"Science, after all, operates both as a social enterprise and an intellectual adventure."

– S. J. Gould, 2000

University of Alberta

Sedimentology of the Late Devonian (Frasnian) Alexandra Reef System, Northwest Territories, Canada: New Insight to the Nature of Devonian Reefs

by

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ABSTRACT

The Alexandra Formation, exposed in the southern Northwest Territories of Canada, consists of limestones from a Late Devonian reef system. High-resolution sequence stratigraphic analysis of these deposits, based on integrated outcrop-core data, has delineated two reef complexes in the formation. Reef Complex #1 developed in an inner ramp area and Reef Complex #2 developed basinwards of Reef Complex #1, on the outer ramp, after a sea-level fall of ~ 17 m. A sequence boundary with palustrine deposits and microkarst separates the two reef complexes. The reef complexes had broad, low-relief profiles; they did not consist of narrow, wave-resistant margins with steep slopes. Reef Complex #2 was only able to develop after sea-level fell because the outer ramp provided a broad area of shallow marine environments conducive to new reef development.

Whereas the reef of Reef Complex #1 was dominated by stromatoporoids, the reef in the lower part of Reef Complex #2 was dominated by stromatoporoid-microbial deposits. Upwards, the microbial components decreased and eventually disappeared, such that the reef margin returned to a stromatoporoid-dominated status. The sequence stratigraphic framework of reef-facies variations in the Alexandra Reef System indicates that sea-level position and nutrient flux determined the types of reef-building communities that flourished. Stromatoporoid-dominated communities flourished in oligotrophic (nutrient deficient) environments and stromatoporoid-microbial communities flourished in mesotrophic (some nutrients available) environments. These variations indicate that traditional perspectives on Devonian reefs, which have generally treated them as static entities of oligotrophic regimes, are oversimplified.

The Alexandra Formation, and underlying Escarpment Formation, host the first known Devonian and North American occurrences of calcareous microfossils that belong to the family Ovummuridae. These include specimens of *Minourella gotlandica*, *Ovummurus duoportius,* and the new species *M. cameroni*. A new calcareous encrusting, reef-dwelling microorganism, *Devonoracemus cameroni*, that appears to have been some type of cyanobacterium, is also found in Reef Complex #2.

ACKNOWLEDGMENTS

A number of funding agencies, colleagues, and friends, who made my thesis research between the years of 2001 and 2006 possible, are gratefully thanked. Funding for my research was provided by the Canadian Circumpolar Institute of the University of Alberta, Northern Science Training Program of the Department of Indian Affairs and Northern Development, American Association of Petroleum Geologists Foundation, and the Natural Sciences and Engineering Research Council of Canada. Anadarko Canada and Canadian Natural Resources Ltd. also contributed much-needed funds to my drilling program.

The materials and data for all of my research originated from fieldwork conducted in the summer and falls of 2002 and 2003. From fighting the bull flies and mosquitoes out in the field to driving endless hours on the highway, this work was always made enjoyable by my field assistants – Neil McCallum, Ryan Ickert (aka The Monkey), Shane Krepakevich, Ray Wheeler, and Kelcey Stilwell. Back at the University of Alberta, Dr. Pat Cavell is thanked for finding storage facilities for > 1000 samples, many of which came in rather large sizes. Likewise, Don Resultay and Mark Labbe are thanked for preparing all of my thin sections – they did a very good job. George Braybrook is thanked for his professional operation of the Scanning Electron Microscope.

On the academic side, Dr. Brian Jones is thanked for years of technical advice and friendship. I am very thankful that he gave me the opportunity to explore Devonian carbonates, in addition to the geology of the Cayman Islands for a Masters thesis. Dr. Brian Chatterton and Dr. Charles Stelck, who sat as members on my thesis committee, are thanked for advice and numerous insightful discussions. Dr. Ross McLean is thanked for helping with the identification of rugose corals in my research materials, and sharing his knowledge of Devonian stratigraphy in the Northwest Territories.

I am also grateful for the numerous friends in Edmonton and at the University of Alberta who made my life as a graduate student truly enjoyable. We've had years of fun. Thanks especially go to Brian's other students – Lisa, Jenny, Rong-Yu, Sam, Morag, Sandy, Hilary, Dustin, Breanna, and Rachel – with whom I shared research facilities and numerous evenings. And lastly, I couldn't have done all of this without the love and endless support from Neil, my parents, and sisters. Thank-you.

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CHAPTER 1 – INTRODUCTION

INTRODUCTION

Almost all petroleum production from Devonian strata in the Western Canada Sedimentary Basin is from reef systems located in the subsurface of Alberta (Mossop and Shetsen 1994). Initial reserves of conventional oil in these deposits is ~ 1.5 billion m^3 and initial reserves of conventional natural gas in these deposits is ~ 716 billion m^3 (Alberta Energy and Utility Board 2005). From these initial reserves, 72 million m^3 of oil and 115 billion m^3 of natural gas remain to be exploited (Alberta Energy and Utility Board 2005). In this regard, the geology of these Devonian reef systems has, and continues to be, of great economic importance to Alberta and Canada.

Despite the economic importance of Devonian reefs in western Canada, many stratigraphic and sedimentary aspects of these systems are enigmatic (Mountjoy 1980; Moore 1989; Kiessling et al. 1999) because studies of the subsurface reefs have (1) been restricted to geophysical methods such as electric logs and seismic surveys with limited resolution, and cored intervals from widely spaced wells, (2) commonly been limited by extensive and destructive dolomitization, and (3) often focussed on only the specific facies from which petroleum is being produced. Studies of subsurface-equivalent deposits in the Rocky Mountains have been limited by tectonic deformation, variable to extensive dolomitization of original textures and fossils, and the sheer size of the mountains that tend to preclude up-close examination. Thus, despite an extensive volume of research that catalogues the biotic composition and different facies of Devonian reefs in western Canada, little is known about the stratigraphic architecture of their facies associations and the nature of their depositional environments (Mountjoy 1980; Moore 1989; Kiessling et al. 1999). As noted by Machel and Hunter (1994), existing facies models for these reefs are fairly generalized and do not incorporate some of the basic concepts important to carbonate sedimentology.

The Late Devonian (mid-Frasnian) Alexandra Formation, located in the southern Northwest Territories of Canada (Fig. 1-1), consists of stromatoporoid-dominated reef and associated carbonate platform deposits that are exposed at surface over a distance of 46 km. As part of the Western Canada Sedimentary Basin, these deposits (< 40 m thick) are time-equivalent to many of the subsurface reefs in Alberta that host significant oil and gas accumulations (e.g., upper Leduc Formation and Grosmont Formation equivalents). Strata of the Alexandra Formation, however, have not been deformed (beyond minor normal faults) or significantly compacted, and are not dolomitized. The Alexandra Formation therefore presents a unique opportunity to gain important insight to the nature of Devonian reefs in the Western Canada Sedimentary Basin and to advance our understanding of Devonian depositional systems.

STUDY AREA AND METHODS

The Alexandra Formation is exposed in the southern part of the Northwest Territories in two areas; the Hay River gorge between Alexandra Falls and Escarpment Creek and along an escarpment that extends from Escarpment Lake to Heart Lake (Fig. 1-1 and Fig. 1-2A-C). The region is readily accessible because the Mackenzie Highway runs along the top of the escarpment near its edge and Alexandra Falls, as well as Louise Falls and Escarpment Creek, are Territorial Parks with various camping and day-use facilities.

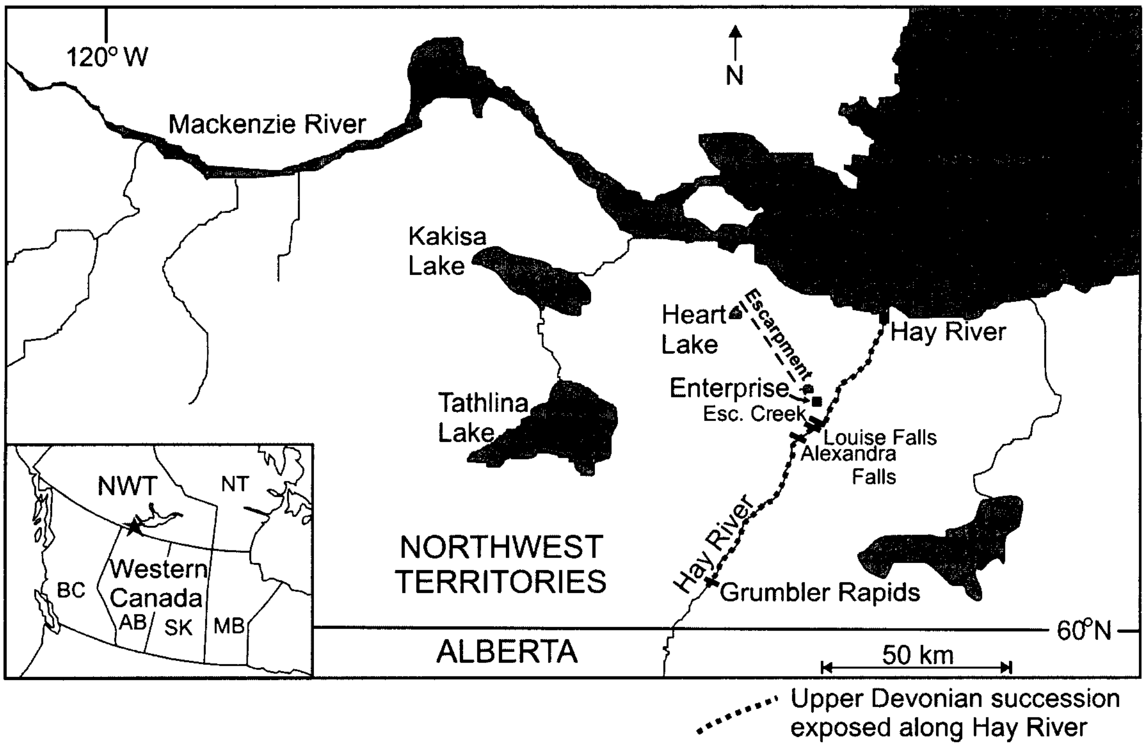

Figure 1-1. Map of study region. Inset shows study region (star) in context of western Canada.

Enterprise is the nearest community, and the nearby town of Hay River has an airport. A research licence issued by the Government of the Northwest Territories regulates study in this region.

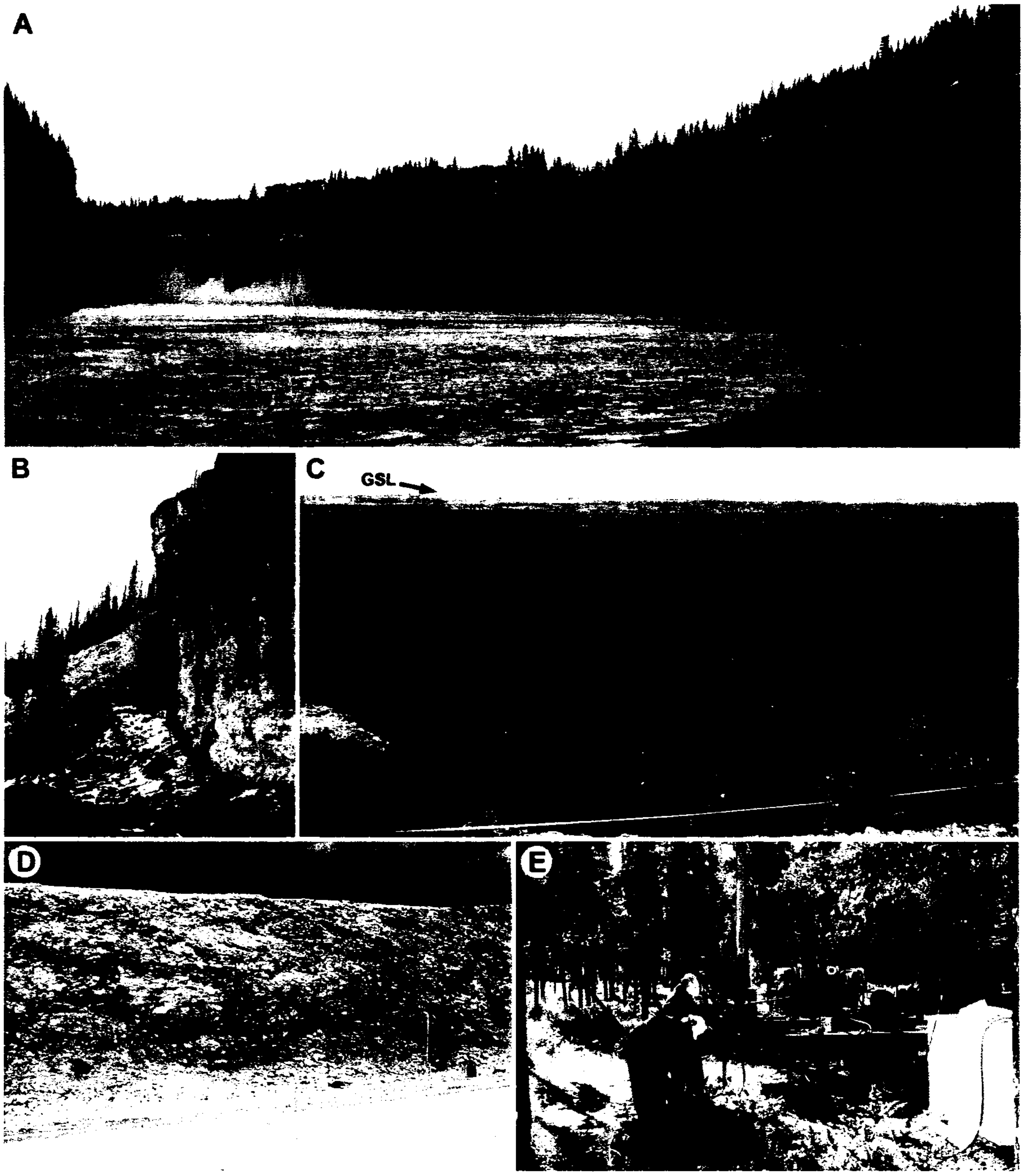

Figure 1-2. General views of study area. **A)** Alexandra Falls on Hay River. Walls of gorge formed of strata that belong mostly to the Alexandra Formation. View to southwest, cliff height ~ 35 m. **B)** Face of escarpment near Heart Lake. Cliff height ~ 20 m. **C)** View to northeast from top of escarpment near Heart Lake. Great Slave Lake (GSL), ~ 20 km away, barely visible. **D)** Study of relatively unaltered limestone at a roadcut on Mackenzie Highway. Locality AM09. **E)** Drill operation at top of escarpment near Heart Lake in September, 2003. Part of core ARC-1 being extracted from core tube by drillers.

Strata of the Alexandra Formation exposed along Hay River show little lateral variation because the exposure-trend is near-parallel to depositional strike. Strata that form the escarpment, however, are oblique to near-perpendicular to depositional strike, thus exposing facies from across the complete span of lagoon to fore-reef environments. A second lower escarpment extends from the east side of Escarpment Lake running parallel to the main escarpment for ~ 15 km before ending (Fig. 1-3). This lesser escarpment is formed of biostromal limestones that are part of the underlying Escarpment Formation (Jamieson 1967; Hadley 1987).

From forty-seven localities along the main escarpment, five roadcuts on the Mackenzie Highway (Fig. 1-2D), a quarry, and three localities along Hay River, eighty stratigraphic sections through different parts of the Alexandra Formation were measured in the summers of 2002 and 2003 (Fig. 1-3). Sections less than a few meters thick were measured with a Jacob's staff whereas sections with high vertical faces were measured by lowering a tape measure from the top, and ropes and harnesses with ascension devices were used to move up the section, record data, and collect samples. Oriented samples (n = 827) were collected from measured sections at one meter intervals. Locally, denser sampling was conducted in order to document specific field observations. In September of 2003, seven continuous cores were also drilled at specific localities that were deemed to be of stratigraphic and sedimentary importance (Fig. 1-2E and Fig. 1-3). These supplemented four continuous cores previously drilled by Cominco that were donated to B. Jones. The outcrop/roadcut/quarry data, 827 rock samples, 11 continuous cores, 362 field photographs, and 294 large (5 x 7.5 cm) thin sections formed the database for this study.

