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Stromatoporoid Growth Forms and Devonian Reef Fabrics in the Upper Devonian Alexandra Reef System – Insight on the Challenges of Applying Devonian Reef Facies Models

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ABSTRACT

Existing facies models for Devonian reef systems can be divided into high- and low-energy types. A number of assumptions have been made in the development of these models and in some cases criteria that distinguish important aspects of the models are poorly defined. The Upper Devonian Alexandra Reef System contains a variety of reef fabrics from different depositional environments and is ideal for studying the range of environments in which stromatoporoids thrived, and the facies from these different environments.

A wide variety of stromatoporoid growth forms including laminar, tabular, anastamosing laminar and tabular, domal, bulbous, dendroid, expanding conical, concave-up whorled-laminar, concave-up massive tabular, and platy-multicolumnar are present in the Alexandra Reef System. The whorled-laminar and massive tabular concave-up growth forms are virtually undocumented from other Devonian reefs but were common in the reef-front of the Alexandra, where they thrived in a low-energy environment around and below fair-weather wave base. In contrast, higher-energy parts of the reef margin were dominated by bioclastic rubble deposits with narrow ribbon-like discontinuous bodies of laminar stromatoporoid framestone. In the lagoon, laminar stromatoporoids formed steep-sided sediment-dominated bioherms in response to sea-level rise and flooding of the lagoon.

Relying mostly on the different reef facies in the Alexandra, a new classification scheme for Devonian reef fabrics has been developed. Devonian reef fabrics can be classified as being (1) sediment-laden metazoan-dominated, (2) metazoan-microbial dominated, (3) metazoan-dominated (framestone), or (4) metazoan-marine cement dominated. Distinction of these fabrics carries important sedimentary and paleoecological implications for reconstructing the depositional environment. With examples from the Alexandra, it is demonstrated that similar facies could accumulate in different depositional environments, and that the simple observation

of massive stromatoporoids with or without microbial deposits does not automatically imply a

high-energy reef margin, as otherwise portrayed in a number of the existing facies models for

these systems.

Keywords: Devonian, reef, stromatoporoids, facies models

INTRODUCTION

Stromatoporoids were significant components in many Silurian and Devonian reef systems, which were among the most diverse and expansive reef systems in the Phanerozoic (Copper 2002). Devonian reef facies models (e.g., Wilson, 1974; Playford, 1980; Wendte and Stokes, 1982; James and Bourque, 1992; Machel and Hunter, 1994; James and Wood, 2010) incorporate various assumptions about stromatoporoids, their growth forms, and necessarily make generalizations about the nature of these reefs (Machel and Hunter, 1994). The paleobathymetric zonation of Playford (1980), which underpins the facies models of Machel and Hunter (1994), for example, is premised on a "belief" that reef (platform)-building Devonian stromatoporoids (and corals) were restricted to water depths less than 10 m. This is probably too restrictive and other stromatoporoid reefs are interpreted to have originated in water more than 10 m deep (e.g., Klovan, 1964; Embry and Klovan, 1972; Mountjoy and Jull, 1978; Kiessling *et al.*, 1999). While existing facies models rely on biofacies and depositional textures (e.g., framestone, bindstone, bafflestone) for differentiation of the reef zones, none of them consider the potential implications of variations in the biota for interpreting the conditions of deposition. Most facies models, for example, imply that stromatoporoid-microbial boundstones and stromatoporoid framestones originated in a high-energy wave swept reef zone. Such interpretations implicitly assume that the presence-absence of the microbes is not significant from an environmental or sedimentary perspective.

Limestone strata that form the Upper Devonian (mid-Frasnian) Alexandra Reef System in the Northwest Territories of Canada contain exceptionally well-preserved stromatoporoids that grew in a number of different reef-related depositional environments. MacNeil and Jones (2006a, 2008) have already outlined the general facies architecture and stromatoporoid distribution in

different parts of this system. Herein, focus is placed on the stromatoporoids and reef fabrics found in two parts of the reef margin and an associated lagoon. The exceptional, well-preserved facies at these localities provide an ideal opportunity for establishing the nature of the environments where the stromatoporoids grew and thrived.

Massive, *in situ* stromatoporoids that grew as closely-packed isolated individuals surrounded by and buried in sediment, or bound to each other by microbial carbonate, characterize the reef front environment in the Alexandra Reef System. Growth forms include unusual metre-scale whorled-laminar forms and massive tabular to broad concave-up forms of *Actinostroma* that are, in some cases, > 2 m in diameter. With the exception of two whorled stromatoporoid specimens in an Australian outcrop documented by Wood (2000), such whorled and concave-up growth forms are not known from other reefs or expected to be found (Kershaw and Riding, 1978; Kershaw, 1998). Millimetre-thick beds of green siliciclastic mud deposited atop of many of these expansive stromatoporoids indicates that much of the reef front accumulated in a low-energy environment below fair-weather wave base. In shallower water, inboard of the reef front, the reef was dominated by bioclastic rubble that was largely derived from the reef front and stabilized into a rigid deposit by microbial carbonate. A narrow belt of framestone, formed of encrusting laminar stromatoporoids, developed along one area of the reef where high-energy waves were common. Although stromatoporoids dominated the main reef building stage of the Alexandra Formation, framestone is not a significant facies. In the low-energy lagoonal environment, laminar stromatoporoids developed small, steep-sided bioherms in response to a relative sea-level rise and incipient drowning of the carbonate factory.

The stromatoporoid growth forms, reef fabrics, and their depositional contexts in the Alexandra Reef System challenge the common facies model (Playford, 1980; Wendte and

Stoakes, 1982; Machel and Hunter, 1994) that Devonian reef margin facies necessarily accumulated above fair-weather wave base in high energy environments, and that framestones dominated the cores of reef margins. The application of existing facies models to Devonian reef systems should give greater consideration to the biogenic nature of the reef fabric, and it should be recognized that some of the facies traditionally considered to indicate high-energy wave swept margins can also be found in lower-energy environments around, and slightly deeper than, fair-weather wave base. In an attempt to better understand Devonian reef systems and the importance of variations in their reef fabrics, four types of reef fabric that are applicable to all Devonian reefs are defined. These are (1) sediment-laden metazoan-dominated, (2) metazoan-microbial dominated, (3) metazoan-dominated (framestone), and (4) metazoan-marine cement dominated reef fabrics. The biogenic and abiogenic consortia responsible for these different reef fabrics influence the rigidity of the accumulated deposit and its ability to exist at different angles of repose. These aspects together influence the ability of the reef to grow into zones of increasing wave energy, determine whether the reef zones covered broad areas of the margin or were very narrow, and their ability to develop relief from the surrounding sea-floor – fundamental aspects of reconstructing depositional environments.

PALEOGEOGRAPHY AND STUDY AREA

The Alexandra Reef System (= Alexandra Formation; ~ 40 m thick) is located in the southern part of the Northwest Territories of Canada (Fig. 1). It developed atop of mixed carbonate-siliciclastic deposits of a gently sloping (< 0.1°) leeward facing ramp that developed on the western margin of Laurussia in the mid-Frasnian (MacNeil and Jones 2006a). At that time, the region was located near the equator and the climate was semi-arid (Kiessling *et al*., 1999;

Scotese, 2004). The ramp complex is interpreted to have extended along the margin of Laurussia

to the south into present-day Alberta, where its deposits are assigned to the Grosmont Formation

(Belyea and McLaren, 1962; Cutler, 1983). As the ramp system evolved, several isolated

carbonate buildups developed in the adjacent basin (e.g., the Leduc reef systems), cumulatively

making this region one of the most extensive reefal provinces of the Late Devonian (Mountjoy,

1980; Moore, 1989).

The high-resolution sequence stratigraphic framework and evolution of the Alexandra Reef

System was described by MacNeil and Jones (2006a, 2006b). The system includes Reef

Complex #1 and Reef Complex #2 (Fig. 2). Reef Complex #2, which is better exposed than Reef

Complex #1, developed basinwards of Reef Complex #1 due to a small fall in relative sea-level

position (MacNeil and Jones, 2006a). Deposits of Reef Complex #2 belong to a series of systems

tracts that relate to changes in relative sea-level position (Fig. 2). The lowest strata, consisting of

a stromatoporoid-microbialite biostrome, belong to a falling stage systems tract and accumulated

as relative sea-level fell and exposed Reef Complex #1, terminating its development. Most of the

strata for Reef Complex #2 belong to the lowstand systems tract that followed the falling stage,

as relative sea-level slowly started to rise (Fig. 2B). The first significant differentiation of reefal

environments took place at that time as peri-tidal, lagoonal, back-reef, reef, and fore-reef

environments developed (MacNeil and Jones, 2006a). MacNeil and Jones (2006a) divided the

lowstand reef area into the inner and outer buildups that covered a large area of the shallow ramp

(Fig. 2B). The outer buildup, composed mostly of bioclastic rubble stabilized by microbial

components, includes large fragments of stromatoporoids that were transported from the reef-

front region during storms (MacNeil and Jones, 2006a, 2008). It protected the inner ramp

environments and basinwards, transitioned to deeper water reef-front and fore-reef zones.

Development of Reef Complex #2 was interrupted by an increased rate of sea-level rise (transgressive systems tract) that caused flooding across the area including the coastal plain above Reef Complex #1 (Fig. 2C; MacNeil and Jones, 2006b). As maximum flooding was reached and the reef system recovered, transgressive deposits were overlain by regressive deposits of the highstand systems tract. Ultimately, reef complex development in the study area terminated as its depositional environments became shallower and sea level dropped (MacNeil and Jones, 2006a).

The Alexandra Reef System is best exposed in (1) a gorge cut by Hay River (northeast-southwest), which trends close to depositional strike, and (2) a northwest trending escarpment that is ~ 46 km long (Fig. 1). The Hay River gorge offers excellent exposure of the lagoonal and peri-tidal deposits, whereas the limestone escarpment provides excellent exposure of facies that are representative of the lagoonal, reefal, and proximal fore-reef environments. This study focuses on three areas along the escarpment from different depositional environments of Reef Complex #2. In paleogeographic and stratigraphic order these are the (1) New Road Cut, (2) Heart Lake Fire Tower traverse, and (3) Mud Mound locality (Figs. 1, 2B and 2C).

TERMINOLOGY

Facies are named using the terminology of Dunham (1962) as modified by Embry and Klovan (1971). Description of stromatoporoid growth forms (Fig. 3) and paleobiology follows Kershaw (1998). The term "framebuilder" is used for metazoans (herein referring to stromatoporoids, tabulate and rugose colonial corals) that secreted large calcareous skeletons and that either lived as individuals or had the ability to coalesce with one another to form a rigid frame of skeletons with or without cavity space. As noted by Tsien (1981), this term is not synonymous with

"framestone" and it does not automatically imply that a rigid frame actually developed. The term

"framestone", following Embry and Klovan (1971), is applied to a fabric formed of massive

skeletons (e.g., stromatoporoids, corals) that encrusted on each other and thereby produced a

rigid frame. Metazoans that lived as individuals but were bound together by microbialite (e.g., by

masses of *Renalcis*) do not constitute framestone even though a rigid frame developed. The

distinction is fundamental to the definition of "framestone", which is intended to have

paleoecological significance (Embry and Klovan, 1971). Framebuilders bound to each other by

microbialite are best described using the general term "boundstone" of Dunham (1962).

Following James (1983), the "reef margin" refers to the margin of the complex and thereby

includes the back-reef, reef core, and reef-front zones. The term "reef core" is preferred over the

terms "reef-flat" and "reef crest" because of their implied geometries. The term "reef-front" is

not the same as "fore-reef", which is the geographic area seaward of the reef margin and may

include a spectrum of environments from a distal outer ramp to a high-relief slope that extends

downwards from a reef-front. The key difference is that the reef-front is part of the active living

reef versus a fore-reef that is devoid of reefal accretion but may be the site of significant debris

deposits derived from the reef.

Herein, identification of the stromatoporoids is based on Stearn (1966) and McLean *et al.*

(1987). When possible, a species level identification has been made. In some cases, however,

identification is only possible to the genus level. Corals are identified to the genus level based on

McLean (1984), McLean and Pedder (1987), McLean and Klapper (1998), and McLean (2005).

THE NEW ROAD CUT LOCATION

Exposures of biostromal strata are found at the New Roadcut (NRC), which is ~300 m long and up to 7.5 m high. Core ARC-2 (17.1 m long), drilled from the top of the biostrome ~ 5 m away from the east face of the roadcut (Fig. 4A), demonstrates that it sits on top of the bioclastic rubble deposits that form part of the outer buildup in the lowstand systems tract of Reef Complex #2 (Fig. 2B). Unfortunately, the exact thickness of the underlying rubble deposits is not known because mechanical problems caused abandonment of the hole before the base was reached. The NRC is unique among the Alexandra Reef System deposits because it is the only locality where stromatoporoid framestone dominates. Five sections were measured along the west wall and seven sections were measured along the east wall of the roadcut.

Biostrome Architecture and Facies

Exposures of medium- and thick-bedded limestones at the NRC are divided into the lower, middle, and upper units based on two prominent bedding planes (Fig. 4A). The lower bedding plane, ~ 4.5 m from the top of the biostrome (the base of the biostrome, below the roadcut base, is not exposed), separates the stromatoporoid framestone of the lower unit from an overlying middle unit that is formed of stromatoporoid framestone and stromatoporoid-coral rudstone with a crinoid-rich matrix. Above the bedding plane the matrix has a green tint and rare wisps of green mud are present. On the east wall of the roadcut, where it is most prominent, this bedding contact dips gently into a shallow depression about 2 m deep, at the south end of the biostrome (Fig. 4A) that is filled with coral bafflestone and bioclastic rudstone. The upper bedding plane, ~ 2 m from the top of the biostrome, which separates the middle unit from the upper unit is overprinted by a conspicuous stylolite. Above this contact, the matrix in the stromatoporoid

framestone is a white packstone-grainstone that contrasts sharply with the green tinted, muddier matrix below the contact. This contact also seems to dip into the depression at the south end of the biostrome.

The beds in these units are formed of a (1) laminar stromatoporoid framestone facies, (2) platy-multicolumnar stromatoporoid framestone facies, (3) coral bafflestone and rudstone facies, and (4) rudstone facies.

Laminar Stromatoporoid Framestone Facies

This facies dominates the biostrome and consists of horizontal planar to gently undulating laminar specimens of *Stromatopora* that laterally and vertically coalesced (encrusted) to form a dense framestone (Fig. 4B). Latilaminae in the skeletons are typically 2-8 mm thick and small cement filled galleries (mm-scale) are common between the latilaminae.

Intergrown with the tightly packed laminar stromatoporoids are (1) low domal to domal stromatoporoids, up to 15 cm across and 25 cm high, with smooth, non-enveloping margins, and (2) undulatory, locally anastamosing tabular stromatoporoids. Latilaminae in the domal and tabular skeletons are up to 3-5 cm thick. Rare domal heads of *Phillipsastea*, thin lenses of *Alveolites*, and encrusting *Aulopora* are present. Intergrown *Syringopora* and solitary horn corals encrusted by laminar stromatoporoids are common.

Micritization of stromatoporoid growth surfaces is intense and in hand sample commonly appears as clean white mud between the latilaminae (Fig. 4C). Sediment is also present, in areas where galleries developed, and as isolated pockets up to ~ 10 cm across in the framestone or in the growth/shelter cavities around the domal stromatoporoids. The sediment in these small

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pockets is typically a crinoidal packstone or a crinoidal packstone-matrix floatstone with

fragmented *Thamnopora*.

Platy-Multicolumnar Stromatoporoid Framestone Facies

In the laminar stromatoporoid framestone facies there are isolated, lenticular bodies formed of

Stachyodes australe, 20-70 cm across and up to 15 cm high (typically ~10 cm high), that are

characterized by a delicate platy-multicolumnar (alternatively could be described as "digitate")

form with cm-scale framework growth cavities (Fig. 5A to D). These skeletons consist of vertical

columns 1-10 cm high and ~5 mm in diameter, from which horizontal, sloping, or arching plates

2-5 mm (up to ~ 8 mm) thick grew. As the vertical columns continued to grow, new columns

arose from the horizontal plates. As a result, columns have an inconsistent geometric

arrangement. Integral to this growth pattern are the large open galleries (0.5-1.3 cm high and 2-5

cm wide) that developed.

Galleries in the platy-multicolumnar stromatoporoids are filled with geopetal sediment and

calcite spar. In some cases one or two isopachous rinds of fibrous cement line the galleries

before spar fills the remaining space. The geopetal sediment ranges from a green siliciclastic

mud (Fig. 5B) to a grainy packstone (Fig. 5D). In many specimens, a single layer of coarse

euhedral ferroan dolomite cement is found along the sediment-spar boundary. Weathering of the

dolomite imparts a bright orange-red colour to the layer.

