

TREMADOCIAN CARBONATE ROCKS OF THE LOWER ST. GEORGE GROUP, PORT AU PORT PENINSULA, WESTERN NEWFOUNDLAND: LITHOSTRATIGRAPHIC SETTING OF DIAGENETIC, ISOTOPIC AND GEOCHEMISTRY STUDIES

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ABSTRACT

Detailed stratigraphic measurements and sampling of rocks of the lower St. George Group on the western shore of Isthmus Bay, Port au Port Peninsula, are the foundation for diagenetic, isotopic, and geochemistry studies of Tremadocian shallow-shelf carbonates in western Newfoundland. This article summarizes the lithostratigraphy that hosts the 3rd-order onlap-offlap sequence that marks the first phase of Ordovician carbonate-shelf buildup on the Tremadocian passive margin of Laurentia (in Newfoundland). The succession, which consists of the Watts Bight Formation and lower and middle parts of the Boat Harbour Formation, is bounded at the top by a regional disconformity, the Boat Harbour Disconformity. The base of the succession rests transitionally on peritidal carbonate rocks of the Berry Head Formation of the Port au Port Group.

Dolomitization of significant parts of the sequence is described within the context of the regional lithostratigraphy.

INTRODUCTION

Lower Paleozoic shelf rocks in western Newfoundland underlie a long sinuous terrain that extends over 400 km from Cape Norman in the north to the Port au Port Peninsula in the southwest (Figure 1). These shallow-water, autochthonous and parautochthonous, siliciclastic and carbonate rocks fringed part of the paleo-southern margin of Laurentia from the late Early Cambrian through to the early Middle Ordovician. The shelf was deposited close to the apex of the St. Lawrence Promontory and along the Newfoundland Embayment (Hibbard *et al.*, 2006). A long-lived passive margin (50 MY), host to Labrador, Port au Port and St. George group rocks, was succeeded by a rapidly evolved foreland basin (4 to 7 MY) in which shelf carbonates of the Table Head Group were deposited before the shelf foundered and was smothered by the influx of siliciclastic flysch of the Goose Tickle Group. A regional erosional unconformity, the St. George Unconformity, marks the transition from the passive margin to the foreland basin (Knight *et al.*, 1991) during a period when regional tectonic instability and passage of a Taconian peripheral bulge across the margin coincided with falling sea level as the last sediments of the St. George Group were deposited (Knight *et al.*, 1991; Cooper *et al.*, 2001).

The autochthonous shelf sequence is hosted by the outer domain of the Humber (Tectonostratigraphic) Zone of Williams (1979). It is shortened and deformed by a number of thrust stacks that transported more outboard stratigraphy and facies inboard an, as yet, undefined distance, and now probably lies at high structural levels in the east of the outer domain. No margin to the shelf is known.

The St. George Group is a complex succession of limestone and dolostone divided into two, long-lived 3rd-order sequences of Tremadocian and Ibexian (Arenigian) age; Knight and James (1987) referred to the sequences as megacycles. Each megacycle is characterized by a three-part architecture of generally thin, lower peritidal, thick middle subtidal and thick upper peritidal layers (Knight and James, 1987). The older Tremadocian sequence is bounded by the Boat Harbour Disconformity at the top, and lies gradationally upon mostly dolomitized peritidal carbonates of the Late Cambrian to earliest Ordovician Berry Head Formation, Port au Port Group at the base (Figure 2). Carbonate rocks, equivalent of western Newfoundland's Tremadoc megacycle, are not present to the west in the nearest Lower Ordovician sections at Anticosti Island and Mingan Islands, Québec. This suggests that as the megacycle is traced west to northwestward offshore into the Anticosti Basin, it will

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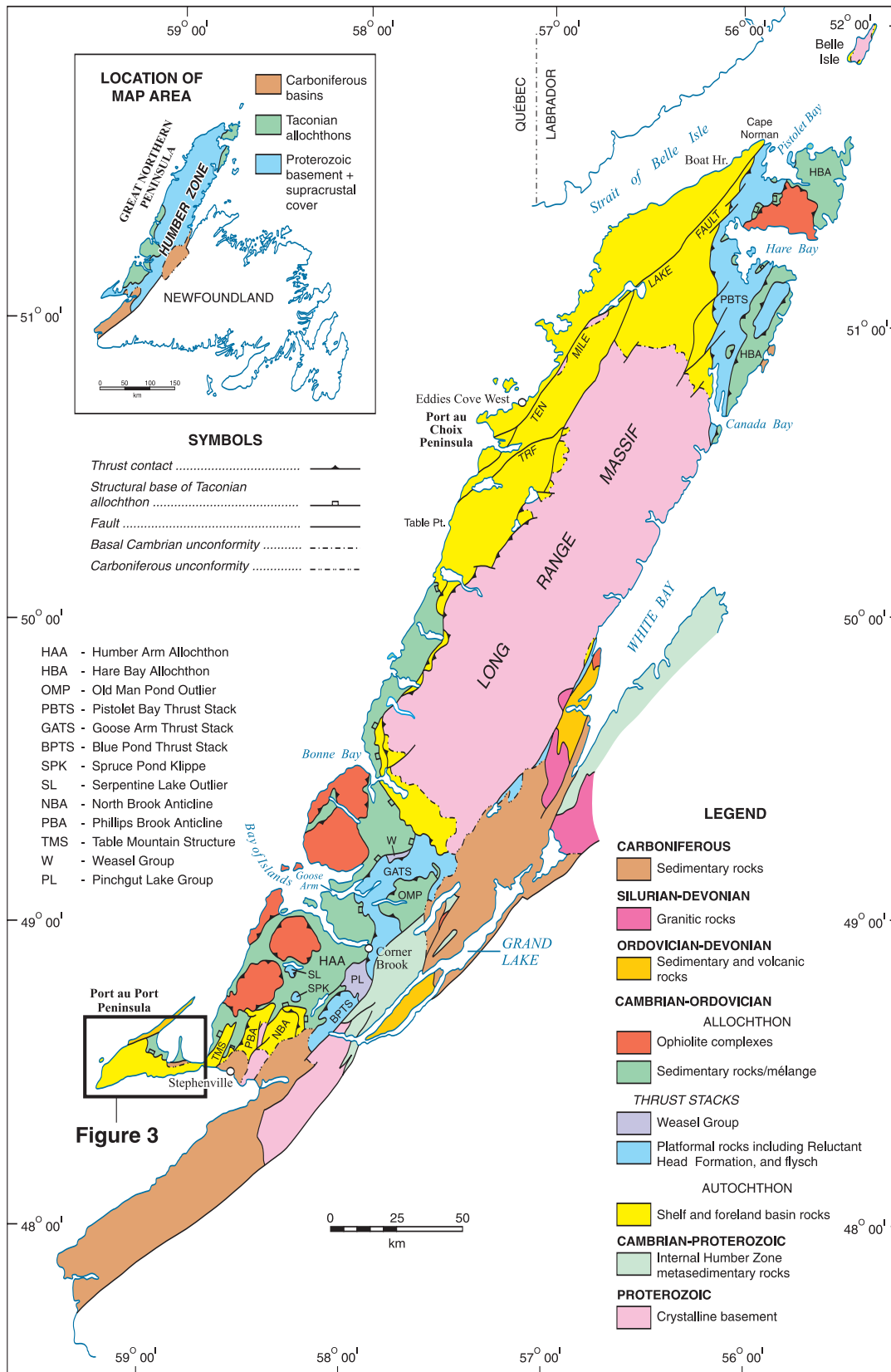


Figure 1. Regional geological map of western Newfoundland showing major terranes, distribution of Lower Paleozoic shelf rocks and location of study areas. TRF: Torrent River Fault.

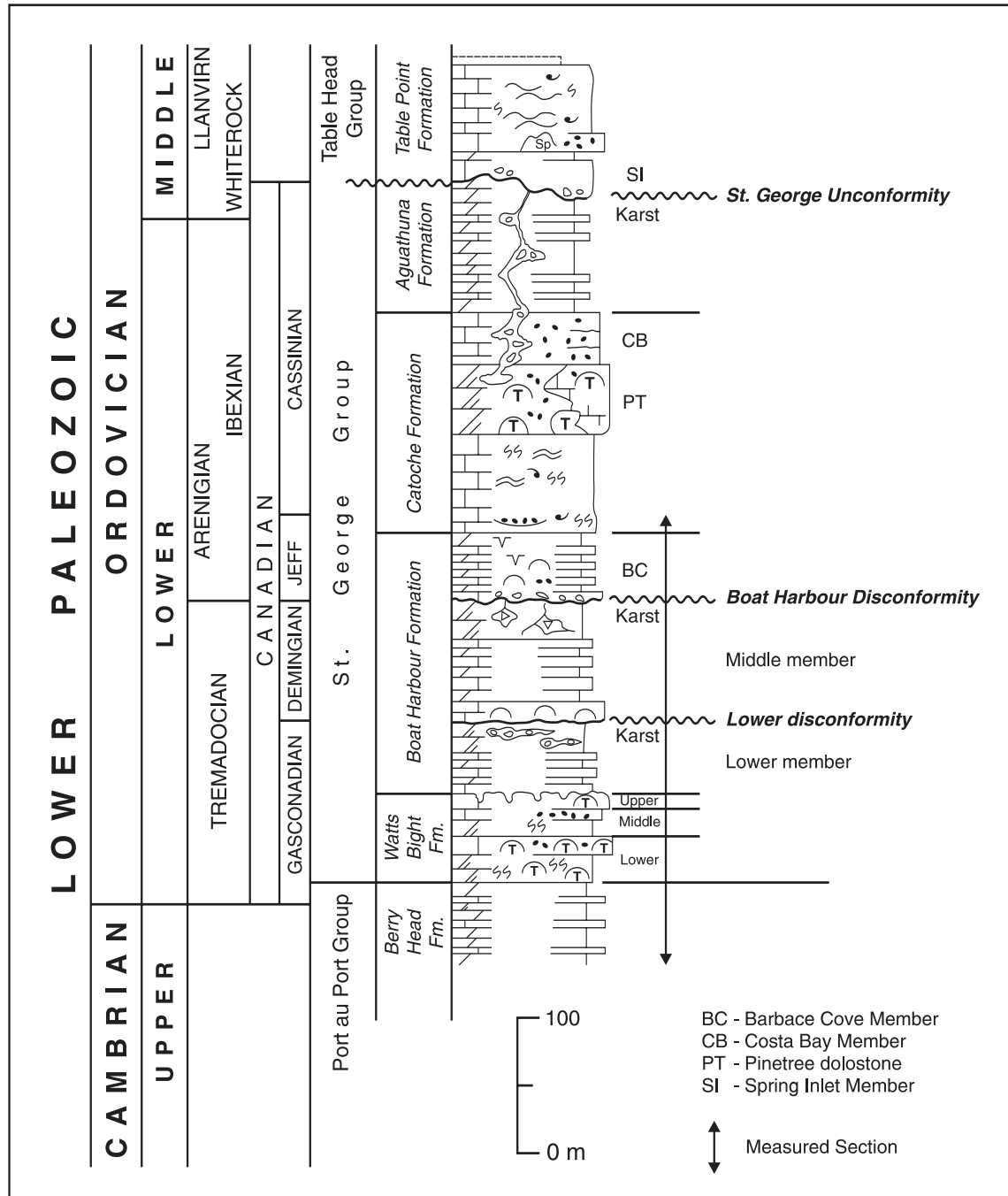


Figure 2. Simplified lithostratigraphy of the St. George Group, Port au Port Peninsula.

probably overstep the landward limit of the underlying Cambrian carbonate shelf and, in turn, be overstepped by the younger Arenig megacycle that is now at Anticosti and Mingan islands. The Arenigian megacycle was the focus of an earlier study (Knight *et al.*, 2007) and is continuing to be the focus of ongoing petrographic, geochemical, diagenetic, fluid inclusion and isotopic studies.

The Tremadocian sequence was studied and sampled, in detail, along the shoreline section of the western side of Isthmus Bay, Port au Port Peninsula (Figures 2 and 3). This section hosts a continuous succession, broken only by a few high-angle faults of small displacement, and a few short-covered intervals, and has been designated as the reference section for the two formations that make up the lower St.

George Group (Knight and James, 1987, 1988)⁴. Rocks of the Watts Bight Formation from this section include the Green Head metazoan-thrombolite mound complex, described by Pratt and James (1982), and the succession of metre-scale peritidal sequences in the Boat Harbour Formation that provided much of the impetus for distillation of the tidal-flat island model proposed for the Lower Ordovician shelf (Pratt and James, 1986).

The Isthmus Bay section formed the basis for diagenetic studies by Pratt (1979) and conodont studies by Ji (1989), and Ji and Barnes (1993, 1994). The conodont sample sites of Ji with their sample number still mostly visible on the rocks of the Isthmus Bay shore are noted on the section⁵. This should allow future correlation of fluctuations of the isotopic curve with the biostratigraphic events defined by Ji and Barnes (1994).

In this study, the Isthmus Bay section was sampled regularly about every two metres (± 50 cm) during the summer of 2007 when the Watts Bight Formation was also logged in some detail. Sampling of the Boat Harbour Formation, however, utilized detailed sectioning completed in 1988 (I. Knight, unpublished data, 1988). (The composite of these sections is displayed in Figure 4.) Sampling continued above the Boat Harbour Disconformity through the overlying Barbace Cove Member of the Boat Harbour Formation into the basal part of the Catoche Formation. This was done to provide an overlap with the ongoing isotopic and diagenetic studies of the Arenigian and Whiterockian rocks of the upper St. George Group (Knight *et al.*, 2007).

The work of Ji (1989) and Ji and Barnes (1994) defined a number of microfaunas in the lower St. George Group. They noted a significant biostratigraphic faunal event heralded by a marked change of conodont faunas at the lower 45 m mark of the Boat Harbour Formation. This change suggested to them that a disconformity probably existed between the lower and middle part of the Boat Harbour Formation, a conclusion supported by detailed logging of the Isthmus Bay section in 1988 by Knight (I. Knight, unpublished data, 1988; Knight and Cawood, 1991). Further, it showed the development of widespread paleo-karst cavities and sediment fills associated with widespread dolomitization of the carbonate rocks for at least 20 m below the 45 m level. This lower disconformity is described, at some length, later in this article (*see page 137*).

The biostratigraphic study of Ji and Barnes (1993, 1994) was innovative in that it divided the conodont faunas of the peritidal carbonates into a series of deep-water and shallow-water assemblages. Using this data, they were able to show that both shallow- and deep-water faunas changed at the two disconformities (the Boat Harbour Disconformity and the lower disconformity; Figure 2) and that the lower disconformity mapped a profound extinction of the fauna found below it. They also interpreted the disconformity as the contact of the Tremadoc and Arenig. This conflicts with other macrofossil and conodont studies done on the formation succession, particularly on the Northern Peninsula, which strongly supports the Tremadoc–Arenig boundary at the Boat Harbour Disconformity (Stouge, 1982; Boyce, 1989; Boyce and Stouge, 1997). The apparent conflict of the studies may perhaps hide some, as yet, overlooked aspect of the accretion of the Newfoundland platform and will await further thought and study. In this paper, the Tremadoc–Arenig boundary is placed at the Boat Harbour Disconformity.

The lower St. George Group has been studied (litho- and biostratigraphically) elsewhere in western Newfoundland, and, in particular, near Boat Harbour, Eddies Cove West, Canada Bay, Schooner Island in Pistolet Bay and Brent Islands in Hare Bay on the Northern Peninsula as well as some parts of the succession at Goose Arm, Bay of Islands (Figure 1).

The study seeks not only to establish a petrogenetic history of the succession, but also to generate an isotopic curve for the Tremadocian part of the Lower Ordovician, which can be linked to the local lithostratigraphy and also, can be compared to isotopic curves established in co-eval successions, globally. This curve will then be combined with the curve for the upper St. George Group succession to define a regional curve for the entire Lower Ordovician of western Newfoundland. The present study is also designed to better appreciate the relationship of the reservoir potential of the succession to the generation of stratigraphic and diagenetic dolomite and other diagenetic features.

