LITHOSTRATIGRAPHY AND CORRELATION OF MEASURED SECTIONS, MIDDLE CAMBRIAN HAWKE BAY FORMATION, WESTERN PORT AU PORT PENINSULA

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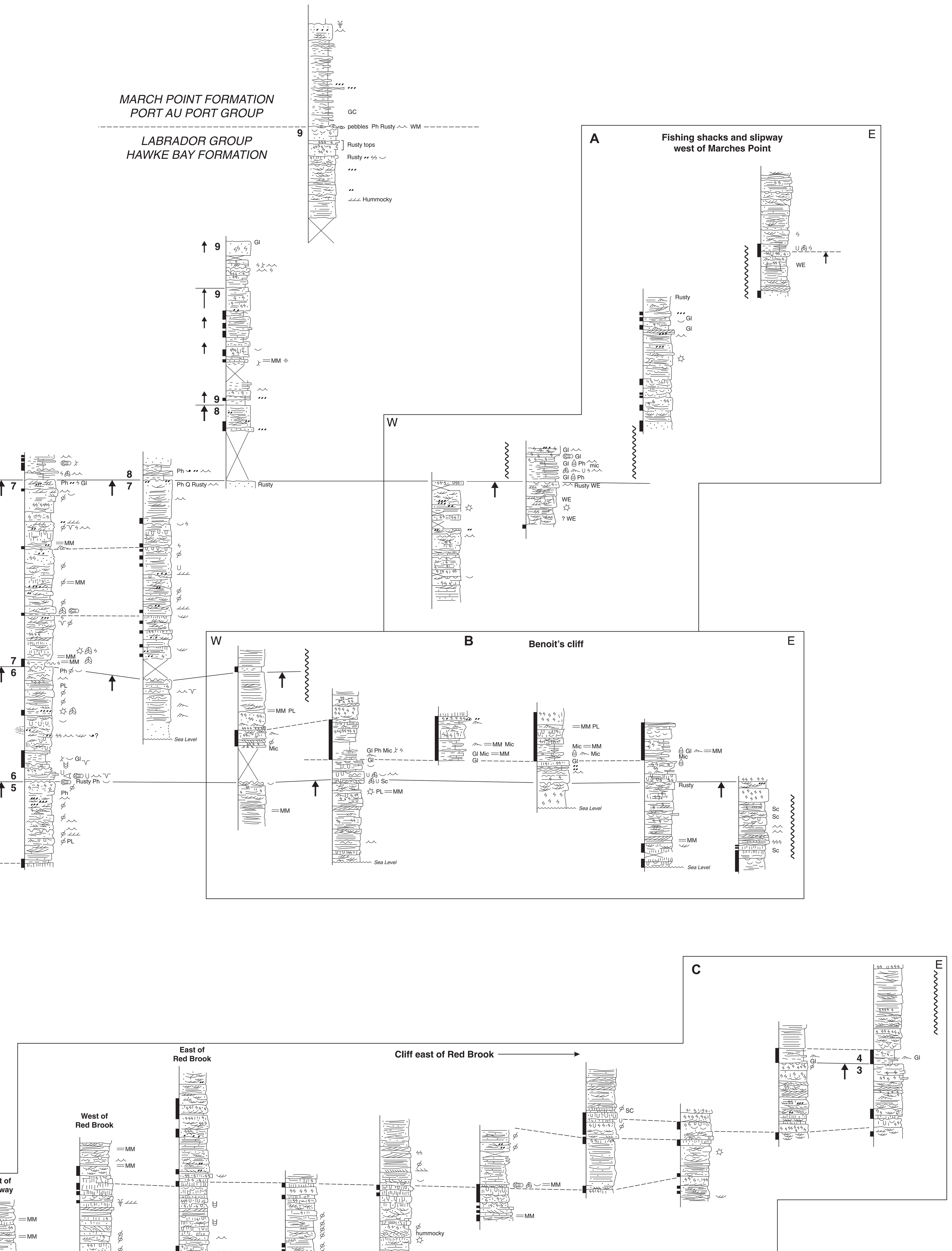
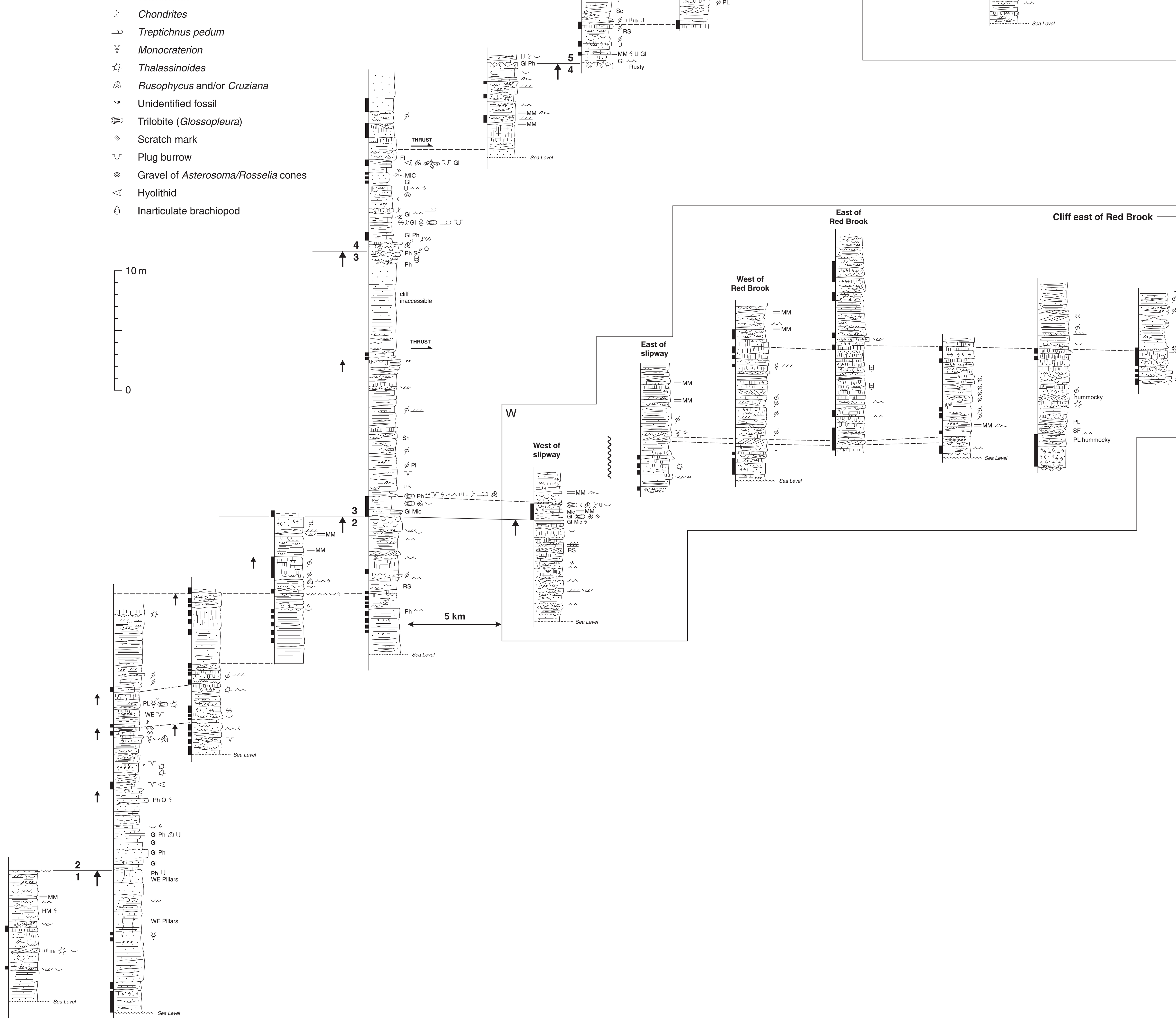
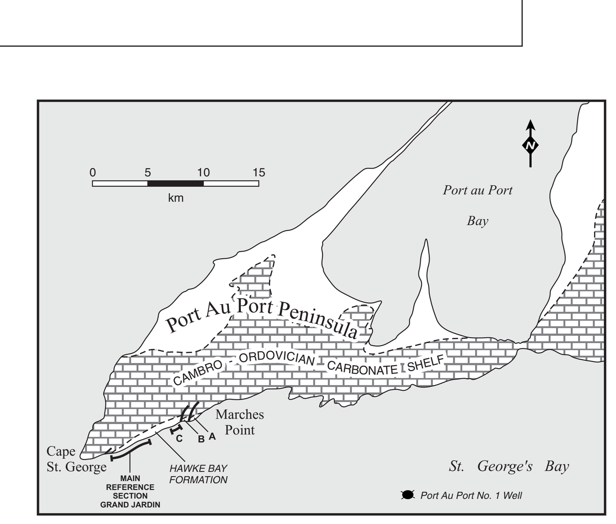
Sections measured in 1998, revisited in 2007, 2009 and 2012