Where rudstone is found in the biostrome, clasts of the platy-multicolumnar stromatoporoids

are common. In many cases, the geopetal fills indicate "way-up" directions that are opposite to

the direction of growth of the stromatoporoid (Fig. 5D and E). This shows that the sediment was

deposited in the gallery after the stromatoporoid was transported and deposited upside-down, or

that the sediment in the galleries was unconsolidated at the time of transport and settled right-way-up after the stromatoporoid was deposited upside-down.

Coral Bafflestone and Rudstone Facies

This facies, found only in the depression, consists of large thickets of rugosan corals (*Smithiphyllum* and *Thamnophyllum*) that are up to 1.1 m thick and > 1 m across that are in place or locally toppled, and rudstone. The rudstone includes (1) cobble- to small boulder-sized clasts of laminar and tabular stromatoporoid and platy-multicolumnar framestone that are, in some cases, upside-down or rotated ~90° into a near-vertical position (Figs 5E and F), (2) fragmented pieces of *Phillipsastrea* and *Alveolites* coral heads, (3) fragments of smaller corals including horn corals and *Thamnopora*, and (4) a packstone matrix with abundant crinoid debris.

Rudstone Facies

In the middle unit of the biostrome, interbedded with laminar stromatoporoid framestone are laterally discontinuous 10-60 m thick beds of rudstone. The rudstone consists of locally derived clasts of laminar and tabular stromatoporoids, broken fragments of *Stachyodes* and the multicolumnar-platy form of *S. australe*, coral fragments (*Thamnopora* fragments are common) and crinoid ossicles that are held in a packstone to grainy wackestone matrix. Locally, it has a slightly muddier, green tinted matrix. Otherwise, it has the same properties as the rudstone deposited around the coral thickets in the crevice area.

HEART LAKE FIRE TOWER TRAVERSE

This traverse (HLFT) is the face of the escarpment, 10 – 25 m high depending on the amount of overburden at its base (Fig. 6A), and extends from the Heart Lake fire tower (Fig. 1) for nearly five kilometers to the southeast at which point the escarpment is bisected by a Quaternary valley and small-scale fault (Figs 1 and 2B; MacNeil and Jones, 2006a). This exposure, which is parallel to partly oblique to depositional strike, shows the transition from the bioclastic rubble deposits of the outer buildup to the reef-front and fore-reef deposits of Reef Complex #2 (Fig. 6B). As such, its paleogeographic position is basinwards of the biostrome at the NRC. Midway along the traverse there is the "paleo-valley" (AM13 – AM29) that divides it into the southern and northern parts (cf. MacNeil and Jones, 2006a).

The traverse was studied in detail at fifteen sections (Fig. 6B). At localities where the height of the escarpment face and a lack of available ledges precluded measurement of the section from the ground, sections were measured by rappelling from the top of the escarpment to its base and using ascension devices to measure up-section at 10 cm intervals; a tape was hung from the top for reference. As such, the height of the escarpment face was not a limitation. In one area of the escarpment, collapse of the cliff face has produced boulders (Fig. 6A) that show minimal weathering and were preferentially split along the growth surfaces of stromatoporoids. These boulders provide unique three-dimensional views of the stromatoporoids and their reef fabric that are not normally afforded by two-dimensional outcrop faces. In addition to the fifteen measured sections and the area of collapsed boulders, a continuous core (ARC-1) was drilled from the top of the escarpment through 24.4 m of limestone to the base of the formation (Fig. 6B) and into the underlying Escarpment Formation.

Stromatoporoid-dominated deposits from the reef front, which dominate the HLFT traverse

(Jamieson, 1967, MacNeil and Jones, 2006a), are herein assigned to a Reef Front Facies

Association. Deposits in the paleo-valley include distal reef-front and proximal fore-reef facies

(MacNeil and Jones, 2006a); the latter are assigned to a Fore-Reef Facies Association.

Reef Front Facies Association

Skeletons or fragments of skeletons from large stromatoporoids and corals characterize the facies

in the Reef Front Facies Association. Facies include thickly bedded *in situ* stromatoporoid-coral

accumulations, stromatoporoid-coral rudstones, and stromatoporoid-coral floatstones. Their

carbonate matrices include varying amounts of green argillaceous material. The stromatoporoid-

coral accumulation facies dominates the reef front, with local variations to the stromatoporoid-

coral rudstone and floatstone facies.

Stromatoporoid-Coral Accumulation Facies

Stromatoporoids in the stromatoporoid-coral accumulation facies are dominated by laminar

(typically 2-3 mm thick), tabular (typically 1-2 cm thick), and anastamosing laminar and tabular

growth forms that are generally < 1 m across (Fig. 7A to D). The material between the

framebuilders is a mix of microbialite and sediment (MacNeil and Jones, 2008) or sediment

without any microbialite, hence use of the general term "accumulation" for the facies. An

unidentified, probably new species of *Stachyodes* (*Stachyodes* sp. aff. *Stachyodes australe*

Riding, 1974), that has a differentiated (pseudohypothallial and pseudoperithallial zones) skeletal

structure that strongly resembles *Stachyodes australe* but differs by having slightly thicker and in

many cases mammillated coenostea, and *Actinostroma clathratum* are the dominant

framebuilders. Other stromatoporoids (cf. Stearn, 1966) include *Stromatopora*, *Trupetostroma*, and *Clathrocoilona*. The less abundant coral framebuilders include domal to hemispherical heads (up to 45 cm high and 35 cm across) of *Phillipsastrea* and slightly larger thickets of fasciculate rugosans that include *Smithiphyllum*, *Disphyllum*, and *Thamnophyllum* (Fig. 7B). Tabular and irregular *Alveolites* and encrusting *Aulopora* are common. These deposits accumulated with fairly uniform thickness although locally dipping tabular stromatoporoids indicate 1-2 m of topographic relief in some places.

In addition to the laminar, tabular, and anastamosing laminar and tabular stromatoporoids that dominate in the exposures along the HLFT transect, other stromatoporoid growth forms include whorled-laminar, massive (>60 cm across) tabular, expanding-upwards conical, and high-domal forms (Figs 3 and 7E-F). The whorled laminar growth forms are typically 40-60 cm in diameter and 10 to 20 cm high, but some ~ 1 m in diameter are also present and exceptionally large individuals up to 1.6 m across have been found. These forms, circular in plan view, are formed of 4-15 stacked laminar sheets, each 3 to11 mm thick, with cm-scale galleries between the sheets (Fig. 8). Jamieson (1967) described this growth form as "saucer-shaped", reflecting the common concave-up appearance of these stromatoporoids. These stromatoporoids resemble *S. australe*.

Several blocks in the collapsed area along the HLFT traverse show that the underside of each whorled complex consists of a centrally-located conical base from which the basal sheet (up to 15 mm thick), concentrically rippled on its underside, grew out in a concave-up manner (Figs 7E, 8 (inset), and 9A). The overlying succession of connected sheets grew at low angles from each other via sub-vertical splays (Figs 8A). These sheets may be concave-up, flat, or slightly

convex-up such that the overall shape of individuals ranges from concave-up, flat, to very low-angle domes. The top surfaces of individual sheets are mammillated (Figs 8B and 9B).

Individuals of the whorled laminar stromatoporoids appear to have grown as discrete entities but in close proximity to each other. Some individuals, perhaps having grown slightly higher than adjacent stromatoporoids, grew outwards and partly overtop of adjacent specimens. Thus, many blocks in the collapsed area show stacked and partly overlapping stromatoporoid "discs" that compacted against each other with shallow burial (Figs 7E, 9C and 9D). Compaction of these skeletons is evident from numerous cracked plates in individual skeletons (Figs 9B and E). The undersides of these stromatoporoids are commonly encrusted by spirorbids (Fig. 8A - inset), *Aulopora* (Fig. 9F), and large (15-20 cm) dendritic growths of a calcareous organism (Figs 9A and G) of unknown affinity (assigned to *Parachaetetes* by Jamieson (1967) and it is consistent with the specimens of *Parachaetetes* illustrated in Leavitt (1968)). Diagenesis has partly obscured the microstructure of these dendritic encrusters, and their restricted distribution to the cryptic, presumably aphotic habitats that existed under the broad stromatoporoids indicates that they were not algal – *Parachaetetes*, in contrast, is regarded as a type of red algae and presumably required illumination for photosynthesis (Johnson, 1961, Wray, 1998).

Massive tabular forms of *Actinostroma clathratum* (Fig. 3), typically ~70 cm across and 8-9 cm thick, but up to 2.2 m across and 20 cm thick, are also found in this facies. Many of these actinostromids developed slightly concave- or convex-up top surfaces (Fig. 7F), and in rare cases developed into expanding-upwards conical forms (>1 metre across and ~60 cm high; Fig. 7G). The massive actinostromids generally grew on top of, and are buried in, rudstones or floatstones with packstone to wackestone matrices (Fig. 9H). In the northern part of the HLFT traverse, the

massive actinostromids are most common in the lower half of the reef front succession (~13 m total thickness), but become increasingly rare towards the top of the succession.

In general, the stromatoporoids in the reef front did not coalesce with each other. Rather, they seem to have grown and died as individuals. Notable exceptions include coalesced whorled laminar stromatoporoids (each up to 1 m across) in section AM-13 that formed a thin but laterally extensive framestone. There are also scattered examples of stromatoporoids and corals that grew together or encrust on each other. Such examples include (1) specimens of *Syringopora* that grew in stromatoporoid skeletons (caunopore structures), (2) an almost sheet-like *Phillipsastrea* that tightly filled the space between two plates of a whorled laminar stromatoporoid - it is not clear if the stromatoporoid was living or dead when the coral grew, and (3) solitary rugose corals and laminar stromatoporoids where either the stromatoporoid encrusted the solitary rugose coral or engulfed it between plates. These examples, however, are localized features and did not contribute towards the development of a rigid reef framework.

The stromatoporoid-coral accumulation facies can be summarized as a facies of *in situ* stromatoporoids and corals that became stacked with varying amounts of cavity space between each skeleton. Calcimicrobial masses, dominated by *Renalcis*, commonly filled these cavities, and stromatolites up to 20 cm across and 4 cm thick are common on the tops of many laminar stromatoporoids (Fig. 10) adding rigidity to their otherwise thin skeletons. The only skeleton-binding agents were calcimicrobial masses that grew between the individual stromatoporoids and corals. The microbial components, however, decrease up-section and towards the more distal, deeper parts of the reef front (MacNeil and Jones, 2008), such that stromatoporoids and corals in these parts lived and died as densely packed individuals with sediment filling spaces between skeletons. Although wackestone is the dominant depositional texture in this facies, lime

mudstone with varying amounts of green clays and intraclastic packstone deposits are also found.

Spar cements occluded the remaining space in many cavities not completely filled by geopetal

fill and microbialite. Dustings (thin lamina) to single beds of green mud, generally not more than

1 cm thick (after compaction) are common across the top surfaces of the laminar and tabular

stromatoporoids, and filled physical compaction cracks in thin stromatoporoid plates (Figs 8B

and 9B-E). In the collapsed-block area along the traverse, preferential weathering of these soft

green muds is responsible for exposing the delicate features of the resistant weathering

stromatoporoid plates that are otherwise difficult to observe in purely limestone deposits. These

include the mammillated top surfaces, the concentrically ringed undersides and various

encrusting organisms, and in surrounding sediment delicate articulated brachiopods, solitary

rugose corals, *Thamnopora* fragments, specimens of *Amphipora*, and in rare cases, fish bone

fragments.

Rudstones and Floatstones

Stromatoporoid-coral rudstones and floatstones in the reef front are formed of fragments from

the types of framebuilders found *in situ*. The rudstones are generally characterized by ~60%

skeletal clasts derived from laminar and tabular stromatoporoids and coral fragments, and ~ 40%

cavities that are filled with sediment and microbialite. Marine cements may or may not be

present, but geopetal fill and spar cement in cavity spaces is common. In some areas, the

rudstones are formed almost entirely of broken and transported laminar and tabular

stromatoporoid skeletons, coral heads (domal growth forms), and/or fragments of corals (Fig.

11A). Where dominated by thin rectangular shaped clasts, these imbricated rudstones commonly

have the appearance of a laminar-tabular stromatoporoid framestone, especially where *in situ*

framebuilders encrusting the clasts are present. Broken edges of the stromatoporoids, and upside-down skeletons, however, indicate that these densely packed deposits are formed predominantly of transported broken skeletons.

Floatstones in the reef front are sediment (generally muddy) rich variations of the rudstones that contain fewer large skeletal fragments.

Reef Front to Fore-Reef Transition

The paleo-valley in the Heart Lake Fire Tower traverse includes reef-front to proximal fore-reef transitions on the flanks of the valley and into its deeper central area (MacNeil and Jones, 2006a). Along the flanks of the paleo-valley, thick-bedded accumulations of the reef front facies start to dip and laterally pass gradually into steeper dipping, more argillaceous and coral-rich deposits (Fig. 11B). At AM13, on the southern flank of the paleo-valley (Fig. 6B), the reef front is dominated by large *in situ* tabular actinostromids and laminar whorled stromatoporoids (up to 1 m across) that are surrounded by densely packed floatstones and rudstones. Most of the whorled stromatoporoids have a dusting of light green mud on their upper surfaces. Tabular actinostromids 10-15 cm thick and 1-2 m across are also present. Laterally to the north these deposits dip into the lowest area of the paleo-valley where numerous bioherms with flanks that generally dip at 25- 30°.

The section at AM16, ~60 m north of AM13, records the vertical succession from horizontal thick-bedded deposits to biohermal deposits. The horizontal reef front deposits (Fig. 11C and D), characterized by laminar and tabular stromatoporoids, large whorled laminar stromatoporoids, and heads of *Phillipsastrea*, pass upwards into an increasingly argillaceous laminar stromatoporoid-coral dominated accumulation with better defined medium- to thin-bedding that

formed a bioherm with 3-4 m relief (Fig. 11E and F). Although rudstones are still common, their matrix is green-grey and more recessive weathering than in the underlying deposits. Compared to the lower part, *Thamnopora* is more abundant and solitary rugosans, either in growth position or locally toppled, are more common. A large nautiloid ~ 10 cm across was found in the bioherm and bituminous partings are present. *Aulopora* is more common and crinoid ossicles, in some cases still articulated into stems, are common, as are large gastropods.

A similar transition is also evident in section AM29 on the north side of the paleo-valley. There, the reef front is characterized by numerous laminar and tabular stromatoporoids and laminar whorled stromatoporoids that commonly overlap each other. The framebuilders (65-75% of the total facies) are separated by green-grey floatstone that contains fragments of stromatoporoid plates. The up-section transition to the first bioherm is marked by the appearance of broken and fragmented laminar stromatoporoids (whorled laminar become rare) that do not appear to have been transported very far. Corals also become more common, including more large domal *Phillipsastrea* heads and irregularly shaped *Alveolites* that locally grew into large heads up to 30 cm high and 80 cm across. Other faunal elements that become more common include *Thamnopora,* large crinoid ossicles (8-10 mm diameter), solitary rugosans, and brachiopods. Beds dip up to 25°, and the recessive weathering argillaceous matrix leaves behind lags of weathered-out brachiopods and corals (e.g., numerous *Macgeea*) on the bedding planes.

In the central part of the paleo-valley, several bioherms are present (Fig. 6B). These typically have 3-4 m of relief but at AM30-2, the relief is on the order of 5-6 m. The width of the bioherms varies from <50 to ~320 m, which may partly reflect the orientation of the section relative to the position of the individual bioherms. Their facies are the same as at AM16 and AM29 – a buildup of stromatoporoids and corals dominated by laminar stromatoporoids and

corals with rudstones of laminar stromatoporoid and coral fragments and a green-grey

argillaceous matrix. *Thamnopora* fragments are abundant as are large crinoid ossicles and in

some cases crinoid stems are preserved.

Fore-Reef Facies Association

Overlying the reef front bioherms found in the paleo-valley is the Fore-Reef Facies Association

that includes (1) thin to medium bedded, bioturbated muddy crinoidal wackestones, (2) rugosan

bafflestones, and (3) medium- to thick-bedded stromatoporoid-coral rudstones. In many parts of

the paleo-valley the flanks of bioherms, composed of laminar stromatoporoid-coral deposits,

pass laterally or abruptly grade upwards into dark grey-brown thin to medium bedded

bioturbated muddy crinoidal wackestones (Fig. 11G). Fragments of *Thamnopora*, and scattered

brachiopods, gastropods, and broken pieces of laminar stromatoporoids are present in the

wackestone. The upper part of each wackestone bed is more argillaceous and recessive

weathering than its lower part.