GENERAL LITHOSTRATIGRAPHY OF THE LOWER ST. GEORGE GROUP AND THE IMMEDIATELY UNDERLYING BERRY HEAD FORMATION

The succession studied begins in the upper member of the Berry Head Formation and continues through the lower

⁴Pratt and James (1982, 1986) lumped both formations together as the Isthmus Bay Formation and also included rocks now mapped as part of the Berry Head Formation. The name Isthmus Bay Formation is discontinued in favour of the present stratigraphy. The base of the formation used here is a few metres above that used by Ji and Barnes (1994).

⁵The painted sample numbers of Ji (1989) are given the designation of GI-42 etc. on the outcrop.

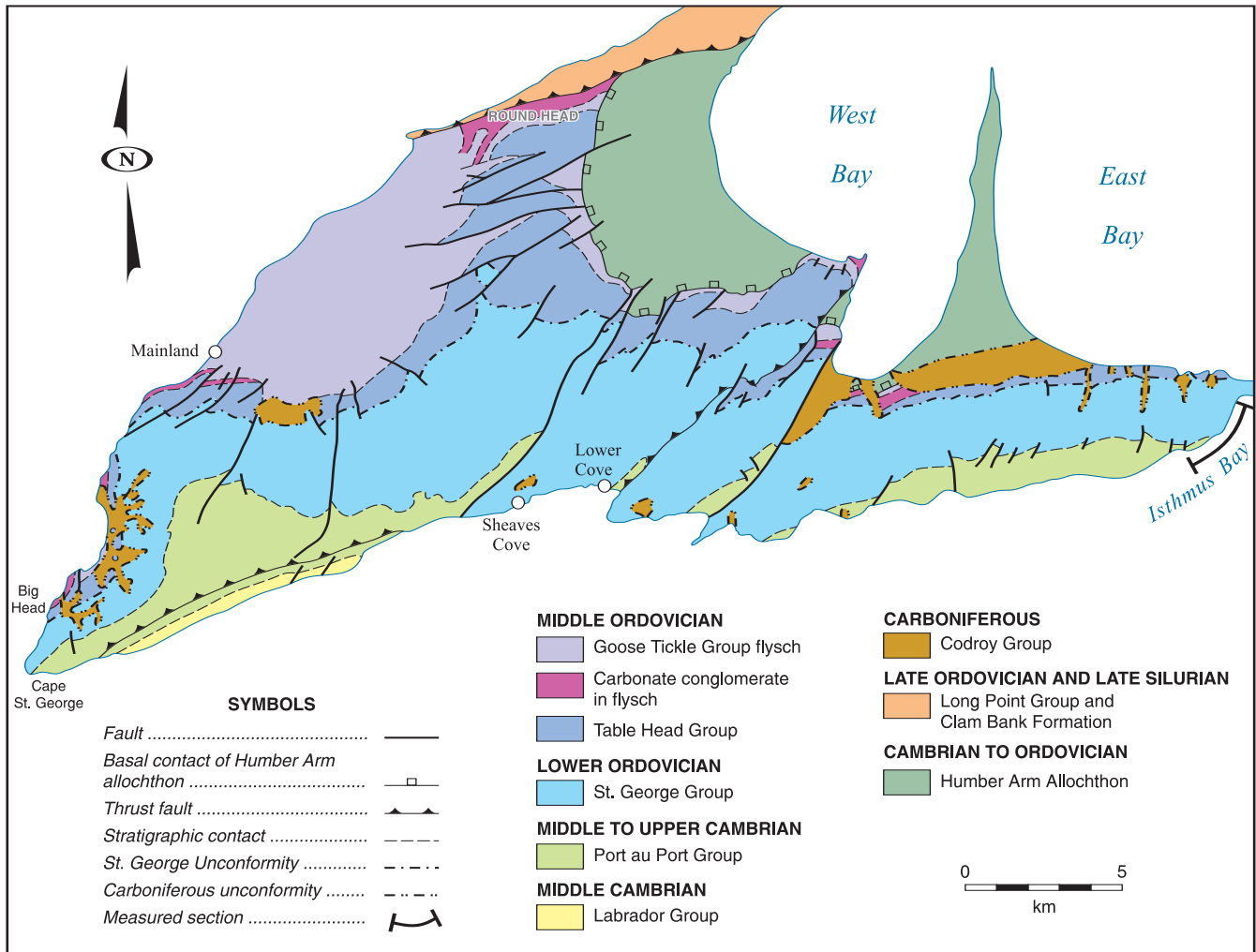


Figure 3. Geological map of the Port au Port Peninsula showing location of Isthmus Bay section (based on unpublished mapping of Knight, 1996).

St. George Group to the Boat Harbour Disconformity, approximately 50 m below the top of the Boat Harbour Formation (Figures 2 and 4). The description that follows is a synthesis of the Isthmus Bay sequence together with published and unpublished work, where appropriate, elsewhere in western Newfoundland. The section begins several hundred metres west of Green Head and continues into the head of Isthmus Bay, a few hundred metres short of the south-facing, steep-faced, stromboli pebble beach of the isthmus itself (Figure 3). The section is mostly a rocky shore of low cliff and a series of saw-tooth steps separated by long bedding-plane ledges of gently north-dipping strata. Locally, the cliff reaches up to 5 or 6 m in height at, and west of Green Head, but is mostly only a few metres high. The rocky ledges are fringed by a narrow pebbly foreshore that is exposed at low tide.

Berry Head Formation (Figure 4, Column A)

West of Green Head, the 50 or so metres of Berry Head Formation consists mostly of yellow-weathering, light-grey to grey, very fine-grained dolostone and some interbeds of mostly dark-grey limestone (Plate 1). Tan-grey-weathering, dark-grey, finely crystalline, locally porous and bituminous, sucrosic dolostone occurs in the upper 15 m of the formation where it mostly replaces burrowed carbonate rocks and a rare boundstone mound bed. Chert is common in boundstone beds. The succession consists of several lithofacies including undulose to smooth and planar thin-bedded dolostone, patterned dolostone, bioturbated, microbial boundstone, intraclastic grainstone and rudstone facies, nodular-bedded dolomitic limestone facies, and dololaminite. Although most of these facies are preserved as dolostone,

SYMBOLS

	Bioturbation (intense, moderate, minor)		Grainstone lense
	Arenicolites / Diplocrateria		Trough cross bedding
	Skolithus		Planar cross bedding
	Chondrites		Uneven stylo-thin stratification
	Trilobite		Planar lamination, thin bedding
	Opercula		Undulose lamination, thin bedding
	Cephalopod		Limestone nodule
	Gastropod		Chert
	High-spired gastropod		Chert outlining mounds
	Brachiopod		Mudcrack
	Pulchrilamina / Lichenaria		Fissure crack
	Sponge		Fenestra
	Mound		Tepee
	Thrombolite (R-Renalcis)		Ripple mark
	Stromatolite		Flaser
	Digitate		Dolostone lens
	Pebbles		Nodular/parted
	Skeletal grain		Gutter cast
	Intraclast		Hardground
	Peloid		Convolute
	Oncolite		Breccia
	Oolite		Vug
			Cauliflower nodule (cte-calcite, dte-dolomite, Q-quartz)
			Geopetal cavity

LITHOLOGY

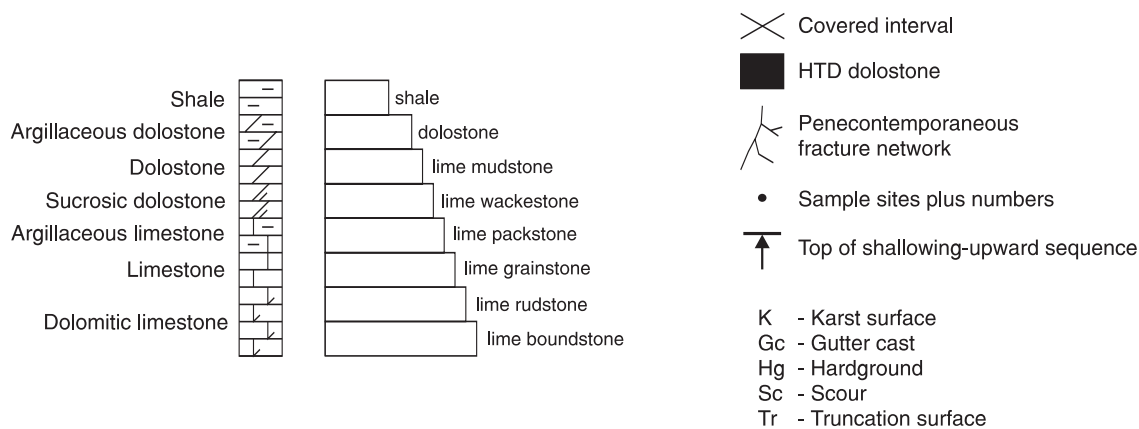


Figure 4. Legend.

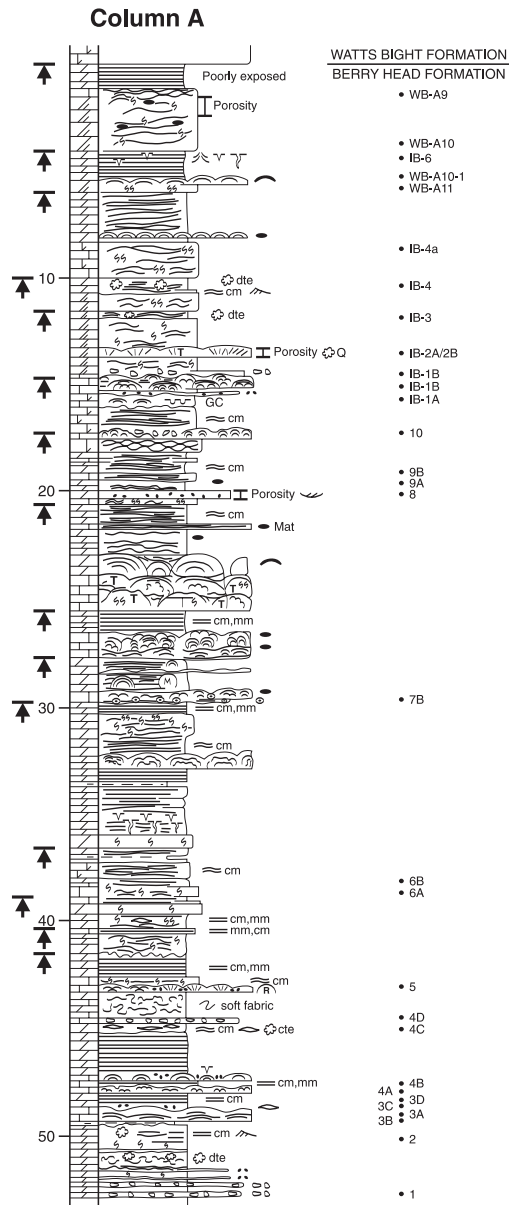


Figure 4. Detailed stratigraphic logs of the Upper Berry Head to Catoche Formation, Isthmus Bay section, Port au Port Peninsula. Column A. All columns are to the same scale.

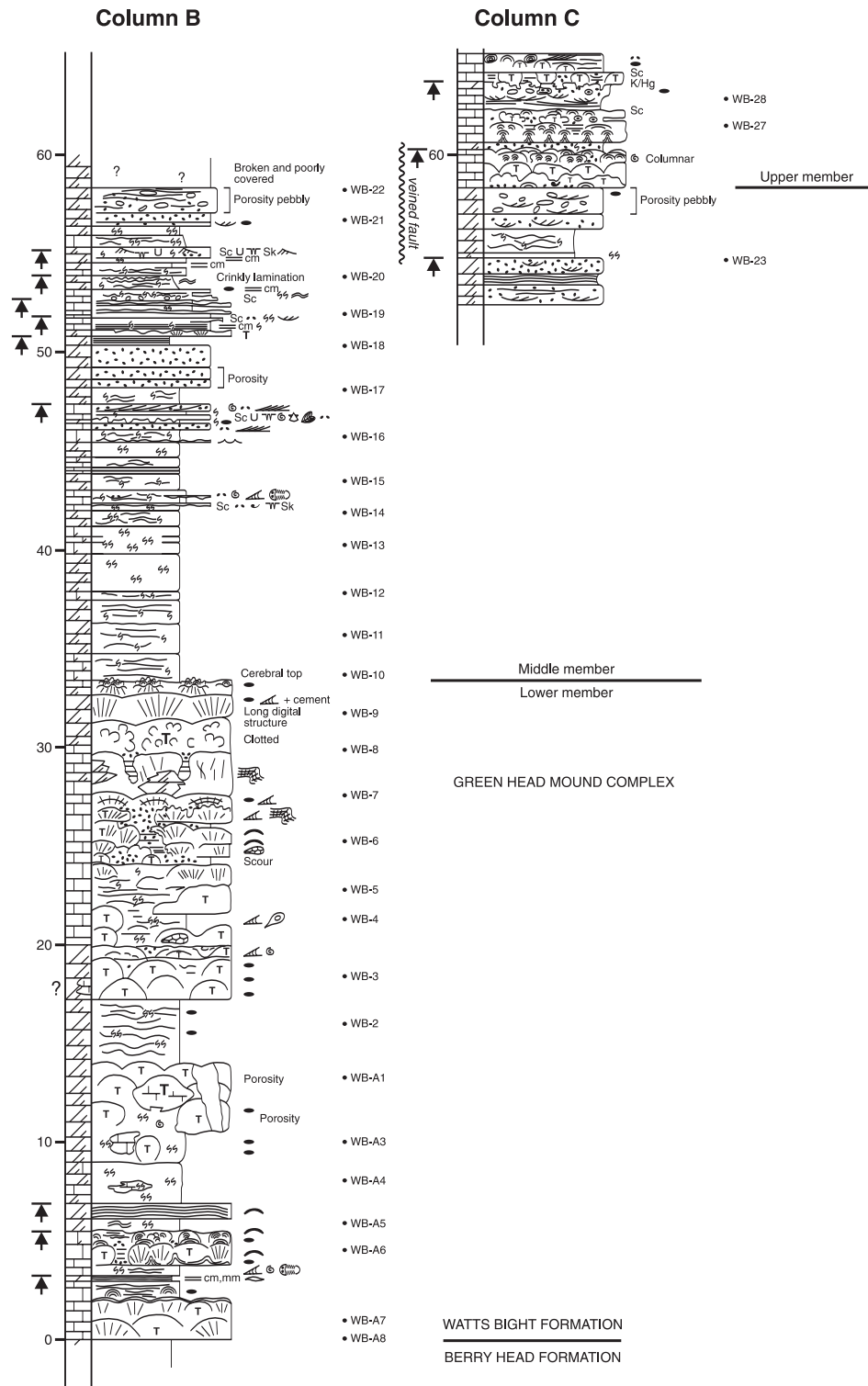


Figure 4. Detailed stratigraphic logs of the Upper Berry Head to Catoche Formation, Isthmus Bay section, Port au Port Peninsula. Columns B and C. All columns are to the same scale.