SYMBOLS

Symbol	Meaning
↑ ↑	Top of cleaning-upward/ shallowing-upward cycle
	Pebble, shale clasts
	Sandstone
	Shale/siltstone
	Red colour
	Flaggy/tabular thin bedding
MM	Lamination
	Trough cross bedding
	Planar cross bedding
	Cross lamination
	Pebble
	Slump fold
	Convolution
	Ripple mark
	Shrinkage crack
	Bioturbation (unidentified)
	Skolithos
	Diplocraterion
U	*Arenicolites*
	Zoophycus
	Teichichnus
	Chondrites
	Treptichnus pedum
	Monocraterion
	Thalassinoides
	Rusophycus and/or *Cruziana*
	Unidentified fossil
	Trilobite (*Glossopleura*)
	Scratch mark
	Plug burrow
	Gravel of *Asterosoma*/*Rossellia* cones
	Hyolithid
	Inarticulate brachiopod
WE	Water escape structure
WM	Wrinkle mark
Sc	Scour
SF	Synsedimentary fault
PL	Parting lineation
RS	Reactivation surface
GC	Gutter cast
Fl	Flute cast
HM	Heavy mineral lamination
Q	Quartz granule/pebble
Mic	Micaceous
Gl	Glauconite
Ph	Phosphate
	Porosity
1-9	Parasequences
	Fault
- - - -	Tying beds
——	Sequence boundaries
X	Covered interval







Digital cartography by T. Paltanavage and K. Morgan

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Descriptive Notes

The most southerly exposure of the Hawke Bay Formation, Labrador Group (Schuchert and Dunbar, 1934) in western Newfoundland is an incomplete, well-exposed section that occurs for 8 kilometres along the southern, cliff-bounded shore of the Port au Port Peninsula between Grand Jardin in the west and Marches Point in the east. The formation there has also been referred to as the Degras formation (Riley, 1962; Levesque, 1977; Williams, 1985). Although incompletely exposed, the formation is logged as at least 250-m thick in the Port au Port # 1 well, at Garden Hill just north of Cape St. George (Newfoundland Hunt Oil Company Inc., 1996). The peninsula is an exhumed mountainous peninsula that projected westward into the northern edge of the Carboniferous Bay St. George Basin (Knight, 1983). Numerous paleo-karst? valleys (wadis) that occur along the trace of late Paleozoic faults are filled by red Carboniferous clastic sediments.

The strata along the shore generally strike east-northeast and dip to the north-northwest at between 5 and 20°. At Marches Point, however, the scattered outcrops along the shoreline conceal an east-northeast plunging anticline. The shoreline sections are broken by several high-angle, northeast-trending reverse faults and normal faults that parallel the shore. Most of the faults appear to have minor throws of up to a few metres. Also some bedding plane faults occur which may be linked to thrusting that affects the lower Paleozoic succession on the peninsula (Waldron and Stockmal, 1991). Anastomosing fracture systems associated with the faults are closed by calcite and red sediment, presumably of Carboniferous age.

Traditionally, the top of the Hawke Bay Formation on Port Au Port Peninsula is placed at a thin conglomeratic bed that sits upon quartz arenite and below a succession of grey shale and siltstone assigned to the base of the overlying March Point Formation, Port au Port Group. This relationship is illustrated in the accompanying graphic log but is presently being reconsidered based on the presence of quartz arenite and sandstone beds above this conglomeratic marker bed and because of other regional considerations of the precise placement of the contact elsewhere in western Newfoundland (I. Knight and W.D Boyce, unpublished data, 2014). The log illustrates the main reference section measured along the cliffs west of the boat basin at Degras continuing westward to Grand Jardin. Other sections measured near and east of Red Brook are correlated with the main section.