Locally, small thickets of fasciculate rugosans (*Smithiphyllum*) grew in the areas between

the bioherms and eventually became encased in the muddy grey-brown wackestones (Fig. 11H).

Solitary rugosans are common in the same horizons. These deposits are assigned as the fore-reef

bafflestone facies. In many cases burial compaction deformed these deposits and aligned the

solitary rugosans with bedding and broke the thickets into smaller pieces. Rugosan bafflestone

was prominent in the ensuing transgressive systems tract (MacNeil and Jones 2006a).

In most areas, the bioherms are overlain by the muddy crinoidal wackestone. In some areas,

however, a resistant weathering 30-80 cm thick dipping bed of rudstone is present (Fig. 11F and

G). The bed includes densely packed laminar stromatoporoid fragments, whole and fragmented

colonial and solitary corals, brachiopods, and crinoids. It sits isolated within the crinoidal

wackestones and is commonly overlain by a thin bed of argillaceous, recessive weathering

wackestone-mudstone, which in turn is overlain by bafflestone. The rudstone bed is interpreted

as a reef-front debris flow but it is not clear if it represents one major event or smaller debris

flow events in different parts of the valley at different times.

THE MUD MOUND LOCALITY

The Mud Mound locality (Figs 1 and 2C) is a famous locality because of several (> 30) exhumed

metre-scale bioherms in a ~30-50 m wide area that trends southeast-northwest along the

escarpment edge for ~ 700 m (Fig. 12A and B). They are called "Mud Mounds" for historical

reasons with Jamieson (1967) describing "beehive-shaped" bioherms that are small, high-relief

buildups that are easy to walk around and over. In addition to mapping and studying the

exhumed bioherms, a core was drilled through one of the mounds and down into the underlying

formation. The bioherms are situated in the lagoonal area of Reef Complex #2 (MacNeil and

Jones, 2006a) and the succession can be divided into pre-bioherm deposits of the lagoon,

bioherm deposits, and deposits that subsequently buried the bioherms.

Pre-Bioherm Lagoon Deposits – *Amphipora* Floatstone

Beds underneath the bioherms are thin-bedded, densely packed *Amphipora* floatstone to rudstone

– a facies informally known in western Canada as "spaghetti-rock". *Stachyodes* fragments are

also present. The light coloured to off-white matrix includes calcispheres and shell fragments,

including possible ostracods. The *Amphipora* deposits are locally bound by laminar

stromatoporoids ~ 2 mm thick and in the vertical core a laminar stromatoporoid is found every 5-10 cm.

Bioherm Facies – Laminar Stromatoporoid Bindstone

The boundary between the light coloured *Amphipora* floatstones and the bioherms is sharply defined (Fig. 12B). The bioherms are exhumed as individual entities, 2-3 m high and 6-10 m in diameter, with steeply dipping flanks (Fig. 12C) or as coalesced bioherms 2-4 m high and up to 30 m in diameter. The coalescence of individual bioherms is evident when fracturing and weathering has removed part of the buildup and the internal architecture of coalesced and 2-4 stacked units is exposed (Fig. 12D). These exposures also show that successive phases of growth did not always envelope the flanks of the underlying deposits. Although the exhumed bioherms may have a relief of ~2-4 m, their synoptic relief in the lagoon may have been less than one meter. There is a general trend from isolated bioherms in the southeast to coalesced bioherms in the northwest, but as the exposure of these bioherms is not complete, it is not known if this is an artifact of the exposure trend or truly represents a depositional trend in the bioherm field.

The bioherms are formed of a dark grey-brown laminar stromatoporoid bindstone (Fig. 12E). The facies consists of stromatoporoid plates 3-5 mm thick (locally up to 3.5 cm) growing over top of each other every 1-4 cm, binding sediment into place. The plates range from being horizontal to dipping up to 50°, depending on if they are in the central part of a bioherm or part of the flank. Vertical spacing of the stromatoporoid plates is not uniform – in some areas the plates are closely spaced whereas in other parts several centimeters of sediment are present between the plates. The facies is estimated to contain 70- 80% sediment, which varies between an organic-rich mudstone and wackestone that includes fragments of diminutive *Amphipora* and

conical microfossils interpreted to be cricoconarids (Fig. 12F). Small solitary rugose corals and rare fragments of *Smithiphyllum* are present.

Sediment Deposited Around and Overtop of the Bioherms

The sediment deposited around the bioherms has been largely removed by erosion, but is assumed to be comparable to the sediment that was bound between the laminar stromatoporoids in the bioherms. Thus, it was probably a dark-coloured, recessive weathering mudstone/wackestone with scattered *Amphipora* fragments. The bioherms are overlain by a light coloured *Amphipora* floatstone with a calcisphere wackestone-packstone matrix, and locally the *Amphipora* are sufficiently abundant to be considered a rudstone. Small subspherical and low-domal stromatoporoids are present in these facies, and were probably growing isolated on the seafloor between meadows of the *Amphipora*. These deposits are comparable to the deposits underneath the bioherms, and represent a normal lagoon depositional environment (MacNeil and Jones, 2006a).

INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS

New Roadcut Biostrome

The NRC biostrome is unique in the Alexandra Reef System because of its dense, low diversity, stromatoporoid framestone. Although it is known (from the core data) that the biostrome developed upwards from the bioclastic rubble that composes the outer buildup, interpretation of its specific depositional environment is difficult because the vertical position of the biostrome relative to the lower boundary of the Alexandra Formation is not known (drilling of the core had to be stopped), and it is located in an isolated position - correlation with other exposures in the

area is difficult because of the lack of marker beds. As such, it is not clear if it is part of the lowstand systems tract or the overlying transgressive systems tract. The uncertainty as to which tract the buildup belongs to has significant implications for whether the buildup is interpreted to be from a shallow, high-energy or deep, low-energy depositional environment.

MacNeil and Jones (2006a) assigned the biostrome to the transgressive systems tract, placing a surface of maximum regression (flooding surface) between it and the underlying bioclastic rubble. It was deemed to have formed in a deepening, low energy environment because (1) some argillaceous content is present in the buildup, (2) crinoids are common, (3) *Actinostroma,* which is a common stromatoporoid in the lowstand systems tract reef front, is absent, (4) marine cements had not been found, (5) the delicate corals in the depression and the platy-multicolumnar stromatoporoids were considered too delicate for a high-energy environment, and (6) microbial components that characterize the lowstand deposits, are absent. New data coupled with a reevaluation of these points, however, suggests that each can be accounted for in different ways.

- Argillaceous mud is present but it is a minor component and in many areas there is no sediment at all, other than small amounts trapped in stromatoporoid galleries. The overall lack of sediment is inconsistent with other low energy environments in the Alexandra Reef System. The regionally extensive biostromes that developed in earlier, deeper water stages of the reef system's development are, for example, rich in carbonate sediment (MacNeil and Jones, 2006a).

- Crinoid ossicles are common in the reef core of other Devonian reefs (Machel and Hunter, 1994).

- The absence of *Actinostroma* may be due to environmental exclusion although the lack of microbialite is puzzling given that many examples of *Renalcis* in high-energy shallow environments are known (e.g., Playford, 1980; Machel and Hunter, 1994).

- New thin sections have shown that thick (up to 5 mm) rinds of fibrous to bladed marine cements are present in some of the platy-multicolumnar stromatoporoid galleries. Such cements are considered indicative of the frequent circulation of water through the galleries, driven by high-energy conditions (Tucker and Wright, 1990) and are common in Devonian reef cores (Walls and Burrowes, 1985).

- The delicate branching corals in the depression may have grown in sheltered areas and sufficiently protected from high-energy waves.

- The low diversity of stromatoporoids (dominated by encrusting *Stromatopora*) is consistent with shallow, high-energy reef zones that are typically characterized by low-diversity assemblages suited to the high-energy environment (James, 1983).

These points lead to an interpretation that is opposite to that advanced by MacNeil and Jones (2006a). Accordingly, the biostrome is now considered to be part of the lowstand systems tract and that it developed as a narrow, discontinuous ribbon-like facies belt in a shallow, turbulent environment (Fig. 13A). According to this interpretation, the biostrome is (1) vertically and laterally gradational with the bioclastic rubble deposits, and (2) discontinuous along the margin. It is considered to have been discontinuous along the margin because this facies has not been found anywhere along the escarpment exposures. In this regard, the facies association of the outer buildup, consisting of bioclastic rubble with local variations to ribbons of stromatoporoid framestone, is similar to the Lennard Shelf reef margin facies as described by Playford (1980).

There, an organic framework formed of stromatoporoids is associated with substantial areas of clastic limestones with only scattered *in situ* framebuilders.

Reinterpretation of the biostrome implies that it is probably the closest feature in the reef complex to a true "reef crest" zone (Fig. 13A). Although it probably developed in a turbulent environment, the biostrome was probably covered by water that was at least a few metres deep where daily turbulence was sufficient to remove most but not all sediment. Such a shallow depth is also supported by the platy-multicolumnar stromatoporoids which, with their irregular profiles, would have been highly susceptible to hydrodynamic drag versus the smooth, low-profile encrusting laminar and tabular stromatoporoids that surrounded them. Some of the platy-multicolumnar stromatoporoids were dislodged and transported, but a number of them are found *in situ* and with sediment, which presumably would have been removed if the biostrome was developing in the zone of maximum turbulence.

One of the most striking aspects of the biostrome is the tight coalescence of the laminar and thin tabular stromatoporoids, which must reflect the paucity of sediment (Fig. 13B). The lack of sediment allowed the stromatoporoids to tightly encrust older, underlying stromatoporoid skeletons without the need to grow overtop of or around beds of sediment. The micritic rinds evident between successive stromatoporoids were probably derived from encrusting algae no longer preserved and support the interpretation of a very shallow, well-illuminated depositional environment. In those areas where sediment did accumulate, it seems that the platy-multicolumnar stromatoporoids developed. Alternatively, for an unknown reason, perhaps these stromatoporoids colonized certain bare areas of the biostrome and their irregular morphology acted as "sediment traps". Regardless, their growth form with large galleries and vertical pillars successively elevated their living areas above the sediment.

The domination of the biostrome by *Stromatopora* is notable and it is not clear why this stromatoporoid dominated – perhaps it grew faster and therefore dominated. As it is likely that some parts of the biostrome are entirely formed of the laminar stromatoporoid framestone, an interesting exercise is to calculate a possible age for the biostrome using the latilaminae. The latilaminae are 2 to 8 mm thick; if the average of 5 mm is used and the total thickness of the biostrome is 10.1 m, the time that it took to accumulate can be calculated as ~2000 years if it is assumed that each latilaminae is an annual growth band and that there were no interruptions in its growth. The lack of interruptions is unlikely and so the calculated age of 2000 years is a minimum for the buildup.

Interpretation of the Heart Lake Fire Tower Traverse

The Heart Lake Fire Tower traverse reveals several important features about the nature of the lowstand reef front of Reef Complex #2 and how its architecture changed as it passed basinwards into deeper water (Fig. 13A and C). Large, plate-like (various laminar and tabular forms) stromatoporoids dominated the reef-front, with heads of *Phillipsastrea* and minor coral thickets growing intermittently between the stromatoporoids. Cavities that existed beneath the living whorled laminar stromatoporoids and between their individual plates provided cryptic habitats for various organisms, including *Renalcis*-dominated calcimicrobial masses, brachiopods, spirorbids, encrusting *Aulopora*, and the dendritic encruster of unknown affinity. These cavities may have also afforded protection to small fish. Solitary horn corals and some larger specimens of *Phillipsastrea* also grew between the plates. Stromatolites commonly grew on top of dead stromatoporoid plates, especially within the laminar stromatoporoid complexes where dead plates were presumably exposed for longer periods before detrital sediment percolating through

the pile covered them. Packstones, wackestones, and mudstones eventually filled remaining

cavity spaces and an abundance of cracked stromatoporoid plates and collapsed whorled

skeletons indicates that with burial the reef framework was not a rigid structure. The general lack

of marine cements in the reef fabric may indicate limited water flow through the reef pile, which

would be consistent with early burial compaction, probably as the reef was still accumulating.

Local relief on the reef appears to have been low. Domal stromatoporoids grew as stacked

individuals, up to 0.5 m high, in areas between the laminar and tabular stromatoporoids.

Although their synoptic relief is not clear, the lack of ragged margins indicates that it was at least

5-10 cm. More indicative of relief on the seafloor are areas where large tabular stromatoporoid

skeletons clearly dip in a common direction, indicating 1-2 m of topography. Modern reef fronts

typically have meter-scale relief between areas, and small reef front knolls of platy *Montastrea*

(e.g., Fig. 13 in James and Bourque, 1992) appear to be good analogues for the Alexandra

stromatoporoid-dominated reef front.

That the stromatoporoids in the Alexandra reef front grew below fair-weather wave base is

supported by the following considerations.

- The green muds that were periodically deposited on top of the meter-scale stromatoporoids

    must have been deposited from suspension, probably following storm events that had

    stirred-up the more distal, outer ramp seafloor, which was an area of green mud deposition

    (Hadley 1987; MacNeil and Jones, 2006a). Such sedimentation could not have taken place

    in a perpetually turbulent environment.

- The delicate, thin plates that characterized the whorled-laminar stromatoporoids were

    probably not capable of surviving high-energy wave environments. Here, it is important to

    remember that these stromatoporoids grew as individuals (not as coalesced framebuilders)

that were supported only by their conical base and points where their skeletons rested upon

the sediment. A similar, low-energy, deep reef-front setting was also proposed for

specimens of *S. australe* in the Canning Basin (Wood, 1998).

The depth of the fair-weather wave base for the oceanographic system in which the

Alexandra Reef System developed is not known in absolute terms. Facing to the west-northwest

(Jamieson, 1967; MacNeil and Jones, 2006a) it would have been a leeward to oblique-leeward

facing system. Embry and Klovan (1972) attempted to assign absolute water depths to

paleoecological zones of similar stromatoporoid reef facies found in Devonian strata on the

northeastern part of Banks Island in the Canadian Arctic. They argued that (1) coral dominated

faunas grew in water below storm wave base at 21 m, (2) tabular stromatoporoids less than 2.5

cm thick dominated between fair-weather wave base and storm wave base at depths of 9-21 m,

and (3) massive stromatoporoids (> 2.5 cm thick) dominated above fair-weather wave base. The

fair-weather and storm wave bases of 9 and 21 m were derived from comparisons with modern

reef systems (Embry and Klovan, 1972).

Mid-Frasnian stromatoporoid-coral reefs that developed over deep-water fore-reef detritus in

front of the Ancient Wall Complex in Alberta (Mountjoy and Jull, 1978) include facies like those

found in the Alexandra reef front. They concluded that the stromatoporoid-coral deposits

accumulated in water that was 10-20 m deep and stromatoporoid-coral-microbial bioherms grew

in even deeper water, probably around 25 m water depth before drowning. The paleo-

reconstruction of the Alexandra Reef System (MacNeil and Jones, 2006a) and comparison with

Embry and Klovan (1972) and Mountjoy and Jull (1978) leads to the conclusion that the

Alexandra reef front accumulated in water that was between 10 and 20 m deep under low-energy

conditions. The paleo-valley probably had an increased water depth in the range of 20 to 25 m.

Burial of the bioherms by crinoidal muddy wackestone is interpreted to indicate drowning of the

bioherms and transition to the fore-reef depositional environment, with depths exceeding >25 m.

Interpretation of the Mud Mound Locality

This field of bioherms developed in the lagoon associated with Reef Complex #2. Their

stratigraphic position between clean carbonate lagoon facies indicates that they developed in

response to the regional flooding event that is recorded across Reef Complex #2 (MacNeil and

Jones, 2006a), and they probably grew in water that was ~ 20 m deep. It is interpreted that

relatively sudden deepening in the lagoon caused a significant reduction in sediment production

and that the bioherms developed in areas where small highs on the seafloor were present.

Perhaps scattered solitary rugosans or isolated stromatoporoids provided hard substrates for

laminar stromatoporoid growth and bioherm initiation. As the stromatoporoids grew up and over

top of the sediment, the covered sediment would have been protected from further disturbance.

Periodic deposition of sediment, probably shed from shallower parts of the reef complex

(MacNeil and Jones, 2006a) buried the stromatoporoids but was not sufficient to kill them –

perhaps because some areas of living plates escaped burial – and new plates grew over top of the

recently deposited sediment. Overtime, differential accumulation (stromatoporoid + sediment at

the bioherm versus only sediment between the bioherms) through such a mechanism resulted in

development of the bioherms – mounds that were clearly elevated above the surrounding

seafloor.