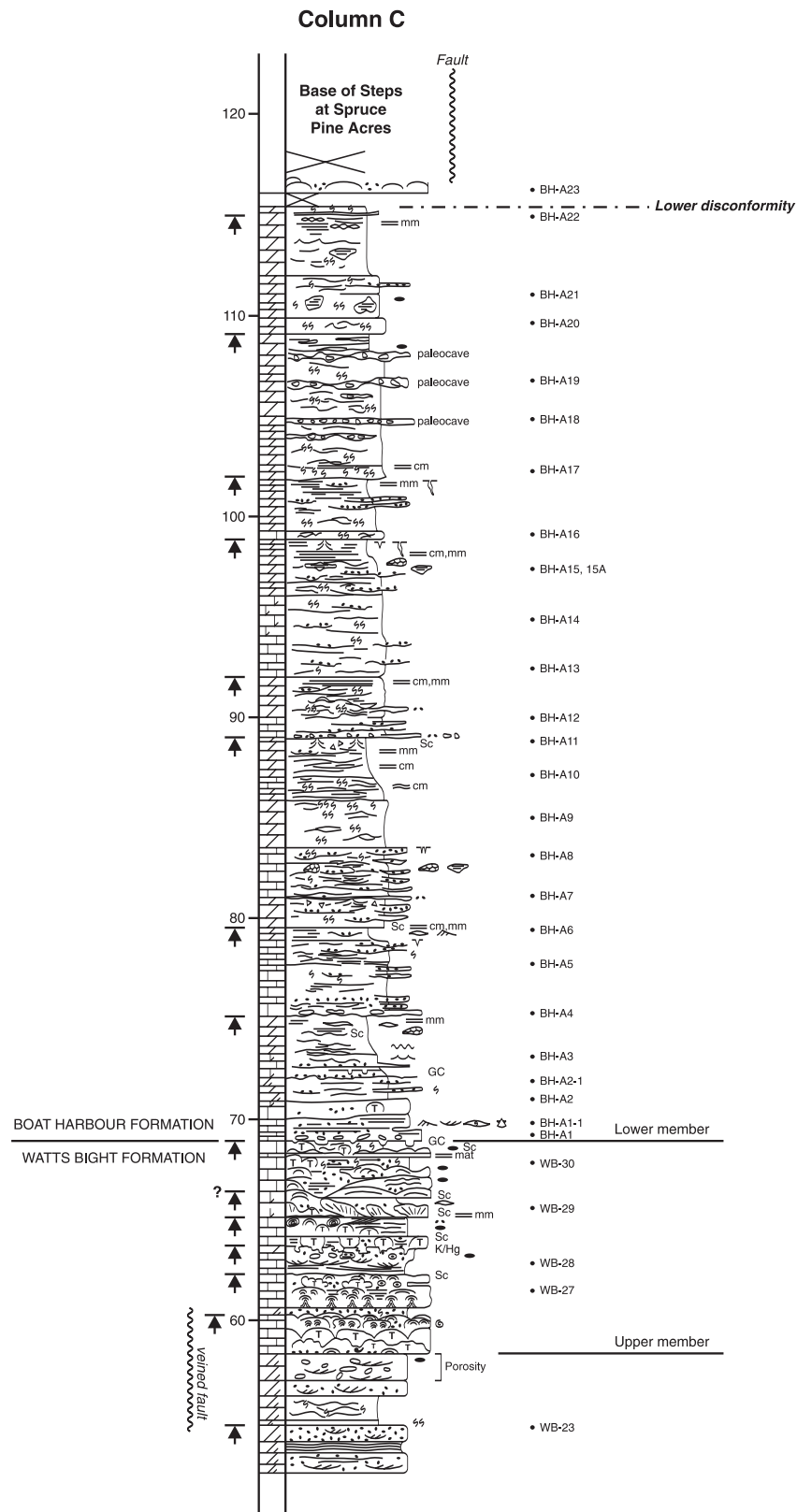


Figure 4. Detailed stratigraphic logs of the Upper Berry Head to Catoche Formation, Isthmus Bay section, Port au Port Peninsula. Column C. All columns are to the same scale.

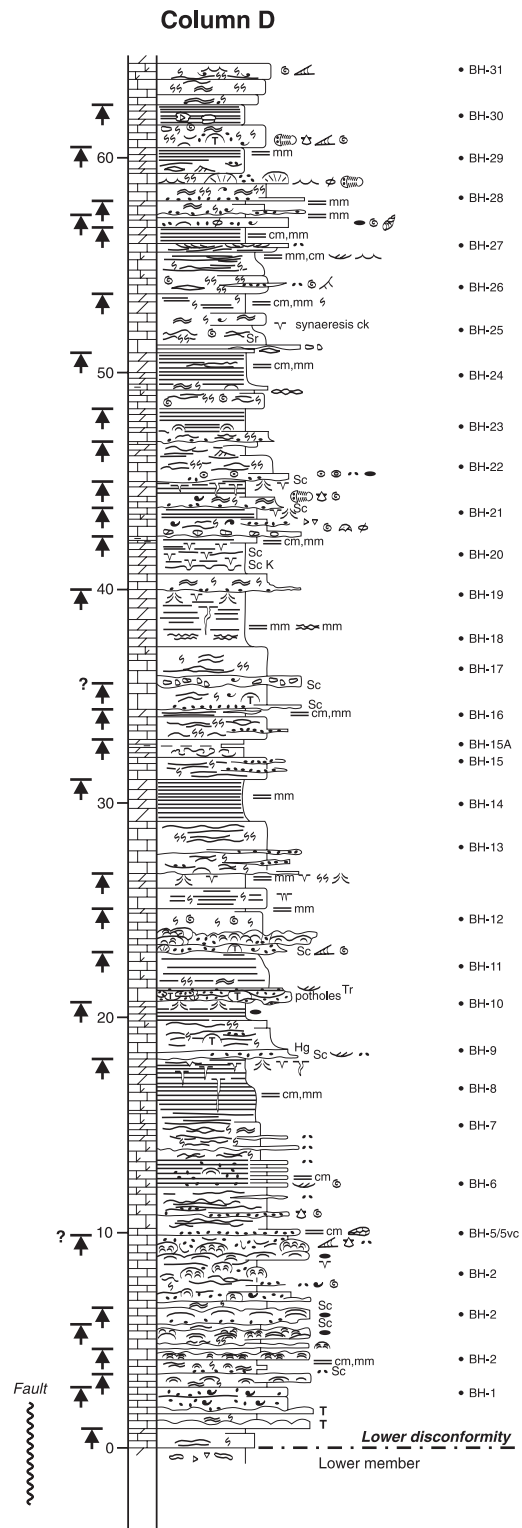


Figure 4. Detailed stratigraphic logs of the Upper Berry Head to Catoche Formation, Isthmus Bay section, Port au Port Peninsula. Column D. All columns are to the same scale.

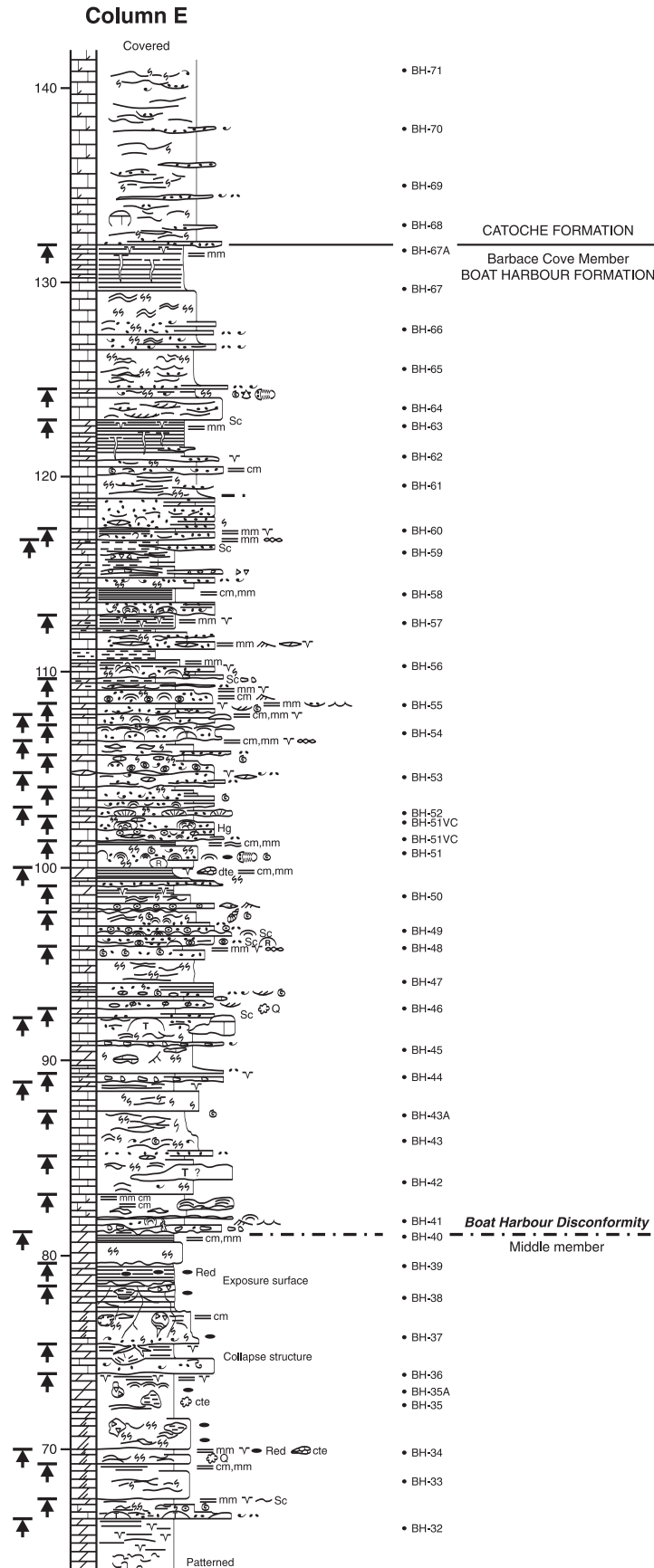


Figure 4. Detailed stratigraphic logs of the Upper Berry Head to Catoche Formation, Isthmus Bay section, Port au Port Peninsula. Column E. All columns are to the same scale.



Plate 1. Section through upper Berry Head Formation, west of Green Head.

limestone is present in small amounts, although upward, it is more abundant in the succession.

The thin-bedded dolostone facies is the dominant facies, forming units up to 4 m thick. It is always very fine grained, and the distinctive character of this facies is its uniformly undisturbed nature, ranging from smooth to undulose to knobby thin stratification and shaly partings, a few simple burrows and little else. Gutter-casts filled with fine-grained dolostone occur in one unit. A rare, intercalated, shale bed, up to 10 cm thick, interrupts the facies locally. Where the facies is limestone, it is always a featureless lime mudstone. In some units, intercalated in the facies there are lenses and interbeds of intraclastic dol-grainstone and dol-rudstone. These coarse-grained beds, which range from a few centimetres up to 15 cm in thickness, have irregular erosional bases and small, centimetre-size discoid clasts of the fine-grained facies. Dolarenites/grainstones are mostly intraclastic although one bed contains some scattered oolites. Crossbeds occur in the thicker beds.

Patterned dolostone is a minor facies in the section. It shows an unstructured mottled fabric that suggests deformed soft sediment. Dololaminite, which is uncommon except in the upper 20 m of the section, is generally planar to undulose finely laminated, and has low-angle discontinuity surfaces, lenses of dolarenite and breccia, and can be locally mudcracked with rare tepee structures and fissure cracks. Crosslamination and flaser bedding are common in some units. Small nodules of white quartz and of dolomite spar are scattered throughout the thin-bedded dolostone and dololaminite.

Bioturbated carbonates are the next most common facies attaining up to 3 m in thickness toward the top of the formation. Where limestone is still preserved it is mostly dark-grey lime mudstone displaying simple tubular burrows and crude uneven thin stratification. In the upper 15 m of the

section, the muddy burrowed limestones are largely replaced by sucrosic dolostone rather than by very-fine to fine-grained dolostone as seen in lower parts of the section.

Boundstone mounds are dominated by stromatolitic fabrics including stacked bulbous and cabbage-head forms mixed with linked hemispheroids and broad laminar layers that outline the mound shapes. Synoptic relief is generally less than 20 cm over a few metres. Some mounds lie upon rudstone layers and pockets of intraclastic rudstone-infill depressions between mounds. A few mounds display digitate structure and some have *Renaleis?* clots interlayered with layers of linked hemispheroidal stromatolite. Roundish stromatolite mounds also occur isolated in the thin-bedded dolostone facies.

A cluster of nodular, dolomitic lime mudstone beds, 15 to 65 cm thick, occurs about 16 to 20 m below the top of the formation where they mark the basal unit of cycles beneath stromatolitic boundstone. These nodular- to ribbon-bedded limestone facies are probably an open-shelf carbonate representing deeper water shelf deposition compared to most of the other facies that likely formed in shallower peritidal settings. Upward-shallowing, metre-scale peritidal sequences of burrowed carbonate, microbial mound and dololaminite facies are readily identified in the upper 15 m of the section approaching Green Head, Isthmus Bay. However, below this, cyclicity is not obvious. There is, also, no strong correlation of the Green Head section with that of other sections measured through the upper Berry Head Formation, e.g., at Goose Arm (87 km to the northeast) and a section at the south end of the Phillips Brook structure, only 18 km to the east-northeast. The top of the latter section is complicated by an interval of collapse breccias affecting an unknown thickness of strata (probably at least several metres) which obscures the upper contact of the formation at Philip Brook. Nonetheless, there are two significant observations regarding the section. First, the uppermost interval of burrowed carbonate intercalated with dololaminites and some boundstone beds appears to be widespread. And second, only the single bed of nodular limestone occurring 16 m below the top of the formation in the Green Head section may provide a link to a similar bed at about the same stratigraphic level below the top of the formation in the Phillips Brook section. No link to the Goose Arm section was possible, however.

No macrofauna was seen in the Green Head section, although Ji (1989) recovered conodonts of earliest Ordovician age from some of the limestones in the upper 20 m of the section. Trilobites and gastropods were recovered from the section in Goose Arm (Knight and Boyce, 1991) indicating that the upper Berry Head Formation spans the Trem-paleauan through the earliest Ordovician.

Watts Bight Formation

The Watts Bight Formation, named after Watts Bight, a small inlet, near Boat Harbour and Boat Head on the Northern Peninsula, is a chert-rich succession dominated by large thrombolitic mounds and burrowed carbonate rocks that has been mapped throughout western Newfoundland (Knight and James, 1987, 1988). The formation outcrops along the shore at Green Head where it consists predominantly of boundstone, grainstone and burrowed carbonate preserved as limestone and sucrosic dolostone (Plates 2 and 3). A rare interbed of dololaminite occurs at the base and in the upper part of the formation, and chert occurs throughout. The formation at Green Head is 69 m thick, and it is divided into three natural but informal stratigraphic intervals, namely, a lower mound member, a middle burrowed carbonate–grainstone member and an upper mound member (Figure 4). Reviewing the succession in the Watts Bight Formation at Isthmus Bay, it appears to comprise two decimetre sequences of low-energy, bioturbated and mound carbonate overlain by high-energy facies associations of mounds and grainstones that may have common truncation surfaces. The lower sequence is contained by the lower mound member, and the upper sequence by the middle and upper members.

Green Head Section

Lower Member (Figure 4, Column B)

The 33-m-thick, lower mound member (Figure 4, Column B) comprises dark-grey limestone, tan-grey-weathering, dark-grey, sucrosic, dolostone, rare buff-weathering, grey dololaminite and abundant chert. The unit is generally thickly bedded, comprising predominantly burrow-mottled, dolomitic limestone, and thrombolitic boundstone. Although these facies occur as limestone, more than 50% of the unit is replaced by fine to medium crystalline, sucrosic dolostone that, commonly, smells bitumenous and is, locally, porous.

The lower mound member has a lower interval of a few shallowing-upward peritidal sequences. These include thrombolitic boundstone overlain by smooth but undulose, thin-bedded lime mudstone and isolated, small-scale, stromatolite heads, capped by a 25-cm-thick dololaminite and burrowed carbonate, overlain by a mound bed that consists of thrombolite overlain by stromatolitic boundstone. The thrombolite locally has a mottled fabric but is generally digitate. The stromatolite includes broad domal structures that enclose digitate and columnar growth forms and has a laminar cap. Skeletal-intraclastic grainstone is associated with the mounds. A few gastropods and a gently curved, horn-shaped cephalopod occur in the interval. Chert replaces the mounds irregularly and commonly forms sheets outlining the top of the mounds.



