreted to be more than 1000 m thick in Evans Strait and Ungava Bay areas, and probably in excess of 2000 m beneath Foxe Channel (Sanford and Grant, 1990). The Cretaceous Mattagami Formation of non-marine sandstone, siltstone and coal has been mapped in the Moose River Basin (Sanford and Grant, 1990, 1998; Norris, 1993b). The similar Cretaceous sediments (up to 70 metres) have been reported from wells in the Winisk River area in the Hudson Lowland of northern Ontario (Ziegler and Rowley, 1994). All these elements suggest that some potential Mesozoic sedimentation over most of the Hudson Bay and Moose River basins in Cretaceous time is with major implications for the burial history of the basin.

3. Exploration History

(1) Pre-1960s

The earliest geological visits to the Hudson Bay region were made by Robert Bell in the 1870's. Before 1960s, many of the early explorers made reference to the physiography of the islands and indirectly to the geology in Hudson Bay Basin. The initial reconnaissance surveys were mostly restricted to Moose River Basin, which provided the information on stratigraphy, paleontology, structural geology, mineral resources and hydrocarbon potential (see Norris, 1993a for references).

Sporadic exploration for oil and gas by drilling started in 1923, as well as a few onshore shallow wells were drilled in the 1940s (Hamblin, 2008).

(2) 1960s–1980s

This roughly 20 year period was the most active one in the exploration and geological studies of the Hudson Bay area.

A. Geological studies: The first detailed reports on Ordovician stratigraphy and paleontology of the northern Hudson Bay Lowland and summaries of the geology of Hudson Bay Platform were made by Nelson (1963, 1964) and Nelson and Johnson (1966). During the Operation Kapuskasing and Winisk, the Ontario Department of Mines and the Geological Survey of Canada mapped the Hudson Bay Lowland at the regional scale. A symposium volume (Hood, 1969) reports on the Precambrian rocks, Paleozoic, Mesozoic and Pleistocene geology of the Hudson Bay onshore and offshore domains. Combing the Paleozoic geology of the Hudson Bay Lowlands with the new seismic and well data from subsurface, a generalized geological map of Hudson Platform was constructed by Sanford (in Sanford and Norris, 1973); this map first illustrated the offshore distribution of Paleozoic formations. The Precambrian and Paleozoic geology of

Southampton, Coats and Mansel islands initially described by Heywood and Sanford (1976) generated more data for understanding the geological history of the Hudson Bay Basin (see Norris, 1993a for detailed history of geological investigations).

B. Petroleum exploration: The industrial drillings for oil and gas started onshore with Kaskattama No. 1 in 1966, and three other onshore wells (Fig. 2; Appendix 1) were drilled during 1970s. The offshore drilling began with Walrus A-71 in 1969, the last two offshore well (Beluga O-23 and Netsiq N-01) were completed in fall 1985 (Fig. 2; Appendix 1). No commercial discoveries have been reported from all these wells. However, most of the offshore wells targeted the structural high associated with the Central Uplift, where only a thin section of primarily Devonian strata is present (Sanford and Grant, 1990; Sanford et al., 1993). Moreover, a large numbers of other hydrocarbon plays are still untested; these include Ordovician–Devonian reefs and Paleozoic hydrothermal dolomites (Sanford and Grant, 1990; Dietrich et al., 2009; Lavoie et al., 2010). Bitumen has been reported from vuggy porosity in Late Ordovician reefs (Procter et al., 1984).

C. Geophysical studies: Geophysical studies have contributed significantly toward establishing the distribution and thickness of the sediments, and basement structure of both Hudson Bay and Moose River basins. These studies are critical given the largely marine nature of the Hudson Platform and the general paucity of outcrops in the onshore belt of the platform in Manitoba, Ontario and Quebec.

- Regional magnetic survey: Regional magnetic profiles interpreted by Bower (1960) and Hood (1964) indicated a substantial thickening of the Paleozoic strata beneath Hudson Bay, which stimulated the interest of the petroleum exploration industry (Norris, 1993b). Shipborne surveys in the summers of 1975 to 1978 provided the first overview of the principal magnetic anomalies (Coles and Haines, 1982). The Geological Survey of Canada (1987) first outlined the interior zone of the Trans-Hudson Orogen within the Precambrian basement of Hudson Bay Basin (Hoffman, 1988; Norris, 1993b).
- Gravity survey: The Geological Survey of Canada (1980) completed a regional gravity coverage over Hudson Bay, James Bay and adjacent onshore regions. This survey improved the knowledge about the Precambrian basement beneath the Hudson Bay Basin. The maps of the horizontal gradient of the Bouger anomaly (Sharpton et al., 1987) depicted the structural trends beneath the Hudson Platform. Based on the gravity domains, Thomas et al. (1988) interpreted that the Trans-Hudson Orogen (Hoffman, 1988) underlies much of Hudson Platform.
- Seismic refraction surveys: The earliest seismic refraction work in the region was carried out in the Hudson Bay Lowlands in 1963 and 1964 (Hobson, 1964a). It was followed by a large-scale crustal refraction experiment in 1965 (Norris, 1993b). Importantly, this work helped to recognize that around 2000 m of Phanerozoic strata are present in the central part of the Hudson Bay Basin (Hobson, 1964a, 1964b, 1967).
- Seismic reflection surveys: Several oil companies carried out seismic surveys in Hudson Bay in the early 1960s. Over 46 000 linear-km of industry seismic data was acquired during the first round of exploration. These seismic lines are of variable quality ranging from poor (most of the lines) with multiple sea bottom reflectors to fair (few lines) and even good quality (Dietrich et al., 2009; Lavoie et

al., 2010). Moreover, in the same general period of time, the Geological Survey of Canada acquired close to 31 000 linear-km seismic lines of high resolution but low penetration, largely for surface-Quaternary sediments projects. The GSC seismic covered almost entirely the Hudson Bay Basin and the Hudson Strait, but not a single seismic line has ever been shot in the Foxe Basin. The tectonostratigraphic model of the saucer-shaped Hudson Bay Basin interrupted by a linear, NNW-trending, central horst block with relief about 1 km (Fig. 5) (Norris, 1993b) is largely derived from the industry seismic; however, given the near total absence of data outside the central domain and the absence of Paleozoic outcrops at the eastern end of the Hudson Bay, the model is still speculative.

(3) 1990s and afterward

Not much hydrocarbon-oriented exploration activities happened during the 1990s and afterward. During 2007–2008, both Geological Survey of Canada and Canada-Nunavut Geoscience Office have initiated and carried out a Southampton Island Integrated Geoscience project aiming at improving our understanding of the Precambrian, Paleozoic and Quaternary geology. This initiative generated significant new data to better understand the Paleozoic history and petroleum potential in Hudson Bay Basin (Zhang, 2008). Finally, in 2009, as part of the new Geo-mapping for Energy and Minerals (GEM) program of the Earth Science Sector, the Geological Survey of Canada launched the "Hydrocarbon potential of the Hudson Bay and Foxe basins" project that aims at 1) recognizing hydrocarbon system elements in these basins, 2) defining the most prospective hydrocarbon plays and 3) quantitatively assessing the potential of hydrocarbon resources in these basins (Dietrich et al., 2009; Lavoie et al., 2010).

4. POTENTIAL PETROLEUM SYSTEM

(1) Source rocks and maturation

The organic-rich "Boas River shale" (Sanford in Heywood and Sanford, 1976) and "Sixteen Mile Brook shale" (Nelson and Johnson, 1966) were discovered on Southampton Island about 40 year ago, but problems of stratigraphic correlations immediately stood out. The recent discovery of three oil shale intervals in the Cape Donovan area on Southampton Island unequivocally demonstrated that 1) the three oil shale intervals in the Cape Donovan area are within the unit 1 of Upper Ordovician Red Head Rapids Formation; and 2) the "Boas River shale" and "Sixteen Mile Brook shale" are stratigraphically correlative to the Cape Donovan lower and middle oil shale intervals, respectively (Zhang, 2008; submitted). The detailed analysis of the gamma-ray logs and bitumen and black shale particles in well cuttings from the Hudson Bay offshore wells led to the recognition of the three oil shale intervals in the lower Red Head Rapids Formation in the offshore area (Zhang, 2008). Rock-Eval[6] data from the three oil shale intervals in the Cape Donovan sections lead to the recognition of Type I–Type II kerogen and much higher yield and TOC than those in the previous report (Macauley, 1986). The middle (0.4 m) and upper (0.5 m) oil shale intervals have average and maximum yields of 136.5 kg HC/tonne and 230 kg HC/tonne, and average and maximum TOC of 20% and 34%; and lower (>1 m) oil shale interval has mean and highest yields of 58.5 kg

HC/tonne and 112.5 kg HC/tonne, and mean and highest TOC of 9.8% and 17.3% (Zhang, 2008).

Upper Ordovician bituminous limy shale has been described from wells as "Boas River Shale" in northern Ontario (McCracken, 1990); these limy shales have been recently sampled for detailed Rock Eval analysis (D. Lavoie, pers. comm. 2010).

In addition, at the top of the Upper Devonian (710–630 m) in Beluga O-23 well (Fig. 2), significant amount of black shale fragments have been found from the well cuttings by the author. However, the geochemistry data have not been collected yet. This interval most likely equates to the Long Rapids Formation in Moose River Basin, where TOC averages 4.3% (Bezys and Risk, 1990).

So far the only available thermal maturity data (Tmax) for Hudson Bay Basin are those provided by Macauley (1986), Zhang (2008) and Zhang and Dewing (2008). Zhang and Dewing (2008) gave equivocal conclusions with the base of the two wells (Polar Bear C-11 and Narwhal O-58) within the oil window, because of the data collected from limestone cuttings (TOC<0.3%). Zhang (2008) provided more reliable data by using the oil shale samples from outcrops on Southampton Island and black shale and bitumen fragments picked from well cuttings in Polar Bear C-11, which basically concluded the immature nature of the oil shale—all Tmax values are below 435°C; however, high PI values (0.1-0.67) are seen at three different intervals roughly correlative with three positive gamma kicks in Polar Bear C-11, showing an inconsistent relationship between Tmax and PI. Therefore, a detailed organic matter reflectance study of the Hudson Bay offshore wells has been initiated (D. Lavoie, pers. comm. 2010).

(2) Potential Reservoir facies

Within the Upper Ordovician succession, the unit 2 of Red Head Rapids Formation, the 10-15 m thick brecciated dolostone and dolomitic limestone with abundant porosity, overlies the upper oil shale interval of the unit 1 (Zhang, 2008). This unit, if porous in the subsurface, would provide an exquisite hydrocarbon reservoir. In the same formation, the unit 3 that consists of thick-massive biostromal dolostone and dolomitic limestone and the unit 4 made up of thin layered dolomitic limestone with biohermal structure up to 300–400 m in diameter and 6–7 m of relief (Zhang, 2008) also offer a significant potential reservoir facies. For all the Upper Ordovician carbonates, the potential of fault controlled hydrothermal dolomitization has to be conceptually envisaged; such hydrothermal dolomites have been tentatively recognized in coeval Upper Ordovician units in Manitoba (Nicolas and Lavoie, 2009).