STROMATOPOROID GROWTH FORMS AND MODES

A wide variety of stromatoporoid growth forms including laminar, tabular, anastamosing laminar and tabular, domal, bulbous, dendroid, expanding-upwards conical, concave-up whorled-laminar, concave-up massive tabular, and platy-multicolumnar are present in the Alexandra Reef System. Although many of these growth forms are common (Kershaw, 1998), the concave-up and platy-multicolumnar forms are rare (Kershaw and Riding, 1978; Kershaw, 1998). Stromatoporoids are generally regarded as sessile filter-feeding animals that thrived best in low turbidity environments (Kershaw and Riding, 1978). Growth forms should be conducive to at least the passive shedding of sediment, so that feeding systems are not impeded. The concave-up growth forms, which could have readily collected suspended sediment, are therefore unexpected and yet they are common in the reef front of Reef Complex #2. Furthermore, the green argillaceous sediment deposited around and overtop of these skeletons is inconsistent with the environmental conditions typically expected for sessile filter feeders.

The concave-up stromatoporoid growth forms in the Alexandra Formation are species-specific; the whorled-laminar forms are *Stachyodes* sp. aff. *Stachyodes australe* Riding, 1974 whereas the massive tabular forms are *Actinostroma clathratum* Nicholson, 1886A. Both genera have variable growth forms (e.g., Riding, 1974; Wood, 2000). In the Canning Basin, thin arching plates of *S. australe* formed open domed cavities that are up to 30 cm high and 1.5 m across, which provided cryptic habitat for various reef-dwelling organisms (Wood, 1998). Preservation of the reef fabric was due to rapid, pervasive, early cementation (Wood, 1998). In the NRC biostrome, *S. australe* adopted a delicate platy-multicolumnar growth form that is nothing like the whorled forms in the Alexandra reef front or the Canning Basin domes.

Wood (1998) concluded that *S. australe* grew only at its margins. In the Alexandra

Formation, the whorled-laminar growth form also appears to have grown at its margins with

periodic upward splaying off-shoots that grew into new plates. From an initiation phase,

successive growth around the margins of the basal sheet increased the diameter of the

stromatoporoid while also allowing it to elevate its marginal areas above surrounding sediment,

resulting in a concave-up growth form. With growth, the weight of the stromatoporoid increased

and it may have partly sunk into the substrate, thereby increasing the need for elevated margins.

This growth model supports the interpretation of Riding and Kershaw (1978) that concentric

rings on the undersides of basal plates mark areas where underlying sediment was touched upon.

Actinostroma is known to have had various growth forms (Mallamo, 1995; Wood, 2000).

The Frasnian section at Windjana Gorge (Australia), for example, contains domal and platy

multicolumnar growth forms of *Actinostroma* that are up to 5 m across (Wood, 2000). The platy

multicolumnar growth forms figured in Wood (2000) resemble some of the anastamosing tabular

growth forms of *Actinostroma* found in the Alexandra Reef System, but none of these were

found to be more than two metres across. Wood (2000) also documented two specimens of

Actinostroma that appear to have been concave-up, whorled forms that, in some respects,

resemble the whorled-laminar specimens of *Stachyodes* in the Alexandra Reef System.

The massive concave-up form of *Actinostroma clathratum* found in the Alexandra Reef

System appears to be a fairly unique example of this growth form. It differs from the Australian

examples because of its thick skeleton (up to 20 cm) and the lack of platy outgrowths, which

imply that part of the skeleton could be living while other parts have died (Wood, 2000). The

Alexandra specimens show continuous, successive growth laminations across the entire skeleton,

which implies that they lived for several years, possibly several decades, without sufficient

sediment accumulation on their tops to cause death. This interpretation is paradoxical with the

laminar whorled growth forms that contain sediment between their plates and often the green

mud deposits across their tops. The contradiction, however, can be resolved if *Actinostroma* is

considered to have grown at a faster rate and sediment deposition atop of living plates was very

infrequent. In other words, the whorled laminar forms may have only been growing at the

margins of their plates, but that does not mean that inner areas of the plates had died and/or were

buried by sediment. A low-energy reefal environment with unusually pristine water and only rare

storm events may explain why concave-up growth forms, that are very rare for stromatoporoids,

are so common in the reef front of Reef Complex #2 and represented by two different genera.

The broad growth forms would have facilitated maximum exposure to illumination, which is

consistent with photosymbiosis, but there is no way to definitively prove that photosymbionts

were present.

The NRC biostrome includes two notable features. First, the mutual encrustation of laminar

stromatoporoids to form dense framestone is a rare mode of growth amongst stromatoporoids

(Stearn, 1982; Kershaw, 1998; James and Wood, 2010). Although use of the term "framestone"

is common in Devonian reef studies, few examples of encrusting stromatoporoids forming

metre-thick successions are known and most stromatoporoids in Devonian reefs probably grew

as closely-packed but isolated individuals or individuals with only local coalescence and mutual

encrustation (Stearn, 1982; Kershaw, 1998; James and Wood, 2010). It is believed that the high-

energy of the depositional environment precluded sediment from accumulating on the essentially

flat stromatoporoids, resulting in a vast area of hard substrate suitable for continuous

encrustation by new stromatoporoids.

The platy-multicolumnar growth form of *Stachyodes australe* is the second notable feature in the NRC biostrome. Platy multicolumnar growth forms are known from other reef systems (cf. Kershaw, 1998), such as platy-multicolumnar *Actinostroma* from the back-reef of the Lennard Shelf (Wood, 2000) but other examples demonstrating such geometric arrangement of the coenosteum, as found at the NRC biostrome, are not known. This form could alternatively be described as "digitate", which Kershaw (1998) notes is rare amongst stromatoporoids and predominantly known from a few Silurian genera. Use of the term "digitate" has been avoided, however, because this term does not necessarily convey the presence of horizontal plates, which is an important part of the growth form in the Alexandra Formation, and because dendroid stromatoporoids (e.g., *Amphipora*, *Stachyodes*) are also commonly described as being "digitate". The more descriptive "platy-multicolumnar" term is therefore applied.

It is interpreted that the platy-multicolumnar form represents a response to sediment accumulation, and in the biostrome may mark areas where slight (cm-scale) depressions, more prone to sediment accumulation, existed. Thus, whereas most areas of the biostrome were characterized by a hard flat substrate suitable for stromatoporoid encrustation, local regions of thin sediment accumulation precluded the regular mode of stromatoporoid encrustation but favoured the plate-column growth form of *S. australe*, which was suited for handling sediment accumulation and shifting sediments.

The best documented Devonian example of densely packed stromatoporoids forming thick buildups of framestone that can be compared to the NRC biostrome are the buildups of "massive stromatoporoids" in the Upper Devonian Mercy Bay Member of the Weatherall Formation by Embry and Klovan (1971). Of comparable thickness, these buildups have minimal amount of sediment deposits (~5%) that consist of bioclastic packstones and grainstones, and *Thamnopora*

fragments are locally abundant. Unfortunately the stromatoporoid growth forms in these buildups

are not explicit in Embry and Klovan (1972), but massive hemispherical forms were noted.

These are not found in the Alexandra NRC biostrome. Interestingly, Embry and Klovan (1971)

noted one area where the buildups include colonial rugosans – similar to the localized area of

colonial rugosans in the NRC biostrome. Embry and Klovan (1972) concluded that these

stromatoporoid buildups accumulated above fair-weather wave base in the zone of turbulent,

rough-water.

Perhaps the best-known examples of laminar-stromatoporoid framestone most comparable

to the NRC biostrome are the Silurian Holmhällar biostromes of Gotland (Ludlow age). Riding

(1981) described these biostromes as being very low-diversity buildups dominated by laminar

stromatoporoids that were densely packed and encrusting each other to form solid framestone.

Stromatoporoids in these biostromes are thicker (2-10 cm) than the laminar forms in the NRC

biostrome and were not as planar, with cm-scale undulations and locally formed low domes up to

15 cm high (Riding, 1981). Similar to the NRC biostrome, large crinoids are present and

sediment is very coarse, gravel-like bioclastic material but locally finer green-grey sediment

formed lenses. Riding (1981) argued that these biostromes developed in very shallow high-

energy environments, possibly as linear reefs. They are probably the best analogue for the NRC

biostrome.

A NEW CLASSIFICATION SYSTEM FOR DEVONIAN REEF FABRICS

Reef facies in the Alexandra accumulated in different reefal environments and have significant

variations in their stromatoporoid growth forms, framebuilder diversity, biologic consortia, and

sediment component. As an aid for capturing the variations in the reef facies that are present, and

relating the variations to their different depositional environments, a classification system of

Devonian reef fabrics has been developed (Fig. 14). The scheme can be extended to other

Devonian reef systems, and used to classify all known types of Devonian reef fabrics.

The scheme consists of the following four fabrics:

A) Metazoan-Microbial Reef Fabric – microbial constituents and their various types of

precipitated carbonate fill cavities and bind skeletal framebuilders to form a rigid mass

(boundstone). In some cases microbial constituents dominate the reef fabric and

metazoans may be minor constituents.

B) Sediment-laden Metazoan Reef Fabric – metazoan framebuilders are abundant but exist

as individual entities or small patch reefs surrounded by and buried in autochthonous

bioclastic sediment. The sediment pile is cemented gradually by early diagenetic

processes and in the subsurface.

C) Metazoan-Dominated Fabric – stromatoporoids and/or coral framebuilders are intergrown

and coalesce to form framestone, providing a rigid reefal mass. Microbial carbonate is

not present or is present but does not play a significant role in building the framework.

D) Metazoan-Marine Cement Fabric – framebuilders are cemented together by marine

cements into a rigid mass and/or marine cements fill a significant amount of the growth

framework pore system, enhancing the strength of the frame.

The fourth class of reef fabric, metazoan-marine cement fabric, is the only type of reef fabric not found in the Alexandra Reef System. An excellent example of this reef fabric is found in the uppermost Frasnian laminar stromatoporoid biostrome in the Kakisa Formation, also in the Northwest Territories. In this biostrome, 2 mm thick rinds of fibrous to bladed milky marine cements encrust the laminar stromatoporoids and fill up to 35% of the growth-framework porosity (Fyvie, 1988).

The four end-members in the scheme are not exclusive and transitions between different fabrics may exist, which can add a level of subjectivity to its application, but its ultimate purpose is to classify the dominant control on the construction of the reef fabric – is it biological or abiological (marine cements), and if it is biological, is it metazoan- or microbial-dominated? Is sediment an important component of the reef fabric?

Plotting the different reef fabrics in the Alexandra Reef System with the context provided by the high-resolution sequence stratigraphic framework (cf. MacNeil and Jones, 2008) provides an effective summary of variability in the reef fabric through the evolution of the reef system (Fig. 14). In this case, the reef fabrics in Reef Complex #1 and the transgressive and highstand stages of Reef Complex #2 are sediment-laden metazoan reef fabrics. In contrast, most of the reef fabrics of Reef Complex #2 in its initial falling stage and lowstand systems tracts are metazoan-microbial dominated with the exception of the NRC biostrome which is metazoan-dominated framestone. MacNeil and Jones (2008) related the reef fabrics to different nutrient levels and used the variability in reef fabric to conclude that the reef system had alternated between oligotrophic and mesotrophic states at different times in its development.

DISCUSSION

Facies models (Fig. 15 and Table 1) for Devonian stromatoporoid reefs treat the reef margin as having developed in a (1) very high-energy wave swept environment more or less at sea-level (Playford, 1980; Wendte and Stokes, 1982; Machel and Hunter, 1994) or (2) low-energy wave swept environment in the lower reaches of fair-weather wave base (Wilson 1974; James and Bourque, 1992). Machel and Hunter (1994) noted that some Devonian reef systems are more ramp-like with broad reef development versus shelf-like with narrow margins, but still placed reef development well above fair-weather wave base. Modern coral reef analogues and the belief that stromatoporoids lived in high-energy shallow environments less than 10 m in depth underpin the "high-energy" models (Playford, 1980; Machel and Hunter, 1994), and a number of Devonian reefs, including the Alexandra, have been interpreted as some form of barrier-reef complex (e.g., Jamieson, 1967; Krebs, 1974; Playford, 1980; Burchette, 1981; Kershaw, 1998).

The elephant in the room is that there are very few studies that actually demonstrate the sedimentary and stratigraphic evidence to support the very high-energy wave swept depositional environment and/or barrier reef interpretation (e.g. Burchette, 1981; Kershaw, 1998). Destructive aspects of dolomitization, burial compaction, structural deformation, metamorphism, as well as issues around outcrop accessibility and accurate correlation of stratigraphic units between study areas, have limited many studies. The classic portrayal of the Canning Basin's Lennard Shelf as a flat-topped platform reef system, for example, is a best-estimate reconstruction of differentially compacted strata by Playford (1980). Subsurface studies are inherently limited by seismic resolution, the availability of core, and core diameter. Questions about the applicability of modern analogues to stromatoporoid-dominated reefs have been asked (e.g., Klovan, 1974; Stearn, 1982), and stromatoporoid framestone, considered to be a key facies for Devonian reef

margins (especially the very high-energy margins), is not very common (Stearn, 1982; Kershaw, 1998; James and Wood, 2010) even though the term "framestone" may be commonly applied. Some of the experienced sedimentologists having worked the Devonian exposures in the Canadian Rocky Mountains, for example, have rarely seen evidence of actual bioconstructed reef framework (framestone) in the exposures (Workum, 2015 pers. comm.). Caution must be exercised when interpreting densely packed stromatoporoids in outcrops and core – just because they are densely packed and in contact with each other does not mean that they were mutually encrusting during life and that they formed a framestone (Tsien, 1981; Wood, 1995).

Historically, the Alexandra Reef System was interpreted as a high-energy barrier (Jamieson, 1967, 1971; Magathan, 1987) and as one of the better-known Devonian barrier reef systems it has influenced the development of "high-energy" facies models (cf. Machel and Hunter, 1994; Kershaw, 1998). The context for understanding the initial barrier interpretation is important. Jamieson (1967) had relatively few studies of Devonian or modern reefs to draw upon, and given the problematic affinity of stromatoporoids, considered the abundant thin laminar stromatoporoids in the Alexandra Formation (Figs 8 and 10) to be a type of crustose coralline algae. Indeed, as Jamieson was completing her thesis work in the 1960s, Wray (1967) described a new form of crustose coralline algae *Keega australe* which is similar in structure to the "algae" that Jamieson (1967) described from the Alexandra Formation. Jamieson (1967) recognized the conspicuous stromatolites growing in the reef framework (Fig. 10) and compared them to the only known modern examples of stromatolites from Florida and the Bahamas that grew in water less than 3 m deep (Jamieson, 1967, 1971). The laminar stromatoporoids interpreted as crustose coralline algae, combined with the stromatolites, were related to modern red-algae dominated

reefs in the south Pacific, and the quite reasonable conclusion that the reef front of the Alexandra

was a barrier more or less at sea-level position was made.

The interpretations offered by Jamieson (1967, 1971) must be questioned in view of

subsequent studies. Riding (1974), for example, redefined the crustose coralline algae *Keega*

australe Wray (1967) as a laminar stromatoporoid (*Stachyodes australe*) using material from

western Canada, and this redefinition has been widely accepted. The laminar "algae" in the

Alexandra Formation are also mammillated, which is consistent with a stromatoporoid, not algal,

affinity. Stromatolites are now known from a variety of reefal environments and water depths,

and they are not restricted to water depths less than 3 m (e.g., Riding *et al,.* 1991; Riding and

Tomás, 2005) Jagathan (née Jamieson) (1987) presented a further interpretation that the

Alexandra Formation included a spur and groove reef front, invigorating the barrier-rim

interpretation. The spur and groove reef front was not, however, documented in Jamieson (1967,

1971) and extensive field-work by the current authors has not been able to document a spur and

groove morpholog) here are areas along the escarpment where the erosional topography has

produced spur-like remnants of reefal limestone, but these are not depositional geometries.

The fundamental problem with the barrier reef-front model for the Alexandra Reef System is

the green mud deposited from suspension onto the stromatoporoids, which was not specifically

recognized in Jamieson (1967, 1971). The physical sedimentology of these deposits precludes

the possibility that the reef front existed above fair-weather wave base; the reef front must have

developed below fair-weather wave base in order for these deposits to accumulate upon the open,

exposed stromatoporoid plates. Even without consideration of the green mud deposits, similar

facies dominated by tabular stromatoporoids have been interpreted in other studies as having

been from deeper, low-energy environments (e.g., Klovan, 1964; Leavitt, 1968; Embry and

Klovan, 1971).