The Hawke Bay Formation on the Port au Port Peninsula is a succession, approximately 170-m thick, of white, pink, green-grey, grey and red, quartz arenite, glauconitic and micaceous sandstone, siltstone and shale deposited in repetitive cleaning- and shoaling-upward parasequences 5 to 30 m thick. Smaller cleaning-upward cycles occur within the thicker parasequences. The parasequences comprise recessive-weathered, lower intervals of red, green and grey shale, siltstone and sandstone and cliff-forming, upper sandstone intervals dominated by clean, generally well sorted, quartz arenite. Red colouration in some cases is secondary and may reflect the sections' proximity to the Carboniferous basin to the south beneath St. Georges Bay (Knight, 1983). Dark-grey to black shale intercalated with bioturbated sandstone make up the recessive interval in the lowest sequence exposed on the peninsula (not illustrated), just below the school at Degras.

The contact between the recessive interval and the cliff-forming sandstone ranges from gradational over a few decimetres to sharp and planar and subtly erosional. Most of the top of the cliff-forming upper sandstone is characterized by a sharp, generally planar, upper surface, locally graced by scattered, washed out, U-shaped burrows and by phosphate detritus. Only rarely does an erosional surface separate the upper sandstone from the overlying recessive facies interval. Both contact expressions are interpreted as the likely flooding surface of the overlying sequence.

The lower recessive intervals consist of several facies. Poorly sorted, commonly coarse grained, locally granular to small pebble, green and grey sandstone facies lie above flooding surfaces. The sandstone, which is often friable and porous, is commonly intercalated with grey, shaly siltstone. The facies is rich in delicate to robust U-shaped *Arenicolites* burrows, the robust *Arenicolites* closely associated with often large trilobite traces, *Rusophycus* and *Cruziana*, suggesting perhaps trilobites preyed on the burrowers. *Teichnichnus* occurs at the base of some units of this coarse sandstone facies. Thin layers of glauconitic siltstone/sandstone intercalate with the facies.

Intercalated red and grey shale, siltstone and fine-grained, micaceous and glauconitic sandstone dominate the middle and upper part of the recessive intervals; grey is overlain by red facies in some intervals. Green glauconite layers drape and intercalate throughout the facies. Extensively bioturbated (*Cruziana* Ichnofacies), and locally fossiliferous, the thinly interbedded shale, siltstone and fine- to coarse-grained sandstone facies displays a variety of sedimentary structures. These include planar and undulose lamination, cross lamination, small scale hummocky cross stratification (HCS), small-scale, straight to sinuous symmetrical ripple marks, 3-D combined flow-ripple marks, local convolution including rare large ball and pillows, some northeast-trending, asymmetrical slump folds, and rare gutter casts. Shale interbeds, mostly red, are common; the thickest shale (with only thin sandstone lenses and interbeds) marks the middle of many sequence intervals.

Intensely burrowed beds of fine, micaceous, red sandstone, siltstone and shale straddle either side of the middle shale. The ichnofacies in the red and grey fine-grained facies includes *Treptichnus pedum*, *Planolites*, *Paleophycus*, small U-shaped burrows, meandering traces, perhaps *Helminthopsis*, *Chondrites*, *Teichichnus,* small branching burrow networks, likely *Thalassinoides*, and small *Rusophycus*, *Cruziana* and scratch marks *Monomorphichnus*. Extent of the bioturbation varies and can, as in parasequence 5, show lam-scram pattern. Gravel beds consisting of centimetre-sized, siliciclastic, oncoloid-like pebbles that show good concentric layering like a carbonate oncolite are likely reworked *Rosselia* funnels or *Asterosoma* bulbous arms; they occur in the grey variation of the facies in parasequence 4 where it is overlain by shale-hosting *Zoophycus*. The grey variant of the facies is also calcareous in contrast to the red version and a few thin lime mudstone ribbons occur in some of the facies associations. Beds of laminated quartz arenite occur in the top of the recessive intervals just below the upper sandstone intervals. Scattered trilobite sclerites occur in these sandstones; trilobite remains have also been found in bioturbated, micaceous, siltstone and sandstone beds.