Within the Lower Silurian succession, small stromatolitic/coral bioherm complexes and mounds are present in the Severn River Formation, although the major potential reservoir unit is represented by patch reefs of the Attawapiskat Formation (Sanford and Norris, 1973; Hamblin, 2008). The patch reefs in the Attawapiskat Formation comprise atoll-like stromatoporoid/coral buildups up to 200 m in diameter and up to 10 m of relief with porosities ranging as high as 35% and averaging 7–10% (Suchy and Stearn, 1993; Hamblin, 2008).

The distribution of the Devonian strata is not as wide as that of the Ordovician and Silurian strata; but the fossiliferous and porous biohermal shelf-edge reefal carbonates of the Middle Devonian Kwataboahegan and William Island formations can be significant potential reservoirs (Sanford, 1987; Hamblin, 2008).

(3) Traps and seals

The time relationships between subsidence, faulting, folding, trap formation, diagenesis and possible hydrocarbon migration are currently poorly understood (Hamblin, 2008). However, the potential traps and seals can be identified from the stratigraphy and the structure developed in the Hudson Bay Basin.

Seismic reflection data in Hudson Bay Basin indicate the widespread presence of structural (block-faulted) or stratigraphic (unconformity, pinch-outs) features that could conceivably be favourable for the entrapment of hydrocarbons (Sanford et al., 1993). Seismic sags have been identified on fair quality seismic lines, supporting the hydrothermal dolomite type of play and its tectono-diagenetic traps (Lavoie et al., 2010). The late Early Silurian timing of uplift was the key to developing the Central Uplift and localizing Attawapiskat reef unit in the center of the Hudson Bay Basin.

The Upper Ordovician, Lower and Upper (?) Silurian, Devonian and Lower Cretaceous stratigraphy offers multiple potential stratigraphic pinch-outs, unconformities and regional evaporite and shale seals. The best source rocks are the Upper Ordovician black shale near the base of the stratigraphic pile; good Upper Ordovician porous breccia dolostone, Silurian and Devonian porous reef reservoir rocks stratigraphically overlie the source rock and thick Silurian and Devonian evaporite/shale seal horizons are commonly developed over the potential conventional reservoirs. In the central segment of the Hudson Basin, the Paleozoic succession is topped by the Upper Devonian Long Rapids Formation shale and capped by Lower Cretaceous strata, which are both dominated by fine grained deposits and may form good regional seals (Hamblin, 2008).

(4) Exploration Plays

Four different conceptual play types in the Hudson Platform have been suggested by Dietrich et al. (2009) and Lavoie et al. (2010) (Fig. 7). They are the basement fault block play, hydrothermal dolomite play, Devonian-Ordovician reef plays, and salt dissolution play.

If high quality source rocks, reservoirs and seals are present in the Hudson Bay Basin, the most critical problem to tackle in order to demonstrate the hydrocarbon prospectivity of the basin is the level of thermal maturity reached by the source rocks. Due to the limited methodology (Tmax) employed by the previous studies (Macauley, 1986; Zhang, 2008; Zhang and Dewing, 2008) in collecting the thermal maturity data, the current “Hydrocarbon potential of the Hudson Bay and Foxe basins” project is using complementary tools, such as Apatite Fission Tracks and Helium gas in Apatites as well as organic matter reflectance, in order to assess the burial/exhumation and thermal histories of the Hudson Bay and Foxe basins (D. Lavoie, pers. comm. 2010).

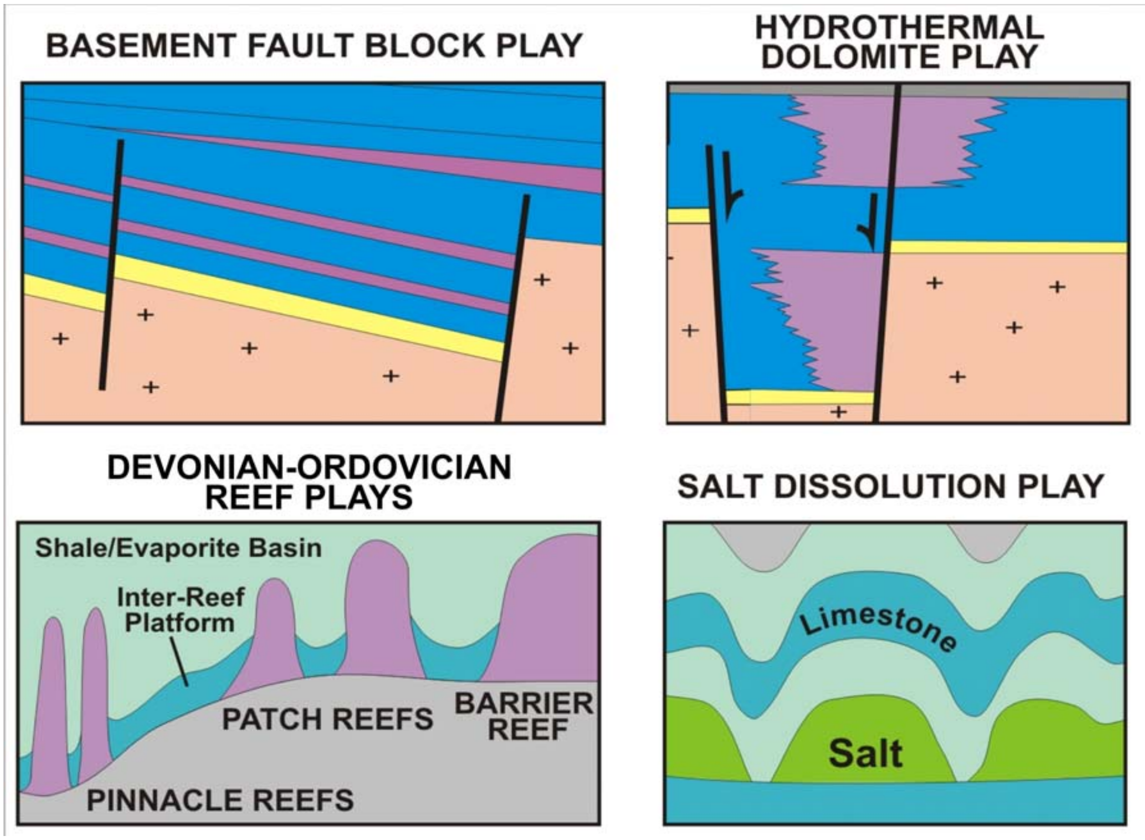

Fig. 7: Some potential hydrocarbon plays in the Hudson Platform (slightly modified from Dietrich et al., 2009 and Lavoie et al., 2010).

5. UPPER ORDOVICIAN STRATIGRAPHY ON SOUTHAMPTON ISLAND

The Upper Ordovician and Lower Silurian units are distributed on the southern and western parts of Southampton Island; the Upper Ordovician rocks are discontinuously exposed along the rivers and creeks in the central and southeastern parts of Southampton Island (Fig. 8).

(1) Bad Cache Rapids Group

The Bad Cache Rapids and Churchill River groups were proposed by Nelson (1963, 1964) for Ordovician strata of the Hudson Bay Lowlands in Manitoba. The Bad Cache Rapids and Churchill River groups were first identified on Southampton Island by Nelson and Johnson (1966).

The Bad Cache Rapids Group unconformably overlies the Precambrian basement. It includes two different lithological units, a thin basal clastic rock interval (~ 2 m) and a dark grey or brownish grey fossiliferous limestone. The basal clastic rock and its unconformable contact with the Precambrian basement can be seen in several localities (localities 1, 3, 5, and 6) on Southampton Island. The limestone unit makes up the bulk of the group; the typical sedimentary feature throughout the limestone unit is the irregular

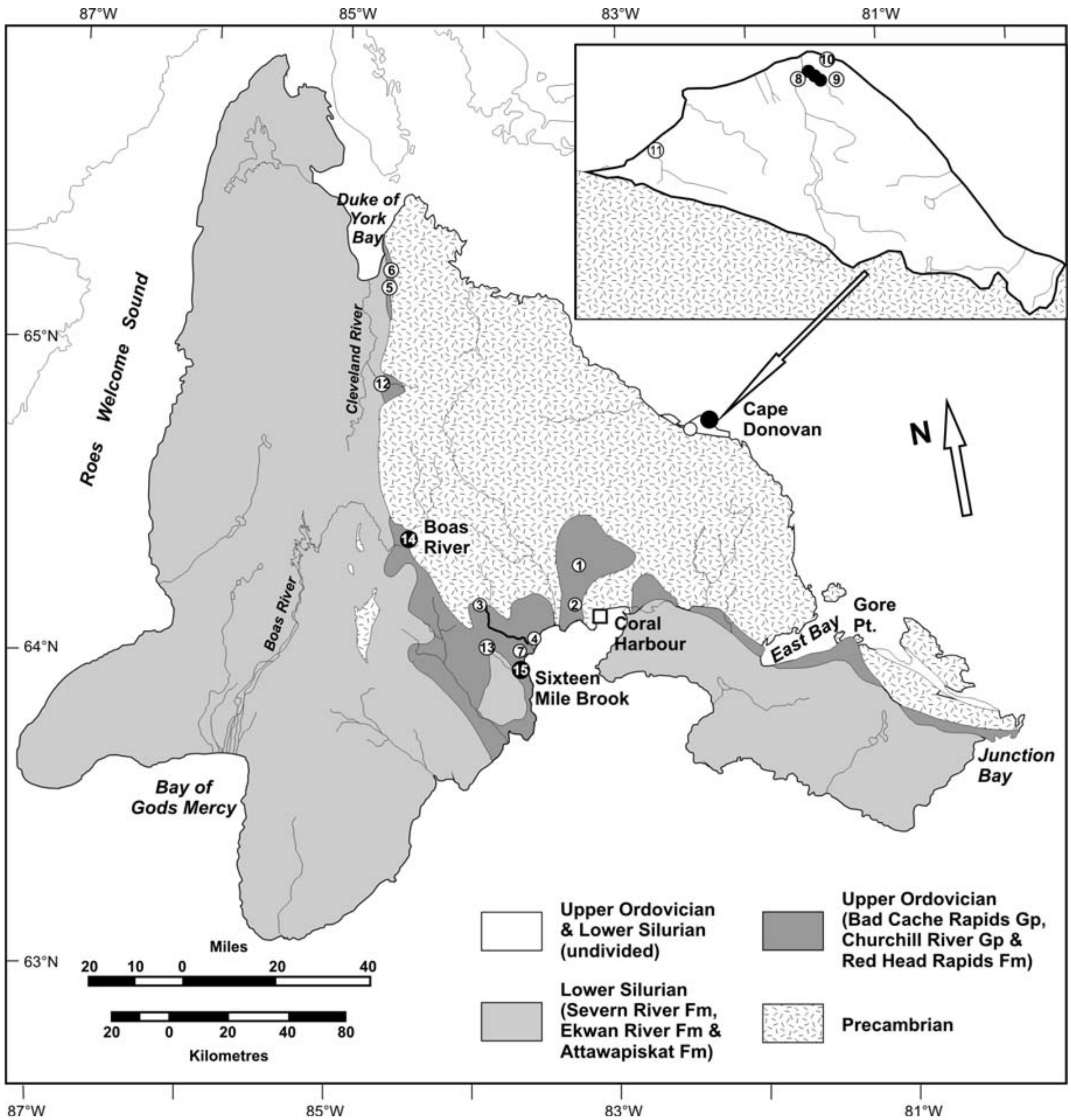

Fig. 8: Simplified geological map of Southampton Island with locations of the outcrops that will be visited during this field trip. See Appendix 2 for location names, geographic coordinates, and stratigraphic units exposed; black circles represent oil shale localities. See Appendix 3 for 1:500,000 geological map (Heywood and Sanford, 1976) with locations.

zones (~ 0.5–1 cm) of yellowish-orange mottling (Fig. 10H) resulted from incipient secondary dolomitization in extensively bioturbated strata (Sanford in Heywood and Sanford, 1976). The middle and upper parts of the limestone unit are rich in fossil corals, gastropods, nautiloids, algae, and crinoids. An Edenian-Maysvillian age is assigned to the Bad Cache Rapids Group based on the conodonts collected from continuous section at locality 6 as well as other sections at localities 2, 3, 5 and 8 on Southampton Island (Zhang, submitted).