Integration of the sedimentology, shapes of the growth forms, stratigraphic relationships,

and history of sea-level change indicates that the reef front probably developed in 15-20 m water

depth and as it passed into deeper water, bioherms were constructed. As such, most of the *in situ*

reef fabrics historically interpreted to be high-energy reef deposits (Fig. 15A) must have actually

accumulated in lower-energy depositional environments (Fig. 15B). This is a significant revision

to the interpretation as it demonstrates that *in situ* stromatoporoids bound by microbial masses

into rigid boundstone, and densely packed stromatoporoids with sediment filling cavity spaces,

cannot be treated unequivocally as a high-energy reef margin facies, as otherwise indicated by

many of the commonly applied facies models. Below depths of 25 m, framebuilder construction

was significantly reduced and bioturbated muddy wackestones with crinoids became the

dominant facies.

Landwards of the reef front, bioclastic rubble dominated the outer buildup and marked the

shallowest and highest-energy part of the outer reef margin. Laterally along the margin of the

outer buildup framestone accumulated, probably as discontinuous ribbons as exposed at the NRC

biostrome, and these deposits, with the bioclastic rubble, form the high-energy rim of the system.

Use of the term "barrier" is avoided because it implies restriction of the interior, which was not

the case in the Alexandra which still experienced significant reef buildup inboard of the outer

buildup (MacNeil and Jones, 2006a). There is also no evidence (e.g., marine vadose cements),

even in the highest-energy part of the margin, that the deposits accumulated right to sea-level.

This discussion does not imply that the "very high-energy" facies models for Devonian reefs are

incorrect, but rather that alternatives exist and care must be taken when applying facies models.

In the interior of Reef Complex #2, the bioherms that constitute the Mud Mound locality offer an example of sharp vertical facies contrasts related to changes in relative sea-level position (MacNeil and Jones, 2006a). In this case, lagoonal bioclastic sediment is overlain by low-diversity bioherms (with sediment-laden metazoan reef fabric) and the muddy, organic-rich sediment deposited between bioherms. The smaller size of the lagoonal bioherms, greater volume of carbonate mud bound between laminar stromatoporoids, and the absence of crinoids and large fasciculate rugosans distinguish these bioherms from the distal reef-front bioherms at the reef-front to fore-reef transition zone. With regards to Devonian facies models, the lagoonal bioherms provide an unusual example of reef fabric development in a lagoon versus reef-margin "proper" location, and demonstrate that similar to mud mounds on modern carbonate platforms (e.g., Florida Bay and the northern Belize shelf), platform interior deposits are not restricted to flat- and cross-bedded clastic facies. Unfortunately, the dataset is too limited to evaluate the potential role of platform interior hydrodynamics on the development of these bioherms, but it is clear that Devonian lagoons were not necessarily limited to restricted deposits dominated by *Amphipora* and calcispheres.

The fourfold reef fabric classification scheme presented in this study is similar to that described by James and Wood (2010) for Phanerozoic reefs (Table 2), but differs by including the "sediment-laden" category, which is probably a more common Devonian reef fabric than is generally acknowledged (cf. Playford, 1980; Tsien, 1981; Rhodes *et al*., 1984; Kershaw, 1998; James and Wood, 2010). Indeed, the only difference between the sediment-laden fabric described here and the definition for bindstone by Emby and Klovan (1972), who noted that the *in situ* fossils in bindstone may represent as little as 15% of the deposit, is the growth form of the framebuilder. In the case of "bindstone", the framebuilders are tabular or laminar. In the case of

sediment-laden reef fabric, the definition recognizes that framebuilders of different shapes may grow over and/or be buried in sediment, resulting in large accumulations of bioclastic sediment and *in situ* framebuilders that over broad areas are can dampen wave energy and restrict the interior.

The proposed scheme also shares similarities (Table 2) with the fivefold scheme of Tsien (1981), which added the terms "coverstone" and "biocementstone" to the terms framestone, bafflestone, and bindstone defined by Embry and Klovan (1971). Whereas the scheme of Tsien (1981) focused on the process that resulted in a rigid framework and the definition of "reef", the scheme presented here is focused on the biogenic/abiogenic composition of the framework. Insalaco (1998) provided a review of various classification schemes for reef (growth) fabrics and proposed a descriptive scheme for scleractinian reef fabrics. Many of the considerations discussed by Insalaco (1998) for scleractinian reefs, and issues around the classification of reef fabrics, apply to Devonian reefs and their fabrics. In many situations a hierarchy of classification and description of reef fabric characteristics is warranted. For example, the detailed classification scheme of Insalaco (1998) could be extrapolated to the description of a Devonian reef fabric that at the first order is classified as being metazoan-dominated.

Understanding the reef fabric contributes towards reconstructing the depositional environment, identifying changes in the reef environment that may have impacted overall reef evolution, and is critical in subsurface petroleum reservoirs where reservoir quality and petrophysical properties are linked to reef fabric (e.g., Walls and Burrowes, 1985). For example, notwithstanding the biostrome presented in this study, it is unlikely that most stromatoporoid-dominated margins grew into the zone of maximum wave energy, more or less at sea-level, and developed narrow, high-relief facies belts, without the binding and cementing aid provided by

microbialite and/or marine cements (Playford, 1980; De Freitas *et al.*, 1993; Kershaw, 1998).

Metazoan-microbial, metazoan framestone, and metazoan-marine cement reef fabrics therefore

may be assumed to be characteristic of these depositional environments, but are not necessarily

exclusive to these depositional environments. Sediment-laden reef fabrics can be assumed to be

less stable in higher-energy environments and less capable of forming high-relief buildups. This

interpretation is consistent with several studies that have placed the zone of active

stromatoporoid growth in the lower reaches of regular wave turbulence, near fair-weather wave

base (Klovan, 1964; Kershaw, 1998). Indeed, the stromatoporoid zonation model of James and

Bourque (1992) places stromatoporoid reef zones in slightly deeper water than equivalent coral

zonations from the modern, and Wilson (1975) summarized massive and encrusting

stromatoporoids as living at, or just into, wave base, well below the zone of maximum

turbulence. Wilson (1974, 1975) classified most Devonian reefs as Type 2 reefs characterized by

sloping margins with reef growth in low-energy depositional environments (e.g, around wave

base), and it is quite likely that many of these reefs are dominated by sediment-laden reef fabrics.

Comparison of the types of reef fabrics within a basin or a region of a basin can also be

useful for identifying trends in reef evolution and for petroleum exploration if a component of

reservoir quality is dependent on the reef fabric. Selective dissolution of *Renalcis* causes

significant micro-moldic porosity and is an important control on reservoir quality, for example,

in the upper Frasnian Jean-Marie reefs of northeastern British Columbia and the Northwest

Territories (Wendte *et al,.* 2009). Plotting of the different Frasnian reef fabrics for the southern

Northwest Territories (Fig. 14) demonstrates that some reef systems contain microbial

constituents whereas others do not, and also reveals that a single trend towards increasing

microbial domination of the reef fabrics is not present. The latter is an important observation as a

global trend towards increasing microbial contributions to reef fabrics towards the end of the

Frasnian is generally evident (Kiessling *et al,.* 1999), but the cause(s) of this trend is not clear.

With regard to the building of digital 3D geological models and accurate reservoir

simulation, which requires proper definition and distribution of facies and reservoir flow zones,

differentiation of reef fabrics can also be used as an important step in the workflow. Flat, narrow,

reef-rimmed margins characterized by stromatoporoid-microbial reef fabric versus sloping,

ramp-like reef margins with sediment-laden stromatoporoid reef fabric covering broad areas will

have, for example, very different facies distributions and flow-zone distributions. For a

subsurface reef system with a limited dataset, a good starting point is using the available core to

characterize the reef fabrics that are present and their spatial distributions, as a guide to which

facies model is applied and how flow zones, which are generally sub-seismic resolution, are

correlated. Likewise, it is likely that reservoir rock types will be closely linked to the

depositional reef fabric, even if significant diagenesis has taken place.

CONCLUSIONS

The Alexandra Reef System contains a number of stromatoporoid growth forms, some of which

are unusual. Three localities from different parts of Reef Complex #2 offer important insight to

the nature of these stromatoporoids, their reef fabrics, and the depositional environments. Key

conclusions include:

- Stromatoporoids with whorled and massive tabular concave-up growth forms were

   common in the reef front even though these growth forms are not expected for sessile

   filter-feeding animals.

- The reef fabric was different at each locality. In the reef front, the reef fabric can be best described as a stromatoporoid-coral-sediment accumulation that was stabilized by stromatolites and calcimicrobial masses in some parts while in other parts the reef fabric was "sediment-laden". Stromatoporoids and corals did not coalesce to form framestone but rather existed as individual entities. In contrast, the NRC biostrome was dominated by laminar and tabular stromatoporoid framestone. Microbial carbonate was not present. In contrast to both of these localities, bioherm fabric in the lagoonal buildups was sediment-laden laminar stromatoporoid bindstone, without any microbial component. Marine cements were not part of the reef fabric in any of these localities.

- The reef front developed below fair-weather wave base in a low energy regime. In shallower waters, deposits of bioclastic rubble and ribbon-like bodies of framestone formed a high-energy rim to the platform.

- Overall, framestone is not a common facies in the formation and contrary to a number of commonly applied facies models, framestone is not a common facies in Devonian reefs (cf. Stearn 1982; Kershaw 1998; James and Wood 2010). Incorrect application of the term, versus the more general term boundstone, and illustrated facies models that imply margins dominated by coalesced framebuilders, have probably contributed to this misconception.

- This study demonstrates that facies commonly assumed to have originated in shallow, high-energy depositional environments can also accumulate in deeper, low-energy depositional environments, which carries significant implications for correlation of strata and reconstruction of platform margins.

An important step in the study of Devonian reef systems is therefore the distinction between sediment-laden metazoan-dominated, metazoan-microbial dominated, metazoan framestone, and metazoan-marine cement dominated reef fabrics and how these fabrics correlate with depositional geometries, changes in sea-level, and the rock properties that impact subsurface reservoir quality.

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FIGURE CAPTIONS

Fig. 1. Alexandra Reef System paleogeography and Reef Complex #2 New Roadcut, Heart Lake

Fire Tower Traverse, and Mud Mound localities. Inset map shows study area (star) in southern

part of Northwest Territories relative to western Canada Frasnian paleogeography. PRI = Peace

River Island.

Fig. 2. Stratigraphic framework. **A)** Sequence stratigraphic framework of the Alexandra Reef

System. Note that section follows trend of escarpment edge (Fig.1) and in northwest perspective

changes as section becomes oblique to parallel with reef front orientation. SB=Sequence

Boundary, TST=Transgressive Systems Tract, HST=Highstand Systems Tract, FSST=Falling

Stage Systems Tract, LST=Lowstand Systems Tract. **B)** Main phase of Reef Complex #2

development (lowstand systems tract). Heart Lake Fire Tower Traverse and New Roadcut

biostrome indicated relative to other parts of the complex. **C)** Flooding (transgressive and

highstand systems tracts) phase of Reef Complex #2 and development of mud mounds in the

muddy back-reef area.

Fig. 3. Stromatoporoid growth forms in the Alexandra Reef System. Modified from Kershaw

(1998). Expanded-conical growth form shown from exterior side view and in cross-section A-A'.

Fig. 4. New Roadcut biostrome. **A)** General view to southeast of east wall of roadcut (~ 7 m

high and ~ 250 m in view). Most of biostrome is composed of laminar stromatoporoid

framestone. Two bedding planes (1) and (2) divide biostrome into lower, middle, and upper

units. Depression (Dp) contains large *in situ* and toppled fasciculate rugosans as well as rudstone

with cobble and small boulder-sized clasts of stromatoporoid framestone and corals. Drill rig is

drilling core ARC-2. **B)** Selected interval (~56 cm thick) of laminar and low domal

stromatoporoid framestone in core ARC-2. Arrow indicates broken edge of framestone and

packstone (PS) has filled the cavity. **C)** Laminar stromatoporoid (*Stromatopora*) framestone

with micritized growth surfaces (arrows). Orange-red speckles are small clusters and

disseminated crystals of ferroan dolomite.

Fig. 5. Stromatoporoids in the NRC biostrome. **A)** General view of platy-multicolumnar

stromatoporoid encased in laminar stromatoporoid framestone. Roadcut wall. Increments on staff

are 10 cm. **B)** Longitudinal section of hand sample of platy-multicolumnar stromatoporoid

interpreted as *Stachyodes austral*e. Note green geopetal muds that partly fill growth framework.

C) Transverse section across top of platy-multicolumnar stromatoporoid with significant cavity

space filled by spar cement. **D)** Platy-multicolumnar stromatoporoid upside-down relative to the

geopetal fabrics. Geopetal sediment is a coarse packstone. **E)** Upside-down clast of platy-

multicolumnar stromatoporoid in rudstone. Sediment is rich in crinoid ossicles. **F)** Small

boulder-sized clast (BD) of laminar stromatoporoid framestone rotated nearly ninety-degrees

from original growth position in depression of biostrome. 10 cm increments on staff.

Fig. 6. Heart Lake Fire Tower Traverse. **A)** View of escarpment at AM03 (~19 m high). Most of

escarpment at this locality is formed of laminar and tabular stromatoporoids of reef front. In

foreground, area of collapsed escarpment with numerous boulders. **B)** Detailed cross-section of

Heart Lake Fire Tower Traverse and the paleo-valley area relative to the south and north parts of

the traverse. Line of section shown on Fig. 1.

Fig. 7. Stromatoporoids in the reef front. 10 cm increments on staff. Locality AMO3. **A)** General view of laminar stromatoporoid dominated reef font facies with local massive tabular (MT) stromatoporoids. **B)** Large fasciculate rugosan (Rg), slightly toppled, in laminar stromatoroid dominated facies. **C)** Typical stromatoporoid-coral reef front facies, with mix of laminar, tabular, and massive tabular (MT) stromatoporoids. Portion of staff=1.15 m. **D)** Anastomosing tabular stromatoporoid. **E)** Large boulder in collapsed area showing underside of laminar whorled stromatoporoid. Note conical base (B) from which stromatoporoid grew and concentric rings on underside which is heavily encrusted by spirorbids (not visible at this scale). Recessive weathering green mud (Md) responsible for exposing delicate features of stromatoporoid plate preserved in several areas. **F)** Massive concave-up tabular stromatoporoid. **G)** Expanding-upwards conical stromatoporoid. Shaped much like a "martini-glass" the front side is partly broken away exposing the inside part of the cone that accumulated sediment. Right side also broken away. Note surrounding tabular and laminar stromatoporoids. **H)** Non-enveloping high-domal stromatoporoid buried in bioclastic sediment.

Fig. 8. Whorled-laminar and laminar stromatoporoid growth form. **A)** Sectioned specimen (unidentified species of *Stachyodes* similar to *S. australe*) showing basal plate overlain by a series of plates that splayed off from each other. Mammilated top surfaces of plates evident. Galleries between plates filled with wackestone to muddy packstone. Inset shows underside of sectioned specimen (arrow indicates location of cut) with concentric rings and conical base (B). Circled are encrusting spirorbids. **B)** Same species as in (A) but growing as laminar stromatoporoids over top of each other. Note mammillated surfaces. Terminal edge of upper stromatopoiroid (labelled "Edge") well preserved and indicates coenosteum had a circular shape.

Between the two stromatoporoids is 1-2 mm thick layer of green mud (MD) – most evident on

back side where part of plate was removed and specimen cut, but also partly preserved at the

Edge where not eroded. Presumably mud covered entire plates but has been eroded. Note

physical compaction cracks in the stromatoporoid plates filled with green mud.

Fig. 9. Stromatoporoids and encrusting organisms. **A)** Underside of boulder formed by whorled

laminar stromatoporoid. Conical base and concentric underside with digitate encrusting organism

(E) in lower left. Note residual green mud on plate. Increments on card = 1 cm. **B)** Close-up of

mammillated top surface of whorled laminar stromatoporoid with green mud across part of top

and filling compaction cracks. **C)** General view of large boulder formed of whorled-laminar

stromatoporoids overlapping with each other and subsequently compacted to form a deposit of

tightly packed plates. Some plates upside-down relative to others, indicated by mammillated

surfaces juxtaposed against undersides with concentric rings. Green mud remains in several

areas. Hammer in lower right corner for scale. **D)** Close-up of overlapping disc-like laminar

whorled stromatoporoids viewed from underside. Green mud (arrows) in several areas. **E)**

Close-up of mammillated surface with compaction cracks. Location of photo indicated by box in

(C). **F)** Encrusting *Aulopora* on underside of plate. **G)** Unidentified encrusting digitate fossil

common on undersides of plates especially near their bases. **H)** Overlapping specimens of

massive tabular *Actinostroma clathratum* in reef front. Note surrounding muddy rudstone with

laminar stromatoporoid fragments.