Intercalated decimetre-thick, dark grey to black shale and bioturbated, very fine- to fine-grained sandstone marks the lowest sequence exposed in the formation on the shoreline near Degras School. The sandstones are characterized by intense *Teichichnus* and *Thalassinoides* burrows and small-scale ripple marks; clusters of phosphatic hyolithid cones mark the top of many sandstone beds. No glauconite occurs.

The upper cliff-forming intervals consist of tabular-stratified to crossbedded, well-sorted, very-fine- to medium-grained, clean, pale green, cream, white and red quartz arenite; red mottling of green and white sandstone is common and the units tend to coarsen upward overall. Some of the thicker sandstone intervals, as in parasequence 2, are punctuated by units, 50 to 200 cm thick, of green and red, silty mudstone, and bioturbated micaceous siltstone and fine sandstone every few metres. The fine-grained beds compare favourably with the upper facies associations of the lower recessive intervals. These fine-grained punctuating beds are viewed as sub-cycles within the overall parasequences and imply that the shelf-shoreface interface was likely mobile, shifting position in response to local conditions on the shelf, or that there were locally developed sub-environments within the shoreline setting.

Swaley- and hummocky cross stratification occurs in the lower parts of some intervals. A single set of large-scale planar tabular foresets associated with small-scale ripple sets (toesets) that climb up the lower part of the large foresets is present at the base of the sandstone interval in parasequence 5. This suggests ripple migration at the toe of a large dune complex formed by flow-separation eddies. Otherwise, the sandstone bodies are dominated by tabular-stratified sandstone with low-angle scours and ?quasi-planar lamination. Sorting of sand layers is common as is variation in the cementation leading to porous alternating with cemented layers in the thin stratification. Small- and large-scale, trough crossbeds displaying bimodal to polymodal paleocurrents and some planar-tabular crossbeds, the latter mostly as isolated single sets, are commonly seen in the cliff sections. Herringbone structure and reactivation surfaces are noted locally. Long crested, straight, gently sinuous to locally branching, ripple marks, some marked by planed off crests, grace bedding planes; rare examples of parting lineation were also noted. Large trough and planar cross sets, locally associated with swales, are noted in the upper part of some upper sandstone intervals.

Paleocurrents in the upper cliff-forming sandstone are polymodal with trough crossbeds dominated by west-southwest and east-northeast vectors at some localities and more southward vectors in others. Planar crossbeds give westward and northward vectors and the dominant crest trend of the straight to sinuous ripple marks is east–west. North-trending, branching sandstone pillars, indicating water escape, cut sandstones in a number of units.

The upper, cliff-forming sandstone is replete with vertical burrows typical of suspension feeders of the *Skolithos* Ichnofacies (Pemberton *et al*., 1992, 2001; MacEachern *et al*., 2010; Buatois and Mangano, 2011). *Arenicolites*, *Diplocraterion* and *Skolithos* may dominate individual beds scattered throughout the units, although intensity varies along strike and the vertical burrows may disappear. Nonetheless, almost entire upper sandstone intervals can be intensely bioturbated by the vertical burrows, especially *Diplocraterion* and can be traced laterally for tens to hundreds of metres laterally along cliff faces. Sandstone beds composed of a mass of tangled, intertwined, fine tubular burrows comparable to *Macaronichnus* and beds of *Teichichnus* are also present locally. Porosity is often high in the intensely bioturbated sandstone beds, which are friable and easily weathered. Thin shale interbeds are commonly tunnelled by extensive, sand-filled polygonal boxwork galleries, likely large *Thalassinoides* burrows. The sand filling of the *Thalassinoides* boxwork is in turn bioturbated by *Planolites* and other burrowers; obscure trilobite traces also occur on the same surfaces. *Cruziana* traces noted at shale-sandstone contacts in the upper sandstone intervals display a meandering form suggesting predatory activity. A rare trilobite sclerite mold occurs in the sandstone.