The total thickness of the group, measured in a complete section at locality 6 on Southampton Island, is about 65 m.

(2) Churchill River Group

The Upper Ordovician Churchill River Group conformably lies on top of the Bad Cache Rapids Group. It is composed of greenish grey or greyish brown argillaceous bioclastic limestone. The contact between the Bad Cache Rapids and Churchill River groups was interpreted as a disconformity, or there is an interval of “Boas River shale” between them as suggested by Sanford (in Heywood and Sanford, 1976).

Sanford (in Heywood and Sanford, 1976) proposed that the “Boas River shale” is a thin unit between the Bad Cache Rapids and Churchill River groups, but this shale interval does not exist in most areas of the Hudson Bay Basin. Therefore, a disconformity between the Bad Cache Rapids and Churchill River groups has been interpreted or illustrated by previous authors (e.g., Ludvigsen, 1979; Dewing et al., 1987; McCracken and Nowlan, 1989; Norris, 1993b). This disconformity has been ascribed to represent a Late Ordovician (Maysvillian) hiatus, or subaerial erosion (Sanford in Heywood and Sanford, 1976; Sanford, 1987; Norris, 1993b).

Several sections on Southampton Island contain the boundary interval between the two groups (localities 4, 5, 6, and 8), where the rocks below and above the boundary can be easily differentiated based on the following field observations: 1) the thick layered dark grey limestone with yellowish-orange mottling in the uppermost Bad Cache Rapids Group is overlain by the thin layered dark greenish grey argillaceous bioclastic limestone in the lowest Churchill River Group; 2) the Bad Cache Rapids Group contains abundant macrofossils whereas the Churchill River Group lacks macrofossils; 3) the lower Churchill River Group is more easily eroded than the upper Bad Cache Rapids Group; therefore, the boundary interval always forms stair-step topography. However, no field evidence was ever found to prove the presence of a hiatus or subaerial erosion, moreover, no oil shale interval was found between these two units. Therefore, the contact between the Bad Cache Rapids and Churchill River groups is conformable, and the oil shale interval does not exist between the two groups.

Nelson and Johnson (1966) discovered the “Sixteen Mile Brook shale”. The stratigraphic position was first interpreted as being at the top of the Churchill River Group (Nelson and Johnson, 1966) and later as being somewhere in the Red Head Rapids Formation (Sanford in Sanford and Heywood, 1976). Only one section (locality 7) found on Southampton Island contains the upper Churchill River Group, where the rocks consist of homogenous limestone without any shale interval.

No complete section containing the entire Churchill River Group was found; because of the limited outcrops, the thickness of the group is unknown on Southampton Island.

Conodonts collected from lower and upper Churchill River Group at localities 5–8 on Southampton Island indicate an early Richmondian age for the group (Zhang, submitted).

(3) Red Head Rapids Formation

The Red Head Rapids Formation conformably overlies the Churchill River Group, and it is disconformably overlain by the Lower Silurian Severn River Formation. An orange-tan color and high dolomitic content allow an easy differentiation of the Red Head Rapids Formation from the underlying units.

The Red Head Rapids Formation was divided into 3 units by Sanford (in Heywood and Sanford, 1976). In addition to Sanford's three units, Zhang (2008) found a breccia unit between Sanford's units 1 and 2. On this basis, the formation was subsequently divided into four units (Zhang, 2008): unit 1 (29 m), thin-layered and laminated argillaceous dolomitic limestone interbedded with three oil shale intervals; unit 2 (10-15 m), massive breccia dolostone/limestone; unit 3 (>10 m), thick, massive biostromal dolostone and dolomitic limestone; and unit 4 (thickness uncertain), thin-bedded dolomitic limestone with bioherms (~ 6–7 m of relief). All the four units are almost consecutively exposed at localities 9 and 10, and partially exposed at localities 7, and 11–15.

The three oil shale intervals in unit 1, discovered at locality 9 in Cape Donovan on Southampton Island, were informally named lower (>1 m), middle (0.4 m) and upper (0.5 m) oil shale intervals; based on both sedimentary and paleontological features, "Boas River shale" (Sanford in Heywood and Sanford, 1976) and "Sixteen Mile Brook shale" (Nelson and Johnson, 1966) were correlated to the lower and middle oil shale intervals (Zhang, 2008, submitted).

The boundary between the Churchill River Group and Red Head Rapids Formation is transitional; practically, the base of the Red Head Rapids Formation was placed at a 15-cm dark brown shaly dolomitic limestone at locality 7 by the author during the field study in 2007.

A late Richmondian age is given to the Red Head Rapids Formation according to the conodonts from sections at localities 7, 9, 10 and 12–15 on the island (Zhang, submitted).

6. Outcrops Showing Upper Ordovician–Lowest Silurian Strata

Locality 1: East of Post River
The lower Bad Cache Rapids Group

Locality 1 (64°17′04.9″N, 83°06′23.8″W) is on the east side of Post River, about 17 km north-northeast of Coral Harbour. It is accessible by ATV from Coral Harbour on a gravel road and a hunting trail.

This outcrop (Fig. 9) best exposes the basal sandstone unit and the lowest part of the limestone unit of the Bad Cache Rapids Group on Southampton Island. About 11–12 m of strata is exposed at this locality; the lower part is a 1.3 m of sandstone containing abundant trace fossils (vertical burrows). The contact between the basal sandstone of the Bad Cache Rapids Group and the Precambrian is not exposed at this locality.

Fig. 9: Outcrop at locality 1, East of Post River – lower Bad Cache Rapids Group.

Locality 2: Fossil Creek
The middle Bad Cache Rapids Group

Locality 2 (from 64˚10′58.73″N, 83˚21′42.29″W to 64˚10′45.98″N, 83˚21′16.66″W) is at the Fossil Creek site, a potential Nunavut Territorial park. It is about 10 km northwest of the community of Salliq (Coral Harbour), and about 1–2 km southwest of the Coral Harbour airport runway. This locality is where "The Great Fossil Hunt" takes place. The outcrops are along Fossil Creek from the bridge piers to the north where the outcrop pinches out, extending for about 300 metres. The macrofossils can be found both in outcrops and amongst the rubble, including corals, gastropods, nautiloids, algae, and crinoids. Fig. 10 shows some representative macrofossils from Fossil Creek. Besides the typical Bad Cache Rapids lithology, the fossil algae *Fisherites arcticus* (Etheridge) and gastropod *Maclurites* sp. are more common than other fossils, and are good indicators of the Bad Cache Rapids Group. Conodonts from this locality define the strata at this locality as near the middle–upper interval of the group (Zhang, submitted).

Localities 3 and 4: Rocky Brook

1) **Unconformity between the Precambrian and the Bad Cache Rapids Group**
2) **Conformable contact between the Bad Cache Rapids and Churchill River groups**

The Bad Cache Rapids Group is well exposed along Rocky Brook. Locality 3 is on its upper reaches at 64°10'02.81"N, 83°56'44.55"W where the Bad Cache Rapids Group unconformably covers the Precambrian basement. However, the basal sandstone is covered at this locality, and it needs some digging to be exposed (Fig. 11). In this area, bedding is almost horizontal; walking a long distance along the brook, you are probably still in the same stratigraphic level. From locality 3 to locality 4 along the brook, the Bad

Cache Rapids Group limestone is intermittently exposed for about 28 km.

Locality 4 is at 64°02'25.8"N, 83°35'51.1"W, near the mouth of Rocky Brook and close to the coast, where the upper Bad Cache Rapids and lower Churchill River groups as well as the boundary between the two units are excellently exposed (Fig. 12). It is easy to differentiate the thick layered dark grey limestone of the uppermost Bad Cache Rapids Group from the thin layered dark greenish grey argillaceous limestone of the lowest Churchill River Group. Because of the argillaceous nature of the upper Churchill River Group, it is more easily eroded than the Bad Cache Rapids Group; therefore, the Bad Cache Rapids-Churchill River boundary interval forms the stair-step topography at this locality. However, there is no evidence of a hiatus, and no oil shale exists between the two groups.