Plate 2. Basal contact of the St. George Group and the Port au Port Group just south of Green Head. The conformable contact of the Watts Bight Formation and the underlying Berry Head Formation is marked by the arrows; the cliff is about 5 to 6 m high.



Plate 3. Looking north across the upper part of the Green Head mound complex, comprising mostly sucrosic dolostone and patches of limestone. A broad zone of intermound carbonate (arrow) occurs between mounds buildups; hammer is 34 cm long.

Above the shallowing-upward basal sequence, the member comprises burrow-mottled, sucrosic dolostone and isolated mounds or interbeds of thrombolitic dol-boundstone. Remnant patches of limestone occur in this dominantly dolostone interval that is also cut by a vertical, metre-wide, dyke-like body of spar-rich hydrothermal dolomite (HTD). The burrowed interval gives way fairly abruptly into an upper interval of thick-bedded, thrombolitic lime boundstone that is replaced widely by sucrosic dolostone at the base and top of the interval (Plate 3). This interval is the Green Head Mound complex of Pratt and James (1982). Chert is common throughout. Burrowed carbonate is most commonly associated with the mounds in the lower part of the complex, whereas grainstone is widespread in the intermound areas in the middle, and coalesced mounds leave no room for other sediment types in the upper few metres. A scour surface truncates the mounds-burrowed carbonate at

the top of the lower part of the mound complex and marks the base of the middle grainstone associated mounds.

The Green Head biohermal mound complex is described and illustrated diagrammatically by Pratt and James (1982). They defined three, mound-building facies, namely 1) thrombolite-*Renalcis*-*Lichenaria*, 2) thrombolite-*Renalcis* and 3) *Renalcis*-thrombolite (for further detailed evaluation of the mound complex, the reader is referred to their publication). In outcrop, the mounds appear to divide



Plate 4. Thrombolite boundstone mounds and digitate structure(s) at the top of the Green Head mound complex, Isthmus Bay; hammer is 34 cm long.

into two types, *i.e.*, those of vague lumpy to clotted structure (megaclots to microclots) and those with long digitate/columnar structure (Plate 4), in some instances forming a fan-like array within the mound. The mounds are generally many metres in diameter and in some beds are, at least, 2 m thick. One mound has essentially straight, vertical to slightly fanning digital columns forming the complete bed (up to 1.5 to 2 m in length). Some mounds appear to include patches and clusters of a sheeted and laminar skeletal organism (perhaps the stromatoporoid *Pulchrilamina*) and, locally, the primitive coral *Lichenaria* is discernable. Acidized outcrop limestone indicates that the clotted fabric comprises a composite of micrite, clustered peloidal clots, dark spots, possibly *Renalcis* or other coccooid blue-green algae, and in some cases, small coral patches of *Lichenaria*. Pratt and James (1982) describe grainstone patches within the mounds. Large gastropods and straight to slightly curved, horn cephalopods (Plate 5) are quite common in the mounds and locally clustered in intermound areas. A rare horn-shaped sponge (?) also occurs locally (Plate 6). Several decametre-sized cavities are cemented with a fibrous cement, and other cavity porosity is closed by a coarse, white, but often pink mosaic calcite cement. The fibrous cement is layered and may well be a marine cement (Pratt, 1979). Similar fibrous cements were noted within the cham-



Plate 5. A cluster of dolomitized unidentified gastropods and cephalopods in a grainstone within (the middle of) the Green Head mound complex, Isthmus Bay.



Plate 6. An isolated sponge (right of penny) enclosed by clotted boundstone, in lower mound member, Watts Bight Formation, Isthmus Bay.

bers of a cephalopod in the upper part of the mound complex (Plate 7). Intermound grainstone is generally coarse to very coarse grained, intraclastic and skeletal and is probably largely derived by erosion of the boundstone mixed with pelmatozoan debris (Pratt and James, 1982).

Middle Member

The 25-m-thick, middle member of the formation (Figure 4, Column B), rests sharply on the top of the lower mound member. It comprises a lower interval of bioturbated carbonates, now mostly sucrosic dolostone, overlain by an upper interval of mostly dolomitized, grainstone and bioturbated carbonate interbeds; some beds of thin-bedded dolomitic limestone and dolostone and a few beds of bound-

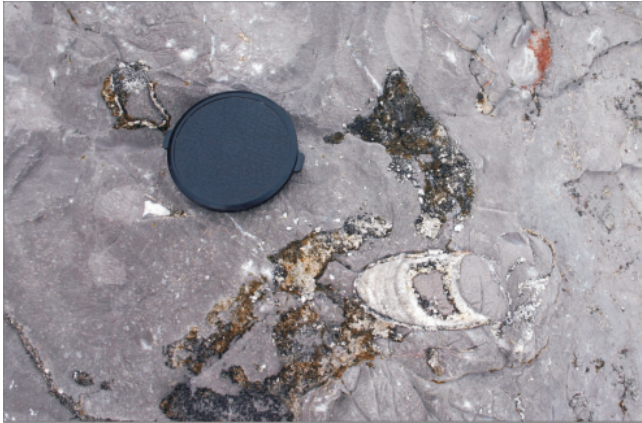


Plate 7. *A straight cephalopod in a thrombolitic boundstone mound, lower member, Watts Bight Formation, Isthmus Bay. Note fibrous calcite cement occluding its chambers; lens cap is 6.5 cm across.*

stone also occur within the upper interval. The top part of the section is cut by a sinuous to locally anastomosing, low- to moderate-angle, south-trending, normal fault that is now the site of a colour-banded, fibrous calcite vein of probable Carboniferous age. Beds were traced across the fault supporting a downthrow to the west of only a few metres.

The burrowed limestone in the lower interval is well bedded and intensely bioturbated (Plate 8); the burrows are replaced by fine-grained dolostone. Undolomitized carbonates are a mix of lime mudstone and peloidal wackestone. Gastropods, straight cephalopods and trilobites are present in some beds. Three metres from the top of the interval, the bioturbated carbonate is interrupted by a 15-cm-thick bed of intraclastic-skeletal grainstone and a few lenses of very fine-grained packstone / grainstone. Flat-based, and having a lumpy to rippled top, the grainstone is burrowed by *Skolithus* and *Arenicolites*. A rippled lens of grainstone is present just below the beginning of the upper grainstone-dominated interval.

The upper grainstone-dominated interval is a heterolithic mix of carbonate facies ranging from fine-grained carbonate to grainstone in which cycles are not readily defined. However, detailed bed by bed logging suggests that there are four cycles comprising a basal unit of rapidly alternating grainstone, fine-grained carbonate and, in some cycles, boundstone (this interval is missing in the topmost cycle), a middle interval of bioturbated carbonate, and an upper interval of grainstone.

The basal interval of the cycles consist of grainstone and pebbly rudstone sheets, 10 to 30 cm thick, intercalated with 10- to 25-cm-thick, stylonodular dolomitic limestone and/or bioturbated skeletal-peloidal wackestone. There is



Plate 8. *Bedded, bioturbated limestone from the middle member of the Watts Bight Formation, Isthmus Bay; measuring stick is 1.5 m long.*



Plate 9. *Dolostone showing centimetre-scale intercalated, grainy and muddy burrowed carbonate. The grainstones have *Skolithus* and U-shaped burrows, low-angle lamination and crossbedding. Upper part of the middle member, Watts Bight Formation; bar is 5 cm.*

one bed of uneven to smooth, planar thin-bedded dolomitic limestone. Some beds grade up into finely crystalline dolostone that has uneven thin stratification, thin beds of bioturbation and layers of flaser bedding. The grainstones sheets are skeletal and intraclastic. They display complex, often overlapping basal scours, some possibly deformed by soft-sediment loading, the trace fossils *Skolithus* and *Arenicolites* as well as other burrows, occasionally low-angle, planar crossbedding (Plate 9), and layers of mudstone-intraclast pebbles and gastropods. The latter plus opercula are common throughout this basal unit.

Mound beds occur in the 2nd and 3rd cycle sandwiched between bioturbated carbonate. Thrombolitic boundstone beds, 15 to 40 cm thick, range from lumpy micrite (largely dolomitized) alone to clotted structures of micrite, peloids, and dark microbial (*Renalcis?*) clots and clusters, to digitate structure. Gastropods and other fossil debris are entrapped in some of the mounds.

The middle interval of bioturbated carbonate is generally dolomitized, internally shows uneven stylobedding, and intense tubular burrowing. Where limestone is preserved, it is generally dolomitic wackestone/mudstone and stylonodular lime mudstone.

The upper grainstone is a thicker unit, ranging from 0.7 to 2.45 m in thickness, again predominantly dolomitized to a fine- to medium-crystalline, grey dolostone in which porosity is commonly preserved and lime sand grains are still visible. This clearly shows that the grainstones were generally coarse to very coarse grained, with layers of intraclastic pebbles, up to 1.5 cm in diameter. They display good planar and trough crossbeds and some intervals of planar lamination. Interbedded fine- to very fine-grained grainstones were extensively burrowed by *Skolithus*, *Arenicolites* and other burrowers but locally there are also crosslaminated beds. The crossbedded, coarse-grained dolarenites appear to pass laterally into the finer grained burrowed dolarenites.

Upper Member

The upper mound member (Figure 4, Column C), which is only 11 m thick, is well exposed at the top of the section where it sits sharply and conformably upon the last thick porous crossbedded dolarenite of the middle member. The mounds include both thrombolite and stromatolite in roughly equal amounts and the boundstones are associated with and, locally, interbedded with grainstone. Unlike the lower or middle member, the upper mound member one is not so strongly affected by dolomitization; chert commonly replaces mounds. The top of the member is placed at a guttered erosional surface that is overlain by a thin conglomerate that marks the base of the first of a succession of thick, peritidal sequences that characterize the Boat Harbour Formation.

The mounds, which are decametre- to metre-scale in diameter, generally show synoptic relief of no more than 20 to 30 cm. They range from low-relief domes to steep-sided pedestals, to irregularly shaped, essentially asymmetrically leaning mounds (Plate 10) with recumbent and inclined sides, to very-broad, low-relief, overlapping biostroms many metres across. The mounds consist of clotted and mottled thrombolite, mixed columnar thrombolite and stromatolite, and stromatolite structure. In some cases, the thrombo-

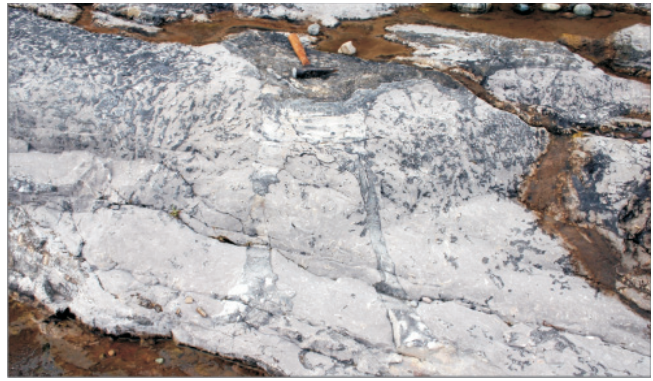


Plate 10. *Thrombolitic boundstone mounds in the upper mound member of the Watts Bight Formation, Isthmus Bay; hammer is 34 cm long.*

lite gives way upward into stromatolite but more commonly stromatolite is overlain by mixed stromatolite/thrombolite or thrombolite. Aberrant stromatolite (Pratt and James, 1982) is common in two mound sequences where it underlies columnar stromatolite. Cavities infilled by laminated geopetal carbonate occur in the mounds with the aberrant stromatolite structure. The broad biostroms occur in the top few metres of the formation. They are almost tapering, sheet-like bodies of short digitate structure associated with grainstone, some burrowed carbonate and erosional surfaces. They sit atop an erosion surface that truncates the irregular, recumbent mounds.

Broad intermound channels/areas and narrow vertical gullies that separate the wide to closely spaced mounds are infilled by unsorted to thinly stratified grainstone, intraclastic floatstone and muddy carbonate. Grainstone interbeds, which range from 35 to 90 cm thick, are burrowed or crossbedded and laminated. The grainstone interbeds are mostly intraclastic (derived by erosion of lime mudstone and the microbial mounds), and some are fairly rich in gastropods. One grainstone bed carries tennis-ball-sized oncolites in the upper part of the bed. The crossbedded grainstone bed consists of a lower interval in which broad scours are overlain by curved to flattening foresets below an interval of festoon trough crossbeds. These are overlain by a pebbly grainstone that displays some lamination and small crossbeds. It is truncated by an erosion surface that is characterized by narrow, invaginated (?)karren, up to 15 cm deep, suggesting a karst surface.

Erosional surfaces are common throughout the upper member where they truncate tops of both mound and grainstone beds. One scour displays erosional pinnacles of thrombolite mounds left protruding up into one of the skeletal and intraclastic grainstone beds (same bed that is oncolitic). A vase-shaped depression (karren?) occurs in one of the erosional pinnacles. Some of the erosion surface is encrusted by

now-partly silicified layers of laminar stromatolite or perhaps tufa.

The narrow strip of rocky shoreline does not display any sense of orientation to mounds in either lower or upper member and this is also the case with crossbeds in the grainstone rocks.

Contact with the Boat Harbour Formation

The erosion surface that is selected as the Watts Bight-Boat Harbour formations contact is a strongly developed surface that truncates and incises into the uppermost bed of the Watts Bight Formation (Plates 11 and 12). The latter is a bioturbated, muddy to grainy, dolomitic limestone with isolated, round boundstone mounds. The erosion surface is characterized by several, irregularly spaced, straight, elongate gutters that penetrate several centimetres into the underlying bed. The gutters have a preferred orientation to the northwest (between 306° and 345°). The surface is overlain by a 1- to 15-cm-thick limestone conglomerate, in which clasts, mostly of lime mudstone, range from a few centimetres to fist size. Traced to the east over 10 to 15 m, the surface appears to merge with a lower erosion surface at the top of an earlier grainstone bed. The limestone between the two surfaces is cut out by the gradual downcutting of the upper erosional contact, which therefore amounts to at least 60 cm of lost section over a distance of more than 10 m. This suggests that the surface is an important surface of incision and possibly ravinement.

Regional Variation within the Watts Bight Formation

Northern Peninsula

The most inboard and northwesterly section measured is the formation type section near Watts Bight on the Northern Peninsula. There, the formation is completely dolomitized to a brownish-weathering, dark-grey, fine- to medium-crystalline dolostone that preserves the general fabrics of the original sediment. The cliff and rocky shoreline section, which is broken by narrow coves and bights and may be faulted, reaches about 110 m in thickness (Knight and James, 1988). The formation in this area has a three-part architecture, very similar to that seen in the Green Head section⁶.

The lower mound sequence begins with large thrombolite and stromatolite mounds capped by thin dololaminites below a massive complex of large mounds that have grainstone fringes. Bulbous, columnar and aberrant stromatolite and mottled thrombolitic textures occur in the mounds.



Plate 11. Upper contact of the Watts Bight Formation with the overlying Boat Harbour Formation (arrow), Isthmus Bay. View looking north; measuring stick is 1.5 m long.

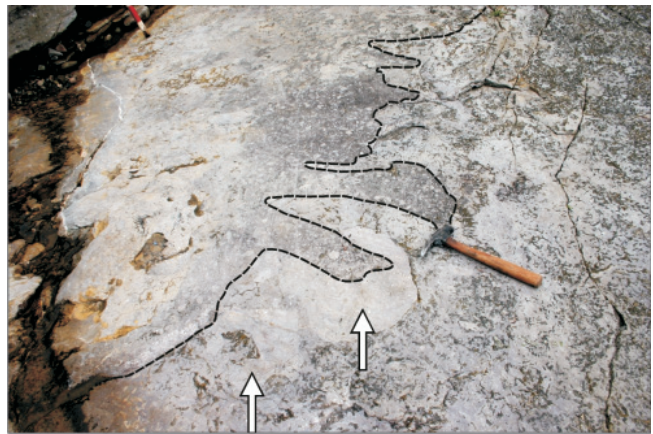


Plate 12. A series of incised, conglomerate-filled gutters at the discordant, erosional basal contact of Boat Harbour Formation. The surface erodes through mounds (arrow) and bioturbated limestone of the Watts Bight Formation; hammer is 34 cm long.