PREVIOUS RESEARCH

The earliest geological reconnaissance of the Hay River region was conducted by R.G. McConnell who reached Alexandra Falls in 1887. McConnell (1891) concluded that the strata exposed along Hay River are of Devonian age. In 1917 A.E. Cameron conducted the first detailed geological study of the Devonian succession exposed along Hay River, and concluded on the basis of its paleontology that it belonged to the Upper Devonian (Cameron 1921). Cameron divided this succession, which extends from Grumbler Rapids

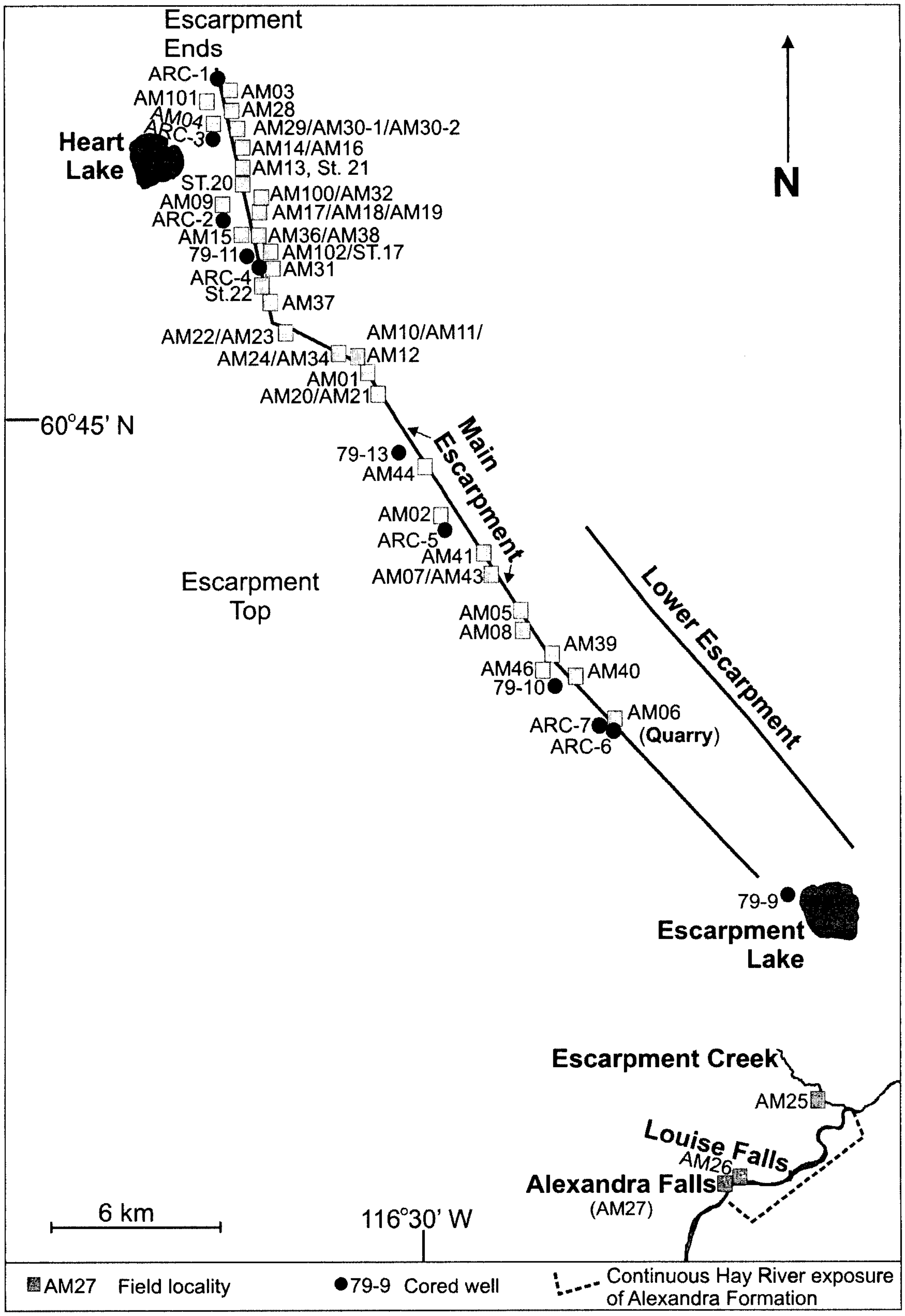

Figure 1-3. Study area map.

near the Northwest Territories–Alberta border to near the delta where Hay River drains into Great Slave Lake (Fig. 1-1), into an upper member, termed the Hay River Limestones, and a lower member, termed the Hay River Shales (Fig. 1-4). The boundary between these two members was placed at the base of the limestones that form Louise Falls, with the Hay River Limestones being the succession from the base of Louise Falls to Grumbler Rapids.

C.H. Crickmay subsequently studied the geology and paleontology of the Hay River region in the early 1950s and designated the limestone succession that composes Louise Falls and Alexandra Falls as the Alexandra Formation (Crickmay 1953). Limestone deposits above Alexandra Falls were named the Grumbler Formation and the name Hay River Formation was used for the shale deposits below the base of Louise Falls (Fig. 1-4). Crickmay (1957) revised these assignments and provided formal type-section descriptions for the different formations (Fig. 1-4). The type section for the Alexandra Formation (41.5 m thick) was defined as the "mostly resistant" limestone unit exposed from ~600 m upstream of Alexandra Falls (thickness of 6.7 m) to the top of a sandstone-siltstone unit (1.8 m thick) at the base of Alexandra Falls (36.6 m high). Underlying strata were placed in the Hay River Formation (Crickmay 1957).

R.J.W. Douglas, as an officer of the Geological Survey of Canada, published the first detailed geological map of the Hay River – Mackenzie River regions in 1959 (a slightly revised version was published in 1973). This was the first map that noted the main and lesser escarpments of Upper Devonian limestones that are located between Escarpment Lake and Heart Lake (Fig. 1-3). Douglas (1959) assigned these limestones to the Hay River Formation and correlated both of them to the limestones that form Louise Falls on Hay River. Douglas (1959) retained the use of the Alexandra Formation (Fig. 1-4), as designated by Crickmay (1957), but lowered its base to include 3.7 m of calcareous sandstones and dolostones that were previously excluded by Crickmay (1957).

H.R. Belyea and D.J. McLaren, also with the Geological Survey of Canada, published a detailed study in 1962 on the geology in the region from Mackenzie River in the Northwest Territories south to the latitude of the Peace River Arch in Alberta. This study integrated all previous studies with new outcrop and subsurface data, and presented a significantly revised stratigraphic column for the region (Fig. 1-4). For the Devonian strata exposed along Hay River, Belyea and McLaren (1962) maintained the top of the Hay River Formation as previously defined by Crickmay (1957), but extended it down to the top of Middle Devonian limestone identified in wells from the region (total thickness of 396 m). Belyea and McLaren (1962) recognized two members in the Hay River Formation; an informally-designated lower member of mostly shales and an upper member named the Escarpment Member. The Escarpment Member includes the biostromal limestones that form Louise Falls and the reefal/biostromal limestones that form the two escarpments to the northwest (consistent with the previous correlations of Douglas (1959)).

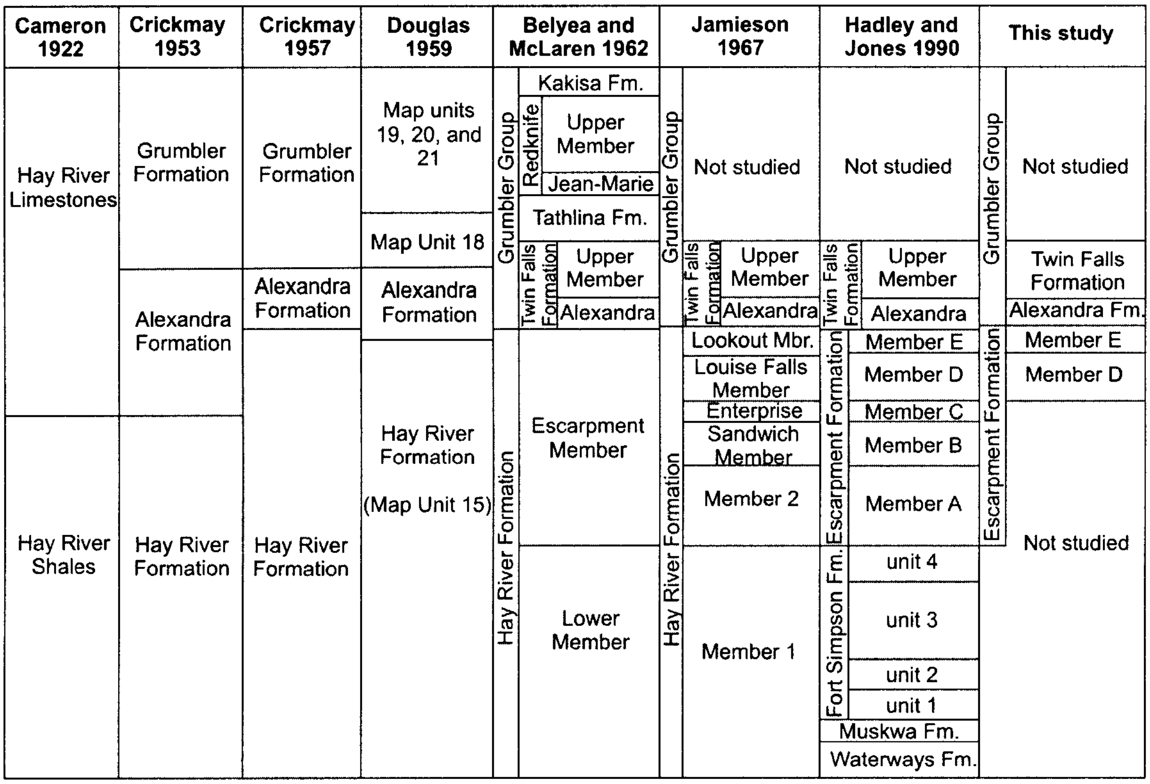

Figure 1-4. Stratigraphic columns for Upper Devonian strata in study region.

With new data from several wells drilled in the southern Northwest Territories, Belyea and McLaren (1962) further redefined the stratigraphic divisions of Crickmay (1957) by reducing the Alexandra Formation to member status and placing it in a new formation named the Twin Falls Formation, and elevating the Grumbler Formation to group status (Fig. 1-4). The Alexandra Formation was reduced to member status because it was considered to only be a local facies, and its uppermost 11.2 m of strata were reassigned to the overlying, informally-designated, upper member of the Twin Falls Formation. The Grumbler Group was defined to include all Upper Devonian strata of the Frasnian stage above the Hay River Formation, and four new formations were named; the Twin Falls Formation at the base, overlain successively by the Tathlina Formation, Redknife Formation, and Kakisa Formation. The Frasnian-Famennian boundary marks the top of the Kakisa Formation.

With encouragement and support from the Geological Survey of Canada, E.R. Jamieson undertook study of the Alexandra Member in the early 1960s for a PhD thesis at the University of Reading in England. Jamieson conducted the first intensive study of the strata exposed along Hay River between Escarpment Creek (then named Twin Falls Creek) and Alexandra Falls, and in the main escarpment between Escarpment Lake and Heart Lake. Jamieson eliminated the Escarpment Member of Belyea and McLaren (1962) and divided the Hay River Formation into six informal members (Fig. 1-4). In contrast to the previous correlations of Belyea and McLaren (1962) and Douglas (1959), Jamieson also determined that only the lower escarpment limestones (Fig. 1-3) correlate with the biostromal limestones that form Louise Falls (Hay River Formation); the main escarpment limestones correlate with the limestones that form Alexandra Falls of the Alexandra Member. This was based on the following:

1. *Amphipora*, common in the main escarpment, are not found in the limestones that form Louise Falls. *Amphipora*, however, are abundant in the limestones of the Alexandra Member that form Alexandra Falls.
2. Dr. D. McLaren indicated as a personal communication that the brachiopod *Adolfia* first appears in the Alexandra Member limestones along Hay River. This brachiopod was also found in the limestones of the main escarpment, supporting its correlation to the Alexandra Member.
3. Regional topography. Louise Falls and Alexandra Falls are formed by two resistant bodies of limestone that are separated by recessive weathering shales. The most parsimonious explanation for regional topography is that the limestones that form Louise Falls correlate with the limestones that form the lower escarpment and the thicker package of limestones that form Alexandra Falls correlate with the main,

upper escarpment. Erosion of the shales between the two limestone units has formed the depression between the two escarpments filled by Escarpment Lake.

Thus, Jamieson (1967) used lithostratigraphy, biostratigraphy, and topography to conclude that the Alexandra Member along Hay River correlated with the main, upper escarpment to the northwest, and that it was more significant than a local facies (cf. Belyea and McLaren 1962). Also, Jamieson (1967) redefined the base of the Alexandra Member to be at the base of coral-stromatoporoid limestones that directly overlie quartzose limestones of the uppermost Hay River Formation. This contact, 6.9 m above the top of the quartz siltstone unit used by Crickmay (1957) and Belyea and McLaren (1962) to mark the base of the Alexandra Formation/Member, is not only obvious in Hay River exposures but is also well-defined at the base of some sections along the escarpment.

Jamieson (1967) produced an impressive thesis on the Alexandra Member given that the knowledge-bank for carbonate sedimentology was in its infancy. Key conclusions of Jamieson (1967) included:

1. Limestones that form the Alexandra Member were deposited across a span of environments that belonged to one reef complex that faced and dipped to the northwest (termed the Alexandra Reef Complex).
2. Calcareous algae were of greater volumetric importance in the reef complex than any other organism.
3. Many of the fossils in the Alexandra Reef Complex that would be identified by most geologists/paleontologists as 'stromatoporoids' are actually different types of coralline algae, hydrozoans, and possibly encrusting foraminifera.
4. Dolomite in the formation was a diagenetic product of subaerial exposure.
5. The Alexandra Reef Complex shares a number of similarities with other reef complexes in western Canada as well as in Europe, Russia, Africa, and Australia.

Following the work of Jamieson, M. Hadley completed a detailed M.Sc. thesis at the University of Alberta on the Hay River Formation. This thesis integrated the stratigraphic succession exposed along Hay River with 3630 m of core from 18 wells that were drilled throughout the region in the late 1970s and early 1980s by Cominco, as part of an exploration project to extend the mining activity at Pine Point. Hadley (1987) did not work directly on the Alexandra Member but his correlations (with the added benefit of core data) supported the interpretation of Jamieson (1967) that the main escarpment correlates with the Alexandra Member exposed on Hay River. Hadley (1987) and Hadley and Jones (1990) determined that the Hay River Formation can be divided into the Waterways Formation, Muskwa Formation, Fort Simpson Formation, and Escarpment Formation (Fig. 1-4), with a total thickness of 371.1 m. The Escarpment Formation directly underlies the Alexandra Member of the Twin Falls Formation. Hadley (1987), however, disagreed with Jamieson (1967) on placement of the base of the Alexandra Member and lowered its boundary to the contact between grey calcareous siltstone-fine sandstone (top part of the Escarpment Formation Member E) and grey quartzose limestone (placed in the basal part of the Alexandra Member). Thus, Hadley (1987) assigned the boundary between the Escarpment Formation and Alexandra Member to essentially the same contact used by Crickmay (1957) and Belyea and McLaren (1962).

In addition to the stratigraphic work of McConnell (1891), Cameron (1921), Crickmay (1953, 1957), Douglas (1959), Belyea and McLaren (1962), Jamieson (1967), and Hadley (1987), a number of important paleontological studies have also been conducted in the Hay River region. J.F. Whiteaves (1891) described the paleontological collection of McConnell, and P.S. Warren and C.R. Stelck correlated the Hay River fossil assemblages to those in the Winterburn Group in Alberta (Warren and Stelck 1950). Klapper and Lane (1985) conducted the first detailed study of conodonts in the Hay River succession and determined that they are mostly of the *Polygnathus* biofacies. R.A. McLean has published extensively on the rugose coral fauna in the Hay River region (McLean 1984; McLean and Pedder 1984, 1987; McLean 1989, 1993, 2005). McLean and Klapper (1998) used conodonts and rugose corals to correlate the Hay River succession to the Upper Devonian succession in other parts of western Canada.

STRATIGRAPHIC FRAMEWORK UTILIZED IN THIS STUDY

The Upper Devonian succession along Hay River has been revised numerous times. In this study (Fig. 1-4), the Alexandra Member of Belyea and McLaren (1962) is elevated to formation status, following Crickmay (1957). It is elevated to this status because it is a regionally mappable unit distinct from underlying and overlying strata (cf. Jamieson 1967, 1971). Placement of its lower boundary follows Jamieson (1967) and it is placed at the contact between stromatoporoid-coral dominated limestones and underlying quartzose, sparsely fossiliferous limestones-siltstones (Fig. 1-5A). The argument of Hadley (1987) to lower this boundary to the contact between grey calcareous siltstone-fine sandstone and grey quartzose limestones is not accepted because 1) as noted by Hadley (1987; p. 93), this contact is difficult to identify in outcrop, 2) the quartz siltstone-fine sandstone passes basinward into quartzose limestones, such that this contact becomes ambiguous, and 3) as noted by Jamieson (1967), the contact between the quartzose limestones and overlying limestones with massive stromatoporoids and corals is much more obvious in outcrop (and core) and is more regionally extensive. Thus, the boundary is placed following Jamieson (1967). Underlying strata are assigned to the Escarpment Formation following the terminology and rank of Hadley (1987) and Hadley and Jones (1990). The Alexandra Formation is overlain by the Twin Falls Formation. Along Hay River, this boundary is the sharp contact between laminated, light grey, sparsely fossiliferous limestones with mudcracks and overlying dark coloured, bioclastic silty limestones with brachiopods and corals (Fig. 1-5B, C). This contact is consistent with Belyea and McLaren (1962) and Jamieson (1967).