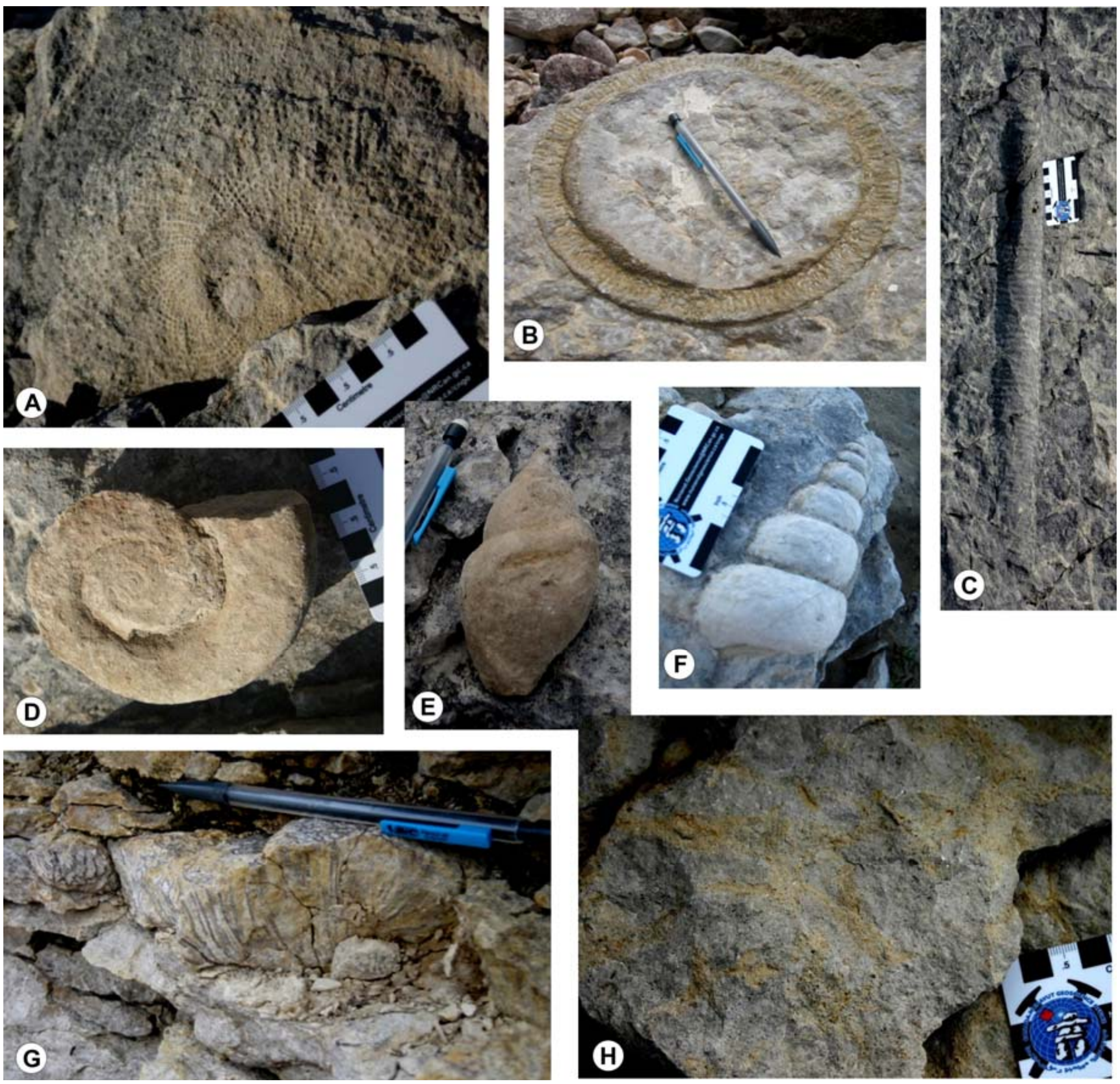

Fig. 10: Macrofossils and mottling on the bedding plane of limestone in the Bad Cache Rapids Group at Fossil Creek. A and B. *Fisherites arcticus* (Etheridge) (algae); C. *Endoceras* sp. (nautiloid); D. *Maclurites* sp. (gastropod); E. *Seelya ulrichi* Schuchert (gastropod); F. *Hormotoma* sp. (gastropod); G. unidentified colony coral; H. mottling on the bedding plane of limestone.

Fig. 11: Unconformity between the Precambrian and Bad Cache Rapids Group at locality 3 on the upper reaches of Rocky Brook.

Fig. 12: Conformable contact between the Bad Cache Rapids and Churchill River groups at locality 4 near the mouth of Rocky Brook.

Locality 5: Duke of York Bay area (1)

1) **Unconformity between the Precambrian and Bad Cache Rapids Group**
2) **Conformable contact between the Bad Cache Rapids and Churchill River groups**

In the Duke of York Bay area, the Bad Cache Rapids Group is well exposed along a couple of creeks running in the same direction as the limestone dip towards the Duke of York Bay. The rocks here are tilted about 10–20° by a possible fault; therefore, in about 400–500 m distance, the entire Bad Cache Rapids Group can be examined. The outcrop starts at 65°12'55.1"N, 84°38'45.4"W where the basal sandstone of the Bad Cache Rapids Group unconformably sits on the Precambrian basement (Fig. 13). To the west at 65°12'55.8"N, 84°39'14.2"W, the upper Bad Cache Rapids and lower Churchill River groups are exposed (Fig. 14). Although the contact between the two groups is covered by the rubble, the difference between the two groups in sedimentary structure and color can be easily recognized. This is also a good locality to see the rich macrofossils in the upper Bad Cache Rapids Group. In contrast, there are almost no macrofossils in the lower Churchill River Group. The Richmondian conodont *Amorphognathus ordovicicus* Branson and Mehl is found immediately above the covered interval (Zhang, submitted), which confirms that the dark greenish thin layered argillaceous limestone seen on the right in Fig. 14 is the lower Churchill River Group. Again, no oil shale interval, and no oil shale rubble are found here at locality 5.

Fig. 13: The contact between the Precambrian and basal sandstone of the Bad Cache Rapids Group at locality 5.

Fig. 14: Upper Bad Cache Rapids Group and Lower Churchill River Group at locality 5; the contact between the two units is covered by rubble.

Locality 6: Duke of York Bay area (2)

1) **Unconformity between Precambrian and Bad Cache Rapids Group**
2) **Conformity between Bad Cache Rapids and Churchill River groups**

The rocks exposed at locality 6 (65°15'51.70"N, 84°37'33.50"W) are similar to those at locality 5. At this locality, the Bad Cache Rapids Group itself is better exposed than at locality 5, but the boundary intervals between Precambrian and Bad Cache Rapids Group and between Bad Cache Rapids and Churchill River groups are not as good as those at locality 5. This locality can be reserved as an option.

Locality 7: Near the coast between Sixteen Mile and Rocky brooks

1) **Upper Churchill River Group**
2) **Transition from Churchill River Group to Red Head Rapids Formation**
3) **Lower Red Head Rapids Formation**

Locality 7 is close to the shoreline between Rocky Brook and Sixteen Mile Brook, and it is about 35 km southwest of the community of Coral Harbour. It is accessible by vehicle or ATV via the gravel road along the coast.

Fig. 15: A scarp at locality 7 where the upper Churchill River Group is exposed; black arrow points a small gully exposing the contact between the Churchill River Group and Red Head Rapids Formation.

First we will stop at 64°02'2.90"N, 83°39'22.10"W, where you can see an approximately 350 m long north-south extended scarp (Fig. 15) that is composed of about

4 m of tightly packed, thin layered argillaceous limestone of the upper Churchill River Group.

This scarp is perpendicularly cut by a small unnamed gully indicated by a black arrow in Fig. 15. Near the mouth of the gully, the contact between the Churchill River Group and Red Head Rapids Formation and the lower beds of unit 1 of the Red Head Rapids Formation are well exposed (Fig. 16A). This is the only known outcrop showing the contact between these two units on Southampton Island. The boundary is transitional; practically, the base of Red Head Rapids Formation was marked by a 15 cm shaly brown dolomitic limestone by the author in 2007 field study (Fig. 16B). Above this shaly brown dolomitic limestone, the rocks are different from both the Bad Cache Rapids and Churchill River groups in color and composition. They are orange-tan color (Fig. 16D) and tend to be more dolomitic. The shaly brown dolomitic limestone (Fig. 16B) marks the point where the conodont fauna changed from *Amorphognathus ordovicicus*-dominated to *Rhipidognathus symmetricus*-dominated (Zhang, submitted). Above this interval the lowest unit 1 of the Red Head Rapids Formation is exposed on the two sides of the gully (Fig. 16D). Two very thin layers of black shale were found almost at the top of the outcrop (Fig. 16C and 16E). The shales are separated by a 15 cm thin-bedded dolomitic limestone; the shales themselves are only 5 mm thick or less, but contain high TOC (30%; unpublished data) and can be burnt easily. To the north of this small gully, it is a boundless stretch of plateau covered by carbonate rubble, among which dark brown argillaceous limestone and some black shale can be easily found (Fig. 16F and 16G).

The very thin black shale layers in the outcrop and the dark brown argillaceous limestone and black shale rubble on the adjacent plateau allow for defining the stratigraphic setting of the very thin black shales at this locality; obviously, these are the lowest stratigraphic occurrences of the oil shale within the Upper Ordovician on Southampton Island, based upon the stratigraphic units observed at the previous localities.

If the “Boas River shale” and “Sixteen Mile Brook shale” were the only two shales on the island, the very thin black shale layers and black shale and brown argillaceous limestone rubble at this locality should represent either of them or both of them, and the stratigraphic position of the “Boas River shale” or “Sixteen Mile Brook shale” or both of them should be within the Red Head Rapids Formation. The strata equal to the three oil shale intervals exposed at locality 9 in Cape Donovan area must have been removed by erosion at this locality.

Locality 8: Cape Donovan area (1)
Conformable contact between the Bad Cache Rapids and Churchill River groups

Cape Donovan is located along the northeast coast of Southampton Island. In the Cape Donovan area, the Paleozoic rocks are isolated in a small triangle area of only about 35 km^2, and are deeply cut by the creeks or exposed by scarps.

Locality 8 (Fig. 17) is near the mouth of a creek running into the Foxe Channel at 64°45'40.01"N, 82°22'40.6"W. At this locality, the uppermost Bad Cache Rapids and lowest Churchill River groups as well as the conformable contact between the two groups are well exposed. The conodont samples were collected at close intervals (< 1 m); the change from *Belodina confluens*-dominated fauna to *Amorphognathus ordovicicus*-

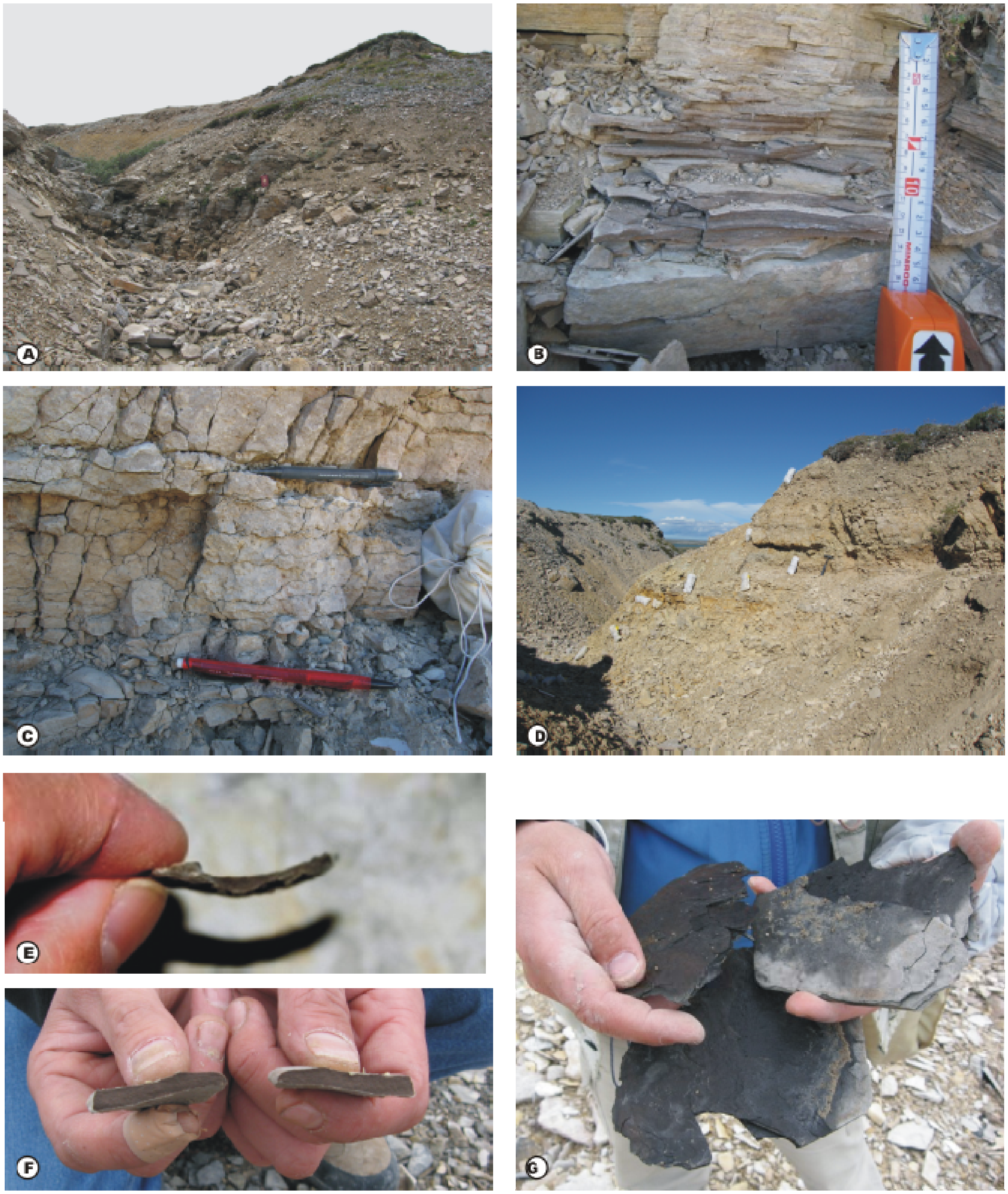

Fig. 16: A. transitional bed between the Churchill River Group and Red Head Rapids Formation; B. close view of shaly brown dolomitic limestone at the base of the Red Head Rapids Formation; C. two very thin layers of black shale at the positions of two pencils; D. outcrop of the Red Head Rapids Formation stratigraphically above that in B; E. a thin layer of black shale taken from the outcrop at the position with a red pencil; F and G. brown argillaceous dolomitic limestone and black shale rubble found at the top of the outcrop.