Fig. 10. Wavy-laminated stromatolite capping laminar stromatoporoids. Note stromatolite

considerably thicker than underlying plates.

Fig. 11. Paleo-valley and fore-reef exposures. **A)** Laminar stromatoporoid rudstone. **B)** Dipping flank of reef-front at the transition from reef-front to paleo-valley. Laminar stromatoporoids and corals dominate. **C)** Laminar and tabular stromatoporoids with argillaceous matrix dominate the reef front in the deeper parts of reef front before bioherms develop. **D)** Massive whorled laminar stromatoporoid in laminar and tabular stromatoporoid-coral accumulation with argillaceous matrix. Note massive tabular stromatoporoid growing across its top. **E)** Argillaceous bedded matrix with abundant coral and stromatoporoid fragments in bioherm. **F)** Paleo-valley bioherms with onlapping (white arrows) thin-bedded bioturbated crinoid wackestone deposits assigned to the fore-reef. Punctuating the fore-reef succession is a resistant bed (RB) of stromatoporoid-coral debris. Overlying succession consists of thin-bedded bioturbated fore-reef deposits assigned to the transgressive systems tract. **G)** Transition (staff points to contact; highlighted with dashed black line) from thick bedded reef front deposits (stromatoporoid-coral accumulation facies) to thin and medium bedded bioturbated and crinoidal fore-reef deposits. A resistant bed of stromatoporoid-coral debris punctuates the succession. Staff = 1.5 m. **H)** Large fasciculate rugosan encased in fore-reef muddy crinoidal wackestone deposits. Coral head may be in place. Increments on staff=10 cm.

Fig. 12. Mud mound locality. **A)** General view of one of several mounds that are exposed. **B)** Two mounds exposed. At the bottom of lower left mound, arrow marks contact between light coloured lagoon deposits and overlying mound. **C)** Close-up of a mound's flank. Steeply dipping note the shingled appearance of the mound layers. These may mark the position of inter-mound muddy sediment deposited against the mound at different stages of its accumulation. Inter-mound sediment has been eroded. **D)** Large fracture set has exposed the inner stratigraphy of
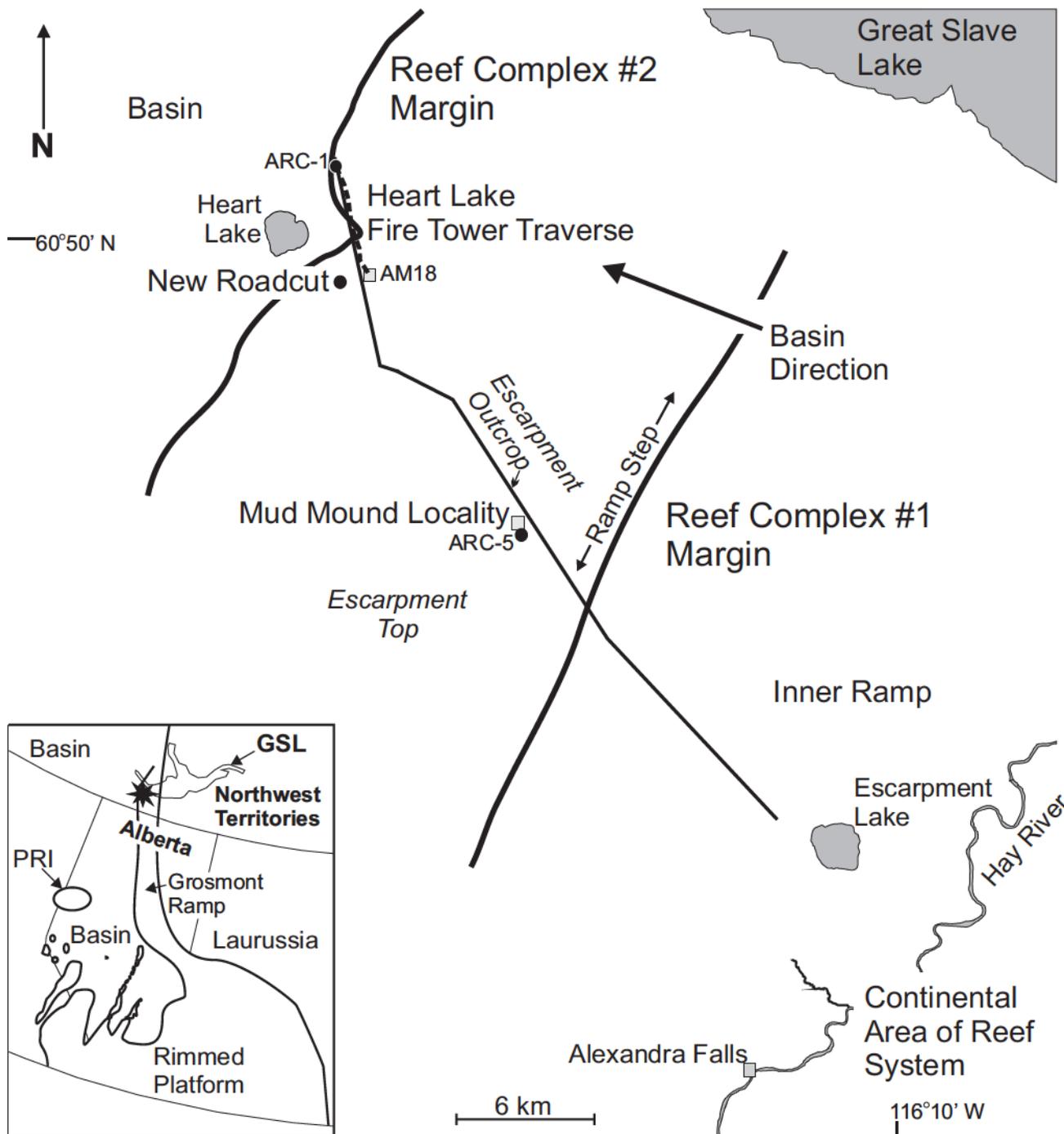
one mound that is part of coalesced mounds. Layers of the mound are stacked but do not

envelope older layers. **E)** Close-up of anastomosing laminar stromatoporoids that bound the

sediment to form the mounds. Lens cap = 5.5 cm. **F)** Thin section photomicrograph of organic

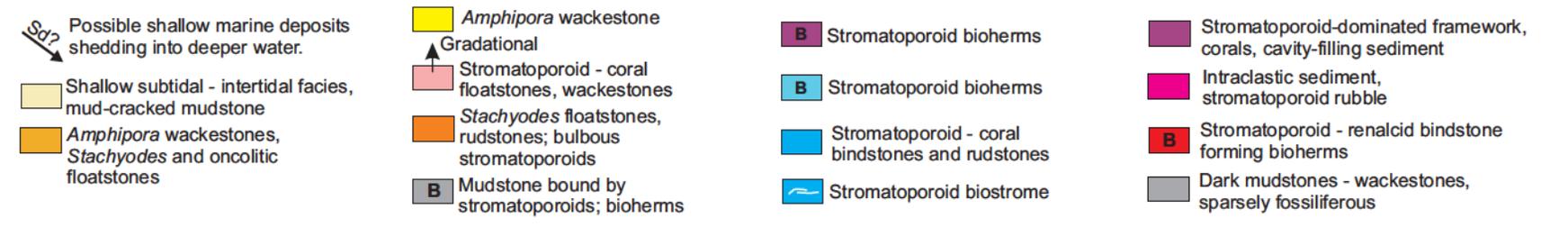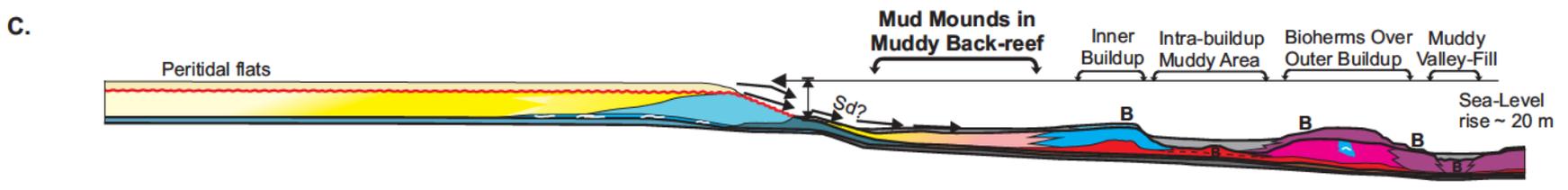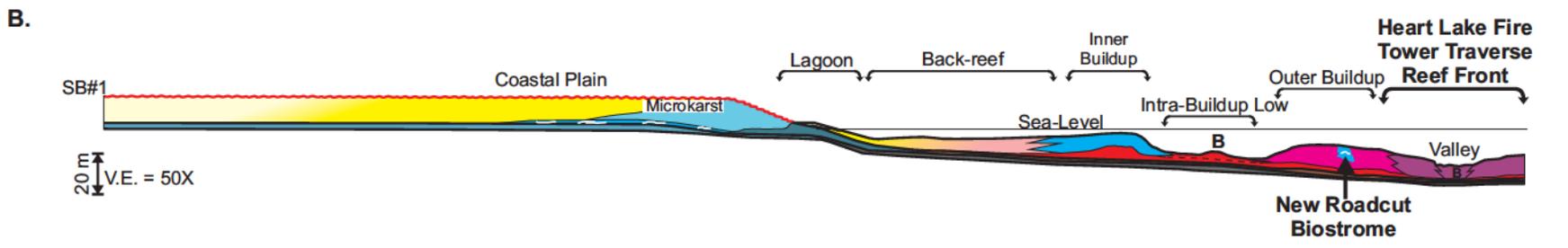rich muddy wackestone that is bound between laminar stromatoporoid plates.
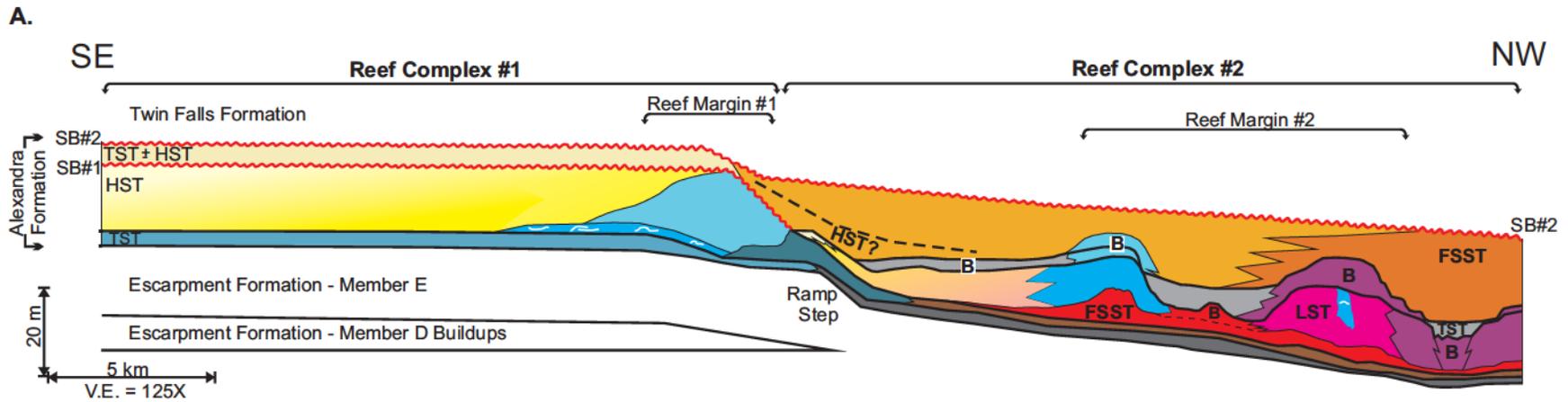
Fig. 13. Reconstruction of Alexandra Reef Complex #2 reef margin. **A)** Outer buildup (reef

core) of the margin dominated by bioclastic rubble and narrow bodies of laminar stromatoporoid

framestone. The reef front, which supplied most of the rubble that formed the Outer Buildup, has

the greatest amount of active reef growth and is mostly below fair-weather wave base. Parts of

reef front may be biohermal, especially deeper parts. **B)** Close-up of laminar stromatoporoid

framestone from edge of biostrome where bioclastic sediment is bound in framestone. Location

of cartoon (B) shown in A. **C)** Close-up of outer reef front dominated by whorled laminar,

massive tabular and massive concave-up tabular stromatoporoids and corals. Location of cartoon

(C) shown in A.

Fig. 14. Classification scheme for Devonian reef fabrics. Plotted is the distribution of different

reef fabrics known from Frasnian reefs in the southern part of the Northwest Territories.

Fig. 15. Commonly applied facies models for Devonian reef systems. **A)** High-energy facies

model composed from Playford (1980); Stokes and Wendte (1982) and Machel and Hunter

(1994) models. **B)** Low-energy model composed from Wilson (1974), James and Bourque

(1992), and the reconstruction of Reef Complex #2 in the Alexandra Reef System.

A.

SE — Reef Complex #1 — Reef Complex #2 — NW

Reef Margin #1

Reef Margin #2

Twin Falls Formation

SB#2
SB#1
Alexandra Formation
TST ± HST
HST
TST

HST?

SB#2

B

B

B

FSST

B

LST

FSST

B

B

TST

Escarpment Formation - Member E

Escarpment Formation - Member D Buildups

Ramp Step

20 m

5 km
V.E. = 125X

B.

Heart Lake Fire Tower Traverse Reef Front

SB#1

Coastal Plain

Lagoon　Back-reef　Inner Buildup

Outer Buildup

Intra-Buildup Low

Microkarst

Sea-Level

B

B

Valley

New Roadcut Biostrome

20 m　V.E. = 50X

C.

Mud Mounds in Muddy Back-reef

Inner Buildup　Intra-buildup Muddy Area　Bioherms Over Outer Buildup　Muddy Valley-Fill

Peritidal flats

Sd?

B

B

B

Sea-Level rise ~ 20 m

Legend:

Sd? — Possible shallow marine deposits shedding into deeper water.