RATIONALE AND OBJECTIVES

Although Jamieson (1967) conducted extensive work on the Alexandra Formation, the forty years of research and numerous developments that have been made in the subjects of stratigraphy, sedimentology, diagenesis, and paleontology, since her pioneering study, warrant new investigation of the Alexandra Formation. In addition, whereas her study was limited to examination of weathered exposures along the escarpment and Hay River, excavation of the quarry and five roadcuts in the 1980s, and drilling of the four continuous cores by Cominco in 1979, has greatly expanded the availability of high-quality data for studying these limestones. This was further enhanced by the drilling of seven continuous cores in 2003 by MacNeil and Jones for this study. Thus, study of the Alexandra Formation can now be based on a much larger database that integrates

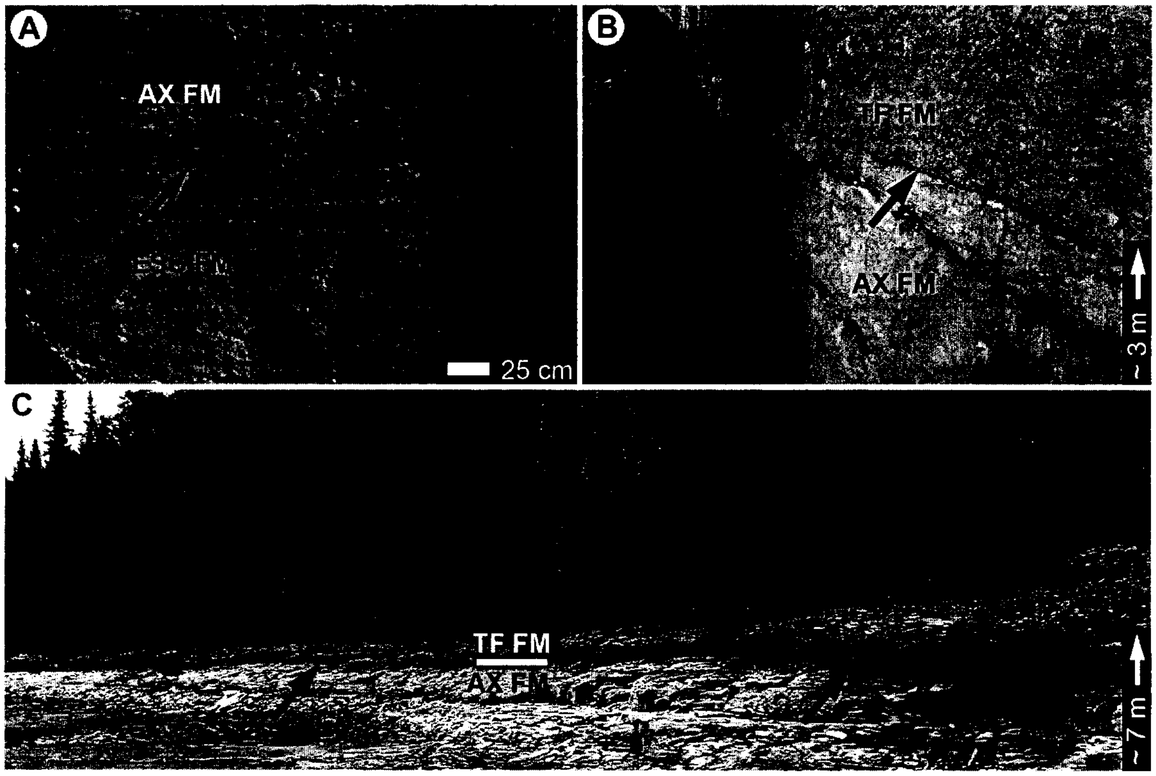

Figure 1-5. Lower and upper boundaries of Alexandra Formation at its type section (Crickmay 1957; Belyea and McLaren 1962) on Hay River. **A)** Lower boundary. Quartzose, sparsely fossiliferous limestones of Escarpment Formation (ESC FM) with a thin bed of hummocky cross-stratified quartzose limestone at top, sharply overlain (arrow) by stromatoporoid-coral deposits of Alexandra Formation (AX FM). **B)** Upper boundary. Sharp contact (arrow) between light coloured, sparsely fossiliferous mudcracked limestones of Alexandra Formation (AX FM) and dark coloured, bioclastic silty limestones of Twin Falls Formation (TF FM). Wall of gorge; vertical height of strata ~ 3 m. **C)** Upper boundary. Limestones of Alexandra Formation (AX FM) sharply overlain (arrows) by more massively weathered, partly cliff-forming limestones of Twin Falls Formation (TF FM). Above lip of Alexandra Falls; vertical height of strata ~ 7 m.

exposures along Hay River and the escarpment with roadcuts that cumulatively expose > 1 km of relatively unaltered limestones from across different parts of the formation, exposures in the quarry, and eleven continuous cores from across most of the study area. The continuous cores, ten of which record the complete succession from surface to below the base of the Alexandra Formation, are particularly important because exposure along many parts of the escarpment is poor and the base of the formation is covered at most localities. As such, whereas past researchers have been forced to essentially 'guess' the stratigraphic position for many of the escarpment sections, the cores provide the necessary framework for *accurately* integrating these sections into the overall stratigraphic framework of the formation.

Generally, Devonian reef systems have not been studied in high-resolution (e.g., 4th and 5th-order sequences) chronostratigraphic contexts (MacNeil and Jones 2006). This type of context, however, is the critical step for moving beyond simply cataloguing fossils and facies and actually advancing our understanding of these systems. Objectives of this study of the Alexandra Formation therefore include (1) exploiting the database to establish a high-resolution sequence stratigraphic framework for these deposits, (2) relating the facies associations to different phases of reef evolution, (3) examining fundamental controls on the evolution of the depositional systems, (4) relating sea-level cyclicity in these deposits to time-equivalent deposits in Alberta, and (5) documenting the morphology and paleoecological significance of new fossils that are found.

The thesis is presented in "paper-format", and each chapter has been published in a peer-reviewed publication or is in review (status indicated in a footnote to each chapter). The chapters present the following topics:

Chapter Two - This chapter documents the sequence stratigraphy of the Alexandra Formation. Integration of facies associations and sedimentology with the sequence stratigraphic framework documents how changes in sea-level position affect the development of ramp-situated reef systems, and how these systems differ from carbonate shelves. (*Published as:* MacNeil, A.J. and Jones, B. 2006. Sequence stratigraphy of a Late Devonian ramp-situated reef system in the Western Canada Sedimentary Basin: dynamic responses to sea-level change and regressive reef development. Sedimentology, **53**, 321-359.)

Chapter Three - Chapter Three documents a sequence boundary in the Alexandra Formation, including the sedimentology of the oldest coastal-plain palustrine deposits known in the geological record. (*Published as:* MacNeil, A.J. and Jones, B. 2006. Palustrine deposits on a Late Devonian coastal plain – sedimentary attributes and implications for concepts of carbonate sequence stratigraphy. Journal of Sedimentary Research, **76**, 292-309.)

Chapter Four—. This chapter examines environmental and ecological controls on the types of reef facies found in the Alexandra Reef System. A nutrient-gradient model is proposed as a new way of evaluating Devonian reef systems, with implications for understanding their facies composition and stages of platform initiation, development, and demise. (*Paper submitted:* MacNeil, A.J. and Jones, B. Nutrient-gradient controls on Devonian reefs: Insight from the ramp-situated Alexandra Reef System (Frasnian), Northwest Territories, Canada. Submitted to a SEPM Special Publication on controls on carbonate platforms. J. Lukasik and J.A. Simo editors.)

Chapter Five—. Chapter Five documents new microfossils found in the Alexandra Reef System and their paleoecological significance. (*First part of chapter published as:* MacNeil, A.J. and Jones, B. 2006. Ovummuridae (calcareous microfossils) from a Late Devonian ramp: their distribution, preservation potential, and paleoecological significance. Canadian Journal of Earth Sciences, **43**, 269-280. *Second part of chapter submitted:* MacNeil, A.J. and Jones, B. The new genus and species *Devonoracemus cameroni* – an encrusting, reef-dwelling microorganism from the Late Devonian. Submitted to the Journal of Paleontology; 14 p. and 3 figures).

Chapter Six—. This chapter contains conclusions of the thesis.

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CHAPTER 2 – SEQUENCE STRATIGRAPHY OF THE ALEXANDRA REEF SYSTEM[1]

INTRODUCTION

Sequence stratigraphy is a potentially powerful tool that has several applications to the study of ancient carbonate platforms and associated reef systems. This study of the Late Devonian (Frasnian) Alexandra Formation, located in the Northwest Territories of Canada, highlights the application of high-resolution sequence stratigraphy towards the understanding of a ramp-situated reef system dominated by stromatoporoids. Although stromatoporoid-dominated reefs have been extensively studied, only a few studies have applied sequence stratigraphic concepts and methods (e.g. Ward, 1999; Whalen *et al.*, 2000a), which have evolved rapidly (Miall and Miall, 2001). As several dynamics of Silurian and Devonian reefs remain enigmatic (e.g. Brunton and Copper, 1994; Kershaw, 1998; Wood, 1998), high-resolution sequence stratigraphy may provide the mechanisms for elucidating poorly understood aspects, thereby enhancing our understanding of these ancient systems. Likewise, study of carbonate ramps with high-resolution sequence stratigraphy should reveal some of their complexities (cf. Wright and Burchette, 1998), and the implications of their differences from carbonate shelves.

Exposed over ≈ 46 km, the reefal carbonates that form the Alexandra Formation (<40 m thick) were deposited on a gently sloping epicontinental ramp in the Western Canada Sedimentary Basin (Fig. 2-1). The formation includes exceptionally well-preserved facies associations of peritidal through to fore-reef depositional environments, and a number of well-defined, regionally developed, sequence stratigraphic surfaces. Integration of the spatial distribution of the facies associations with their bounding sequence stratigraphic surfaces, and interpretations of respective depositional environments, delineate two separate reef complexes in the formation. Collectively termed the Alexandra Reef System, the second reef complex developed basinward of the first in response to lowered sea-level, and is separated from it by a Type I sequence boundary.

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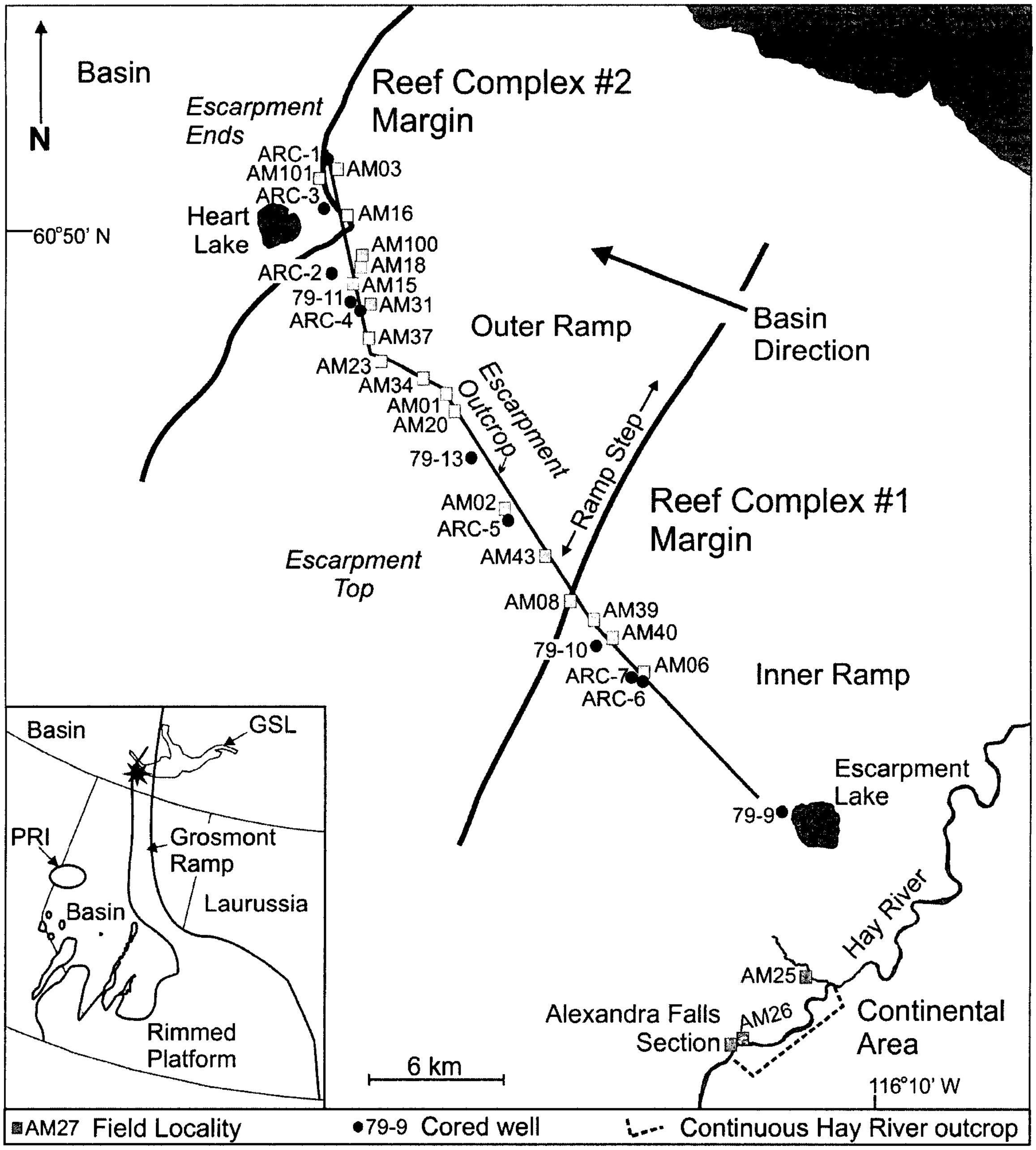

Figure 2-1. Map of study area and paleogeography of reef system. Trend of escarpment outcrop and location of eleven cored wells and twenty-one field localities, that are specifically referenced in text, indicated. Inset shows study area (star) in context of simplified Late Devonian (Frasnian) paleogeography of western Canada (modified from Cutler (1983) and Weissenberger and Potma (2001)). GSL = Great Slave Lake; PRI = Peace River Island.

The dominant control on the evolution of the Alexandra Reef System was the interplay between the inherited platform geometry and changes in relative sea-level. This study illustrates that 1) changes in reef architecture (e.g. biostromes, bioherms) correlate in some instances with changes in relative sea-level, 2) the stratigraphic complexity of each reef complex was controlled by interactions between sea-level change, antecedent topography, and platform geometry, 3) for carbonate ramps, excessive carbonate sedimentation is not a unique feature of the highstand systems tract (cf. Schlager *et al.*, 1994), and may be closely associated with forced regression, 4) sequence stratigraphic surfaces can be used to delineate the chronostratigraphic framework of reef systems in which high-resolution biostratigraphic zonations are not present – a longstanding problem with stromatoporoid-dominated reefs (e.g. Wilson, 1975; Mountjoy, 1980; Burchette, 1981; Stearn, 2001), and 5) sea-level fluctuations recorded in the Alexandra Formation correlate to other platforms in western Canada and indicate that mid-Frasnian deposition in the Western Canada Sedimentary Basin was punctuated by a relatively significant sea-level fall (cf. Whalen *et al.*, 2000a; Potma *et al.*, 2001). As many Silurian and Devonian reef systems were characterized by knoll-reef belts on gently sloping platforms, and lacked elevated, steep rims (e.g. Wilson, 1975; Mountjoy, 1980; Walls and Burrowes, 1985; Nestor, 1995; Kershaw, 1998; da Silva and Boulvain, 2004), the style of regressive reef development that is documented in the Alexandra Formation may be more common in these systems than previously realized.

PALEOGEOGRAPHY AND REGIONAL STRATIGRAPHY

The Alexandra Formation crops out in the Northwest Territories of Canada, southwest of Great Slave Lake (Fig. 2-1). In the Late Devonian, this region was located in an equatorial position on the western edge of Laurussia (Kiessling *et al.*, 1999; Scotese, 2004). Continental hinterland lay to the east and the continental margin was located to the north and west (Moore, 1989; Switzer *et al.*, 1994). To the south, inundation of western Canada by a series of transgressions (Johnson *et al.*, 1985) had formed an intracratonic basin in which extensive carbonate platforms existed (Moore, 1989; Potma *et al.*, 2001). Belyea and McLaren (1962) suggested that the Alexandra Formation is a northern extension of the Grosmont Platform (inset; Fig. 2-1), which was a vast, carbonate-dominated system that rimmed the eastern continental edge of the basin (Cutler, 1983; Thériault, 1988). Although the Alexandra Formation lacks the fossil assemblages (e.g. conodonts) needed for biostratigraphic zonation of its deposits (e.g. McLean and Klapper, 1998), conodont and rugose coral assemblages in underlying and overlying strata constrain its age to the mid-Frasnian (Montagne Noire conodont zones 8-10) and confirm that it is time-equivalent to lower and lower-middle strata of the Grosmont Platform (Klapper and Lane, 1989; McLean and Klapper, 1998). These data indicate that it was deposited in the upper part of T-R cycle IIc of Johnson *et al.* (1985; cf. Joachimski *et al.*, 2004).

Stratigraphic nomenclature for the study region has been revised numerous times (Chapter 1). In this study, the reefal strata are referred to as the Alexandra Formation (Fig. 2-2), following Crickmay (1957). The base of the formation is placed at the contact between sparsely fossiliferous, light-coloured quartzose limestones and bioclastic limestones with corals and stromatoporoids (Jamieson, 1967). Quartzose limestones beneath the Alexandra Formation belong to the Escarpment Formation, which is formed of mixed carbonate–siliciclastic regressive ramp deposits (Hadley and Jones, 1990). Unconformably overlying the Alexandra Formation are bioclastic limestones and *Hexagonaria*-dominated patch reefs that belong to the Twin Falls Formation.

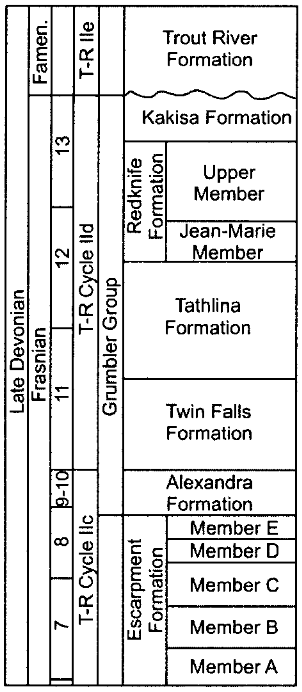

Figure 2-2. Late Devonian stratigraphic column for study area, modified from Hadley and Jones (1990). Conodont biostratigraphy (Montagne Noire conodont zones 7-13) follows McLean and Klapper (1998). T-R cycles follow Johnson *et al.* (1985) and modifications of Joachimski *et al.* (2004)

STUDY AREA AND METHODS

The Alexandra Formation (< 40 m thick) is exposed along a southwest–northeast gorge cut by Hay River and in a series of fault-bounded uplifted blocks that form a southeast–northwest trending escarpment (Fig. 2-1). Strata along Hay River show little variation because the exposure trend is near-parallel to depositional strike. In contrast, the escarpment is oblique relative to depositional strike, providing an almost continuous section through strata of the formation. Eighty stratigraphic sections were measured from forty-seven localities along the escarpment edge, five roadcuts on top of the escarpment, a quarry, and three localities along Hay River. The roadcuts, located up to one kilometer from the escarpment edge, cumulatively expose more than one kilometer of relatively unaltered limestone from across different parts of the formation. Sections less than a few meters thick were measured with a Jacob's staff. Sections with high vertical faces were measured by lowering a tape measure from the top, and ropes and harnesses with ascension devices were used to move up the section, record data, and collect samples.