Toward the top of the interval, mottled thrombolite mounds are spatially separated within the bioturbated carbonate. Chert is widespread, often outlining tops of mounds and replacing small stromatolite heads. Ghosts of gastropods and cephalopods are common.

The middle of the formation is dominated by bioturbated carbonate and isolated mounds in its lower section, below an upper interval of bioturbated beds that are intercalated with crossbedded dolarenite. Digitate stromatolite mounds capped by erosion surfaces and some dololaminite interbeds are also present in the upper grainy part of the member. The top part of the formation is a mix of stromatolitic and throm-

⁶The formation in this area is well illustrated in Knight and James (1988).

bolitic mounds, grainstone and bioturbated carbonate. Mounds with spectacular columnar to radiating columnar and digitate growth patterns seen in cross section are well exposed at Boat Head. The upper contact of the formation at Boat Head is locally crosscut by large transgressive, although stratabound, bodies of collapse breccia.

The sucrosic dolostones replace the formation from Boat Harbour southwest to Daniel's Harbour, and although no sections have been measured in this large area, regional mapping indicates that the formation retains its stratigraphic character as seen at Boat Head and Watts Bight. Collapse breccias are extensively developed at the top of the formation throughout this inboard terrain. Only at Fish Point, just north of Eddies Cove West is a bed of off-white limestone preserved within a long coastal stretch of collapse breccia close to the top of the formation. This limestone comprises thrombolite mounds, and intraclastic grainstone, the latter enclosing large oncolites, and has yielded the trilobite *Parahystricurus* (= ?*Hystricurus*) sp. I (Ross, 1951) and the conodont *Variabiloconus bassleri* (Furnish, 1938) indicating a Tremadocian/Gasconadian age for these beds (Knight, 1991; Boyce and Stouge, 1997).

The completely dolomitized formation can be traced east to the northeastern extension of the Ten Mile Lake Fault (Figure 1), a major, regional, northeast-trending, high-angle fault. However, east of the fault, the dolomitization feathers out and replaces only the lower 15 m of the formation in sections near Canada Bay and is completely absent at Brent Islands, Hare Bay. This feathering out of the dolostone is also seen at Goose Arm and in the Blue Pond thrust stack.

Pistolet Bay and other Eastern Thrust Stacks

The formation in the eastern thrust stacks is, essentially, two parts. For instance, on the southeast shore of Brent Islands, Hare Bay, Northern Peninsula, the formation is dominated by thick intervals of massive, stacked and amalgamated boundstone mound complexes that have grainstone fringes and channel fills, minor interbedded bioturbated limestone and thin dololaminite caps to cycles. For the most part, the large domal mounds are dominated by clean, colour-mottled, thrombolitic boundstone and irregular to clotted fabrics as well as some mounds of distinctive digital structure. Thin bulbous, columnar and linked stromatolites occur below and topping thrombolite in mound sequences at the base of the formation; columnar stromatolite and linked stromatolitic mats were noted in a few beds near the top of the member. The upper part of the interval in the Canada Bay area is host to some spectacular mound complexes seen

in the horseshoe cliff at the drawdown swallow-hole cave on Beaver Brook (Knight and Saltman, 1980).

At Brent Islands, the lower, mound-dominated, member is overlain by an upper interval of off-white, peloidal and intraclastic, skeletal and pebbly grainstone that can be traced south 40 km into the Canada Bay area and is also present in the Goose Arm and Blue Pond thrust stacks 200 to 300 km to the south. This suggests that this two-part eastern stratigraphy may represent a regional, more outboard facies belt.

Western Port au Port Peninsula

The most southerly and westerly sections observed on the Port au Port Peninsula near Lower Cove, Sheaves Cove and Cape St. George⁷, are dominated by thick-bedded, stylobedded to stylo-thin-bedded, sparsely to moderately burrowed, dolomitic limestone (Plate 13). The limestone is mostly lime mudstone (with disoriented, scattered, mostly trilobitic, skeletal grains). Sharp, planar surfaces in the stylobedded mudstones suggest the presence of possible hard-ground surfaces. Intraclastic rudstone and grainstone lenses

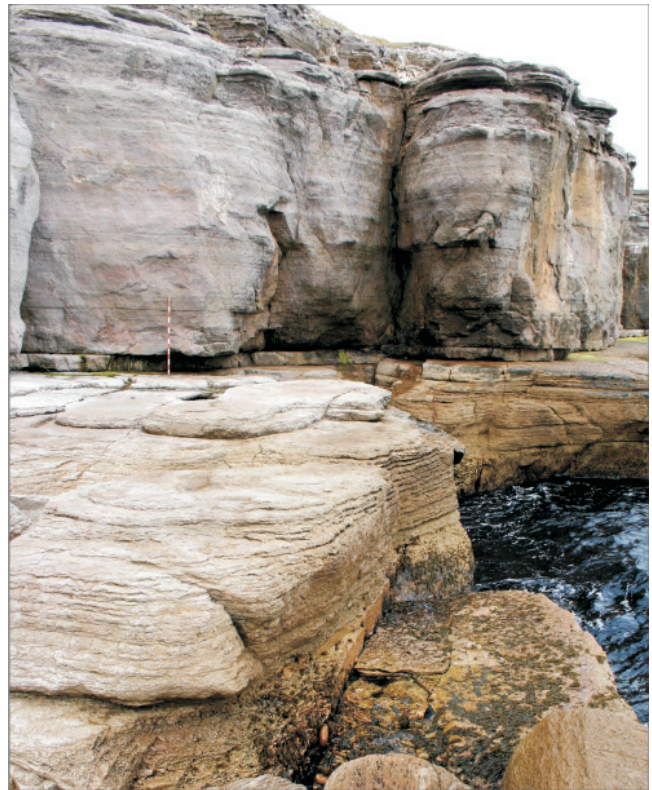


Plate 13. Thick beds of stylobedded, lime mudstone to wackestone, Watts Bight Formation at Sheaves Cove; measuring stick is 1.5 m long.

⁷No detailed section has yet been measured at any of these places, but will be attempted in the coming year (2008).

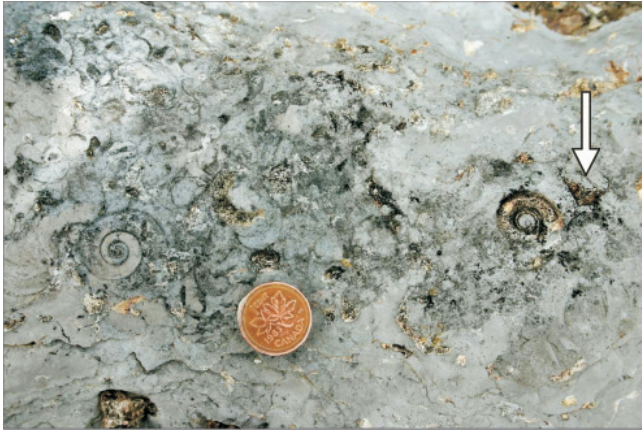


Plate 14. A cluster of gastropods and a brachiopod (arrow) in the Watts Bight Formation, Sheaves Cove.



Plate 15. Two trains of long to gently curved, megaripples (obliquely oriented to each other) between thick beds of stylonodular to bedded, bioturbated and fossiliferous, lime mudstone and wackestone, Watts Bight Formation, Sheaves Cove; hammer is 34 cm long.

and thin beds, some fairly skeletal rich, are interbedded in the muddy carbonates. Silicified gastropods, some brachiopods and rare opercula commonly occur in the grainstones (Plate 14). Megaripples of skeletal intraclastic grainstone, including hummocky forms (suggestive of hummocky cross-stratification, HCS) where the ripples intersect, occur locally (Plate 15). Some biohermal mounds of thrombolitic boundstone, fringed by grainstone, occur isolated in the mudstone facies near Lower Cove (Figure 2). The mounds are truncated by impressive erosion surfaces.

Boat Harbour Formation

The Boat Harbour Formation was named for a succession of cyclic, peritidal limestone and dolostone recognized first at, and later named after, Boat Harbour on the Northern Peninsula and regionally mapped throughout western New-

foundland (Knight and James, 1987, 1988). The formation at Isthmus Bay is divided into three members, each separated from the one above by a disconformity across which faunal changes occur, at both macro and micro level. This tripartite stratigraphic architecture is extended to the formation throughout western Newfoundland. In previous studies, only two members were defined, namely, an unnamed lower member and the upper Barbace Cove Member; the two members are separated by the Boat Harbour Disconformity. Detailed biostratigraphic studies of the formation include trilobite and conodont studies (Stouge, 1982; Stouge and Boyce, 1983; Boyce, 1989; Ji, 1989; Ji and Barnes, 1993, 1994; Boyce and Stouge, 1997).

Recent lithostratigraphic analyses of a number of sections but, in particular, the one at Isthmus Bay showed that there was a lower disconformity in the lower unnamed member (I. Knight, unpublished data 1988; Knight and Cawood, 1991). This was supported by concurrent conodont studies (Ji, 1989; Ji and Barnes, 1994) who proposed an important break about 50 m into the formation.

Lower Member (Figure 4, Column C)

Isthmus Bay

The lower member (Figure 4, Column C), which is about 46 m thick, is a succession of at least 9 metre-scale, upward-shallowing, peritidal cycles, 2.2 to 6.5 m thick. The cycles commonly have a scour base that is overlain by a thin lag or bed (10 to 95 cm thick) of rudstone and/or pebbly grainstone, grainstone and thin, intercalated, burrowed wackestone lenses; the grainstones are dominantly intraclastic. At the very base, however, the grainstone is rich in skeletal material, especially brachiopods and has thin beds and lenses of brachiopod coquina. Small-scale crossbeds, cross-lamination, thin beds and lenses of burrowed wackestone and ragged remnants and rip-ups of laminated cryptalgal mats characterize this basal unit. Other basal lags carry rip-up plates derived by erosion of the underlying dololaminite. In most of the other cycles, the basal grainstone facies is overlain by extensively bioturbated, irregularly interstratified muddy to grainy limestone that is in turn, overlain by undulose thin-bedded dolomitic limestone capped by dololaminite.

In the upper 30 m, the lower member is dolomitized to a yellow- to buff-weathering, finely crystalline dolostone (Plate 16) in which uneven stylobedding, bioturbation, and dololaminite are still visible. The interval is peppered with irregular, bedding-parallel bodies of breccia, rudstone, grainstone and locally geopetal dolostone (Plate 17). The irregular shape of these bodies, which thicken and thin before tapering and lensing out, and the markedly irregular



Plate 16. Upper dolomitized part of the lower member of the Boat Harbour Formation, Isthmus Bay. The disconformity (arrow) with the middle member occurs just left of the staircase. A high-angle fault downthrows middle member at the stairs (block arrow).



Plate 17. A matrix-supported breccia above a mottled dolostone. Note irregular contact and a small disconcordant lens of finer breccia (arrow), both implying they are the product of dissolution. A few metres below top of the lower member of the Boat Harbour Formation, Isthmus Bay.

floors and roofs that partly transgress stratification suggests that they are dissolution cavity fills. Silicification affects both the host dolostone and some of the cavity fills. Close to the top of the dolomitized section, the breccias are as thick as 25 cm with centimetre-size rubble; some beds have long narrow horizontal fissures partly filled with fine-grained sediment and by dolomite cement. All these features are attributed to the disconformity that is postulated to occur at the top of the dolostone interval as outlined by Ji and Barnes (1993, 1994). Some omission surfaces shown on Figure 3 of Ji and Barnes (1993) may correlate with these near-bedding parallel paleocavity fills. A pronounced negative $\delta^{13}\text{C}$ anomaly occurs at the lower disconformity.

Faunas Associated with the Lower Disconformity

Below the Lower disconformity, there are three shallow-water (SW) and two deep-water (DW) conodont faunas recovered by Ji and Barnes (1993, 1994). The lowest SW

assemblage fauna, *Teridontus nakamurai*–*Semiacontiodus nogami*, occurs in the upper Berry Head Formation and continues to the base of the middle part of the Green Point mound complex where the mounds and grainstone overlie isolated mounds and burrowed carbonate rocks above an erosional contact. Deep-water lineage zone *Cordylodus lindstromi* essentially matches this range before giving way to *C. angulatus* lineage zone a few metres above the base of the middle grainy part of the Green Head mounds. *Polycostatus falsioneotensis*–*Rossodus tenuis* is the new SW assemblage that continues to the base of the Boat Harbour Formation where it is replaced by the *Rossodus manitouensis*–*Polycostatus sulcatus* assemblage. This SW assemblage and the second DW lineage are both terminated at the Lower disconformity.

Macro fossils are rare in the lower member of the Boat Harbour Formation and the Watts Bight Formation and no fossils were found in the upper Berry Head Formation, pointing to the utility of the conodont studies for understanding the chronology of the Isthmus Bay section. In the Watts Bight Formation, only the limestones of the Green Head mound complex have yielded fossils, namely the brachiopod *Finkelburgia* sp. undet., the gastropod *Lecanospira* sp. undet., the cephalopod ?*Diphragmoceras* sp. undet.⁸, and the trilobite *Hystricurus ellipticus* Fisher, 1954⁹. An undetermined brachiopod and the trilobite *Hystricurus oculilunatus* Ross, 1951 are the only fossils from the lower member of the Boat Harbour Formation.

Other Sections in Western Newfoundland

The lower member of the Boat Harbour Formation generally is poorly exposed at Boat Harbour, where it forms a 39 m, wrack-covered section exposed at low tide in the harbour itself. The section comprises largely dolostone in the lower part and a mix of limestone, sucrosic dolostone, salt-and-pepper dolomite and spar-rich, HTD complexes replacing the limestone and dolostone. Burrow-mottled and laminated fabrics occur in the dolostones. Gastropods are common in the dark-grey, dolomitic burrowed limestones. The HTD complexes are essentially bedding parallel, replacing the limestone beds, and not uncommonly, are rich in vuggy porosity. Bodies of collapse breccia are common in the member throughout the Boat Harbour area. In drillholes (2M/12 0001 and 0002) several kilometres south of the Boat Harbour section, the member is 43 to 50 m thick and has a basal zone of collapse breccias (10 to 15 m thick), overlain by a thick succession of mostly laminated, patterned and cryptalgal dolostones (I. Knight, unpublished field logs 1991). In this area, the breccias commonly have a dolostone

matrix and sparry dolomite cements. Some breccias show snow-on-roof textures on top of breccia clasts, and others are sparsely mineralized by pyrite, galena and sphalerite.

At Eddies Cove West, north of Port au Choix, the lower member appears to be replaced by an extensive network of collapse breccias that also affect the topmost strata of the underlying Watts Bight Formation (Knight, 1991).

At Brent Islands, the lower member is about 24 m thick, and the base of the section is mostly covered. Above the covered interval, burrow-mottled dolomitic limestone intercalated with undulose thin-bedded, dolomitic limestone and dololaminite, occur in cycles, 0.85 to 1.5 m thick; there is no evidence of collapse breccias or extensive dolomitization. Correlation with other sections is uncertain.

Yellow-weathering, burrow-mottled, patterned and laminated dolostones, and locally developed collapse breccias occur in the Goose Arm and Bonne Bay areas. A distinctive unit, it is easily mistaken for dolostones of the Cambrian Port au Port Group.

Middle Member (Figure 4, Columns D and E)

The middle member of the Boat Harbour Formation, which is 83 m thick, is bounded by the lower disconformity at the base and the Boat Harbour Disconformity at the top (Figure 4, Columns D and E). Between these two surfaces, the middle member consists of a basal boundstone marker interval, 10.5 m thick, overlain by a distinctly cyclic succession of limestone and dolostone. In the Isthmus Bay section, there are at least 39 metre-scale, shallowing-upward cycles in the member, of which 7 are likely in the basal boundstone unit.