dominated fauna coincides with the change from thick layered dark grey limestone of the Bad Cache Rapids Group to the thin layered dark greenish grey argillaceous limestone of the Churchill River Group (Zhang, submitted). The same stratigraphic interval is exposed at locality 4, and like the latter locality, the interval at locality 8 also forms the stair-step topography.

Again, no oil shale interval is found between these two units, and no field evidence can prove the existence of a hiatus between the two units.

Fig. 17: Conformable contact between the Bad Cache Rapids and Churchill River groups at locality 8.

Locality 9: Cape Donovan area (2)
Units 1–3, Red Head Rapids Formation

Another partially snow/ice-covered creek is located east of the locality 8. Units 1–3 of the Red Head Rapids Formation are well exposed along the creek from 64°45'43.9"N, 82°22'37.9"W close to the coast line to 64˚45'42.7"N, 82˚22'31.3"W in the middle reaches of the creek.

The overall appearance of the rocks exposed along the creek is obviously different from that at locality 8; it is orange–tan weathering, light–medium brown in color, which is an important feature for all the units of the Red Head Rapids Formation.

Unit 1

Unit 1 is composed of thin-bedded and finely laminated argillaceous limestone, platy and shaly limestone and dolostone interbedded with thick dolostone and fossiliferous limestone, as well as oil shale in three distinct intervals.

The lowest stratigraphic interval exposed on the two sides of this creek is the lower oil shale interval (> 1 m) of unit 1 (Zhang, 2008) at 64°45'34.3"N, 82°22'23.3"W (Fig. 18A–C). This locality is likely above the strata at locality 7, although not much strata are likely missing between localities 7 and 9.

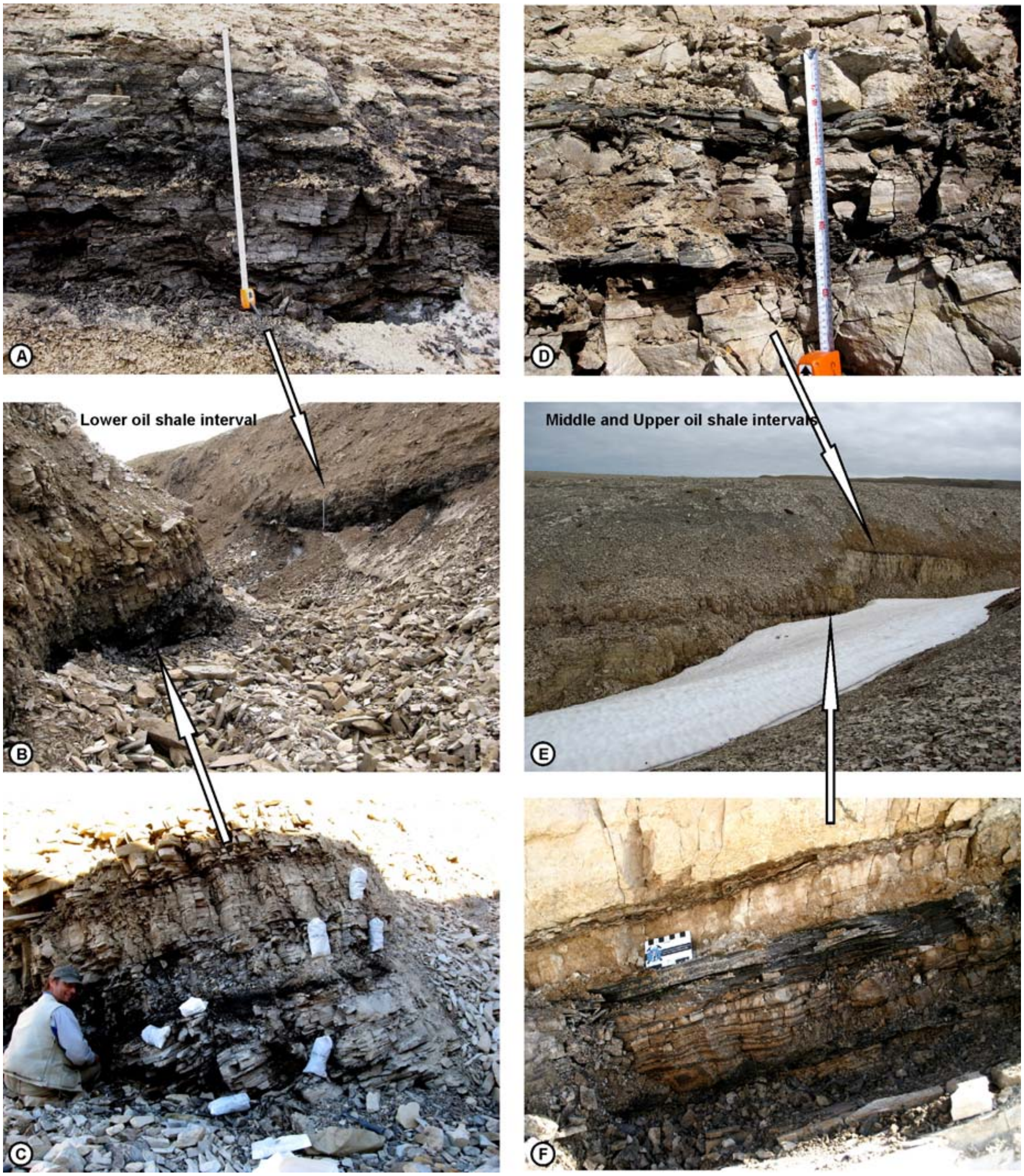

Fig. 18: The three oil shale intervals in unit 1, Red Head Rapids Formation exposed in the same partially ice-covered creek in the Cape Donovan area. B. the lower oil shale interval exposed on the two sides of the creek at 64°45'34.30"N, 82°22'23.30"W; A and C. close view of the lower oil shale interval in B; E. the middle and upper oil shale intervals exposed at 64°45'32.40"N, 82°22'18.20"W in the same creek as the lower oil shale interval (A–C); D and F. close view of upper and middle oil shale intervals in E.

At this exposure, please pay attention to

1) typical orange–tan colour of the Red Head Rapids Formation;
2) the dominant rock type: brown–black argillaceous limestone;

3) the sedimentary structure: a) fine lamination (Fig. 19A); b) a *circa* 10 cm thick layer near the top of the lower oil shale interval formed by abundant, 5–20 cm in diameter, disc-shaped limestone concretions (Fig. 19B);
4) the trilobite *Peudogygites hudsoni* Ludvigsen (Fig. 19C).

This is the only stratigraphic interval within the entire Upper Ordovician and lowest Silurian where limestone concretions have been observed in place together with the trilobite *P. hudsoni*. These lithological and paleontological features are important to understand the stratigraphic position of the "Boas River shale" at locality 14.

Twenty one (mostly shale) samples from this interval have average and maximum yields of 58.5 kg/tonne and 112.5 kg/tonne, and average and maximum TOC of 9.8% and 17.3% (Zhang, 2008).

Stratigraphically upward, along both the upper and lower reaches of the creek, the middle and upper oil shale intervals of unit 1 (Zhang, 2008) can be examined; each of them is about 0.5 m thick. The middle and upper oil shale intervals shown in Fig. 18D–F are exposed in the middle reaches of the creek at 64°45'32.40"N, 82°22'18.20"W. At this exposure, the nicely exposed lithological features of the shale and the shaly and platy structure of the surrounding rocks are useful elements for identifying the stratigraphic setting of the "Sixteen Mile Brook shale" at locality 15.

The middle and upper oil shale intervals contain higher TOC than the lower oil shale interval. Eight samples from the middle oil shale interval have mean and maximum yields of 145.9 kg/tonne and 216.1 kg/tonne, and mean and maximum TOC of 22.4% and 34.1%; and 11 samples from the upper oil shale interval have mean and maximum yields of 128.7 kg/tonne and 230.3 kg/tonne, and mean and maximum TOC of 18.3% and 31% (Zhang, 2008).

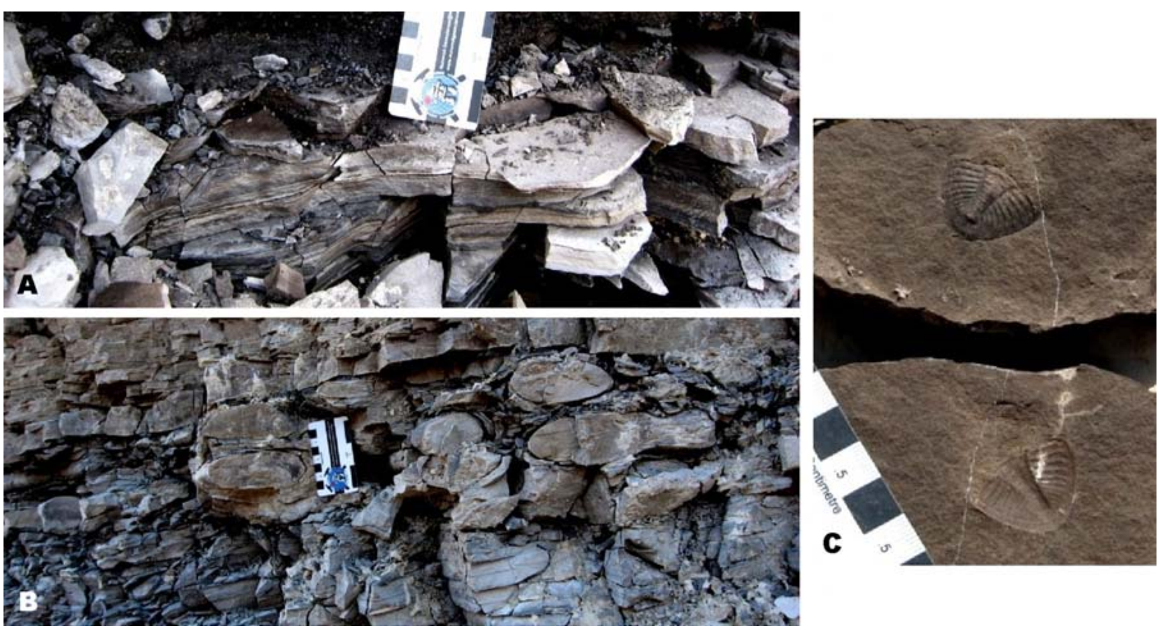

Fig 19: The sedimentary structures and macrofossil within the lower oil shale interval at locality 9. A. fine laminated structure; B. disc-shaped limestone concretions form an approximately 10 cm thick layer near the top of the lower oil shale interval; C. trilobite *Pseudogygites hudsoni* within the laminated argillaceous limestone.