The location of each section, determined with a global positioning system, was plotted on 1:50 000 government issued (1977) topographic map sheets contoured at 10 m intervals. Contours trace the escarpment edge for km-scale distances, and with spot elevations, allow elevations to be estimated for the measured sections. Selected localities were checked against elevation measurements for the escarpment top that Jamieson (1967) made with an altimeter, and always found to be in close agreement (±2 m). Where access permitted, a transit was used to measure elevation differences between sections. Correlation between outcrop sections was thereby based on walking-out facies and tracing surfaces in the field, and elevation differences between sections.

Samples (n = 827) were collected from measured sections at one meter intervals. Locally, denser sampling was conducted in order to document specific field observations. In addition, 362 photographs were taken in the field to document stratigraphic relationships and depositional features. Over 90% of the samples were slabbed and etched in dilute (≈ 10%) HCl for study of macroscopic features. Four continuous cores (previously drilled by Cominco) and seven new continuous cores (Fig. 2-1) were also studied. All cores penetrated through to the base of the formation, with the exception of ARC-2, due to mechanical problems. As such, ten of the cored sections record the complete stratigraphic succession (≈ 100% recovery) from the surface through to the base of the formation, and provide essential data for accurate correlation of the sections that are located along the escarpment into the overall stratigraphic framework.

Large (5 x 7·5 cm) thin-sections were made from outcrop (n = 134) and core (n = 160) samples for detailed petrography and fossil identification. Facies were defined on the basis of depositional textures and fossil content using the classification scheme of Dunham (1962), as modified by Embry and Klovan (1971). The term "bioherm" is used for a mound-shaped buildup with flanking beds and a skeletal framework, whereas the term "biostrome" is applied to tabular shaped buildups with a skeletal framework that may be locally reworked into detritus (cf. Kershaw, 1994). The term "reef system" is used to describe a succession of two or more reef complexes, each separated by a sequence boundary. "Type I sequence boundary" is used following the definition of Posamentier and Vail (1988), for a subaerial unconformity produced by a fall in relative sea-level sufficient to cause a relatively abrupt basinward shift of the coastal system. Additional sequence stratigraphic terminology applied in this study follows the definitions in Sarg (1988) and Catuneanu (2002).

Restoration of the original depositional profile

The Alexandra Formation is tilted gently to the southwest (Douglas, 1959), and a series of northeast and northwest-trending post-depositional normal faults (most offsets are <15 m) bound the uplifted blocks that form the escarpment. Restoring the depositional profile for the formation must therefore consider 1) corrections for the regional structural tilt, 2) corrections for fault displacements, 3) depositional and erosional topographic variations on the formation base, and 4) original depositional slopes on the platform.

The regional dip of strata was calculated as ≈ 5 m km^{-1} towards 247° using the base of the Alexandra Formation in the Alexandra Falls Section (AM27), AM25, and core 79-9 (Fig. 2-1). No evidence of faulting has been detected in the area of these sections (cf. Douglas, 1973; Hadley and Jones, 1990). To restore the Alexandra Formation to its pre-tilting position, thirteen sections and cores that span the study area, considered to have accurately measured elevations (±2 m), were selected (Fig. 2-3A). Using the strike line that cuts through the Alexandra Falls Section as a base line, the remaining twelve sections

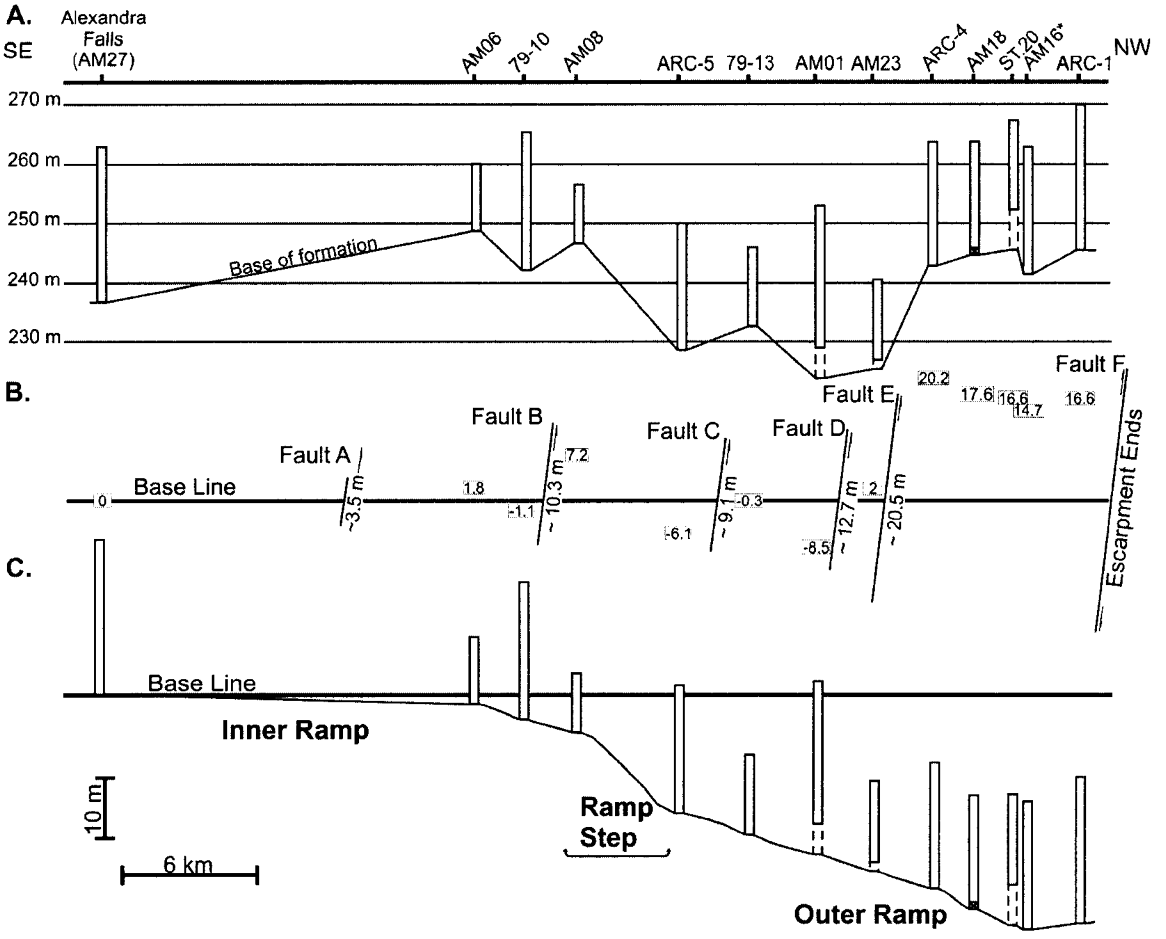

Figure 2-3. Restoration of study area stratigraphy to original position. **A)** Position of sections relative to sea-level, no corrections. *Core ARC-3 projected to locality AM16. **B)** Position of each section in A corrected for regional tilt and locations of interpreted faults. Measurement in box indicates position of formation base at that section relative to base line. **C)** Restored depositional profile.

were corrected for the calculated regional tilt (≈ 5 m km^{-1}) by measuring their distance perpendicular from the base line, and increasing or decreasing their basal elevation accordingly. As the shallowest facies are exposed along Hay River, all corrected sections (Fig. 2-3B) should lie on or below the base line. Corrected sections that lie above the base line and/or have abrupt vertical displacements relative to adjacent sections, indicate post-depositional fault offset, significant topographic changes on the original depositional profile, or a combination of both. Supported by field observations that included locally developed prominent joint sets, steep-walled gullies, stream traces and waterfall locations, marked changes in topography along the escarpment, and of particular importance, the similarity of facies between adjacent sections, six post-depositional faults (or fault zones) were identified and their displacements calculated (Fig. 2-3B).

Displacements associated with Fault E are evident in the field (Douglas, 1973) and Faults B, D, and F correspond with prominent lineaments previously mapped by Jamieson (1967). Fault F terminates the escarpment abruptly north of ARC-1.

On a large scale, the area between AM08 and ARC-5 divides the study area into the southeast and northwest regions, which have different depositional characteristics. The drop between AM08 and ARC-5 on the corrected profile (Fig. 2-3B) also corresponds with a significant facies change in the basal part of the Alexandra Formation that is indicative of a relatively rapid transition from shallow to deep water (≈ 13 m over 4 km). The basal part of the Alexandra Formation in 79-10 and AM08 is characterized by relatively shallow marine, bioclastic limestones whereas the basal ≈ 5 m of the Alexandra Formation in ARC-5, only 4.5 km away, is characterized by dark, bioturbated mudstone, characteristic of deeper water depositional conditions. Given the regional contrasts and these local facies contrasts, the drop on the corrected profile is treated as either natural topography on the original profile or a syn-depositional fault, rather than displacement across a post-depositional fault. Geographically, this area coincides with the immediate basinward edge of bioherm and biostrome development in the Escarpment Formation (Douglas, 1973). Thus, it seems most probable that the drop was a result of antecedent topography, rather than syn-depositional faulting, for which no evidence has been found.

Facies variations in the Escarpment Formation and Alexandra Formation indicate a platform with a gentle slope (Fig. 2-3C). Original depositional gradients for the base of the Alexandra Formation were determined by correlation of facies in the Escarpment Formation (cf. Hadley and Jones, 1990), and measurement of slopes at the base of the Alexandra Formation, between restored sections not separated by faults. The area to the south of AM08 has minimal facies variations in the Escarpment Formation or basal Alexandra Formation. Available data indicate the depositional surface at the base of the Alexandra Formation sloped basinward at <0·05° in this region. The area north of ARC-5, in contrast, had a steeper slope gradient, averaging ≈ 1·2 m km^{-1} (0·07°). Consideration of the oblique angle of the restored profile, which involves a fair amount of interpretation and judgement, indicates that the averaged slope may be as steep as 0·1°.

The geometry of the restored profile (Fig. 2-3C), and distribution of facies belts in the uppermost Escarpment Formation, from high-energy landward facies grading down-slope into muddy, low-energy facies (cf. Hadley and Jones, 1990), is consistent with a ramp (Ahr, 1973; Read, 1985; Burchette and Wright, 1992). As such, the platform is treated as that of a ramp, and divided at the drop between AM08 and ARC-5 (termed the *ramp step*) into *inner ramp* and *outer ramp* areas (Figs. 2-1 and 2-3C). The ramp step is analogous to the concept of a 'ramp slope crest' (cf. Burchette and Wright, 1992).

STRATIGRAPHIC ARCHITECTURE

The Alexandra Formation is herein divided into 1) a regionally extensive Basal Onlapping Succession, 2) Reef Complex #1, situated on the inner ramp, and 3) Reef Complex #2, situated on the outer ramp.

THE BASAL ONLAPPING SUCCESSION

Facies Framework

The Basal Onlapping Succession consists of open marine carbonate deposits, 1-3.5 m thick, that progressively onlapped carbonate–siliciclastic ramp deposits of the underlying Escarpment Formation (Fig. 2-4A). Its basal contact, which also marks with the base of the Alexandra Formation, is sharp on both the outer and inner ramp and appears to be erosional (Fig. 2-5A–D). In ARC-5, however, the lower part of the succession interfingers with light-coloured sparsely fossiliferous, quartzose limestones of the Escarpment Formation. Likewise, at AM40, immediately south of the ramp step, stromatoporoids encrusted on toppled corals are hosted in thin-bedded quartzose limestone in the Escarpment Formation (Fig. 2-6A), before being sharply overlain by bioclastic facies of the Basal Onlapping Succession (Fig. 2-6B). At AM06, hardground development at the base of the formation preceded deposition of the Basal Onlapping Succession (Fig. 2-5D).

Deposits in the Basal Onlapping Succession on the outer ramp differ from those on the inner ramp. On the outer ramp, isolated stromatoporoids and corals (<10-30% of facies) are hosted in a brown mudstone-wackestone with gastropods, brachiopods, bryozoans, crinoid debris, and foraminifera (Fig. 2-5C and E). The stromatoporoids have laminar (≈ 5 mm thick) and irregular-laminar growth forms and colonial (e.g. *Thamnopora*, *Phillipsastrea*, *Alveolites*) and solitary horn corals are found *in situ* or show evidence of

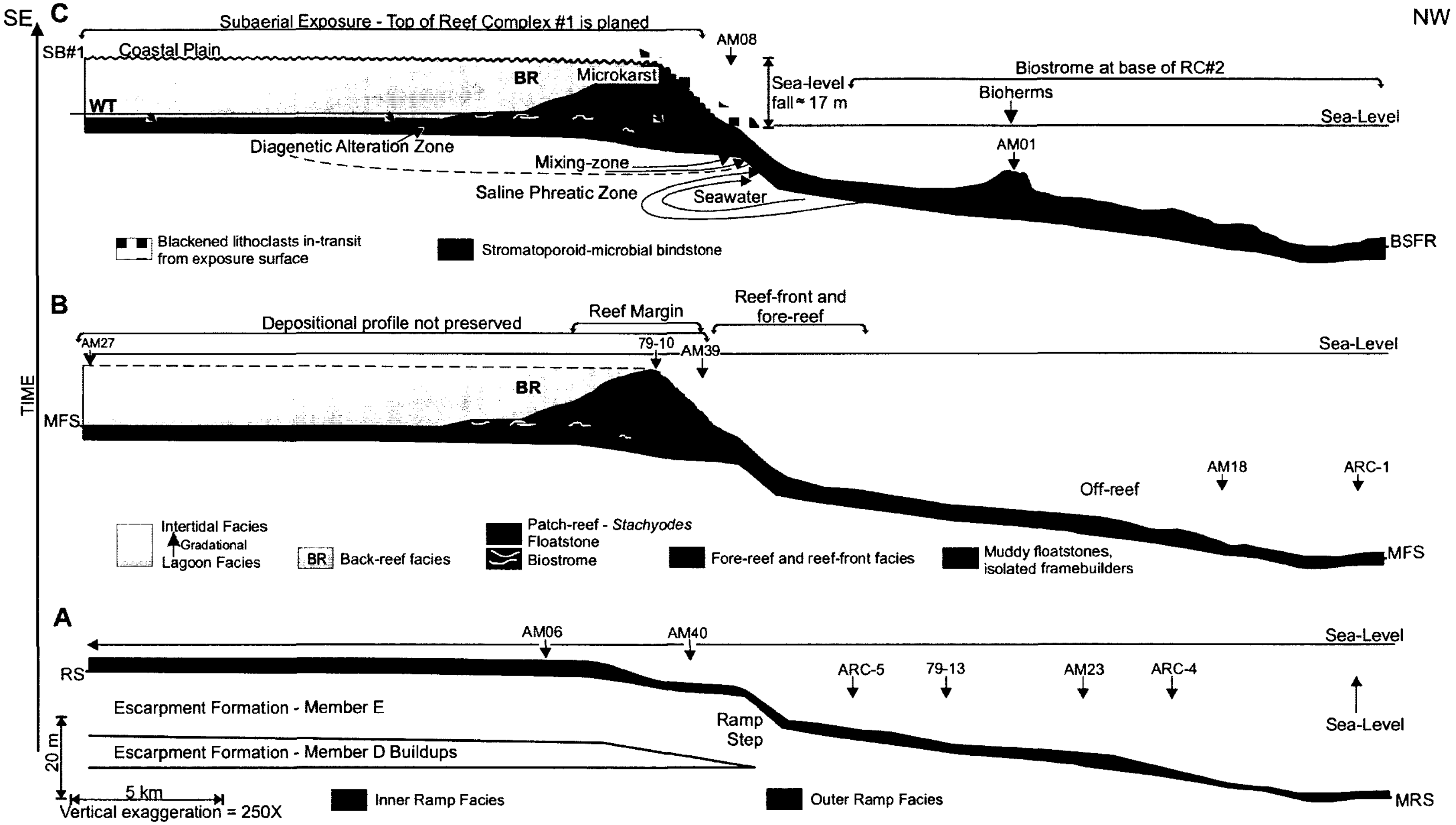

Figure 2-4. Sequence stratigraphic evolution of Alexandra Formation. Orientation of profile SE-NW, as in Fig. 2-3. Positions of some key sections described in text are plotted once for reference. MRS=Maximum regressive surface; RS=Ravinement surface; MFS=Maximum flooding surface; BSFR=Basal surface of forced regression; SB#1=Sequence Boundary #1. **A)** Basal Onlapping Succession, transgressive systems tract. Note position of ramp step above edge of Member D buildup in Escarpment Formation. **B)** Growth of Reef Complex #1 on inner ramp, in highstand systems tract. **C)** Termination of Reef Complex #1 as relative sea-level falls ~17 m and initiation of Reef Complex #2 in falling stage systems tract. Schematic of possible coastal hydrology included. Note water table (WT) is only slightly above sea-level, as per semi-arid conditions.