The Hawke Bay Formation, dominated by well sorted, quartz sand-rich parasequences supports a high-energy, wave and storm-dominated shelf and shoreline. The cleaning- and coarsening-upward sequences suggest repeated flooding of the shelf and subsequent progradation of facies belts. Bioturbated, storm-deposited sheet sands intercalated with muds, were deposited low in the shoreface to proximal offshore setting and are succeeded by well-sorted, clean sands of the shoreface and possible foreshore. Thin layers of glauconitic sandstone and siltstone drape micaceous sandstone and siltstone in upper offshore to lower shoreface deposits and glauconite sand grains are common in both sandstones and locally in burrows. The plethora of simple and complex bedding-parallel burrowers exhibiting a range of feeding, locomotion and dwelling activities typical of the *Cruziana* Ichnofauna suggests a shelf setting below fair-weather wave base, the variation in the degree of bioturbation likely suggested that energy conditions affecting the shelf ranged from moderate to strongly storm dominated. Simple but robust U-shaped burrows in coarse sands and storm-deposited sand beds of the base of recessive intervals supports opportunistic colonization by elements of the *Skolithos I*chnofauna and seems to have been a favoured substrate for arthropod predators. The sporadic low-diversity skeletal remains of the lower recessive shelf intervals probably reflect the unfavourable depositional setting rather than unusual salinity or oxygen-poor conditions of the shelf. Swaley and hummocky cross stratification present locally low in the upper quartz arenite sands of the parasequences, coupled with the domination by tabular-stratified sandstone with low-angle scours and quasi planar lamination higher in these sandstone bodies suggests much of the quartz arenite sands were laid down in a storm and wave-dominated, lower to mid shoreface setting. Nonetheless, trough crossbedding, some planar-tabular crossbeds, herringbone crossbedding as well as reactivation surfaces and sinuous to straight ripple marks support upper shoreface and shallow tidal sand flat setting dominated by foreshore dunes, bars and ripples in the upper part of sequences. The extensive abundance of vertical, predominantly U-shaped burrows in sandstone intervals that can be traced laterally along long cliff sections suggest that *Diplocraterion* and *Skolithos* thrived in the frequently shifting sandy setting of such a tidal, wave-dominated shoreline (Pemberton *et al*., 1992; 2001; MacEachern *et al*., 2010; Buatois and Mangano, 2011).

The predominance of sandstone in the succession at Port au Port Peninsula suggests that the early Middle Cambrian shelf was supplied with abundant sand. This may reflect a prograding strandplain succession (Plint, 2011), supplied with abundant sand carried to the shelf perhaps by small rivers rather than by a single large deltaic system or perhaps a complex barrier system seaward of the ancient shoreline. Regardless, the sedimentary structures, ichnofauna, and predominance of sand indicate the importance of storms, waves, and currents subsequently reworking the sediment to form a long sandy coastal strand, in stark contrast to co-eval successions elsewhere in western Newfoundland (I. Knight and W.D. Boyce, unpublished data, 2014). Large cross sets associated with flow-separation toe-of-set ripple marks as in parasequence 5 likely suggests tidal inlets locally. The association of dark shale interbedded with *Teichichus*-rich sandstones at the base of the formation succession may imply variable salinity perhaps suggesting some development of back barrier lagoons.

The Hawke Bay Formation hosts a low diversity trilobite-hyolithid-inarticulate brachiopod fauna, generally in lower shoreface to proximal shelf facies. Locally abundant, variably preserved, monospecific *Glossopleura* assemblages - comprising either *Glossopleura lodensis* (Clark, 1921), *Glossopleura walcotti* Poulsen, 1927 or *Glossopleura* sp. indet. - indicate that the formation was deposited during the *Glossopleura* zone. However, *Dolichometopus* sp. in a sequence near the top of the formation indicates a slightly younger *Polypleuraspis* subzone age late in the formation. These confirm a Middle Cambrian, Delamaran Stage age for the succession exposed on the peninsula. There is no apparent correlation of the fossil-rich intervals with distinctive parasequences. The oldest faunas in the overlying March Point Formation belong to the upper part of the *Ehmaniella cloudensis* zone (Boyce and Knight, 2005); they occur in limestone, 25 m above the base of the formation.

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