Unit 2

Unit 2 is composed of thick-bedded to massive, brecciated dolostone and limestone with a thickness of 10–15 m. This unit is also well exposed in the same creek as the three oil shale intervals of unit 1, where the base of unit 2 is 5.7 m above the upper oil shale interval at 64°45'39.8"N, 82°22'30.1"W (Fig. 20A). The rock is made up of about 80–90% dolostone and limestone clasts and 10–20% calcareous cements; the clasts are angular and poorly sorted, ranging from less than 1cm to about 40 cm with abundant porosity (Fig. 20B).

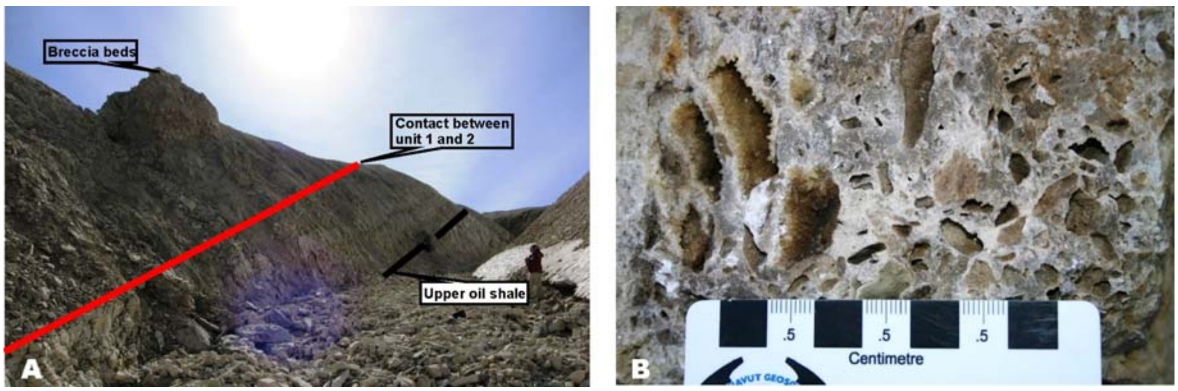

Fig. 20: Unit 2, massive breccia beds of the Red Head Rapids Formation at locality 9. A. relationship between the upper oil shale interval of unit 1 and massive breccia beds of unit 2 at 64°45'39.8"N, 82°22'30.1"W; B. close view of porosity of unit 2, massive breccia beds.

Fig. 21: Unit 3, the thick-massive biostromal dolostone and limestone of the Red Head Rapids Formation at locality 8, lower reaches of the same creek as the three oil shale intervals.

Unit 2 is also exposed to the east of the outcrop seen in Fig. 20, the upper reaches of the creek at 64°45'30.1"N, 82°22'03.6"W.

The good porosity (Fig. 20B) in unit 2 makes it a good candidate for reservoir rock.

Unit 3

Unit 3 is composed of fossiliferous dolostone/dolomitic limestone and stromatolitic dolomitic limestone with a total thickness probably greater than 10 m.

Walking along the creek towards the coast from where unit 2 is exposed, you will see unit 3, the thick-massive biostromal dolostone and limestone, which is equivalent to unit 2 of Sanford (in Heywood and Sanford, 1976). Unit 3 generally forms a conspicuous topography (Fig. 21). Macrofossils are seen at this locality, including solitary and colonial corals, brachiopods, and abundant crinoids.

Locality 10: Cape Donovan area (3)
Boundary between the Red Head Rapids and Severn River formations (Ordovician-Silurian boundary)

Looking northeast from locality 9 where unit 3 is exposed, a high escarpment is visible (see top of Fig. 21). This high escarpment is formed by the uppermost part of unit 4 of the Red Head Rapids Formation (Upper Ordovician) and the base of the Severn River Formation (Lower Silurian). This locality is at 64°45″49.2′N, 82°22″13.8′W, and right beside the shore line at the tip of Cape Donovan.

Unit 4 was previously defined as unit 3 by Sanford (in Heywood and Sanford, 1976). It is composed of light to medium brown, thin-bedded micritic dolomitic limestone, and it also contains a number of biohermal structures. The former is best exposed at locality 10 below the contact between the Red Head Rapids and Severn River formations. Here, about 2 m of thin bedded limestone is exposed. The biohermal structure of unit 4 will be visited at locality 13.

At locality 10, a paleo-karst surface (the white dashed line in Fig. 22A and the pencil’s position in Fig. 22B) is exposed. Below the karst surface, the thin-bedded structure of the micritic dolomitic limestone of unit 4, Red Head Rapids Formation was

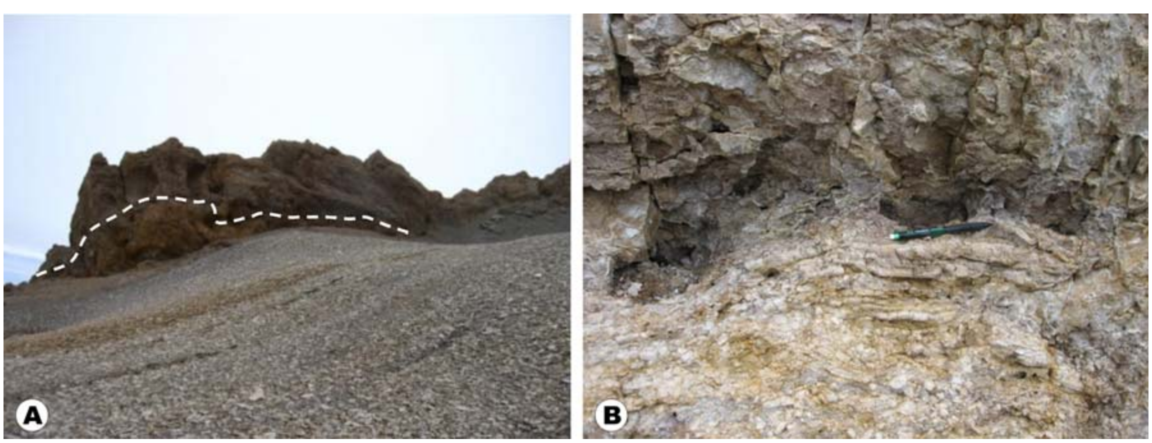

Fig. 22: Distant (A) close-up (B) views of the Ordovician-Silurian boundary.

reworked by erosion; above the karst surface, the thick bedded brown dolomitic limestone of the basal Severn River Formation is well exposed.

This paleo-karst surface represents the global end-Ordovician regression leading to the non-deposition or erosion of the Gamachian or part of the Gamachian.

Locality 11: Cape Donovan area (4) Unit 3, Red Head Rapids Formation

Locality 11 is along a creek from 64°44'22.10"N, 82°27'49.10"W to 64°44'09"N, 82°27'36.3"W about 5 km southwest of localities 8 and 9. Unit 3 of the Red Head Rapids Formation is well exposed along its strike in this creek for about 500 m; the exposure is better than that at locality 9. The outcrop of thick-massive biostromal dolostone and dolomitic limestone of the Red Head Rapids Formation displays conspicuously along the two sides of the creek (Fig. 23A). Fossils are easily found in unit 3 of the Red Head Rapids Formation along the creek at this locality, such as crinoids (Fig. 23B) and corals (Fig. 23C); and stromatolites are common (Fig. 23D).

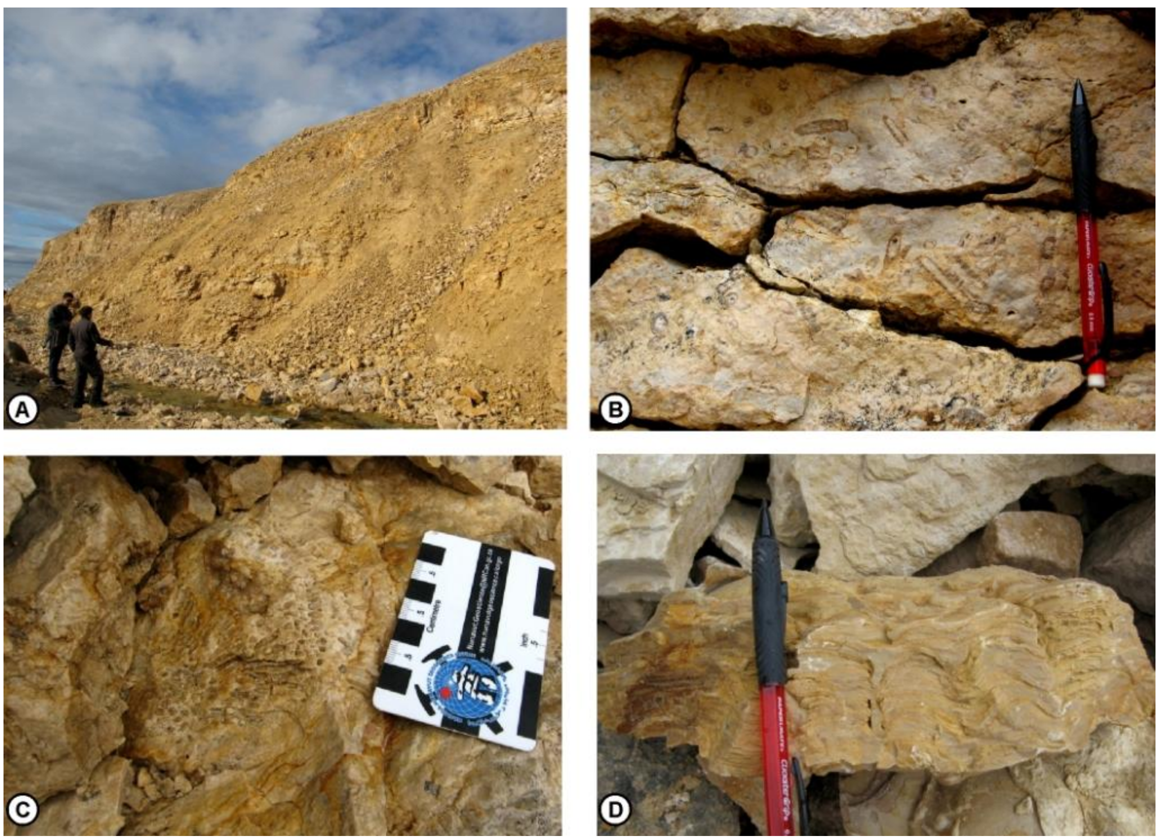

Fig. 23: A. outcrop of unit 3, the thick-massive biostromal dolostone and limestone of the Red Head Rapids Formation at locality 11; B, C and D. crinoids, corals and stromatolites in unit 3 at locality 11.