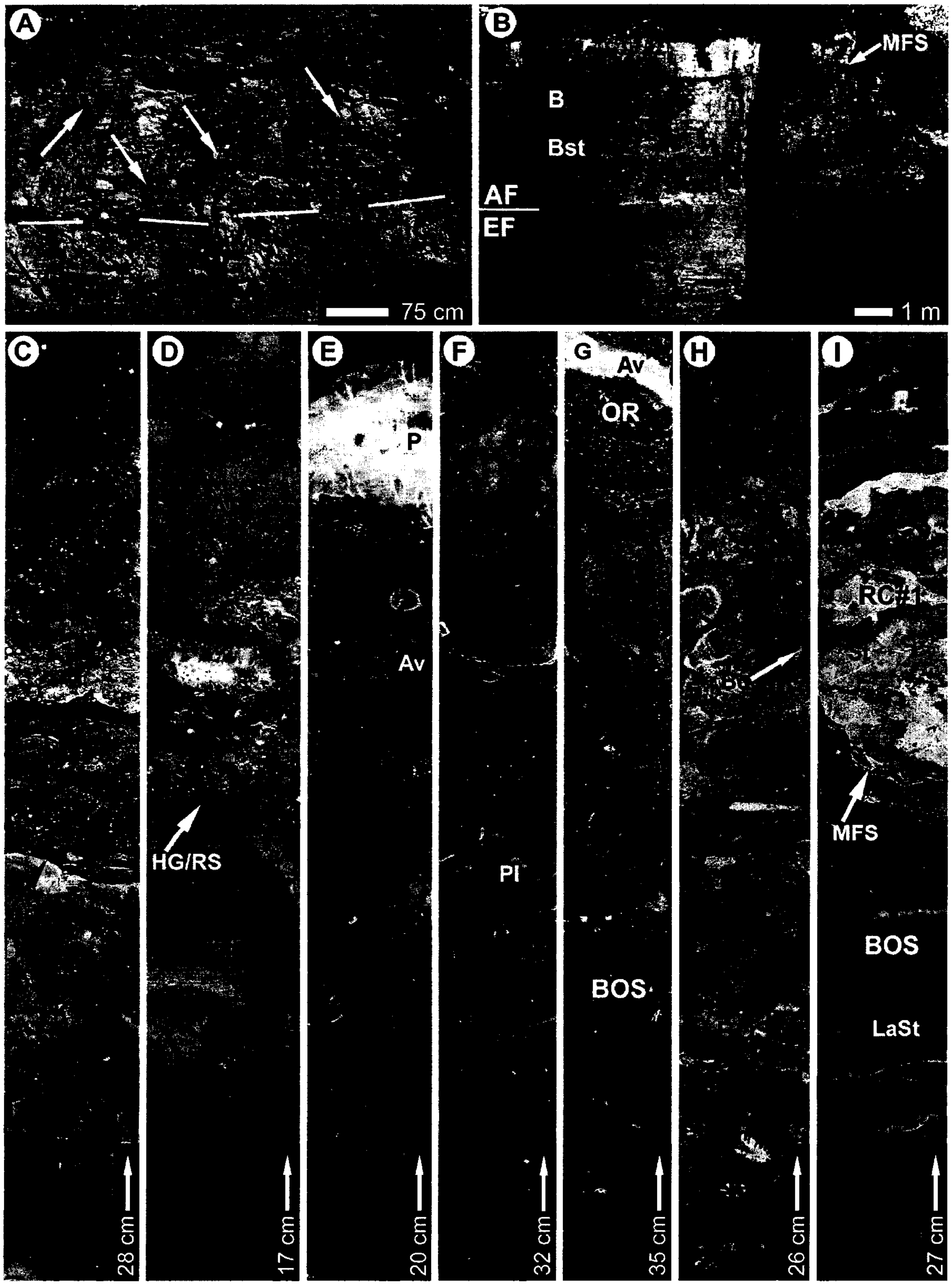

Figure 2-5. Facies and surfaces of Basal Onlapping Succession (BOS). EF=Escarpment Formation; AF=Alexandra Formation. **A)** Base of Alexandra Formation (black arrow) at Alexandra Falls Section. Bioclastic facies in BOS grades up (dashed line) into stromatoporoid–coral biostrome. Some framebuilders indicated by white arrows. **B)** Biostrome deposits (Bst) in BOS abruptly overlain (black arrows) by dark muddy, thin-bedded (B) *Amphipora* floatstones. Ravinement surface at base of BOS

(base of formation) and maximum flooding surface (MFS) at its top are sharp. Locality AM25. **C)** Maximum regressive surface (MRS) at base of BOS on outer ramp. Core ARC-4. **D)** Partly mineralized and bored hardground (HG) developed on ravinement surface (RS) at base of BOS on inner ramp. Core ARC-6. **E)** Muddy floatstone in lower part of BOS on outer ramp with *Phillipsastrea* (P), *Alveolites* (Av), and horn corals (H). Core ARC-4. **F)** Bioturbated (e.g. *Palaeophycus*; Pl) dark mudstone deposited on outer ramp close to ramp step. Core ARC-5. **G)** Bioturbated mudstone–wackestone with crinoid debris, capped by firmground (FG) that marks the maximum flooding surface (MFS) at top of BOS on outer ramp. Overlying sediment (orange-brown colour contrast) with *Alveolites* (Av) fragment is off-reef (OR) facies to Reef Complex #1. Core ARC-4. **H)** Partly mineralized (black arrows) and bored (Bo) hardground (HG) caps muddy floatstone at top of BOS on outer ramp. The hardground is the maximum flooding surface. Muddy floatstone above hardground belongs to off-reef (OR) area of Reef Complex #1. Core ARC-1. **I)** Laminar stromatoporoids (LaSt) bind dark muddy matrix in biostrome on inner ramp in BOS. Maximum flooding surface (MFS) at top of BOS, overprinted by stylolite, separates lower biostrome from overlying biostrome of Reef Complex #1 with tabular stromatoporoids (St) and porcelain-like matrix. Note matrix contrast across the maximum flooding surface. Core ARC-6. Length of each core interval indicated at its bottom right.

having been displaced. These deposits grade up into a dark, sparsely fossiliferous bioturbated mudstone and muddy floatstone that is capped by a firmground to incipient hardground (Fig. 2-5F-H). This succession probably represents progressive deepening that culminated in sediment starvation. Towards the ramp step (cores ARC-5 and 79-13), a clearly defined surface is not present at the top of the Basal Onlapping Succession.

The Basal Onlapping Succession on the inner ramp is characterized, in its lowest part, by a brown, bioclastic facies with abundant but isolated domal and tabular colonial corals (*Alveolites*, *Phillipsastrea*), and laminar, tabular, and low-domal stromatoporoids, sometimes with ragged margins (Figs. 2-5A and B and 2-6B). Associated sediment (≥60% of facies) is a bioturbated floatstone (<5% quartz) with numerous fragments of *Thamnopora*, horn corals, brachiopods, crinoid debris, and locally, fragments of *Amphipora*. The bioclastic facies is gradationally overlain by a biostrome (Fig. 2-5A and B) dominated by laminar and thin tabular stromatoporoids with accessory domal stromatoporoids and domal to irregular colonial corals. Some stromatoporoids and corals in the biostrome encrusted each other, and in places stromatoporoid-coral encrustations alternated. In other areas, stromatoporoid-dominated framework changes laterally into thickets up to 30 cm high and ≈1.5 m across of fasciculate rugosans (*Smithiphyllum*, *Disphyllum*, *Thamnophyllum*) with abundant horn corals (Fig. 2-6C). Sediment between and underneath the framebuilders (Fig. 2-5I) is a brown mudstone-wackestone with brachiopods and crinoid debris, as well as minor amounts of *Stachyodes* and *Amphipora*. The transition from the bioclastic facies with isolated stromatoporoids and corals to the

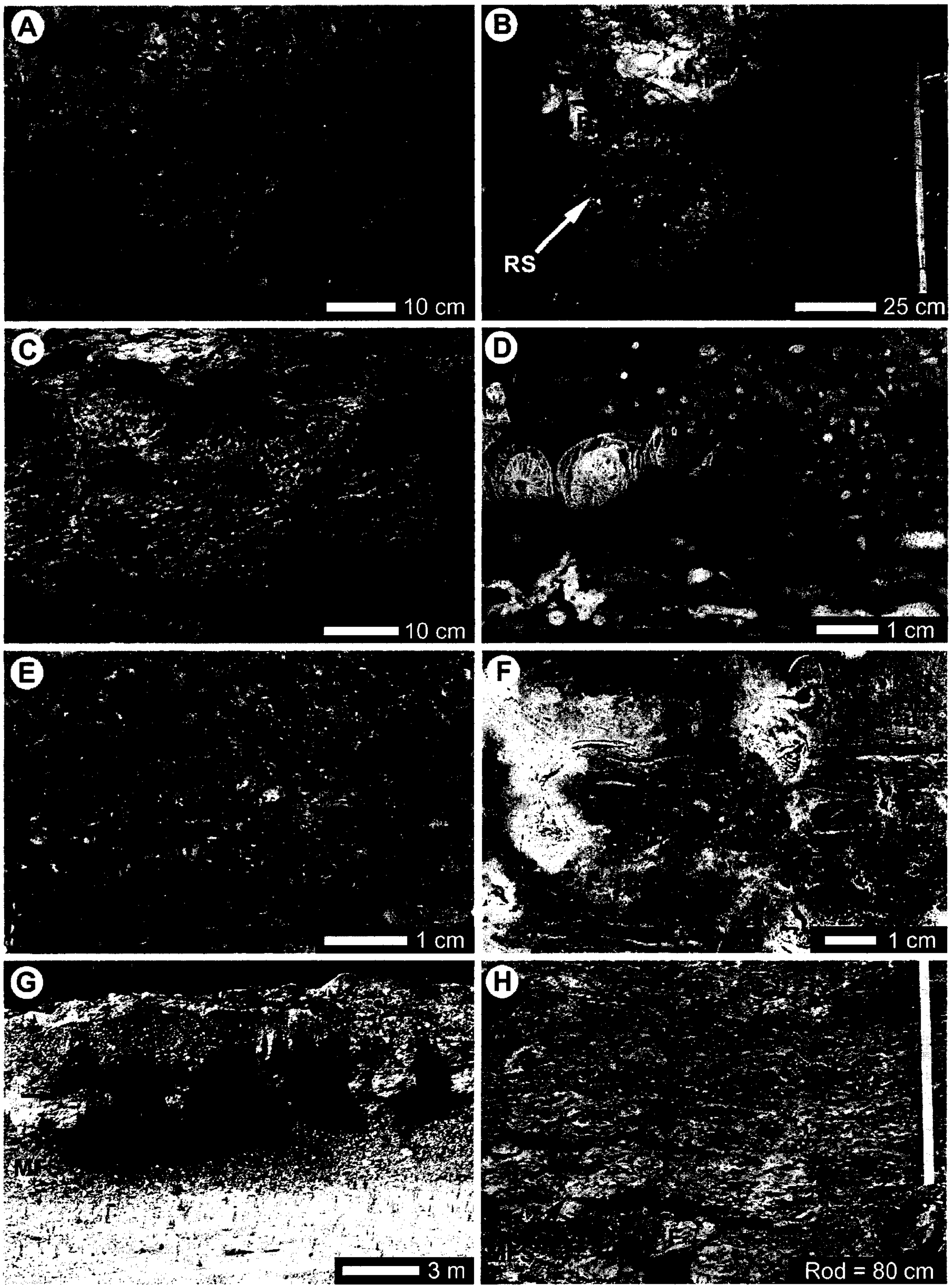

Figure 2-6. Facies and surfaces of Basal Onlapping Succession (BOS) and Reef Complex #1. EF=Escarpment Formation; AF=Alexandra Formation. **A)** Fasciculate rugosan (F) encrusted by stromatoporoid in quartzose limestones of Escarpment Formation at AM40. **B)** Ravinement surface (RS) at base of BOS and overlying bioclastic facies with framebuilders (F). Locality AM40. **C)** Large *Disphyllum* thicket in biostrome in BOS on inner ramp. Locality AM06. **D)** *Smithiphyllum* fragment in

Amphipora floatstone with dark matrix, from upper part of BOS. Locality AM25. **E)** Densely packed *Amphipora* floatstone in lagoon facies of Reef Complex #1, immediately above maximum flooding surface. Locality AM25. **F)** Stromatolites disrupted by desiccation cracks and bioturbation in intertidal facies of Reef Complex #1. Alexandra Falls Section. **G)** Maximum flooding surface (MFS) at top of biostrome in BOS. Upper horizontal arrow indicates top of biostrome in Reef Complex #1 and contact with overlying stromatoporoid patch reef facies. Locality AM06. **H)** Close-up of maximum flooding surface (MFS) and biostrome facies at AM06. Fasciculate rugosan (F) at contact is truncated. Note abundance of laminar stromatoporoids (≈ 60%), without corals, in biostrome of Reef Complex #1.

biostrome may reflect community succession associated with environmental stabilization on the inner ramp (cf. Walker and Alberstadt, 1975). In sections located near and along Hay River, a thin-bedded brown *Amphipora* floatstone with small stromatoporoids and fragments of *Stachyodes* and corals overlies the biostrome (Figs. 2-5B and 2-6D). Similar, dark coloured *Amphipora*-dominated facies are well-known from Devonian reef complexes of central Europe, where they are associated with biostromes and back-reef environments (Krebs, 1974). As such, deposition of the *Amphipora* floatstone over the biostrome in the southeast part of the study area is interpreted to indicate that this area contained the shallowest environments. This is supported by conformably overlying strata of Reef Complex #1 that contain lagoon and intertidal facies. The top of the Basal Onlapping Succession on the inner ramp is sharp (Fig. 2-5B and I).

Sequence Stratigraphic Interpretations

Facies in the Basal Onlapping Succession record deepening of the ramp and establishment of open marine environments over the regressive deposits in the Escarpment Formation. Accordingly, the succession is placed in a transgressive systems tract (TST) and its base defined as a maximum regressive surface (Fig. 2-4A). On the inner ramp, the sharp erosional base is interpreted as a ravinement surface on the underlying quartzose limestones of the Escarpment Formation (Figs. 2-5A and B and 2-6B). The change from the Escarpment Formation to Alexandra Formation, across this surface, is marked by a significant decrease in quartz content (from ≈ 10-50% to <5%) and significant increase in fossil content and diversity. Hardground development at the base of the Alexandra Formation (Fig. 2-5D), found at some localities, is consistent with a lag period that followed erosion at the top of the Escarpment Formation.

The interfingering relationship between quartzose limestones of the Escarpment Formation and the Basal Onlapping Succession at ARC-5, and *in situ* stromatoporoids in thin-bedded quartzose limestones of the Escarpment Formation at AM40, is consistent with onlapping of transgressive deposits against and over the ramp step. These stratigraphic relationships indicate the diachroneity of the transgression and suggest that the rate of initial transgression of the inner ramp was dampened by the ramp step. With progressive sea-level rise, the inner ramp became the locus of biostrome development, with the shallowest depositional environments in the southeast part of the study area. The outer ramp became increasingly sediment starved and progressively deepened, as indicated by the firmground to incipient hardground that developed across its top. In contrast to "clean" carbonate sediment, the brown colour of the Basal Onlapping Succession reflects a small percentage of organic and clay impurities in these deposits, which probably resulted from slightly reduced rates of carbonate sediment production relative to background sedimentation, as sea-level rose (cf. Krebs, 1974; Hunt and Tucker, 1993; Brett, 1995).

REEF COMPLEX #1

Facies Framework

Reef Complex #1 developed on the inner ramp conformably above the Basal Onlapping Succession while a sparsely colonized muddy seafloor blanketed the outer ramp (Fig. 2-4B). Reef Complex #1 has a maximum thickness of ≈ 21 m (core 79-10) and can be divided into shallow lagoon and intertidal, back-reef, reef, reef-front, and fore-reef depositional environments, with biotic zonations comparable to other Devonian reef complexes (e.g. Klovan, 1964; Krebs, 1974; Playford, 1980). Sections north of the ramp step include off-reef deposits, with a maximum thickness of ≈ 3 m (core ARC-4).

Lagoon deposits of Reef Complex #1, exposed along Hay River, consist of medium- to thick-bedded light-coloured *Amphipora*-dominated floatstones and rudstones (Fig. 2-6E), with abundant calcispheres, ostracods, and peloids. Fragments of *Stachyodes* are locally common in the lower part of the succession. Surfaces that bound bedsets are typically sharp and scoured. These deposits grade up into restricted deposits with oncolites and peloidal packstones, and shallow restricted to intertidal successions that include stromatolitic horizons and in some cases, desiccation cracks (Fig. 2-6F).

Back-reef deposits, recovered from core 79-9 and exposed at the top of AM06, include small domal, subspherical, and irregular stromatoporoids and thin- to medium-bedded *Amphipora*-dominated wackestones and floatstones that contain calcispheres and small oncolites. The reef, present in the area between AM06 and the top of the ramp step (AM08), is formed of a biostrome (2–3 m thick) at its base, which sharply overlies the biostrome in the Basal Onlapping Succession (Figs. 2-5I and 2-6G and H), and a series of overlying patch reefs and associated sediment up to 18 m thick. In contrast to the underlying biostrome in the Basal Onlapping Succession, which consists of stromatoporoids and large corals (e.g. *Disphyllum, Smithiphyllum, Thamnophyllum, Phillipsastrea, Alveolites*) and a brown muddy matrix (Figs. 2-5I and 2-6C), the biostrome at the base of Reef Complex #1 is dominated by laminar and tabular stromatoporoids and an off-white, porcelain-like matrix. Ostracods are the only common constituent in the matrix and colonial corals, with the exception of *Thamnopora*, are absent (Figs 2-5I and 2-6H). Truncated framebuilders at the top of the first biostrome (Fig. 2-6H), lag deposits at the base of the second biostrome, and topographic relief (±30 cm) on the surface that separates the two biostromes, indicate scour at the top of the Basal Onlapping Succession prior to growth of the second biostrome.