Shallow subtidal - intertidal facies, mud-cracked mudstone

Amphipora wackestones, Stachyodes and oncolitic floatstones

Amphipora wackestone

Gradational

Stromatoporoid - coral floatstones, wackestones

Stachyodes floatstones, rudstones; bulbous stromatoporoids

B — Mudstone bound by stromatoporoids; bioherms

B — Stromatoporoid bioherms

B — Stromatoporoid bioherms

Stromatoporoid - coral bindstones and rudstones

Stromatoporoid biostrome

Stromatoporoid-dominated framework, corals, cavity-filling sediment

Intraclastic sediment, stromatoporoid rubble

B — Stromatoporoid - renalcid bindstone forming bioherms

Dark mudstones - wackestones, sparsely fossiliferous

Low Profile Stromatoporoid Growth Forms

Laminar

Tabular

Massive Tabular
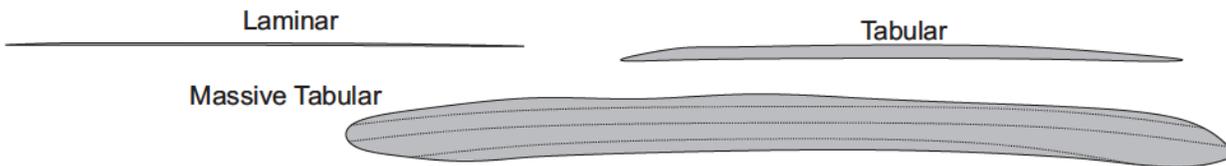
Anastamosing Low Profile Growth Forms

Laminar-Anastamosing

Tabular-Anastamosing

Whorled Concave-Up Growth Forms

Whorled Laminar

Whorled Massive

Expanded-Conical

A

A

A'

Cross-Section

A'

Domal Growth Forms

High-Domal
(Non-enveloping)

Low-Domal (Enveloping)
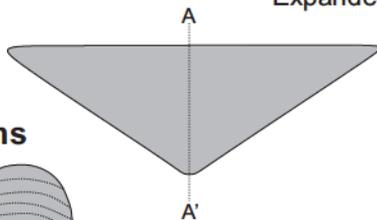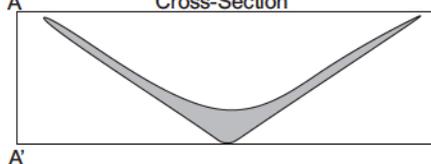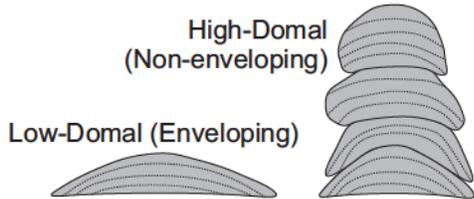
Platy-Multicolumnar Growth Form

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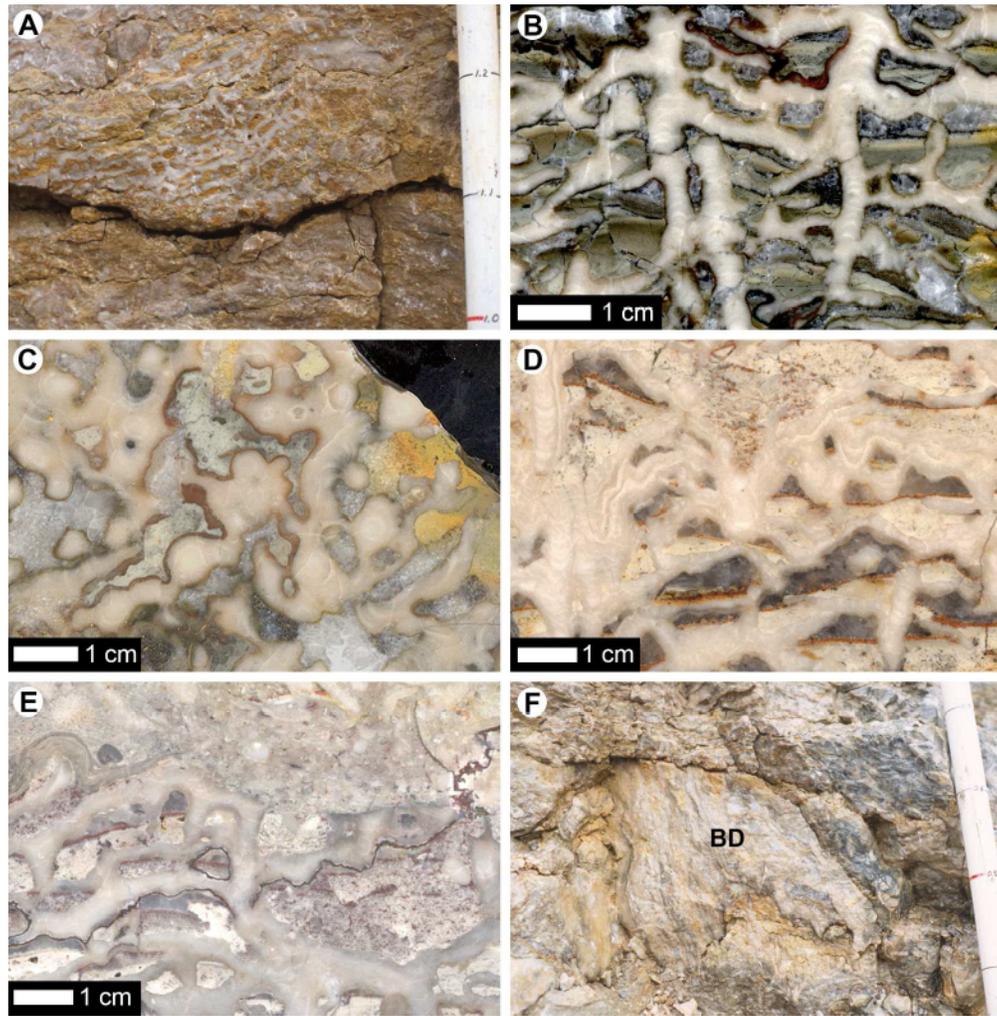

Figure 4
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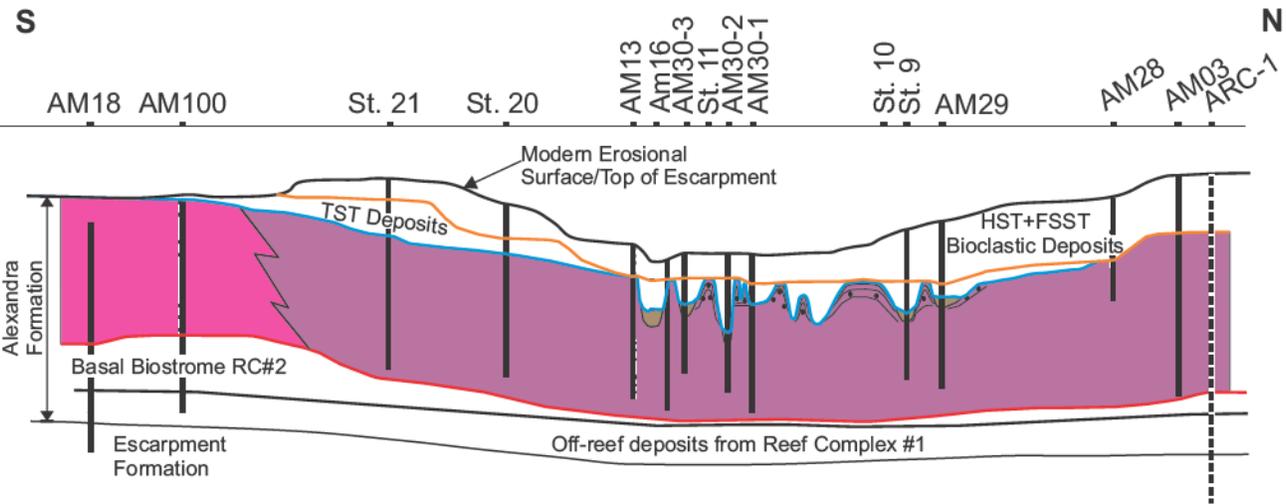
Figure 5
170x172mm (300 x 300 DPI)

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A

B

South Part of Traverse   **Paleo-Valley Area**   **North Part of Traverse**

S   N

AM13
Am16
AM30-3
St. 11
AM30-2
AM30-1

St. 10
St. 9

AM18   AM100   St. 21   St. 20   AM29   AM28   AM03   ARC-1

Modern Erosional
Surface/Top of Escarpment

TST Deposits

HST+FSST
Bioclastic Deposits

Alexandra
Formation

Basal Biostrome RC#2

Escarpment
Formation

Off-reef deposits from Reef Complex #1

10 m

50X VE

500 m

Key Surfaces

Measured
Section

Drilled
Core

Basal Surface Forced Regression (truncates
Transgressive Systems Tract deposits)

Surface of Maximum Regression
(Top of Lowstand Systems Tract)

Base of RC#2 Lowstand Systems Tract

Facies Associations

Fore-Reef Facies Association

Reef-Front Facies Association

Outer Buildup (Reef Core)
Facies Association

Figure 7
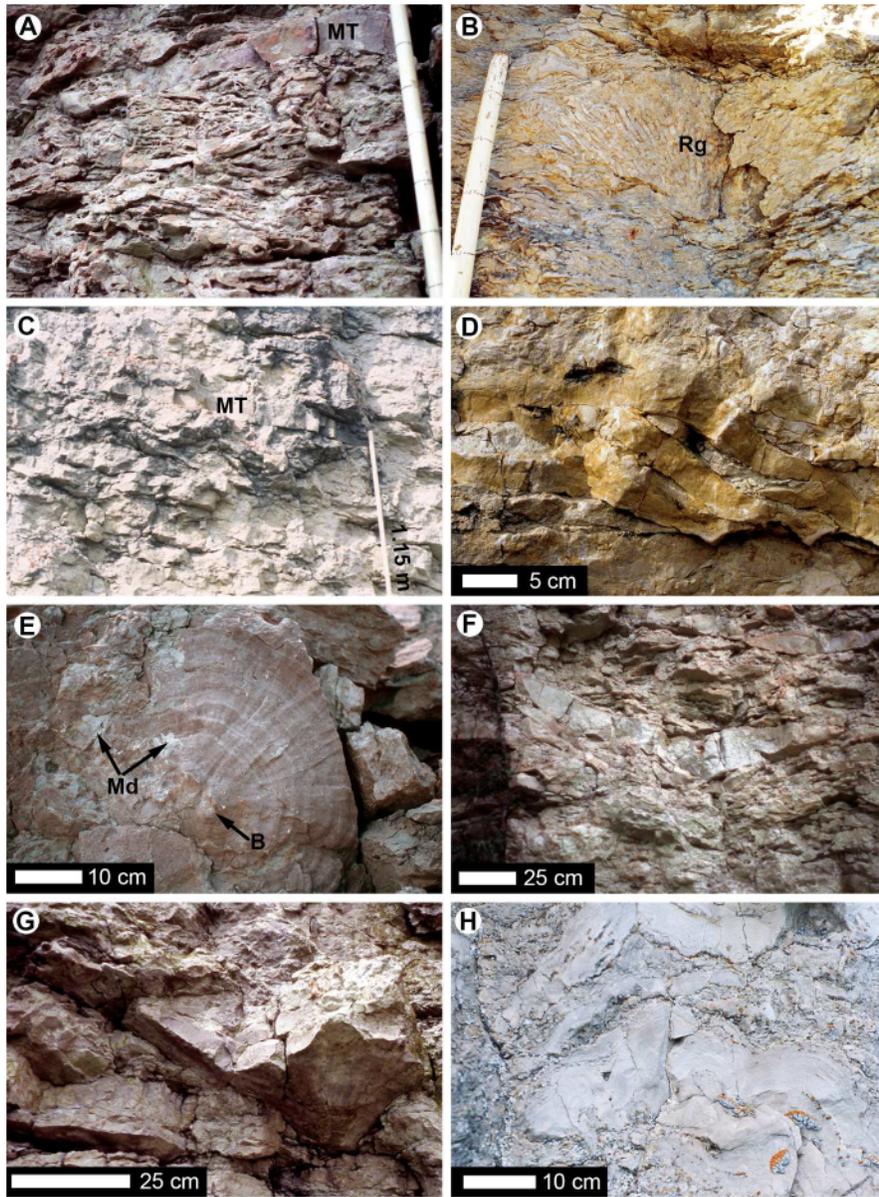170x230mm (300 x 300 DPI)

Figure 8
170x167mm (300 x 300 DPI)

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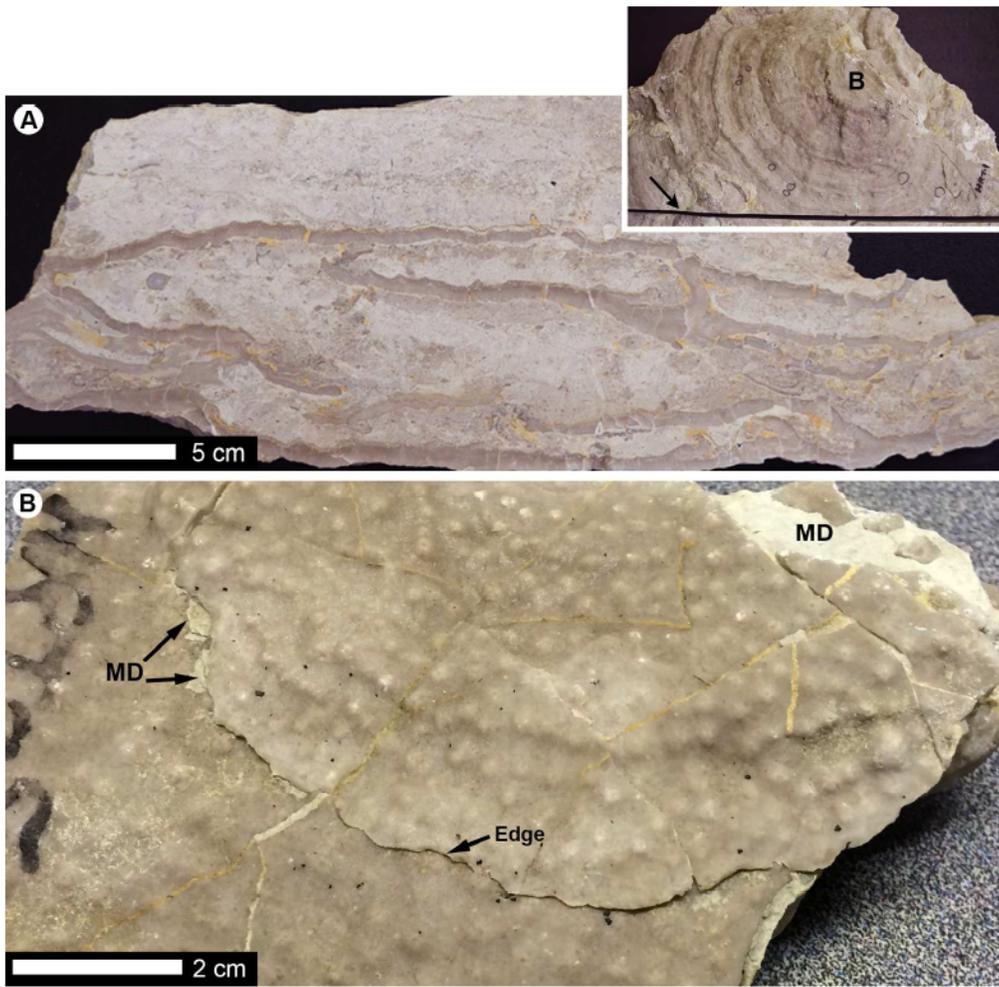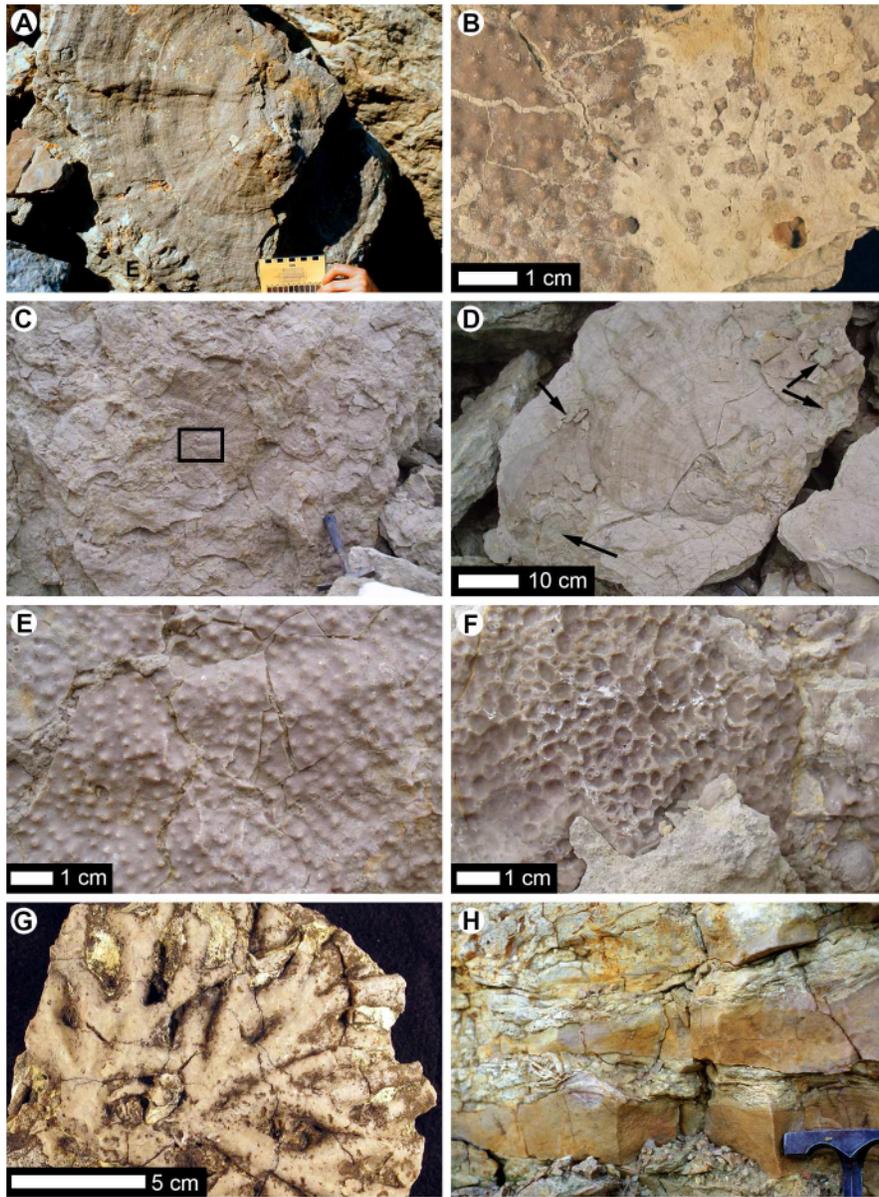41
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Figure 9
170x230mm (300 x 300 DPI)