The basal boundstone unit consists of grey limestone with zones of chert that preserve beautifully developed, broad oblate to domal, bun-shaped, stromatolite mounds, each a few metres in diameter and tens of centimetres thick (Plates 18 and 19). In the lower cycles, the mounds are poorly structured thrombolites intercalated with burrowed limestone and skeletal-intraclastic grainstone. Upward the mounds intercalate with decametre-thick beds of undulose thin-bedded limestones that have rippled surfaces, pin-cushion stromatolite layers, mudchip pavements and locally mudcracks. The thin-bedded facies infills the intermound channels and surrounds the top of mounds in the middle cycles. Well-developed truncation surfaces scour the tops of some of the mounds, and together with the other intercalated facies, suggest cycles in the marker interval are sedi-

⁸This is from the the same bed collected by Flower (1978).

⁹Collected by Dr. R.K. Stevens in 1977; identified by D. Boyce, GSNL).



Plate 18. Bun-shaped stromatolite mounds overlapped by thin-bedded limestone and overlain by thicket mounds of *Renalcis*-thrombolite boundstone and grainstone (arrow), basal boundstone interval of the middle member of the Boat Harbour Formation, Isthmus Bay; lens cap is 6.5 cm wide.



Plate 19. Closely spaced, columnar to cabbage-head, linked stromatolite heads in a broad, oblate mound. Chert is common between heads. Boat Harbour Formation, Isthmus Bay; same locality as Plate 18; lens cap is 6.5 cm wide.

ment-mound couplets, some of which are topped by the truncation surfaces.

The stromatolite mounds (Plate 19) range from those composed of smooth to crenulate, continuous lamination to those composed of layers of linked hemispheroidal columns, discrete finger-sized columnar forms, layers of small bulbous cabbage heads and broad drapes of continuous lamination that encapsulate a complete mound above the other growth forms. Layers of intraclastic rudstone composed of discoid, lime-mudstone ripups form the substrate for nucleation of some mounds. Others appear to nucleate on the top of mounds that protrude through the thin-bedded limestone interbeds.

The uppermost mounds in the marker interval include a lower bed of broad stromatolite mounds overlain by *Renalcis* thrombolite (Plate 18). The lower mounds consists of continuous lamination and some clusters of small, hemispheroidal bulbous heads that appear to be the substrate for nucleation of the overlying *Renalcis* thrombolite. The thrombolite mounds are surrounded by crossbedded to massive, intraclastic-skeletal grainstone that is host to brachiopods, gastropods, and straight cephalopods. Much of the grainstone consists of a mix of dark and tan microbial sand grains. The mounds in cross section resemble bush-like thickets of spaced digitate microbial fronds and spurs that disperse in the thickets in vertical to inclined to radiating to locally flat-lying attitude. Fine-grained dolostone and some grainstone infill between the microbial framework suggesting that the microbial mound grew as an open reef that baffled both grainstone and fine-grained sediment; downward-facing *Renalcis* occurs in the roofs of some of the open space before the sediment infill occurred. A narrow zone of linked and discrete columnar stromatolite occurs in the upper part of the thrombolite mound suggesting that the mound grew in a succession of stages. The overall stratigraphic architecture of the upper mounds of the marker unit is one of gradual deepening so that the *Renalcis* mound is succeeded by a succession of nodular thin-bedded lime mudstones and sheeted rudstone and grainstone at the base of a very thick (8 m) deepening to shallowing-upward cycle (see below).

Above this basal marker, the cycles, which are 0.46 to 8.0 m thick, generally comprise a basal, scour-based rudstone and/or grainstone, overlain by the dominant middle-of-cycle facies, which include stylobedded to nodular, parted, dolomitic lime mudstone with sparse bioturbation and/or extensively bioturbated, dolomitic lime wackestone and packstone (Plates 20 to 23). The basal grainstones are most-



Plate 20. A scour-based grainstone (indicated by finger), base of a shallowing-upward small-scale sequence, middle member of the Boat Harbour Formation, Isthmus Bay.

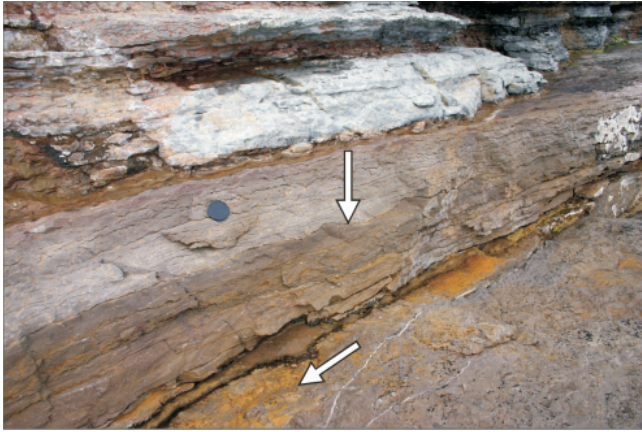


Plate 21. A bed of stylo-ribbon-bedded lime mudstone/wackestone having layers, some ripple marked (arrow), of grainstone, overlain by a nodular dolomitic lime mudstone. A bedding plane rich in brachiopods and other fossils occurs at the base of the cliff (lower arrow; see Plate 23). Middle member, Boat Harbour Formation, Isthmus Bay; lens cap is 6.5 cm wide.

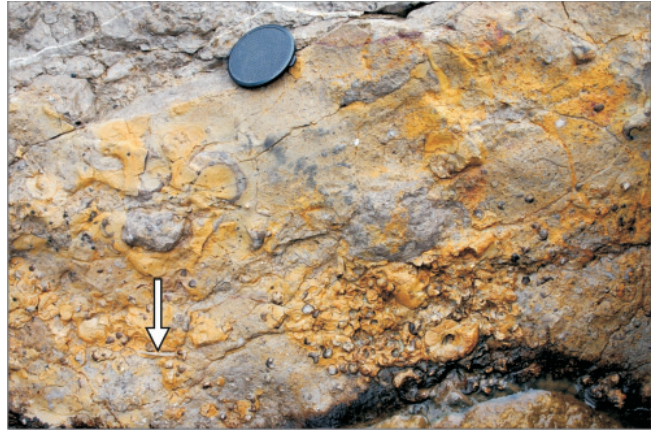


Plate 23. Common brachiopods *Diaphelasma*, and a few gastropods and a long crinoid stem (arrow) from the bedding plane seen in Plate 21. Middle member, Boat Harbour Formation, Isthmus Bay; lens cap is 6.5 cm wide.

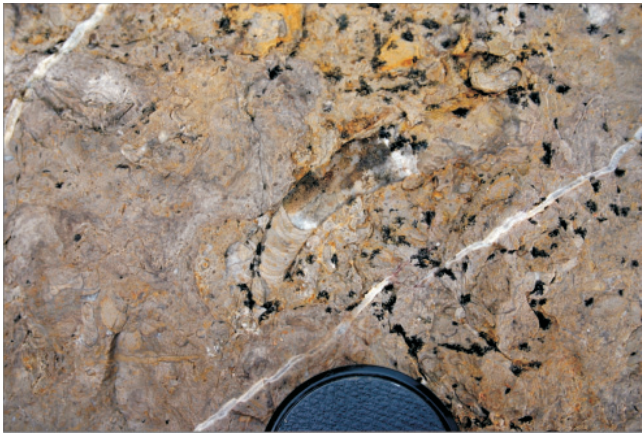


Plate 22. The horn-shaped cephalopod, *Bassleroceras* and gastropods in a basal grainstone of a small-scale cycle. The mollusk is partly filled by sediment and a late calcite cement. Middle member, Boat Harbour Formation, Isthmus Bay; lens cap is 6.5 cm wide.

ly intraclastic and carry small pebbles and rare skeletal remains. Oolitic and peloidal grainstones are rare, occurring mostly above the intraclastic grainstones on the top of a few beds. Sharp truncation surfaces, probably hardgrounds, occur in some of the basal lime sands. Intraclastic, often pebbly, and skeletal grainstone layers and lenses intercalate in the mid-cycle facies and gastropods occur locally. The bioturbated limestone beds generally pass up into undulose, thinly stratified dolomitic limestone (Plate 24) that may host sparse burrows, layers of lenticular and flaser bedding, layers of crosslamination and clusters of gastropods, and occasionally brachiopods; the latter locally form coquina-like



Plate 24. A bed of smooth, undulose, to pinching, thin-bedded limestone with thin beds/partings of yellow dolostone, and two small heads of stromatolite, overlying a bioturbated dolomitic limestone. Middle member, Boat Harbour Formation, Isthmus Bay; lens cap is 6.5 cm wide.

lenses. The cycles are capped by thinly stratified to laminated, dolomitic limestone and dolostone/dololaminite (Plate 25). Fissure cracks, mudcracks, tepees and low-angle scours characterize many of the upper laminites. Spar-cemented laminar fenestrae were noted in one clean limestone laminites.

Boundstone mound beds occur sporadically but are not a common feature of the section compared with other sections elsewhere in western Newfoundland. The boundstones may occur isolated in other facies, such as the bioturbated limestone facies, but mostly occur as clusters of mounds associated with grainstone (Plate 26). Some of the mounds comprise stromatolites of cabbage-head structure and digitate columns of stacked hemispheroids; others mounds com-



Plate 25. Finely laminated dololaminite capping a shallowing-upward cycle in the middle of the middle member, Boat Harbour Formation, Isthmus Bay. Small tepee structures, low angle scour, and mudcracks are common in the unit; measuring stick is 1.5 m long.

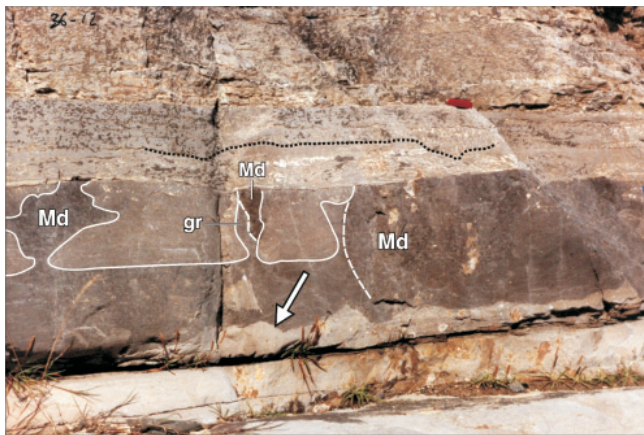


Plate 26. A planar truncation surface decapitating grainstone-filled potholes (outlined) that earlier eroded a bed of thrombolite boundstone mounds and grainstones leaving only pinnacles, themselves truncated, of the bed. A rudstone lies on the truncation surface and is overlain by scour-based, bioturbated limestone, the scour (dotted line) overprinted by a stylolite. Note the irregular basal scour into white lime grainstone and fenestral laminite below the mound-grainstone bed. Middle member, Boat Harbour Formation, Isthmus Bay; knife is 9 cm long. Md—mound; gr—grainstone.

prise thrombolite, including *Renalcis*. A few of the mound beds occur at the transition from the bioturbated facies up into the overlying thin-bedded facies or laminite cap, but, more commonly, they lie in the basal grainstone of the metre-scale sequences where they may be associated with frequent scour surfaces.

One such grainstone-*Renalcis* thrombolite mound bed (Plate 26), close to sample site BH-10 (Figure 4; equivalent of Ji bed Gi-42 in outcrop) is replete with irregular and karst-sculpted scours (illustrated by Pratt and James, 1986, figure 13). This complex interval is no more than 60 cm thick but contains more than 11 distinct depositional and erosional events. The most impressive surface locally erodes deeply into a bed of spaced, bun- to balloon-shaped, *Renalcis*-thrombolite mounds with intermound areas filled by a lower current-bedded and sorted, *Renalcis* grainstone, a middle bioturbated, intraclastic-skeletal, structureless, granular grainstone and locally at the top, bioturbated wackestone. The surface has deeply incised, pot-hole-like depressions, up to 20 cm deep and 25 to 80 cm wide with flat floors and smooth, though irregular, mostly overhanging walls. Between the potholes, there are erosional pinnacles of mound and mound and intermound grainstone. The potholes were infilled by more intraclastic grainstone before both pinnacles and pothole fill were decapitated by a later markedly planar erosion surface. Draped locally on this truncation surface lie centimetre thick lenses of hummocky-crosslaminated dolostone that are, in turn, eroded beneath a bed of intraformational rudstone that has imbricated clasts and which rests mostly on the planar truncation surface. The rudstone is, in turn, eroded by an irregular scour whose small highs are overlapped by pockets of pebbly grainstone. This lies below a 12-cm-thick bed of intraclastic grainstone and packstone that marks the base of a metre-scale, predictable shallowing-upward sequence.

The mound-grainstone bed rests upon an earlier, irregular, scalloped scour that passes laterally (down dip) into a flat surface with some local, downcutting steps. The mounds disappear above the planar part of the scour. Beneath the scalloped scour, there are small localized remnants of an underlying scour-based grainstone itself derived by erosion of the top of a fenestral lime mudstone laminite that marks the top of the previous fining-upward cycle (mentioned previously). This complex interval provides abundant evidence of multiple depositional cycles in a shallow, high-energy peritidal setting, and evidence for significant early lithification and erosion, including the likely development of shoreline karst that sculpted the potholed surface in the mound-grainstone bed.

Other Sections through the Middle Member in Western Newfoundland

The middle member is well exposed in three sections on the Great Northern Peninsula, namely Boat Harbour in the far north, Eddies Cove West near Port au Choix, and Brent Islands in Hare Bay. The type-section succession at Boat

Harbour is complicated by covered intervals, faults and a few bodies of HTD sucrosic and sparry dolomite that obscure the understanding of this section. Nonetheless, the Middle member is approximately 90 m thick (based on the coastal section and drillhole 2M/12 0002 (I. Knight, unpublished field log, 1991) and there are at least 28 shallowing-upward metre-scale sequences, most of which are dominated by stromatolitic and thrombolitic boundstone mounds overlain by undulose, thin-bedded dolomitic limestones. Burrowed limestone and laminite facies are less well-developed in most of the cycles although bioturbated limestone dominates a few sequences in the middle and top of the member. Grainstones are generally thinly developed and include skeletal–intraclastic and rarely oolitic kinds.

The section at Eddies Cove West is characterized by at least 36, small-scale, shallowing-upward sequences in a section, approximately 80 m thick. Its metre-scale shallowing-upward sequences are dominated by bioturbated and undulose thin-bedded dolomitic limestones some with thin laminite caps. Stromatolite and thrombolitic boundstone mounds occur sporadically at the base, middle and top of the formation. A few, thin oolitic grainstones occur near the base of the formation, but most grainstones are skeletal–intraclastic beds that also occur within the mound units. Anhydrite nodule and crystal-lath rosette pseudomorphs occur in some of the dololaminites.

The section at Brent Islands is the only one measured in the Pistolet Bay thrust stack where it ranges between 80 and 90 m thick and has at least 24 shallowing-upward sequences. (The number is likely to be a minimum because there are a number of thick covered intervals.) The succession is characterized by very dark-grey to black limestones, and by cycles, some unusually thick (up to 11 m), dominated by stylobedded, nodular, parted and bioturbated limestone and dolomitic limestone. The upper parts of the cycles consist largely of undulose, thin-bedded dolomitic limestone alone, although some cycles are capped by dololaminite. One laminated and desiccation-cracked, dolomitic limestone and dololaminite, 5 to 7 m thick, close to the base of the member, forms a prominent marker that can be mapped south to Canada Bay and north to Pistolet Bay (Green Island section) and Boat Harbour. Thick, black lime boundstone occur scattered throughout the upper half of the member; all but one bed comprise thrombolite and associated intraclastic grainstone. The lone stromatolite bed occurs associated with thin-bedded limestone.