The patch reefs that overlie the biostrome are dominated by large (20–40 cm across and 20–30 cm high) asymmetrically ragged domal and irregular tabular stromatoporoids (Figs. 2-7A and 2-8A). Small nodular and bulbous stromatoporoids are common and thin- to medium-bedded, densely-packed *Stachyodes* floatstones and rudstones surround and bury the patch reefs (Figs. 2-7B-D and 2-8A). The patch reefs and associated *Stachyodes*-dominated sediment collectively form most of the reef. In core 79-10, the upper 10 m of the reef includes pores lined with milky-white isopachous marine cements (Fig. 2-7C). The reef-front, partly exposed at AM39, includes a framework facies dominated by laminar, tabular, and thick irregular stromatoporoids. Tabular forms of *Actinostroma* are common, as well as fasciculate rugosans, isolated skeletons of compound corals (*Phillipsastrea, Alveolites*), and horn corals. These deposits grade to the northwest into thin-bedded, rubbly, recessive brown weathering wackestones and floatstones with coral fragments, brachiopods, crinoids, laminar stromatoporoids, and *in situ* corals. This facies extends to AM08, where brachiopods are especially abundant. The thin-bedded, dark

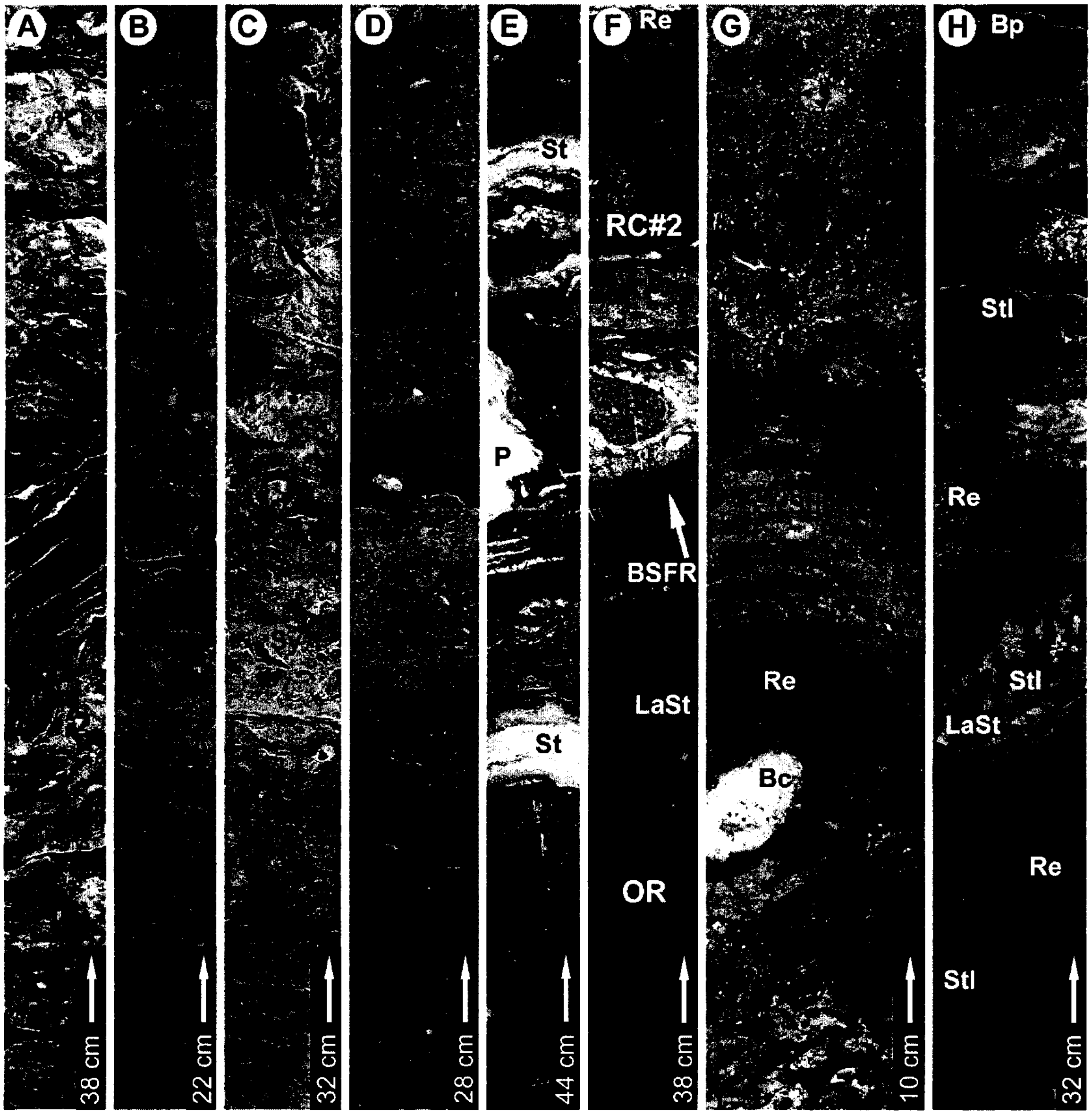

Figure 2-7. Representative facies of Reef Complex #1 (A–F) and basal biostrome of Reef Complex #2 (F–H). A–D = reef facies of Reef Complex #1 in core 79-10. **A)** Stromatoporoids (St) trap and bind *Stachyodes*-dominated sediment. **B)** *Stachyodes*-dominated (Sy) floatstone and rudstone. **C)** *Stachyodes*-dominated (Sy) floatstone and larger stromatoporoids. Marine cements (arrows) line cavities. **D)** Tabular stromatoporoid (St) overlain by *Stachyodes*-dominated (Sy) floatstone–rudstone. **E)** Off-reef facies to Reef Complex #1. Tabular stromatoporoids (St) bind dark mudstone-wackestone. P=*Phillipsastrea*. Core ARC-1. **F)** Laminar stromatoporoids (LaSt) bind mudstone in off-reef (OR) deposits of Reef Complex #1. Sharp basal surface of forced regression (BSFR) with evidence of erosion separates these deposits from overlying deposits of basal biostrome. *Renalcis* (Re) is abundant constituent in biostrome but not present below the basal surface of forced regression. Core ARC-4. **G)** Bioclasts (Bc) bound by renalcids (Re) and stromatolite (Stl). Wackestone with conspicuous black-rimmed and blackened lithoclasts partly truncate and bury stromatolite. Core 79-13, immediately above basal surface of forced regression. **H)** Renalcid (Re)–stromatolite (Stl)–laminar stromatoporoid (LaSt) bindstone with blackened pebbles (Bp). Core 79-13. Length of each core interval indicated at its bottom right.

brown, muddy nature of this facies, with crinoids and abundant brachiopods, is consistent with a marginal-slope facies (cf. Krebs and Mountjoy, 1972; Playford, 1980), and these deposits are interpreted to represent part of the fore-reef of Reef Complex #1.

At AM39, the reef-front facies is abruptly overlain by patch-reefs formed of coalesced laminar, low-domal, and irregular domal stromatoporoids, up to 60 cm across and 20 cm high, and minor domal colonial corals (*Phillipsastrea, Alveolites*). The surrounding sediment is a clean, white carbonate with abundant fragments of *Stachyodes*. These patch reefs and associated sediment are comparable to those that form the bulk of the reef, as recovered from core 79-10 and exposed at AM06, with the exception of the colonial corals. The presence of large colonial corals in the patch reef facies at AM39 is attributed to the transitional position of this locality between the reef and fore-reef environments, where these types of corals are common. At AM08, the fore-reef facies is overlain by light-coloured stromatoporoid-coral floatstones and rudstones that locally contain *in situ* colonial corals, bound by laminar and thin tabular stromatoporoids (Fig. 2-8B–D). This facies is also transitional between the fore-reef and reef environment, and is thereby treated as part of the reef-front.

Across the outer ramp, the firmground–hardground at the top of the Basal Onlapping Succession is overlain by a brown, muddy floatstone with isolated (generally ≤ 25% of facies) stromatoporoids and corals (Figs 2-5G and H and 2-7E and F). *Syringopora* commonly grew in the coenostea of stromatoporoids (caunopore structures) and corals including *Alveolites* and *Phillipsastrea* were encrusted by auloporids. Horn corals, including *Macgeea*, *Temnophyllum*, and *Tabulophyllum*, are locally abundant. Crinoids, foraminifera, *Thamnopora*, gastropods, and brachiopods are common in the dark matrix. This facies, which is predominantly muddy, is interpreted as a deeper, off-reef deposit to Reef Complex #1, indicating renewed sedimentation and minor re-colonization on the outer ramp, after drowning at the top of the Basal Onlapping Succession. In cores ARC-5 and 79-13, located close to the ramp step, sedimentation appears to have been continuous between the Basal Onlapping Succession and growth of the overlying reef complex.

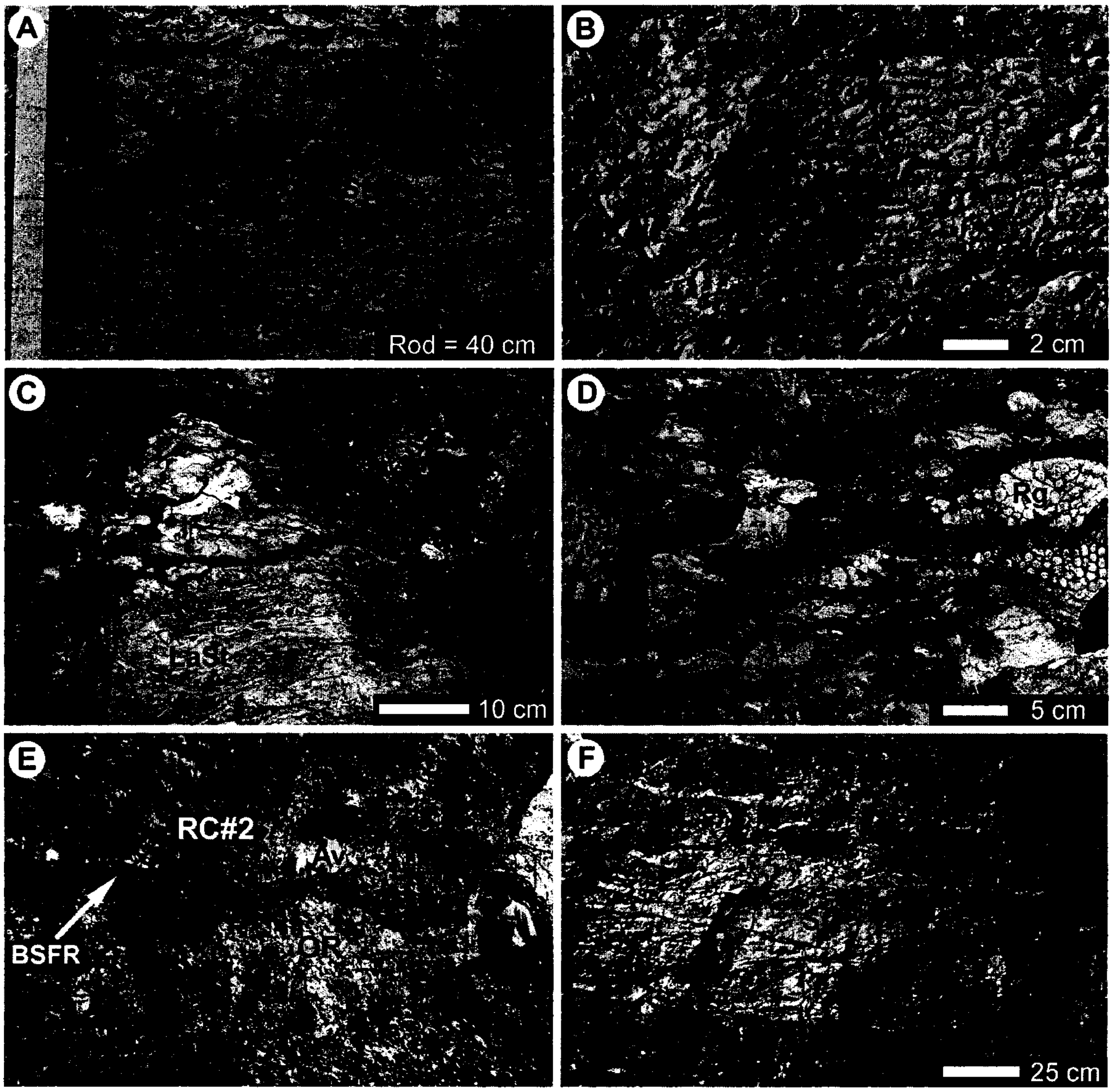

Figure 2-8. Representative facies of Reef Complex #1 (A–E) and basal biostrome of Reef Complex #2 (E and F). **A)** Patch reef facies. Large ragged asymmetrical domal stromatoporoid (St) overlying medium-bedded *Stachyodes* floatstone–rudstone (Sy). Locality AM06. **B)** Reef-front facies. *Stachyodes–Thamnopora*–laminar stromatoporoid rudstone. Locality AM08. **C)** Reef-front facies. Laminar stromatoporoid (LaSt) bindstone and floatstone (FSt). Locality AM08. **D)** Reef-front facies. Fasciculate rugosans (Rg) and floatstone. Locality AM08. **E)** Sharp, irregular basal surface of forced regression (BSFR) separating off-reef (OR) facies of Reef Complex #1 from basal biostrome of Reef Complex #2 (RC#2). Biostrome consists of ≈ 60% stromatoporoids and corals, including large *Alveolites* (Av), at this locality (AM31). **F)** Tabular stromatoporoid bindstone (≈ 40% framebuilders). Locality AM102.

Sequence Stratigraphic Interpretations

Reef Complex #1 conformably overlies the transgressive deposits that form the Basal Onlapping Succession (Fig. 2-4B), and is placed in a highstand systems tract (HST). The base of Reef Complex #1 is the maximum flooding surface at the top of the underlying transgressive systems tract. It separates the brown, muddy biostrome and *Amphipora* floatstones in the Basal Onlapping Succession from off-white lagoon facies in the Hay River area (e.g. compare Fig. 2-6D with E) and the biostrome in the middle and outer areas (Figs. 2-5I and 2-6G and H) of the inner ramp. The maximum flooding surface on the outer ramp is the firmground and incipient hardground at the top of the Basal Onlapping Succession (Fig. 2-5G and H). Continued sedimentation in the area close to the ramp step, however, precluded its development in cores ARC-5 and 79-13.

The vertical succession of lagoon to intertidal deposits along Hay River, reef to back-reef facies at AM06, reef-front to reef facies at AM39, and fore-reef to reef-front facies at AM08, is consistent with gradual shallowing-upwards of marine environments located above the ramp step, as carbonate production outpaced the rate of relative sea-level rise and accommodation in the shallow marine realm was consumed. In contrast, only patchy colonization of the outer ramp is apparent; there is no indication of shallowing environmental conditions, consistent with the assignment of these deposits to the HST.