Locality 12: Tungalik Creek
Unit 2, Red Head Rapids Formation

Locality 12 is located in the northern part of Southampton Island; it is close to the junction of Cleveland River and Tungalik Creek, immediately above the water of Tungalik Creek at 65°01′07.2″N, 84°40′51.6″W. A cliff section exposes the breccia dolostone and dolomitic limestone of unit 2, the Red Head Rapids Formation. At this locality, an unusual Arctic "karst topography" is spectacular (Fig. 24A). This results most likely from the high porosity of the breccia dolostone and dolomitic limestone which makes it easy for running water to dissolve the rocks. However, the porosity at this locality is not as well developed as that of locality 9 in the Cape Donovan area.

Walking about 1.5 km to the west long the creek, you will see another outcrop of the same unit at 65° 1'3.70"N, 84°42'49.60"W. This outcrop is not as conspicuous as the cliff section at the last outcrop at Tungalik Creek, but being away from the creek makes it easier to observe the porosity.

Fig. 24: A. Outcrop of unit 2, the massive breccia dolostone and dolomitic limestone of the Red Head Rapids Formation at locality 11 (note the "karst caves"); B. close view of the breccia.

Locality 13: Between Sixteen Mile and Rocky brooks, 6 km northwest of the coast
Bioherms of unit 4, Red Head Rapids Formation

Locality 13 is located at 64° 2'36.68"N, 83°49'40.70"W, between Sixteen Mile and Rocky brooks, about 6 km northwest of the coast and about 37 km west of Coral Harbour. It is accessible by ATV.

The domal structure is clearly visible from the air. It is a circumscribed mass of rock about 300 m in diameter with roughly 6–7 m of vertical relief (Fig. 25A, 25B). Unit 4 is composed of both thin layered dolostone and dolomitic limestone and the bioherms. In some localities (e.g., locality 10), only the thin layered dolostone and dolomitic limestone are exposed, whereas at other localities such as this one, only the bioherm structure is exposed (Fig. 25A, 25B).

Based on Sanford's (in Heywood and Sanford, 1976) description, this is an algal bioherm. Very few macrofossils (Fig. 25C) and very few layered sedimentary structures (Fig. 25D) are found within the bioherm. The bioherm is highly porous (Fig. 25E).

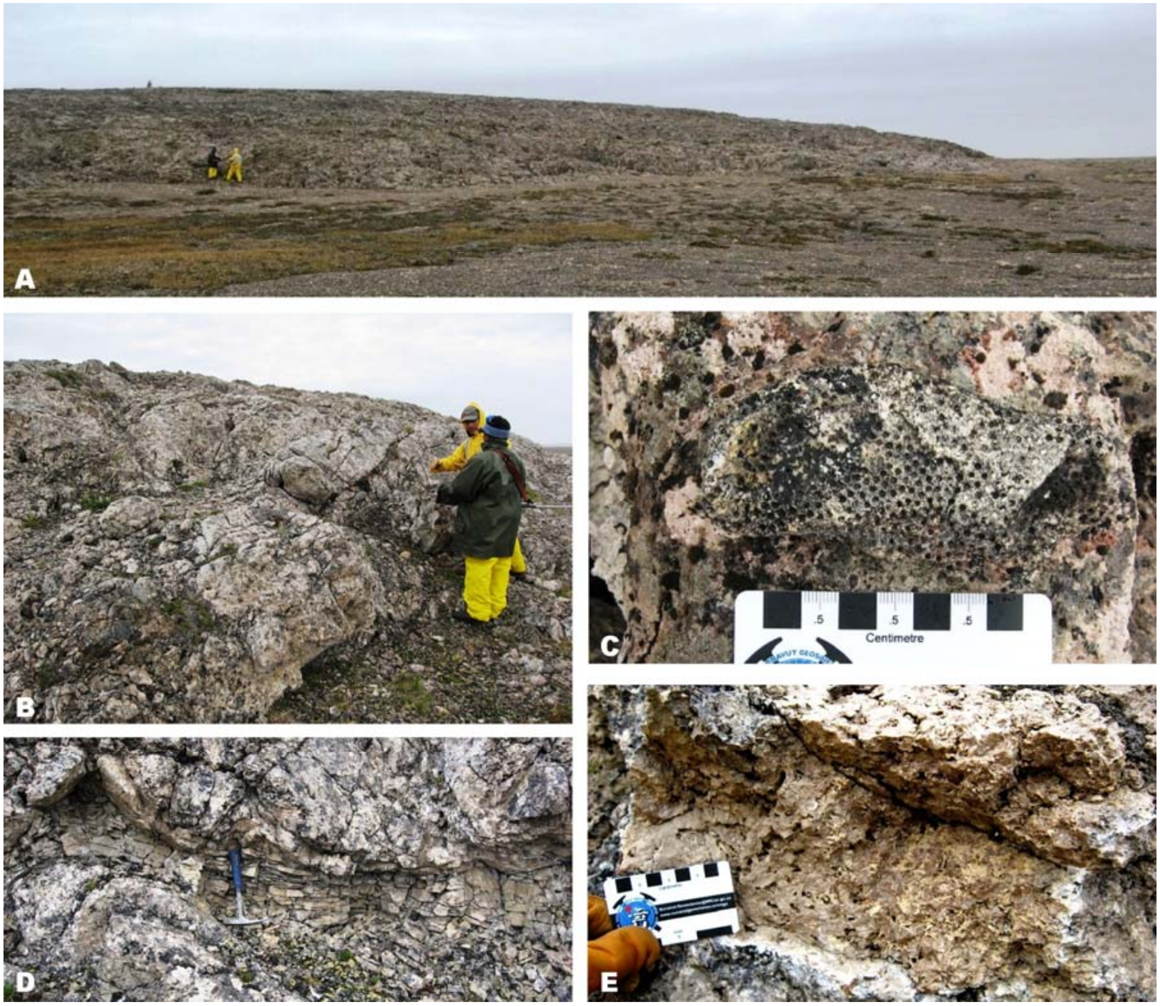

Fig. 25: Bioherm at locality 13. A and B. distant and close-up views of the bioherm structure; C and D. the rare macrofossil (coral?) and thin layered dolostone within the bioherm; E. porosity of the bioherm.

Locality 14: Boas River

Lower oil shale interval of the Red Head Rapids Formation

Locality 14 is located at 64°22'39.7"N, 84°31'45.3"W in the upper reaches of the Boas River, which is the type locality of Sanford's (in Heywood and Sanford, 1976) "Boas River shale" (Fig. 26A). At this locality, slightly over 1 m of dark brown–black bituminous, argillaceous limestone interbedded with black shale is exposed on the river bank, but it has been heavily eroded (Fig. 26B). This stratigraphic interval was interpreted as being between the Bad Cache Rapids and Churchill River groups by Sanford (in Heywood and Sanford, 1976), but as being stratigraphically displaced in the lower unit 1 of Red Head Rapids Formation by Zhang (2008). This new assignment is based on the author's extensive field work on Southampton Island and fossil data (Zhang, 2008; submitted). The field and stratigraphic elements outlined in previous shale and carbonate outcrops, especially at locality 9, as well as the rubble at this locality will support the new stratigraphic interpretation.

Fig. 26: Outcrop and rubble at the Boas River locality. A and B. distant and close-up views of the outcrop; C. the most common rubble with orange-tan color; D. disk-shaped limestone concretion among the rubble; E. the second most common rubble, laminated argillaceous limestone; F. the real color of the laminated argillaceous limestone and fossil trilobite; G. trilobite and graptolite in the limestone layer from the outcrop.

The following lithological and paleontological features can be observed at this locality and compared with the Cape Donovan lower oil shale interval:

1) The most common rubble is angular dolostone and dolomitic limestone with an orange–tan color (Fig. 26C), which is the typical rock type and color of the Red Head Rapids Formation that is nicely exposed in the Cape Donovan area.

2) The second most common rock type among the rubble at the Boas River locality is the dark brown–black, finely laminated argillaceous limestone (Fig. 26E), which is the dominant rock type within the Cape Donovan lower shale interval (Fig. 19A).

3) Disc-shaped limestone concretions are found among the rubble at the Boas River locality (Fig. 26D), which are similar to the limestone concretions forming the 10 cm thick layer near the top of the Cape Donovan lower oil shale interval (Fig. 19B).

4) The trilobite *Pseudogygites hudsoni* is found both within the outcrop and among the rubble at the Boas River locality (Fig. 26F, 26G). The same trilobite species is also found in the Cape Donavan lower oil shale interval (Fig. 19C).

The evidence at the Boas River are compelling for a reassessment of the "Boas River Shale" in the lower Red Head Rapids Formation, rather than the previous stratigraphic positioning at the contact between the Bad Cache Rapids and Churchill River groups (Sanford in Heywood and Sanford, 1976).

Locality 15: Sixteen Mile Brook
Middle oil shale interval of the Red Head Rapids Formation

Locality 15 is located at 63°59'14.00"N, 83°40'9.90"W in the lower reaches of Sixteen Mile Brook; it is about 1 km from the shore line and 35 km southwest of Coral Harbour, and accessible by vehicle and ATV. This is the type locality of Nelson and Johnson's (1966) "Sixteen Mile Brook shale". At this locality, about 3–4 m of thin layered laminated dolomitic limestone is exposed (Fig. 27A), in the middle section of the outcrop, there is an interval of about 30–50 cm of oil shale (Fig. 27B). Originally, this shale interval was interpreted as being at the top of the Churchill River Group (Nelson and Johnson, 1966).

Field observations at the well exposed Cape Donovan locality (locality 9) allow for better defining the stratigraphic setting of this "Sixteen Mile Brook shale". The thickness of the shale at this locality is similar to that of the middle or upper oil shale interval at the Cape Donovan section; the rocks above and below the shale are thin-layered laminated dolostone or dolomitic limestone with orange-tan color. Based on these observations, the "Sixteen Mile Brook shale" can be correlated to either the middle or upper oil shale interval of the unit 1, the Red Head Rapids Formation in the Cape Donovan area. The recent study on conodonts (Zhang, submitted) makes the correlation more precise: both the "Sixteen Mile Brook shale" and Cape Donovan middle oil shale of the Red Head Rapids Formation contain the conodont *Amorphognathus ordovicicus*, but this species disappears above the middle oil shale.

At this locality, near the east end of the outcrop, the oil shale interval is pinching out (in Fig. 27A with a person pointing at the pinched out point); suggesting that the distribution of this shale interval is restricted.