Boat Harbour Disconformity

The Boat Harbour Disconformity is a cryptic to readily recognized, regionally developed surface that was first noted at Boat Harbour on the Northern Peninsula (Knight,

1977; Boyce, 1989) where it is marked by a karren surface draped by a lag of scattered intraformational quartz and dolostone pebbles and locally by a 2-m-thick, intraformational quartz- and dolostone–pebble conglomerate (Knight, 1986). The surface also occurs at Port au Choix just north of Barbace Cove, where it truncates stromatolitic dolostone and is veneered by pockets of breccia (Knight, 1991; Knight *et al.*, 2007, Plate 2). Silicification, dolomitization, and porosity are common immediately below the surface. The disconformity, if it exists, is not exposed in the section on Brent Islands. The contact, based on the first appearance of post-disconformity faunas, suggests it can be placed within a covered interval of a few metres of section. Peloidal grainstones appear to mark the base of the upper member.

Isthmus Bay

In the Isthmus Bay section, as many as seven, small-scale, shallowing-upward cycles are extensively dolomitized at the top of the Middle member of the Boat Harbour Formation, immediately below the disconformity (Plates 27 to 31). Where this dolomitization is most pervasive, it replaces some, but not all, of the burrowed, dolomitic limestone that forms the base of the shallowing-upward sequences in this part of the succession. Red chert masses and nodules are abundant throughout the same section. Paleocavities infilled by dolostone breccia and geopetal-laminated dolostone occur down to 10 m below the disconformity. A few cavities are filled by green shale. Although it is plausible to link all these features to the disconformity, detailed measurement of the section indicates that syndepositional karst was an intrinsic part of the history of at least two or three of the last metre-scale, shallowing-upward



Plate 27. *The Boat Harbour Disconformity (arrow) overlain by a matrix-supported conglomerate of dolostone and chert pebbles and a thin-bedded, grainy limestone. The onlap sediments are cut by a compacted, sediment-filled narrow fissure (block arrow), Isthmus Bay section; measuring stick is 1.1 m long.*



Plate 28. Close-up of the conglomerate overlying a fractured dolostone at the top of the middle member of the Boat Harbour Formation, Isthmus Bay section; lens cap is 6.5 cm wide.

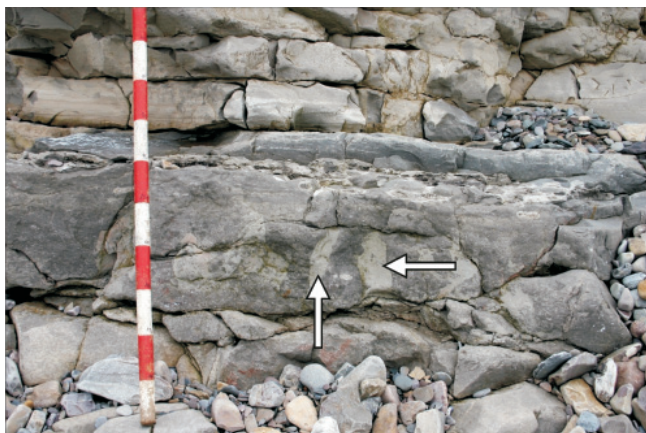


Plate 29. A cluster of paleocavities (arrow) filled by green, silt-sized geopetal dolostone, 7 m below the Boat Harbour Disconformity, Isthmus Bay Section; each division on measuring stick is 1.0 m.

sequences in the member. Features such as sub-karst paleocaves linked to extensive, millimetre- to centimetre-wide fractures cut dololaminite capping a cycle. Burrowed dolomitic limestone below the dololaminite thins out laterally and rapidly over a few metres. A thin deposit of partly silicified, grainy looking sucrosic dolomite (possibly the insoluble residue of burrow dolomite) lies against the last of the limestone and is interpreted as residual sand left in a paleocave before the roof caved in. This appears probable because above the dissolution zone, the overlying dololaminite collapsed, creating a broad zone of broken carbonate and open fractures that were infiltrated by geopetal sediment, breccias and locally some cement. The fractures project to the upper surface of the dololaminite where they widen into a series of angular fissures and local depressions that are infilled by grainy limestone of the overlying



Plate 30. A small paleocavity filled, in part, by angular pieces of the laminated dolostone host set in a sandy matrix, 4 m below the Boat Harbour Disconformity, Isthmus Bay section. Narrow brittle fractures are common (arrows). Penknife is 9 cm long.



Plate 31. Red chert nodules and large spherical cavities lined by dolospar and calcite cements. Ten metres below the Boat Harbour Disconformity, Isthmus Bay section; measuring stick is 1.5 m long.

sequence. A metre-scale basin above the collapse is infilled by significantly thicker limestone than outside the basin, indicating the temporal nature of the timing of this process. Fractures and paleocaves occur in the dololaminite above the collapse-fill limestone but no collapses are noted. However, a couple of hummocky surfaces in the dololaminite suggest that exposure surfaces interrupted deposition of the laminite.

The disconformity is placed at the irregular base of a bed of poorly sorted, dolomite- and quartz-pebble, dolomite-matrix conglomerate at the top of the last dolomitized and fractured carbonate of the member (Plate 27). Re-examined in 2007, the conglomerate is quite irregular, thickens and thins and locally forms irregular pockets on top of

the underlying dolostone. This suggests that the conglomerate forms a lag-on, and infills local holes beneath the disconformity. In addition, a narrow, compacted dyke-like fissure, a few centimetres wide, of grainy dolostone cuts the conglomerate and, locally, the overlying thin-bedded grainy and muddy limestone bed. This might hint that the conglomerate is localized in an erosional low on the disconformity and subsequently these post-disconformity sediments were penetrated by fissures that were filled by dolostone sand possibly washed off the disconformity surface before compaction.

Faunas Associated with the Middle Member and the Extinction Coinciding with the Boat Harbour Disconformity

The conodont studies of Ji and Barnes (1993, 1994) at Isthmus Bay indicate that the Boat Harbour Disconformity is a surface of marked, although not as dramatic, faunal change similar to the faunal change encountered at the Lower disconformity. Two SW and one DW faunas occur in the middle member below the disconformity. *Glyptoconus floweri*-*G. bolites* faunal assemblage occurs in the lower 34 m of the Middle member, overlain by the *Striatodontus prolificus*-*S. lanceolatus* faunal assemblage, which ranges up to the Boat Harbour Disconformity. The contact of these two faunas coincides with a very hummocky, almost egg-carton-like surface atop a dololaminite. The surface carries irregular burrows and possibly borings that are partly filled by sediment but include vugs and spaces now occluded by calcite cement. Whether this is a drowned karst surface that separates the two faunas has not been determined. The *Drepanoistodus nowlani*-*Macerodus diana*e deep-water assemblage zone ranges throughout the member and is terminated at the Boat Harbour Disconformity.

The middle member of the formation at Isthmus Bay is not generous with macrofossils but has yielded, in a number of beds, the brachiopods *Clarkellid* gen. et sp.(p). undet., *Diaphelasma* sp. undet., Orthid gen. et sp. undet., and *Lingulella*, the gastropods, *Lecanospira nerine*, *Lecanospira* sp. undet., *Rhombella* sp. undet., and silicified opercula, the cephalopod *Bassleroceras* sp. undet. and a few trilobite scraps including *Hystricurus deflectus* Heller, 1954 or *H. oculilunatus* Ross, 1951.

The middle member at the Boat Harbour and Eddies Cove West sections, both part of relatively undeformed basement-cored foreland, is blessed with a well-preserved macrofauna and a less prolific conodont fauna (Stouge, 1982; Stouge and Boyce, 1983; Boyce, 1989; Boyce and Stouge, 1997). The conodonts, which include faunas 1 and 2 of Stouge (1982), renamed the *Striatodontus prolificus* and *Macerodus diana*e faunas respectively in Boyce and Stouge

(1997), are readily correlated with those in the member at Isthmus Bay and are abruptly terminated at the Boat Harbour Disconformity. The trilobite faunas include, in ascending order, the *Hystricurus oculilunatus*, *Leioestegium proprium*, and *Randaynia saundersi* faunas, the latter abruptly terminating at the disconformity. Gastropod faunas dominated by *Lecanospira* occur in the member and are absent above the disconformity. The brachiopod *Diaphelasma* is, as in the Isthmus Bay section, the preeminent brachiopod.

The middle member on Brent Islands has yielded few fossils. Only trilobites of the *Hystricurus oculilunatus* and *Leioestegium proprium* zone have been recovered, leaving only about 24 m of section below the first Barbace Cove Member faunas to accommodate trilobites of the *Randaynia saundersi* zone that has yet to be found. The gastropod *Lecanospira* is recognized in the lower *H. oculilunatus* zone but gastropods in the *L. proprium* zone cannot be identified because of their poor preservation. The brachiopod *Diaphelasma* is the only brachiopod recognized to date. No conodont data is available for this section and because of the paucity of macrofossils in the section may be an important future project.

Post-Boat Harbour Disconformity Sequence - Barbace Cove Member and Catoche Formation (Figure 4, Column E)

The Barbace Cove Member, which was first recognized at Boat Harbour and Port au Choix (Knight, 1977) and later defined by Knight and James (1987, 1988), is regionally developed throughout western Newfoundland overlying the Boat Harbour Disconformity. The member is variable in thickness ranging from 10 to 15 m in the sections from Daniel's Harbour to Port au Choix to Boat Harbour, to 35 m in the Brent Island section of the Pistolet Bay thrust stack, to 52 m in the Isthmus Bay section.

The Barbace Cove Member is a succession of peritidal carbonate sequences, commonly ranging in thickness from a few 10s of centimetres to about 1.5 m, and rarely, to 7.5 m. The member is significantly more fossiliferous and grain-dominated than the peritidal sequences of the Middle member. Only a few broad generalizations are made here and the reader is referred to Knight and James (1987, 1988), Pratt (1979), Pratt and James (1982, 1986), Knight (1991), Knight and Cawood, (1991) and Knight *et al.* (2007) for more detailed information. In the innermost belt from Port au Choix to Boat Harbour, the member is dominated by thin cycles rich in skeletal, intraclastic, ripple-marked grainstones and rudstones alternating with lime mudstones, suggesting deposition on a mud to sand-dominated tidal flat. Some mounds occur locally including a widely developed thrombolite marker immediately above the disconformity at Boat Harbour.

In the two thicker sections of Isthmus Bay and Brent Islands, the member is rich in thick grainstones often associated with thrombolite mounds. Most of the cycles shallow-up into mudcracked, laminated limestone and dolostone with some shale in the Isthmus Bay section. A significant negative $\delta^{13}\text{C}$ anomaly approximately coincides with a shale-bearing interval in the middle of the member. The topmost cycles everywhere, comprise Catoche-like burrowed limestones capped by thick, desiccation-cracked lime and dolostone crypt-algal laminites, a facies association seen in the topmost sequences in the section at Isthmus Bay and in the three thrust stacks. The top of the member is mapped regionally as the top of the last laminated unit. Detailed mapping in the Port au Choix area indicates this contact is slightly diachronous between sections in the area.

The Barbace Cove Member is everywhere succeeded conformably by the Catoche Formation, a succession of bioturbated, dolomitic fossiliferous limestones, grainstone storm beds, and interspersed thrombolitic boundstone mounds. The latter form a significant barrier–mound complex in more outboard parts of the shelf mapped in the three thrust stacks. As in the case of the Barbace Cove Member, the reader is directed to Knight and James (1978), Pratt (1979), Knight (1991), Knight and Cawood (1991) and Knight *et al.* (2007) for further information. Only the first 10 m of the formation is exposed at Isthmus Bay.

Trilobites of the *Strigigenalis brevicaudata* Zone occur in the post-disconformity Barbace Cove Member in all three sections of the Northern Peninsula. This diverse and prolific fauna is accompanied by common gastropods, cephalopods and brachiopods and succeeded by the equally prolific *Strigigenalis caudata* Zone faunas beginning close to the base of the overlying Catoche Formation. This faunal explosion seen widely on the Northern Peninsula, however, appears to not be matched in the sections on the Port au Port Peninsula.

Conodont faunas commencing above the disconformity at Isthmus Bay include the *Acodus delicates-A.? primus* DW assemblage, which essentially spans the Barbace Cove Member to the base of the penultimate cycle of the formation. It is matched by the co-eval SW *Protopanderodus inconstans-Scolopodus subrex* fauna. These faunas are followed by the *Oepikodus communis-Protoprioniodus simplicissimus* DW fauna and the *Parapanderodus carlae-Stultodontus ovatus* SW faunas in the overlying Catoche Formation. *Drepanoistodus concavus* and *Oepikodus communis* were defined for the same stratigraphic interval in the Eddies Cove West area (Boyce and Stouge, 1997).

A BRIEF REVIEW OF DOLOSTONES IN THE LOWER ST. GEORGE GROUP

Dolostones have been studied in the St. George Group by Haywick (1984) and by Lane (1990). Both these authors recognized that dolostones ranged from microcrystalline to very fine grained to sucrosic and are often rich in sparry/saddle dolomite veins and open-space cements, the latter equated with hydrothermal high-temperature dolomite (HTD). The succession in the lower St. George Group at Isthmus Bay is host to a number of dolostone types as outlined below.

Stratigraphic Dolostone A

Finely crystalline dolomite has commonly replaced burrows in bioturbated carbonate rocks, is disseminated in the matrix of most limestones, and, in general, has partially replaced allochems in grainstones, cryptalgal fabrics in boundstones, and depositional fabrics in sedimentary structures. Pervasive microcrystalline dolostone occurs as intrinsic parts of small-scale sequences, particularly in the upper shallower portions of a sequence. This includes dololaminite, and dolomitized thin-bedded and bioturbated dolostones lying below the dololaminites in the upper parts of many sequences in the lower and middle members of the Boat Harbour Formation and in the upper Berry Head Formation. These dolostones are essentially synsedimentary to early shallow burial in origin. This is supported by 1) the micrite-sized crystallinity of the dolomite, 2) the excellent preservation of sedimentary structures, 3) the presence of pebbles of the dolostone in the conglomerates at the Boat Harbour Disconformity, and 4) the dolostones at the top of some cycles are fractured and brecciated below local, top-of-sequence karst, and the fractures are infilled by undolomitized limestone sediment of the overlying sequence (*see* discussion of the Boat Harbour Disconformity, page 139 and 140). The repetitive nature of the dolostones in the upper half of the peritidal cycles suggests that dolomitization is largely controlled by diagenesis during, or soon after, the completion of each depositional cycle.

Disconformity-related Pervasive Dolostone B

As already noted, finely crystalline, grey, pervasive dolostone replaces a significant interval of the Boat Harbour Formation below each of the disconformities (up to 20 to 30 m). The dolostone, which also preserves sedimentary fabrics, likely formed by mixing-zone processes, in part related to the periods of subaerial exposure of the shelf. Some of these dolostones host porosity, which is mostly intercrystalline and rarely vuggy (Plate 32). Preliminary $\delta^{13}\text{C}$ data



Plate 32. Intercrystalline porosity developed in a dolomitized grainstone, below the lower disconformity in the Boat Harbour Formation, Isthmus Bay section.

suggests that markedly negative isotopic shifts occur in the carbonates associated with the two disconformities.

Pervasive Dolostone C of the Watts Bight Formation

The Watts Bight Formation throughout much of western Newfoundland is completely to extensively dolomitized to a tan-grey-weathering, dark-grey, commonly bituminous-smelling, fine to medium crystalline, sucrosic dolostone. The dolomite preserves depositional fabrics, some of the more robust skeletal elements, *e.g.*, molluscs, and does not obscure the original character of the stratigraphy, *e.g.*, mounds, burrowed, grainstone, etc. Large vugs in the dolostones are filled by laminated, fine geopetal dolomite.