Termination and diagenesis of Reef Complex #1

Reef Complex #1 was terminated by a fall in sea-level and subaerial exposure (Fig. 2-4C), as indicated by 1) a coastal plain succession of palustrine deposits and subaerially weathered marine carbonates, ≈ 50 cm thick, that caps intertidal deposits exposed along Hay River (MacNeil and Jones, 2006; Fig. 2-9A–C), 2) breccias and small (1–2.5 cm) solution vugs lined with pendant cements and microstalactites (Fig. 2-9D–H) in the upper 2 m of reef deposits in core 79-10, and 3) eventual deposition of lagoon and intertidal deposits of Reef Complex #2 at AM08, directly above the fore-reef and reef-front deposits of Reef Complex #1. This abrupt facies change in the fore-reef of Reef Complex #1 could only be produced by a significant fall in sea-level and an abrupt, basinward shift of the coastal environment (cf. Emery and Meyers, 1996; Lehrmann and Goldhammer, 1999). The difference of ≈ 17 m between the top of Reef Complex #1 and the base of the intertidal facies that would be later deposited at AM08 (measurement shown on Fig. 2-4C) is considered indicative of the magnitude of relative sea-level fall, although discontinuous exposure of the escarpment in this area allows for the possibility that it actually fell to a slightly lower position on the outer ramp. Irrespective, the known

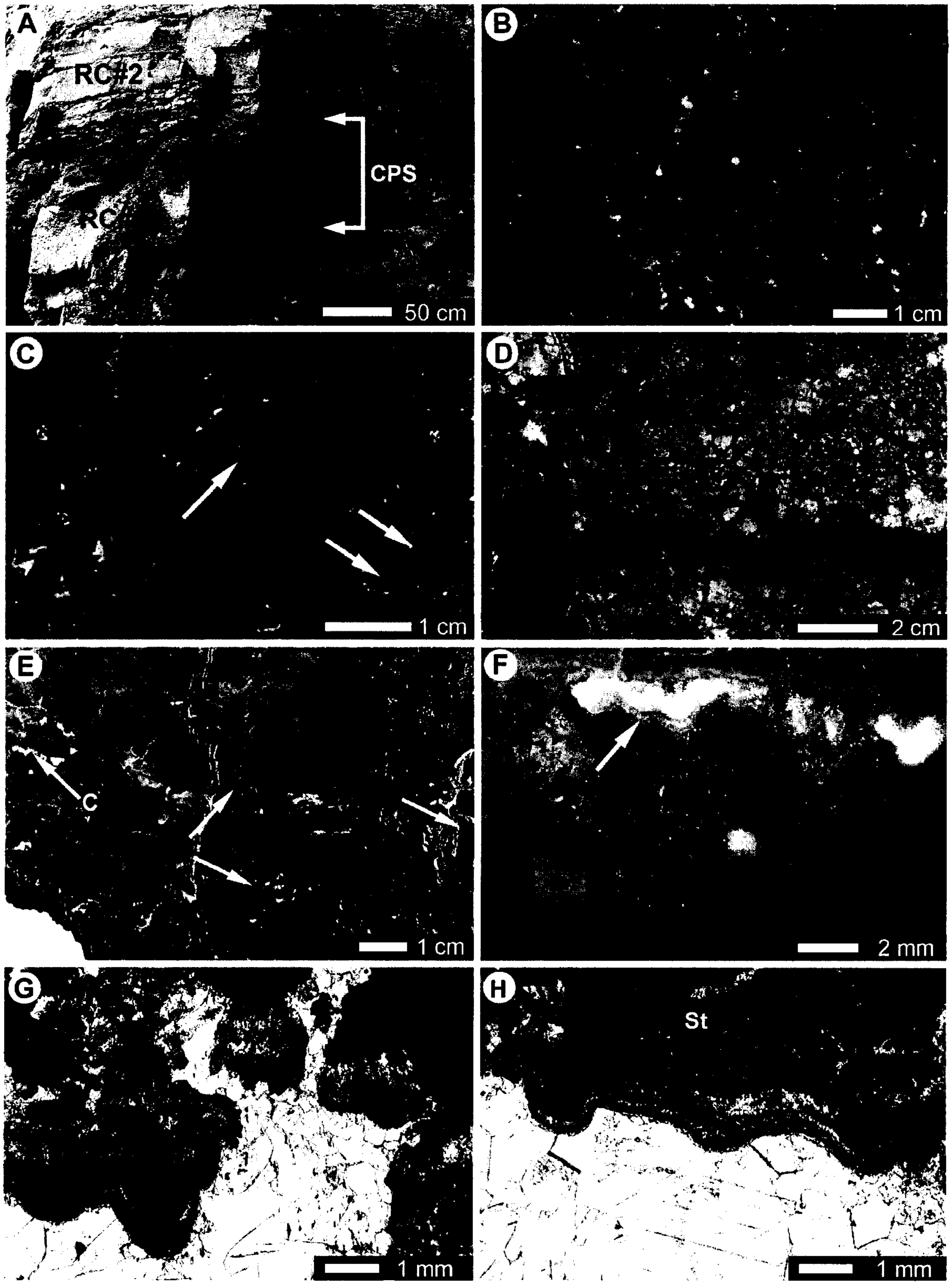

Figure 2-9. Features of Sequence Boundary #1. **A)** Coastal plain succession (CPS) of palustrine deposits and weathered marine deposits at top of Reef Complex #1 (RC#1). Peritidal deposits of the transgressive systems tract of Reef Complex #2 (RC#2) overlie the coastal plain succession. Alexandra Falls Section. **B)** Polished sample of palustrine deposit. Incipient nodular texture and white blebs are

partly clay-filled root-traces. **C)** Polished sample of palustrine deposit with blackened lithoclasts (arrows). **D)** Brecciation texture associated with solution vugs. Coarse calcite cement fills vugs. Drill location of 79-10. **E)** Polished sample of D. Arrows indicate irregular solution channels and vugs, some lined with vadose cement (C). **F)** Detail of vug in E with vadose pendant cement (arrow). **G)** Photomicrograph of F. Pendant and microstalactitic cements in vug, filled with late-stage coarse calcite cement. **H)** Photomicrograph of microstalactite below stromatoporiod (St).

magnitude of sea-level fall (≈ 17 m) must have exposed most of Reef Complex #1, and its top is defined as a Type I sequence boundary (Sequence Boundary #1).

The lack of karst across the top of Reef Complex #1 suggests that the climate of the region was likely semi-arid (cf. Esteban and Klappa, 1983), consistent with global climate models for the Late Devonian (Golonka *et al.*, 1994). Under these climatic conditions, meteoric alteration of Reef Complex #1 above the phreatic zone was probably minor (Wright, 1988; James and Choquette, 1990), especially as plants with deep root systems had not yet evolved (Gensel and Andrews, 1984; Raven and Edwards, 2001). A unique zone of intense limestone dissolution on the inner ramp (1–3 m thick), situated at the base of Reef Complex #1 and in the Basal Onlapping Succession (Fig. 2-4C), however, may be attributed to dissolution in or below a meteoric phreatic zone.

At AM06, bioclasts and framebuilders in the dissolution zone, including corals up to 25 cm across, were partly to completely dissolved to produce large biomoldic and vuggy porosity (Fig. 2-10A and B), comparable to meteoric dissolution features found in Cenozoic carbonates (e.g. Back *et al.*, 1986; Jones and Hunter, 1994). Matrix between the framebuilders was replaced by sucrosic dolomite, and in many cases, intricate dolomite replacement preserved the morphology of corallite molds (Fig. 2-10C). Some vugs in non-dolomitized framebuilders were filled, or partly filled, by dolomite cements (Fig. 2-10D), indicating porosity evolution prior to or concurrent with dolomitization. Stratabound by limestone, the dolomitization extends as far north as 79-10, where it overprints the base of the formation. As this dolomitization trend may have been controlled by enhanced porosity in the dissolution zone (e.g. Dawans and Swart, 1988; MacNeil and Jones, 2003), its distribution is used to interpret the original extent of alteration (Fig. 2-4C).

Key points about the alteration zone include its 1) horizontal geometry, 2) intensity of alteration, not found elsewhere in the Alexandra Formation, and 3) development below the subaerial exposure surface at the top of Reef Complex #1, coincident with the

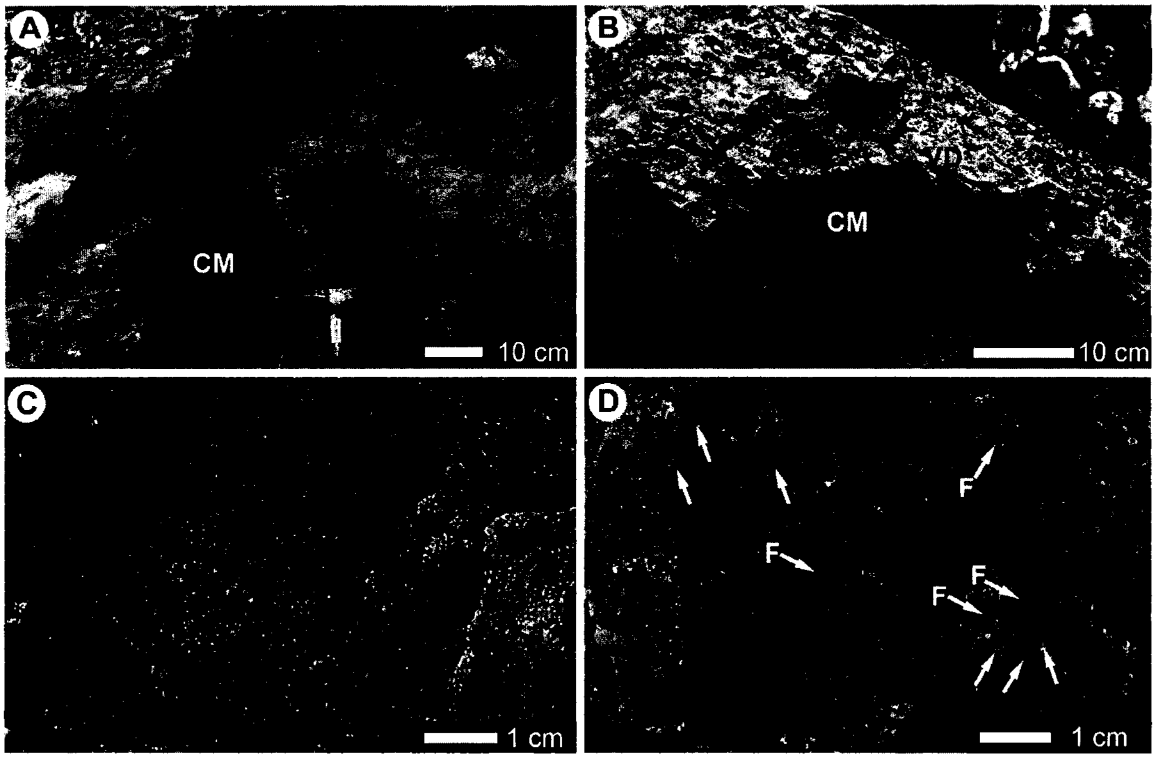

Figure 2-10. Features of diagenetic alteration zone at base of Reef Complex #1 and in Basal Onlapping Succession. Locality AM06. A) Vuggy dolostone (VD) with large irregular coral molds (CM). Corallite molds visible inside coral mold indicate cavity evolved through dissolution of large fasciculate rugosan. B) Vuggy dolostone (VD) with large coral mold (CM) after dissolution of *Phillipsastrea*. C) Partial mold of *Phillipsastrea* with individual corallite molds well-preserved by sucrosic dolomite. D) Calcitic, partly dissolved, stromatoporoid. Some vugs (arrows) are partly filled with euhedral dolomite cement. Other vugs (arrows labeled 'F') and fracture (Fr) completely filled with dolomite cement (alizarin red-S used to distinguish dolomite).

approximate position of the meteoric phreatic zone and/or meteoric phreatic–saline water mixing-zone (Fig. 2-4C). Although both of these hydrological zones may favour carbonate dissolution, intense carbonate dissolution is well known from mixed-water zones (e.g. Plummer, 1975; Hanshaw and Back, 1980; Smart *et al.*, 1988). As such, it seems reasonable to suggest that the zone of dissolution on the inner ramp developed as a function of subsurface, meteoric-related diagenesis, associated with the lowered sea-level position. The timing and mediating fluids of dolomitization, however, remain unknown and are beyond the scope of the chapter.

REEF COMPLEX #2

Development Stage of Reef Complex #2 – Facies Framework

Reef Complex #2 was initiated by the development of a stromatoporoid-dominated biostrome (up to 4 m thick) across most of the outer ramp (Fig. 2-4C). The contact between underlying off-reef deposits and the base of the biostrome, in the landward and middle region of the outer ramp is sharp, and locally erosive (Figs. 2-7F and 2-8E). Basinward of AM100 (Fig. 2-1), however, the contact is gradational over a thickness of ≈ 1 m. Laminar and tabular stromatoporoids in the biostrome, some of which exceed 1 m in width (Fig. 2-8F), are often capped by stromatolites and bound to other stromatoporoids and corals by thick masses of renalcid boundstone (Fig. 2-7F-H). Locally, the microbial component exceeds ≈ 75% of the framework. Sediment bound in the framework commonly includes conspicuous blackened and black-rimmed lithoclasts (Fig. 2-7G and H). Also found in the coastal plain succession that was developing above Reef Complex #1 (Fig. 2-9C), these lithoclasts almost certainly originated from subaerial exposure and weathering of the limestones at the top of Reef Complex #1 (MacNeil and Jones 2006), followed by transport to the outer ramp by storms.

Between AM20 and AM23, the biostrome developed upwards into bioherms that are 300–400 m wide and have 5–7 m of synoptic relief (Fig. 2-4C). These were dominated by anastamosing laminar stromatoporoids, with accessory stromatolites, *Thamnopora*, and large colonial corals (*Phillipsastrea*, *Alveolites*). Subsequent development of an inner buildup above these bioherms, and an outer buildup above the biostrome in the area between AM37 and ARC-2, defined a margin to the developing reef complex (Fig. 2-11D). A broad reef-front developed in front of the outer buildup, whereas a back-reef and shallow lagoon developed behind the inner buildup. In a low area between the inner and outer buildups, termed the intra-buildup low, laminar stromatoporoid-renalcid bioherms developed. The transition from the biostrome at the base of Reef Complex #2 to these deposits of differentiated environments was gradational over ≤ 1 m and marks the last occurrence of black-rimmed lithoclasts.

The inner buildup (≈ 8 m thick) is characterized by *in situ* and reworked laminar stromatoporoid–coral (*Phillipsastrea*, *Alveolites*, *Thamnopora*) deposits. In many cases, stromatoporoid–coral debris is bound by tabular and anastamosing stromatoporoids (Fig.

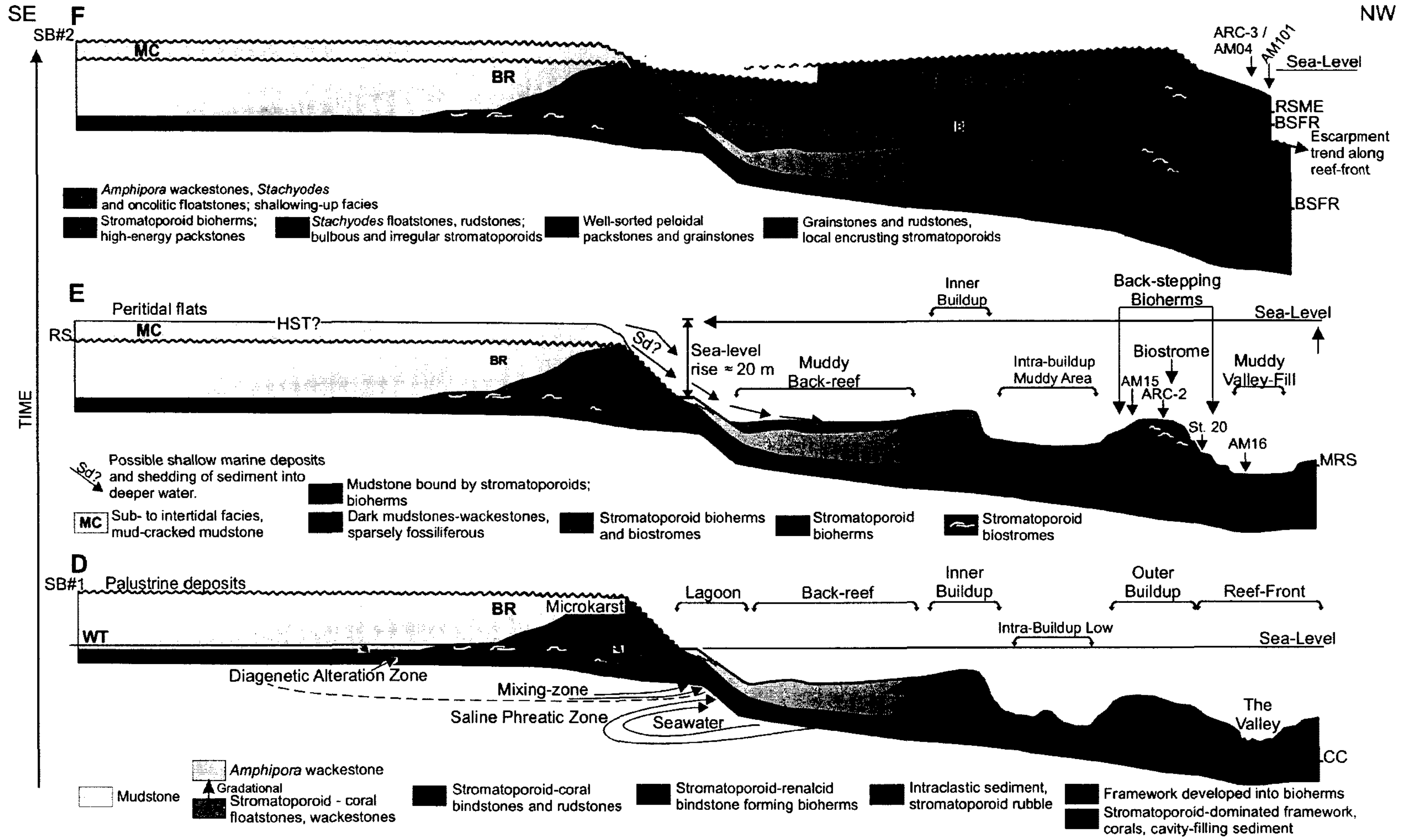

Figure 2-11. Sequence stratigraphic evolution, continued from Fig. 2-4. CC=Correlative conformity; RSME=Regressive surface of marine erosion. Note perspective in reef-front of Reef Complex #2 is viewing down long axis of reef-front valley, toward fore-reef, due to change in escarpment orientation (see Fig. 2-1). **D)** Lowstand systems tract and differentiation of environments in Reef Complex #2. **E)** Flooding stage and transgressive systems tract (±highstand systems tract), as sea-level rose ~20 m. **F)** Fence diagram. Sea-level fall and termination phase. Deposits proximal to ramp step probably deposited in highstand systems tract (HST) from shallower environments, before sea-level started to fall (depicted in Fig. 2-11E). Remaining deposits assigned to falling stage systems tract. Sequence Boundary #2 (SB #2) caps Reef Complex #2.

2-12A). The outer buildup (≈ 14 m thick in ARC-4) is formed of stromatoporoid–coral debris and intraclastic sediment lithified by renalcid masses, stromatolites, and marine cements (Fig. 2-12B and C). Fragments of laminar stromatoporoids and large (locally > 1 m) tabular actinostromids, in a variety of orientations that include upside-down and sub-vertical, relative to their initial growth positions (determined from their latilaminae), are found throughout the outer buildup (Fig. 2-12B). Large *in situ* stromatoporoids have not been found, but the reef-front area is dominated by *in situ* and locally transported stromatoporoids, including tabular actinostromids (Fig. 2-12D). As such, most of the outer buildup appears to be reworked storm deposits, with a significant component having been "pruned" from the reef-front (cf. Blanchon and Perry, 2004).