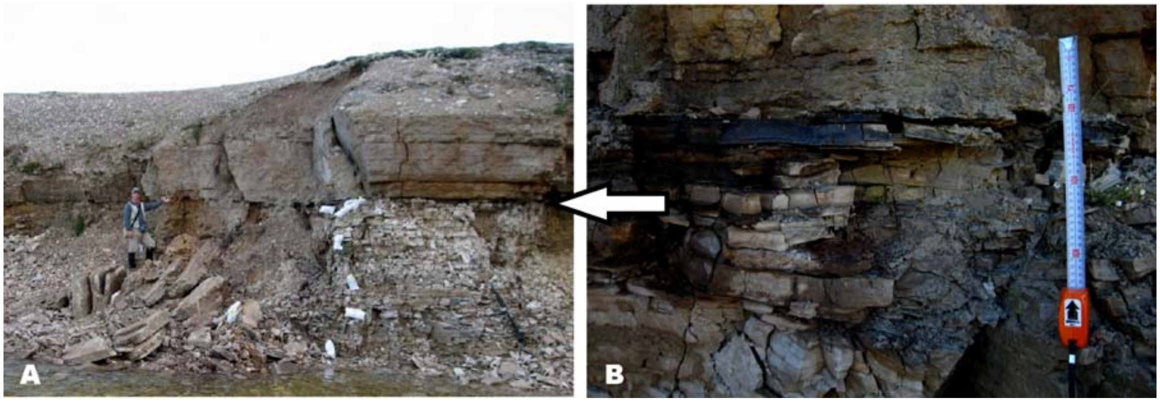

Fig. 27: Outcrop at Sixteen Mile Brook. A. a distant view of the outcrop with a person pointing to the position where the oil shale interval pinches out; B. close-up view of the oil shale.

A summary of Upper Ordovician and lowest Silurian stratigraphy

Figure 28 summarises the Upper Ordovician and lowest Silurian strata that are exposed at the 15 visited localities and their stratigraphic correlation based on the sedimentary features and conodont data (Zhang, submitted). The location names and their geographic coordinates are provided in Appendix 2.

7. ACKNOWLEDGEMENT

Financial and logistic supports for the field trip are from GEM Energy Program and Polar Continental Shelf Program, respectively.

I wish to sincerely thank Donald James (Canada-Nunavut Geoscience Office) and Denis Lavoie (GSC Quebec) for supervising the publication, reviewing the manuscript and providing the valuable suggestions and comments on a previous version of the manuscript, which significantly improved this guide book.

I also wish to thank Celine Gilbert (CNGO) for help in making 1:250 000 location map.

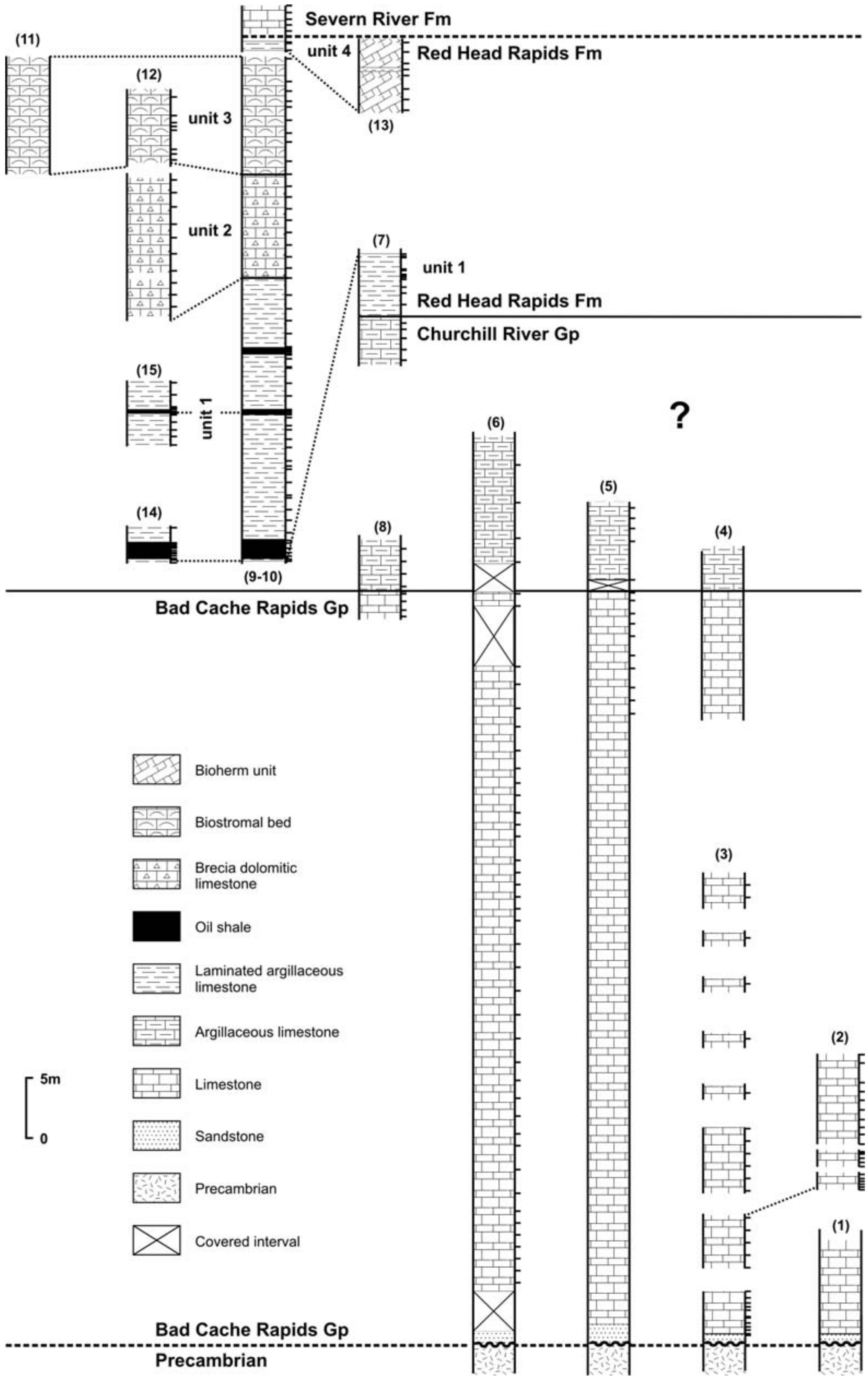

Fig. 28: Upper Ordovician lithostratigraphic units and their correlation among 15 visited localities on Southampton Island. The short horizontal bars on the right of most stratigraphical columns represent the conodont sample locations (modified from Zhang, submitted). See Appendix 2 for locality information.

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Appendix 1. Summary of geographic data of on-shore and off-shore wells drilled in Hudson Bay Basin during 1960s–1980s

Wells		Company	Year	Location (latitude / longitude; NAD 27)	Well depth (m / ft)	Precambrian - Paleozoic contact (m / ft)	Storage Location
on-shore	Kaskattama Province No. 1	Sogepet-Aquitaine	1966	57.07181N / 90.17484 W	below 1192.7 / 2913	1192.7 / 2913	Manitoba Department of Energy and Mines, Winnipeg, Manitoba
	Comeault Province No. 1	Houston *et al.*	1968	56.66666 N / 90.83333 W	647.7 / 2125	616.3 / 2022	Manitoba Department of Energy and Mines, Winnipeg, Manitoba
	Pen Island No. 1	Aquitaine Sogepet *et al.*	1969	56.75194 N / 88.75417W	1036.3 / 3400	1021.4 / 3351	Ontario Oil, Gas & Salt Resources Library, London, Ontario
	Whitebear Creek No. 1	Merland *et al.*	1970	57.3833N / 92.4667W	1401 / 427.02	?	Manitoba Department of Energy and Mines, Winnipeg, Manitoba
off-shore	Walrus A-71	Aquitaine *et al.*	1969	58.50056N / 87.18015W	1196.7 / 3923.5	unknown	Canada-Nova Scotia Offshore Petroleum Board, Data Archive, Core Storage and Laboratory
	Narwhal O-58	Aquitaine *et al.*	1974	58.13327N / 84.13416W	1323.2 / 4338.2	1306.1 / 4282.2	Canada-Nova Scotia Offshore Petroleum Board, Data Archive, Core Storage and Laboratory
	Polar Bear C-11	Aquitaine *et al.*	1974	58.50121N / 86.78847W	1575.8 / 5166.7	1566.7 / 5136.7	Canada-Nova Scotia Offshore Petroleum Board, Data Archive, Core Storage and Laboratory
	Beluga O-23	Trillium Soquip Onexco *et al.*	1985	59.215111N / 88.557389W	2215 / 7267.06	2194 / 7181.76	Canada-Nova Scotia Offshore Petroleum Board, Data Archive, Core Storage and Laboratory
	Netsiq N-01	Aquitaine *et al.*	1985	59.84667N / 87.51664W	1040 / 3412.07	1009 / 3310.37	Canada-Nova Scotia Offshore Petroleum Board, Data Archive, Core Storage and Laboratory

Appendix 2. Summary of geographic data of Upper Ordovician and lowest Silurian outcrops on Southampton Island

Locality ID	Location	Geographic coordinates				Lithostratigraphic unit exposed
		start		end		
		Lat	Long	Lat	Long	
1	East of Post River	64°17′04.9″N	83°06′23.8″W			lowest Bad Cache Rapids Gp
2	Fossil Creek	64˚10′58.73″N	83˚21′42.29″W	64˚10′45.98″N	83˚21′16.66″W	upper Bad Cache Rapids Gp
3-4	Rocky Creek	64˚10'02.81"N	83˚56'44.55"W	64˚02'25.80"N	83˚35'51.10"W	Bad Cache Rapids Gp & lower Churcill River Gp.
5	Duke of York (1)	65°12'55.1"N	84°38'45.4"W	65°12'55.80"N	84°39'14.2"W	Bad Cache Rapids Gp & lower Churcill River Gp.
6	Duke of York (2)	65˚15'51.7"N	84˚37'33.5"W			Bad Cache Rapids Gp & lower Churcill River Gp.
7	near coast between Sixteen Miles and Rocky Brook	64˚02'02.9"N	83˚39'22.1"W	64˚02'12.5"N	83˚39'47.9"W	transition from Churchill River Gp to Red Head Rapids Fm
8	Cape Donovan (1)	64˚45'40.0"N	82˚22'40.6"W			Bad Cache Rapids & Churchill River groups' boundary
9	Cape Donovan (2)	64˚45'43.9"N	82˚22'37.9"W	64˚45'42.7"N	82˚22'31.3"W	unit 1-3, Red Head Rapids Fm
10	Cape Donovan (3)	64°45'49.20"N	82°22'13.8"W			unit 4 (layered bads), Red Head Rapids Fm; O-S boundary
11	Cape Donovan (4)	64°44'22.10"N	82°27'49.1"W			unit 3, Red Head Rapids Fm
12	Tungalik Creek	65˚01'07.2"N	84˚40'51.6"W	65°01'3.70"N	84°42'49.60"W	unit 2, Red Head Rapids Fm
13	near Sixteen Mile Brook	64˚02'36.68"N	83˚49'40.7"W			unit 4 (bioherm), Red Head Rapids Fm
14	upper reaches of Boas River	64˚22'39.7"N	84˚31'45.3"W			lower oil shale interval, Red Head Rapids Fm
15	Sixteen Miles Brook	63˚59'14"N	83˚40'09.9"W			middle oil shale interval, Red Head Rapids Fm