Figure 10
109x69mm (300 x 300 DPI)

Figure 11
170x230mm (300 x 300 DPI)

Figure 12
170x162mm (300 x 300 DPI)

A

Sea-Level

Highest Energy

Above FWWB

Below FWWB

20-25 m Water Depth

>25 m

Reef Core

Reef Front

Fore-Reef

1-4 km

B

1 m

C

1 m

Bioclastic rubble stabilized by microbialite

Framestone of encrusting laminar stromatoporoids

Stromatoporoid-Coral-Microbial deposits and/or Stromatoporoid-Coral-Sediment deposits

Stromatoporoid-coral bioherms

Crinoid fields, isolated rugosans, muddy substrate

Debris aprons

Stromatoporoids

Massive concave-up tabular

Laminar or Tabular

Whorled laminar

Domal

Stachyodes/Thamnopora

Massive Corals

Fasciculate

Domal (*Phillipsastrea*, *Alveolites*)

Sediment and/or microbialite

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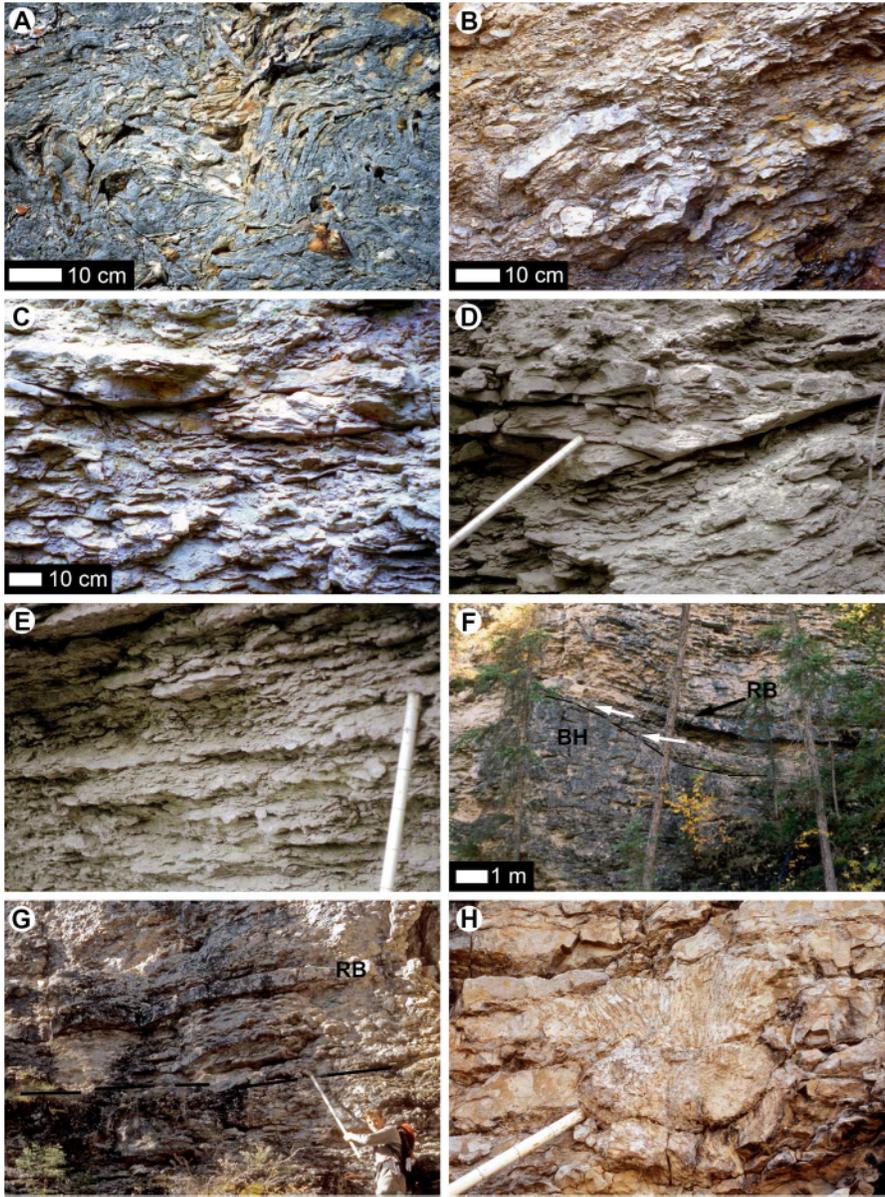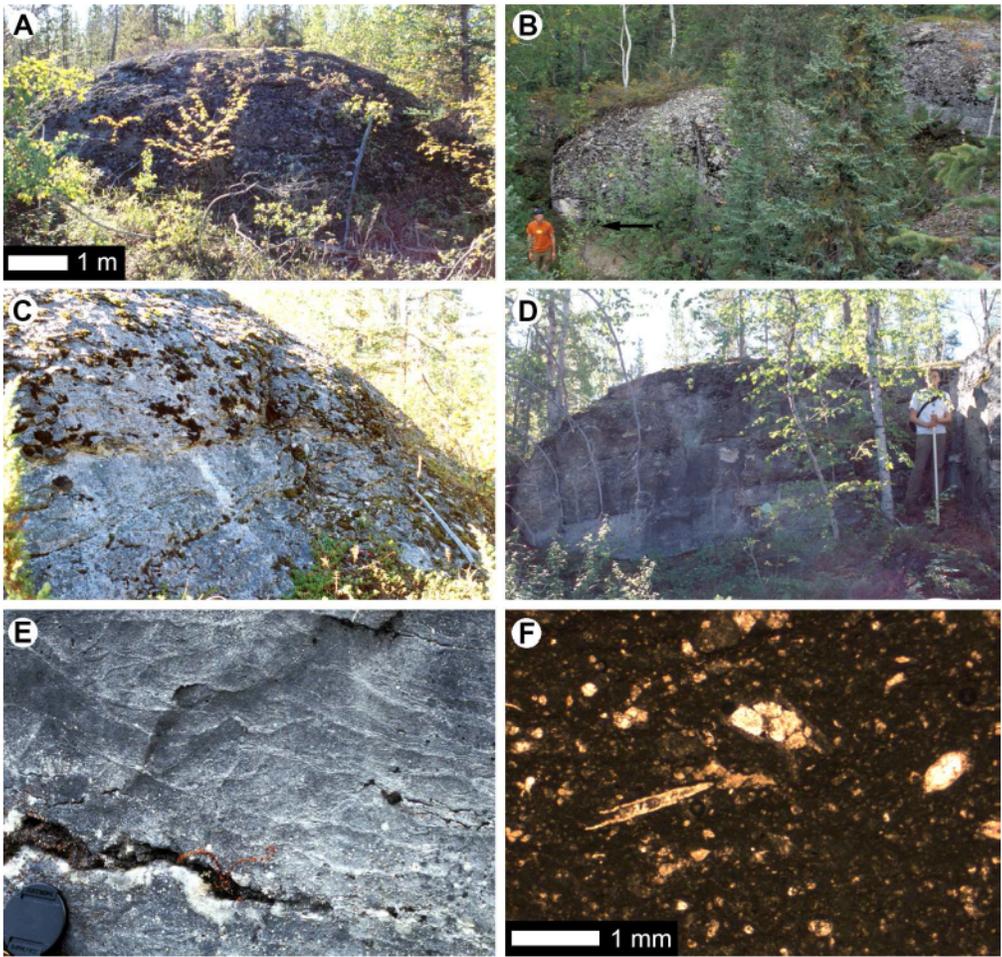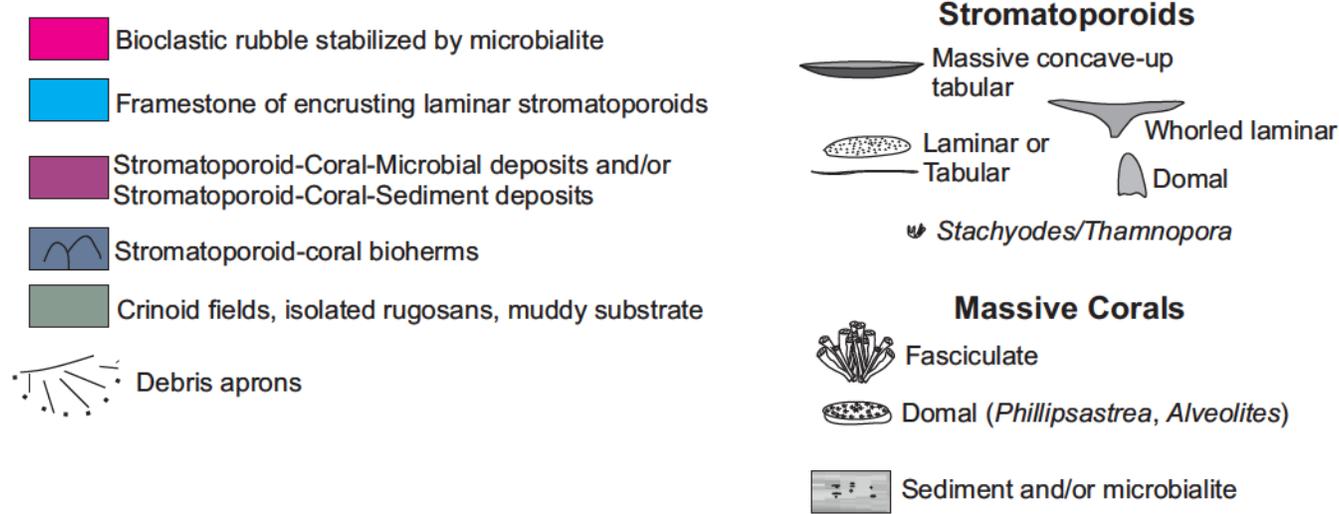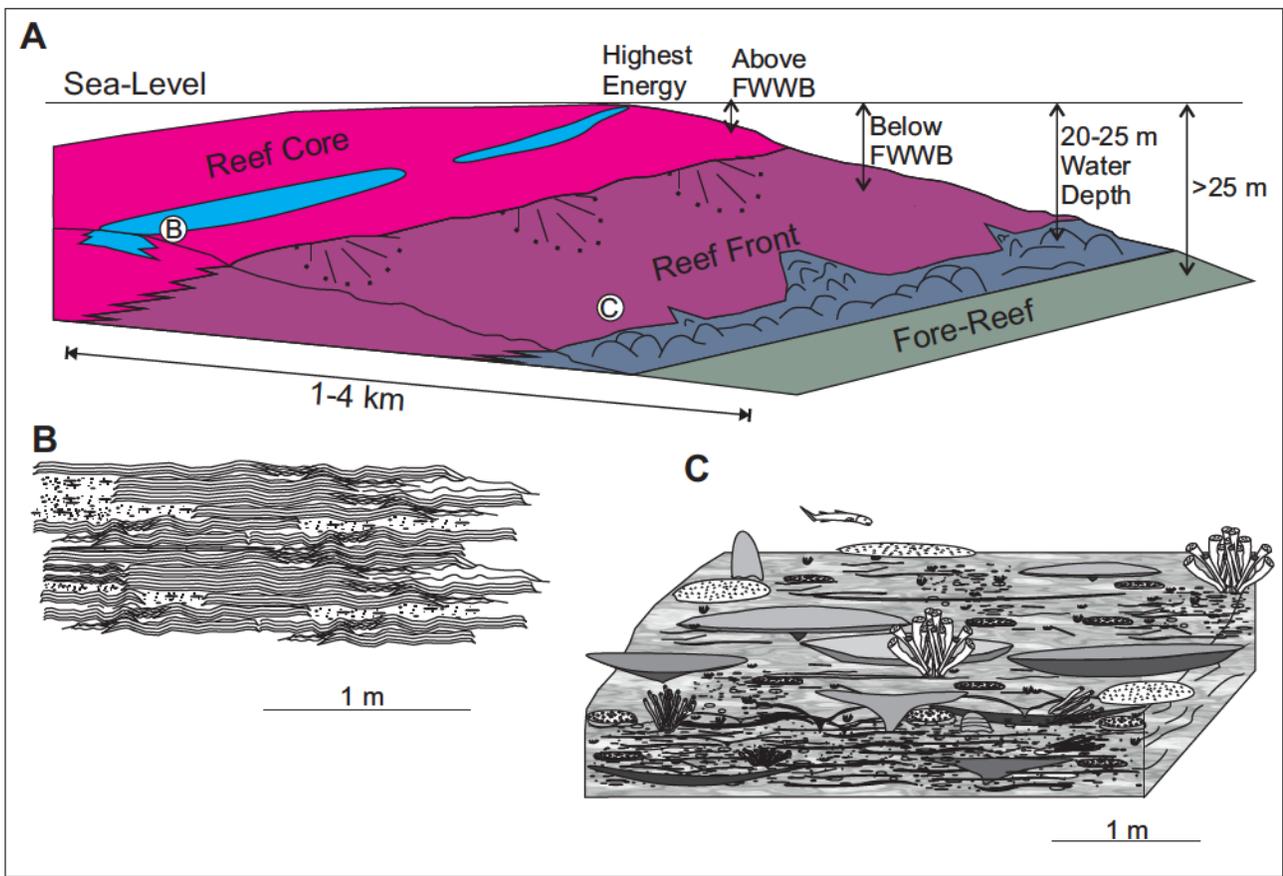41
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AXRS RC#2_FSST
AXRS RC#2_LST
Jean-Marie Member Reefs

Metazoan-Microbial

**Metazoan
Dominated**

Devonian
Reef Fabrics

**Sediment-
Laden Metazoan**

AXRS RC#2 NRC Biostrome
Twin Falls Fm. Patch Reefs

**Metazoan-
Marine Cement**

AXRS RC#1
AXRS RC#2_TST+HST
AXRS RC#2_FSST2
Kakisa Fm. Reef Margin

Kakisa Fm. Biostromes

Stratigraphic Order

Latest Frasnian   Kakisa Fm. Biostromes
                    Kakisa Fm. Reef Margin
                    Jean-Marie Member Reefs
                    Twin Falls Fm. Patch Reefs
Mid-Frasnian   Alexandra Reef Complex #2
                    Alexandra Reef Complex #1

A

Flat top with Patch Reefs and Sands

Narrow Zone of Active Reef

Broad Foreslope Sand and Debris to Nodular Mudstones

Laminites

Sea-Level

Back Reef

Reef Core

Reef Front

FWWB ~10m

Maximum Energy

Foreslope

Floor

>30 m

300-500 m

B

Sloping to Flat Top with Patch Reefs and Sands

Broad Zone of Sand, Patch Reefs, Ribbon-like Framestone Bodies

Broad Zone of Active Reef/Bioherms that Extend Below FWWB

Highest Energy

Above FWWB

Sea-Level

Below FWWB

20-25 m Water Depth

>25 m

Reef Front

Fore-Reef

1-4 km

Table I. Devonian Reef Facies Models

Model	Zone of Active Reef Growth	Key Reef Margin Facies	Ability to resist high wave energy	Margin Width	Platform Geometry at/near margin
High-energy model	All above fair-weather wave base; into maximum turbulence	Framestone*, boundstone, bioclastic rudstones and sediment	High	Narrow, may only be a few hundred metres wide	Flat top, steep and potentially high-relief margin
Low-energy model	Above and below fair-weather wave base; not into maximum turbulence	Framestone*, boundstone, bioclastic rudstones and sediment	Low to moderate	Broad, may cover 1-4 kilometres	Sloping over broad area, probably mounded in deeper areas, may be distally steepened

*Framestone may not be present or volumetrically a minor facies

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Table II. Comparison of classification schemes for reef fabric. Only MacNeil and Jones (this paper) is specific to Devonian reef systems.

Scheme	Fabric 1	Fabric 2	Fabric 3	Fabric 4	Notes
MacNeil and Jones, this paper	Metazoan-Microbial	Sediment-Laden Metazoan	Metazoan-Marine Cement	Metazoan Dominated	Scheme based on biogenic/abiogenic consortia, less emphasis on texture
James and Wood (2010)	Skeletal-Microbial, Microbial	N/A	Skeletal Reef	Skeletal Reef	Scheme based on biogenic/abiogenic consortia, less emphasis on texture. Noted these are simple endmembers
Dunham (1962) modified by Embry and Klovan (1971)	Boundstone	Bindstone, Bafflestone	Boundstone	Framestone	Scheme based on depositional texture; consideration of biogenic consortia implicit
Tsien (1981)	Biocementstone	Bafflestone, Bindstone, Coverstone	Coverstone	Framestone	Scheme based on texture and relationship between framebuilders and sediment, definition of reef