Porosity is also hosted by some of the dolostones at Isthmus Bay. In outcrop, porosity, which is both intercrystalline and vuggy, occurs in two intervals, namely, dolomitized, crossbedded, metre-thick grainstones from the top of the middle member (Plate 33) and in thrombolitic boundstone dolostone just 12 m above the base of the formation (Plate 34). This porosity is closely associated with a body of sparry dolomite.

In the Isthmus Bay section, pervasive dolostone C forms substantial parts of the lower and middle members of the formation, replacing both bioturbated and thrombolitic carbonates. Similar sucrosic dolostones dominate a recently exposed section along a new woods road on Table Mountain Anticline, 15 km northeast of Isthmus Bay. This is in contrast to the formation in the Phillips Brook and North Brook anticlines farther east again where the dolostones are restricted to the base of the formation (Knight and Boyce, 2000, 2002; Knight, 2003). West of Isthmus Bay, the dolostones are absent from sections visited near Lower Cove, Sheaves Cove and Cape St. George. This absence, perhaps, coincides with the marked facies change from mound-dom-



Plate 33. Porosity, partly enhanced by recent dissolution, in a crossbedded, dolomitized grainstone, middle member of the Watts Bight Formation, Isthmus Bay; hammer head is 8 cm.



Plate 34. A vertical body of porous dolostone (arrow) associated with a network of dolomite veinlets abutting a narrow remnant of limestone (just right of stick); rest of the outcrop consists of dark, bituminous, sucrosic dolostone. Basal 12 m of the Watts Bight Formation, Isthmus Bay section; measuring stick is 1.5 m long.

inated succession at Isthmus Bay (dolomitized) to deep-water lime-mud-dominated deposition that occurs in the formation in the more southwesterly sections (limestone). Dolostones appear to dominate the formation in the Garden Hill (Port au Port No 1, Newfoundland Hunt Oil Company Inc., 1996) and Long Point wells.

The Watts Bight Formation, from Daniel's Harbour north to Boat Harbour, in essentially undeformed foreland, is completely dolomitized. The dolomitization however, feathers out as the formation is traced east into the three thrust stacks and in so doing occupies only the basal few metres of the formation (Canada Bay) if at all, as at Brent Islands, Hare Bay (Knight, 1986, 1987, 1997).

Dark-grey sucrosic dolostone of the type described above is present as scattered pebbles in Middle Ordovician Cape Cormorant Formation conglomerate that was deposited adjacent to the Round Head paleo-fault scarp along the northwest edge of the Port au Port Peninsula. The conglomerates (*see* Stenzel *et al.*, 1990; Stenzel, 1992, and Waldron *et al.*, 1993 for descriptions of the conglomerate) show that much of the fine-grained (dolostone A and ?B) and, in this case, sucrosic dolostone C was formed by the Middle Ordovician, implying burial of less than 1 km before uplift and erosion.

The distribution of the dolostones in wells and outcrop suggests that the formation will most likely be dolostone in much of the deep subsurface beneath the leading edge of the Humber Arm Allochthon and the Anticosti Basin, Gulf of St Lawrence, west of Newfoundland. This implies that the dolostone forms a very extensive, stratabound, stratiform body that likely extends northwestward to the foreland edge of the formation in the offshore (This will probably coincide with the inboard limit of Tremadocian transgression.)

Sparry and Saddle Dolomites

White, sparry dolomite complexes are the product of hydrothermal processes and often spacially linked to high-angle faults that cut the shelf sequence. However, sparry dolomite is a minor part of the Isthmus Bay section. Where it is seen, it usually occludes or lines vugs in the dolostones. A single body of dolostone, which is rich in vuggy porosity and lined by sparry dolomite as well as a network of fine, sparry dolomite veinlets, crosscuts pervasive dolostone C of the Watts Bight Formation, just 12 m above the base of the Watts Bight Formation. The body, which is 2 to 3 m wide, trends 310° and is essentially vertical with a diffuse western contact against a narrow (40 cm) body of massive limestone itself contained by its contact with dolostone C. Red calcareous siltstone, probably of Carboniferous age, locally, infills the porosity.

On the Great Northern Peninsula from Daniel's Harbour north to Boat Harbour, sparry dolomite complexes are very common. White sparry dolomite occurs as veins and cement in collapse breccias, in dolostones associated with the Boat Harbour Disconformity at Port au Choix, and in dolomitized beds of thrombolitic boundstone as at Eddies Cove West and bioturbated limestone interbeds in the lower member of the Boat Harbour Formation at Boat Harbour itself. At both Eddies Cove West and Boat Harbour, the bedding-parallel spar-sucrosic dolostone complexes occur close to faults cutting the formation and pass abruptly into limestone away from the locus of the fault. Minor base-metal mineralization occurs in some of these bodies.

SOME THOUGHTS ON THE STRATIGRAPHIC CHRONOLOGY OF THE LOWER ST. GEORGE GROUP

The Tremadocian succession logged at Isthmus Bay and other sections in western Newfoundland combined with the detailed macro and micro biostratigraphy known for the Watts Bight and Boat Harbour formations suggests that the simple, deepening to shallowing model (*i.e.*, peritidal, subtidal, peritidal) proposed as a Tremadoc megacycle by Knight and James (1987) is an oversimplification for the oldest part of the St. George Group. The Watts Bight Formation at Isthmus Bay comprises two decimetre sequences of low-energy bioturbated and microbial mound carbonate overlain by high-energy facies associations of mounds and grainstones plus or minus truncation surfaces. These sequences probably reflect the response of sedimentation to transgression and drowning of the shelf followed by gradual shallowing (progradation) into the tidal zone where exposure often occurred. An incised erosion surface at the top of the upper sequence marks the upper formation contact possibly suggesting ravinement linked to transgression as the margin was bathed by renewed marine flooding to deposit the Boat Harbour Formation.

The Boat Harbour Formation is now shown to have a tripartite architecture, linked to defined disconformities and to significant changes of faunas. The previously overlooked lower disconformity in the Boat Harbour Formation is a surface associated with localized and regional dolomitization, local subsurface karst features such as at Isthmus Bay, and widely developed collapse breccias as on the Northern Peninsula. Its biostratigraphic importance is confirmed by major faunal events such as the termination of older conodont faunas below, and replacement by different ones above and by the appearance above the disconformity of a much more diverse, new macro fauna.

Traced west along the Quebec edge of the St. Lawrence Promontory, rocks equivalent of the Watts Bight Formation are absent in the nearest Cambro-Ordovician sequences of Anticosti and Mingan Islands (Desrocher and James, 1988; Knight *in* Baker and Knight, 1991). In this region, Grenvillian basement remained above rising sea levels until the Arenig. Thus, no rocks equivalent of either the Watts Bight Formation or the lower and middle Boat Harbour Formation are present.

In the Quebec Reentrant, there is also no complete counterpart to the Watts Bight Formation in the Phillipsburg Group of southwestern Quebec. There, Late Cambrian rocks of the Strites Pond Formation are erosionally and disconformably overlain by late Tremadocian rocks of the Wallace

Creek Formation, supporting a pronounced erosional episode (Salad Hersi *et al.*, 2002). However, conodonts of the *Cordylodus angulatus* zone imply that the lower Wallace Creek Formation correlates with the upper sequence of the Watts Bight Formation. The lower member of the Boat Harbour Formation probably correlates with the middle part of the Wallace Creek Formation of the Phillipsburg Group and with the Tribes Hill Formation of New York state (Landing *et al.*, 1996, 2003; Salad Hersi *et al.*, 2002).

To the northeast, in the Caledonides of the United Kingdom and Greenland, the Watts Bight Formation and the lower Boat Harbour Formation can be lithologically matched to the earliest Ordovician Sailmhor and Sangomore formations of the Durness Group in northwest Scotland (I. Knight, unpublished data, 1990) and correlated with the Anticlinabugt Formation in central East Greenland (I. Knight and D. Boyce, unpublished data, 2000, 2001; Stouge *et al.*, 2002).

The middle member of the Boat Harbour Formation has no counterpart at Anticosti and Mingan islands where Grenvillian basement was yet to be drowned by marine onlap. It does, however, roughly correlate with the upper Wallace Creek Formation (and perhaps the Morgans Corner Formation) of the Phillipsburg Group of southwestern Quebec and with the Fort Ann Formation of the Champlain Valley, New York (Boyce, 1989; *see* Salad Hersi *et al.*, 2002). The middle member also has no counterpart in the rocks of central East Greenland where a cryptic disconformity separates rocks of the Anticlinabugt Formation from overlying stromatolite- and grainstone-rich peritidal carbonates of the September S \emptyset formation¹⁰ which host macrofaunas equivalent to those of the Barbace Cove Member (*i.e.*, Arenig; I. Knight and D. Boyce, unpublished data, 2000, 2001). This means that there can be no certainty that the middle member of the Boat Harbour Formation correlates with the Balnakiel Formation of the Durness Group, a formation consisting of peritidal carbonates, including interesting stromatolite mounds (I. Knight, unpublished data 1990). Rather, the Balnakiel Formation may better correlate with the September S \emptyset formation in East Greenland and be part of the Arenig transgression.

This suggests that active platform buildup that deposited the Watts Bight Formation at the apex of the St. Lawrence Promontory and in the Newfoundland Reentrant, *i.e.*, western Newfoundland, preceded deposition in the Quebec reentrant and in New York. Tremadocian flooding of the

margin bringing carbonate deposition to the Reentrant, however, coincided with the deposition of the upper sequence of the Watts Bight Formation, *i.e.*, basal Wallace Creek Formation. Deposition of the lower member of the Boat Harbour Formation coincided with expanding shelf deposition in the Quebec Reentrant and New York State marked by deposition of the middle part of the Wallace Point Formation in Quebec, and the Tribes Hill Formation in New York. This perhaps suggests step-like onlap within the reentrant during the earliest Ordovician. Whether the incised surface at the base of the lower member of the Boat Harbour Formation is a ravinement surface sculpted in response to flooding of the exposed top of the Watts Bight Formation and in step with the onlap history in the Quebec Reentrant is speculative but nonetheless attractive.

The post-Boat Harbour Disconformity succession comprising the Barbace Cove Member and the overlying Catoche Formation is the deepening part of the younger Arenigian megacycle of Knight and James (1987). It can be correlated on a global scale with other co-eval shelf sequences around the paleo-continental margins of Laurentia. This eustatic event hosted rocks of the Romaines Formation of Anticosti and Mingan islands (Desrocher and James, 1988; Baker and Knight, 1993), the Hastings Creek, Naylor Ledge and perhaps Morgans Corner formations of the Phillipsburg Group (Knight *et al.*, 1995; Salad Hersi *et al.*, 2002), the Beauharnois Formation of the Beekmantown Group, St. Lawrence Lowlands, Quebec (Bernstein, 1992; Salad Hersi *et al.*, 2003), the Fort Cassin Formation of New York state (Fisher, 1954; Boyce, 1989), the Croisaphuill and Ben Suardal Limestone formations of the Durness Group, Scotland (I. Knight, unpublished data, 1990; Fortey, 1992), and the September S \emptyset (co-eval with the Barbace Cove Member) and Kap Weber (co-eval of the Catoche Formation) formations of central East Greenland (Smith, 1991; I. Knight and D. Boyce, unpublished data, 2000, 2001; Stouge *et al.*, 2002) all fit well with Arenig global marine flooding of the continental margins of Laurentia during the Arenig.

This suggests that the accretionary history of Laurentia's margins during the Early Ordovician is a composite of many episodes of marine flooding that was probably facilitated by geographic position on promontories and reentrants, by local margin tectonics and by eustasy. The first cycle (Watts Bight—lower member of the Boat Harbour Formation) dominates the Newfoundland Reentrant, east of the St. Lawrence Promontory and extends past northwest Scotland to central East Greenland and beyond.

¹⁰The September S \emptyset formation is an informally proposed name (Knight, unpublished data, 2000, 2001) for a distinct unit of peritidal carbonates previously included in the base of the Kap Weber Formation by Cowie and Adams (1957) and Smith (1991).

Looking to the west of the promontory, however, there is no evidence for a carbonate platform deposited unconformably on Grenvillian basement along the Quebec edge of the St. Lawrence Promontory until the Arenig. Cambrian carbonate rocks are also conspicuously absent in that area. The absence of both Cambrian and earliest Ordovician age carbonate shelf rocks in this region (although they might be concealed in the subsurface of the Gulf of St. Lawrence, south of Anticosti Island) may hint that the carbonate platform of this period was either not continuous or was very narrow. If it is not continuous along the Canadian paleo-margin, then it must comprise two discrete Tremadocian platforms, one in the inner Quebec Reentrant and the other along the Newfoundland Reentrant.

Recent studies in central East Greenland indicate that rocks equivalent of the Middle Boat Harbour Formation are missing below a cryptic disconformity between the Anticlinabugt Formation and overlying rocks of Arenigian shelf sedimentation. If the Balnakiel Formation¹¹ is also part of the younger Arenig megacycle (as discussed above), this would imply that the disconformity is a regional feature of the Greenland–Scotland margin, and that the shallow-water, middle Boat Harbour Formation shelf does not extend beyond the confines of the Newfoundland Reentrant. Tectonic uplift related to a peripheral bulge coinciding with eustatic sea-level fall is promoted to explain the loss of Tremadocian section below Arenig carbonates of the Wandel Valley Formation (Bryant and Smith, 1985, 1990; Surlyk, 1991) in the very northeast of Greenland, and these two factors may be the control of the subtle disconformity in the co-eval East Greenland and Scottish successions.

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¹¹Only a modern micro- and macro-faunal study will resolve the age of the Balnakiel Formation and determine its position and correlation with co-eval sequences in Scotland and Newfoundland.

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ADDENDUM

In the section entitled, "Some thoughts on the stratigraphic chronology of the lower St. George Group", it was suggested that the Watts Bight Formation and the lower and middle members of the Boat Harbour Formation correlated with formations in the Phillipsburg Group, Quebec as follows: the upper sequence of the Watts Bight Formation with the lower part of the Wallace Creek Formation; the lower member of the Boat Harbour Formation, probably with the middle part of the Wallace Creek Formation and with the Tribes Hill Formation of New York State; the middle member of the Boat Harbour Formation approximately with the upper Wallace Creek Formation (and perhaps the Morgans Corner Formation); and the Barbace Cove Member and the overlying Catoche Formation with the Hastings Creek, Naylor Ledge and perhaps Morgans Corner formations of the Phillipsburg Group (based on the work of Salad Hersi *et al.*, 2002, 2003). The recent study of the Quebec sequence by Salad Hersi *et al.* (2007) abandoned the use of the name, Phillipsburg Group, in favour of three new groups and suggests that our correlation is invalid¹. Rather, it indicates the following correlation – the upper Watts Bight Formation and lower member of the Boat Harbour Formation correlates with the Wallace Creek and Morgans Corner formations; the middle member of the Boat Harbour Formation correlates with the Hastings Creek Formation, and last, the Naylor Ledge Formation correlates with the Catoche Formation.

This still suggests that the initiation of the earliest Tremadocian platform in Quebec postdates that of the Watts Bight platform in Newfoundland but that the Wallace Creek and Morgans Corner formations and its correlative Tribes Hill Formation of New York State is essentially co-eval with the upper part of the first St. George Group sequence i.e., upper Watts Bight and lower Boat Harbour formations. Even though the Fort Ann Formation overlies, disconformably, the Tribes Hill Formation in New York State (Landing *et al.*, 2003) and the Fort Ann Formation correlates with the middle Boat Harbour Formation (Boyce, 1989), no disconformity is shown separating the Morgans Corner and the overlying Hastings Creek formations. Likewise, no disconformity separates the Hastings Creek Formation from the overlying Naylor Ledge Formation (Salad Hersi *et al.*, 2007). These data strongly suggests that ideas about the chronostratigraphic evolution of the platform proposed in the paper will need re-evaluation.

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¹ The responsibility for the ideas discussed in the original section and this addendum is that of the senior author.