The escarpment, which changes orientation to a more northerly trend in the northern part of the study area (Fig. 2-1), provides a unique perspective through the outer margin of Reef Complex #2. Rather than cutting into and exposing fore-reef deposits, the escarpment cuts along the reef-front until it is terminated at Fault F. Most of the exposed reef-front is characterized by laminar and tabular stromatoporoids (up to 2.2 m wide), with accessory colonial and solitary horn corals (Fig. 2-12D and E). Sediment is characterized by grey-green wackestones and floatstones with brachiopods, crinoids, ostracods, and fragmented pieces of stromatoporoids and corals. Thin layers of green mud, generally < 0.5 cm but locally up to 2 cm thick, periodically cover the flat, top surfaces of stromatoporoids (Fig. 2-12F). The green muds were probably derived from deeper, outer ramp environments and deposited from suspension onto the skeletons as storms diminished.

The escarpment trend that exposes the reef-front also exposes a relatively deep 'valley' that divided the continuity of the reef-front and presumably opened into the fore-reef (Fig. 2-11D). Stromatoporoid-coral bioherms, with abundant *Alveolites*, horn corals (*Macgeea, Temnophyllum*), brachiopods, and crinoids with large ossicles (e.g. ≈ 1 cm diameter), grew in the deepest parts of the reef-front valley. Flanks of the bioherms dip up to ≈ 30°, and in some cases are interbedded with dark mudstones and wackestones (Fig. 2-12G and H). Controls on development of the valley are not fully understood, but probably included lower accumulation rates, relative to the surrounding reef-front.

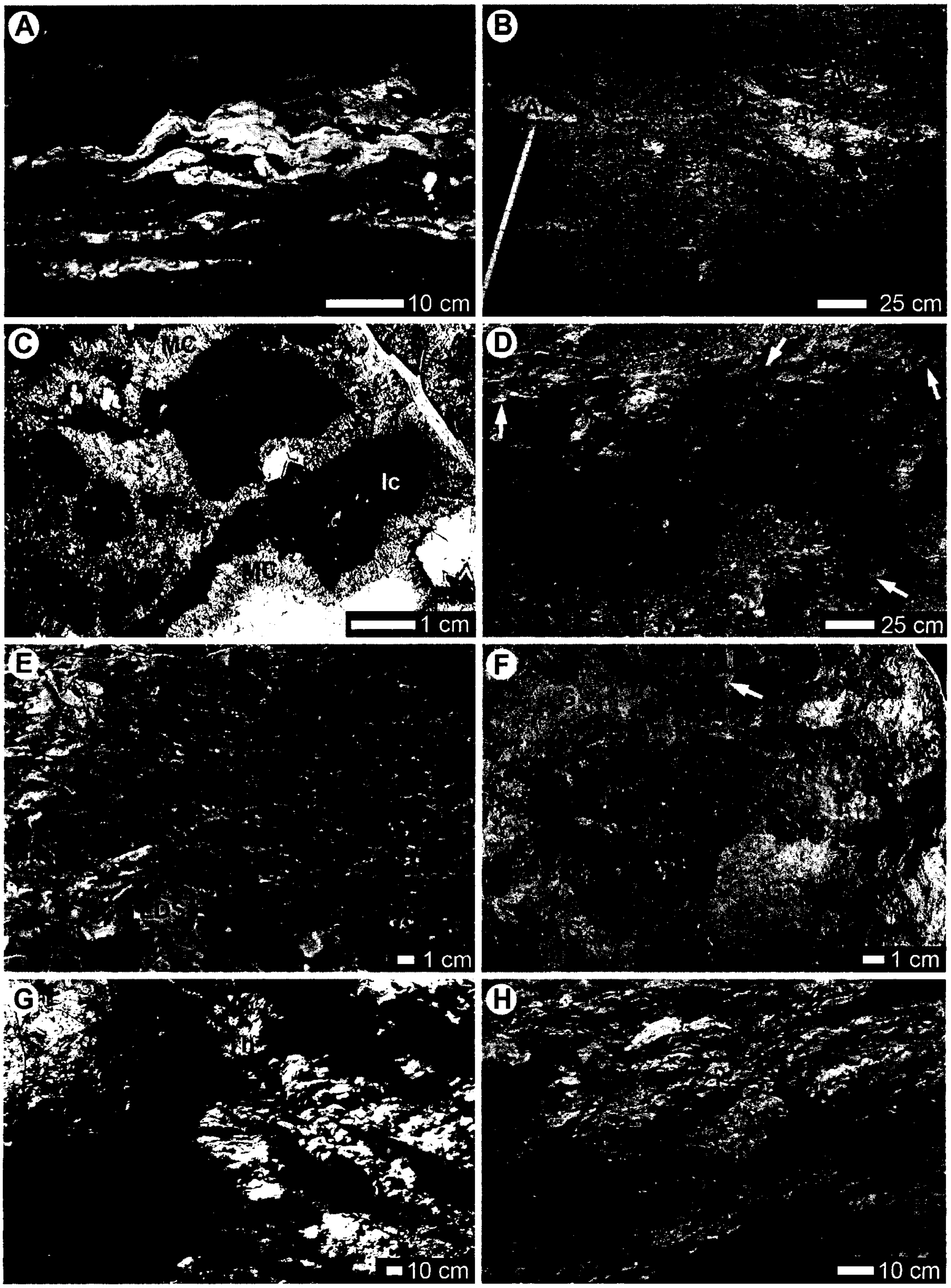

Figure 2-12. Representative facies of Reef Complex #2, lowstand systems tract. **A)** Anastamosing tabular-low domal stromatoporoids bind skeletal floatstone in inner buildup. Near locality AM20. **B)** Large fragmented pieces of *Actinostroma* (Ac) in intraclastic wackestone-grainstone lithified by microbial constituents and marine cements. Locality AM18. **C)** Photomicrograph of intraclastic grainstone

lithified by isopachous coarse-fibrous marine cements (MC). Note angular nature of intraclasts (Ic). Core ARC-4. **D)** Large tabular and concave-up *in situ Actinostroma* (Ac) and tabular stromatoporoids (some indicated with arrows) in reef-front facies. Locality AM03. **E)** Densely-packed framework of laminar-tabular and low-domal *in situ* stromatoporoids (LDSt) in reef-front facies. Near locality AM03. **F)** Bedding-plane exposure of laminar stromatoporoid (LSt) – coral (P=*Phillipsastrea*) framework of reef-front facies. Note partly preserved green muds (G) that dusted top-surfaces of skeletons. Physical compaction cracks (arrow) in laminar stromatoporoid (top-center of photograph) filled with green mud. Locality AM03. **G)** Thin-bedded flank of bioherm in reef-front valley. Note that dip of beds decreases towards left of photograph, away from bioherm core. Large thicket (Th) of *Smithiphyllum* overtop of bioherm flank developed in succeeding transgressive systems tract. Locality between AM16 and AM03. **H)** Close-up of dipping flank of bioherm in G. *In situ* tabular and low-domal (arrow) stromatoporoids (St) common.

Behind the inner buildup, reef-front deposits at the margin of Reef Complex #1, exposed at AM08 (Fig. 2-8B–D), are onlapped by shallowing-upward lagoon deposits of Reef Complex #2 (Fig. 2-13A–C). The lagoon deposits are characterized by *Amphipora*-dominated floatstones – rudstones (Fig. 2-13D and E), sharply overlain by thin-bedded, fenestral, partly bioturbated and locally intraclastic mudstone (Fig. 2-13F–H). Finely crystalline, distinctly yellow-weathering dolomite rhombs are present in the fenestral mudstone and burrow fills (Fig. 2-13I). Similar facies described by Read (1973) and Shinn (1983) were deemed to have been deposited in shallow, restricted subtidal and intertidal environments, which probably also characterized this area of the lagoon in Reef Complex #2. Increased restriction of environments, evident from the vertical succession, may reflect development of the margin to Reef Complex #2 and increased sediment production. The approximate sea-level position indicated by these deposits is coincident with the alteration zone on the inner ramp (Fig. 2-11D).

Sequence Stratigraphic Interpretations

Development of shallow marine environments over the gently sloping outer ramp, as a result of the falling sea-level that terminated Reef Complex #1, facilitated initiation and

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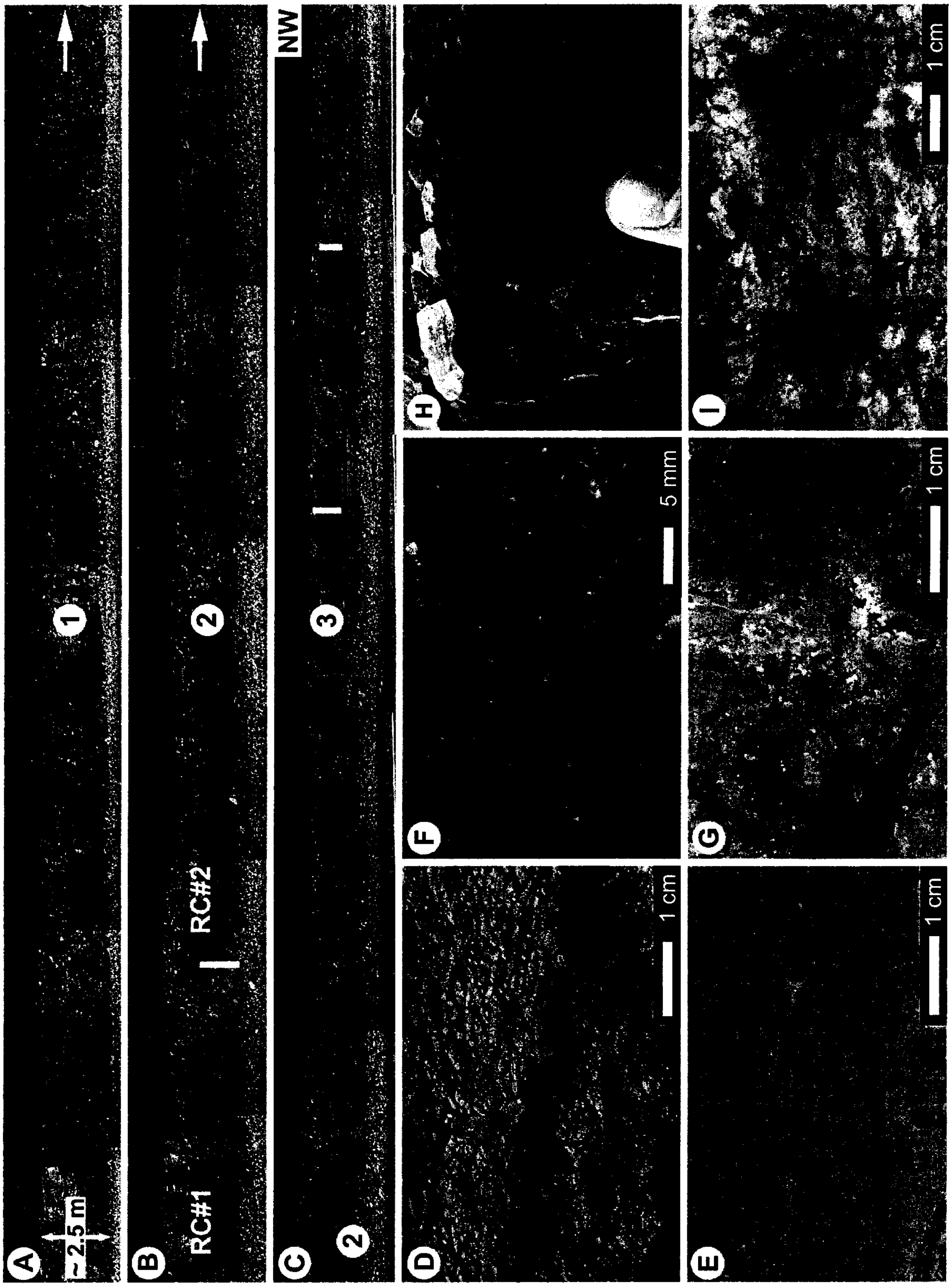
Figure 2-13. Deposits of Reef Complex #2 onlapping margin of Reef Complex #1. Locality AM08. A–C) Composite image. Right edge of A (arrow) connects with left edge of B, right edge of B (arrow) connects with left edge of C. **A)** Reef-front strata (1) of Reef Complex #1. **B)** Approximate contact of Reef Complex #2 lagoon facies (2) against reef-front strata of Reef Complex #1. White bar indicates location of samples figured in parts D and E. **C)** Restricted, possibly intertidal facies (3) sharply overlie lagoon facies (2) of Reef Complex #2. White bars indicate location of samples figured in parts F–I. **D)** *Amphipora* rudstone in lagoon facies. **E)** Polished sample of *Amphipora*-dominated floatstone in lagoon facies. Abundant calcispheres in matrix. **F)** Fenestral mudstone in restricted facies. **G)** Burrow-mottled, sparsely fossiliferous mudstone of restricted facies. Calcispheres common. **H)** Intraclastic wackestone in restricted facies. **I)** Partly dolomitized (dark, irregular patches) burrowed mudstone.


A
~2.5 m
1
B
RC#1
RC#2
2
C
2
3
NW
D
1 cm
E
1 cm
F
5 mm
G
1 cm
H
I
1 cm

development of Reef Complex #2 (Figs. 2-4C and 2-11D). As the basal biostrome lacks evidence of restricted marine deposits (e.g. a lagoon) or high-energy, wave-dominated facies, which would be expected to characterize deposits in a lowstand systems tract (e.g. Hunt and Tucker, 1993), it is interpreted to have developed as sea-level was falling, rather than after sea-level reached its lowest relative position. As such, the basal biostrome is assigned to the falling stage systems tract (FSST). Its basal surface, sharp and well-defined over the part of the outer ramp landwards of AM100, is the basal surface of forced regression and reflects a period of non-deposition that preceded its development. The presence of this lag period is supported by the blackened lithoclasts in the biostrome, which first needed to be produced on the coastal plain above Reef Complex #1, and then transported to the outer ramp, before they could be incorporated into its framework. Incorporation of such lithoclasts is characteristic of forced regressive deposits (Hunt and Tucker, 1995).

Differentiation of reef environments above the basal biostrome is attributed to sea-level reaching its lowest position and the largest portion of the outer ramp being transformed into shallow marine environments. This can be anticipated to have facilitated higher rates of carbonate production (cf. Schlager, 1981) and increased depositional energies. This is exemplified in the area of the outer buildup, where the framework of the basal biostrome (Fig. 2-8F) passes abruptly upwards into high-energy deposits of stromatoporoid debris and intraclastic sediment (Fig. 2-12B and C), that cumulatively form the outer buildup. As such, the differentiation phase of Reef Complex #2 is assigned to the lowstand systems tract (LST). The FSST-LST change is gradational over ≈ 1 m and contains the correlative conformity to Sequence Boundary #1 (Fig. 2-11D).

Consumption of accommodation in the LST was variable. In the back-reef and lagoon, carbonate production increased such that lagoon deposits onlapped the reef-front of Reef Complex #1. In contrast, the absence of a progradational margin suggests that accretion of the margin did not outpace the rate of rising sea-level. The extent of margin accretion was probably a function of a number of factors that included the rate of carbonate sediment production, framebuilder growth rates, and the magnitude of sediment redistribution across the reef complex, as mediated by storms.

Flooding of Reef Complex #2 – Facies Framework

Development of Reef Complex #2 was interrupted by an acceleration in the rate of relative sea-level rise, such that flooding of its environments and significant depositional changes took place (Fig. 2-11E). Reefal facies in the distal reef-front (core ARC-3) are sharply overlain by a sparsely fossiliferous bioturbated dark mudstone–wackestone, interpreted to indicate that this region of the reef-front drowned. Bioherms in the reef-front valley ceased developing (Fig. 2-14A), and large (up to 6 m across and 1 m thick) thickets of fasciculate rugosans (*Smithiphyllum*) grew between their crests (Figs. 2-12G and 2-14B). Similar rugosan coral thickets have been documented as occurring in deep fore-reef and lower ramp environments, well below normal wave base (e.g. Klovan, 1964; Embry and Klovan, 1972; Madi *et al.*, 1996). Deposition of dark, organic-rich, thin-bedded mudstones (up to 4.5 m thick) eventually buried the thickets and surrounding bioherms (Fig. 2-14A, C, and D).

The reef-front architecture changed from massive to biohermal (Fig. 2-14E). Bioherms in the reef-front graded into a stromatoporoid-dominated biostrome (≈ 10 m thick) that covered the outer top half of the outer buildup. The biostrome is dominated by tabular stromatoporoids that unlike stromatoporoids in any other part of the reef complex, tightly coalesced with each other to form a dense framestone. Locally, small patches of fasciculate rugosans are present. The biostrome graded to the south into bioherms, which covered the inner flank of the outer buildup (Fig. 2-14F). Some of these bioherms, situated lower down its inner flank, were eventually buried in dark mudstones. Most bioherms were small (<30 m diameter and <3 m high), but by coalescing (maximum thickness ≈ 8 m), continued to build the profile of the outer buildup. On the flanks of the outer buildup, the change to bioherm development was abrupt. On the top of the outer buildup, the change was gradational over 1–2 m.

Bioherms in the intra-buildup low were buried under dark, organic-rich mudstone-wackestones, similar to those in the reef-front valley, with abundant cricoconarids (Fig. 2-15A). Flooding over the inner buildup filled depressions with dark muddy sediment bound by laminar and tabular stromatoporoids. Fasciculate rugosans and horn corals are locally abundant. The top of the inner buildup was covered by *Stachyodes* floatstone with crinoid debris and colonized by larger tabular stromatoporoids that formed broad

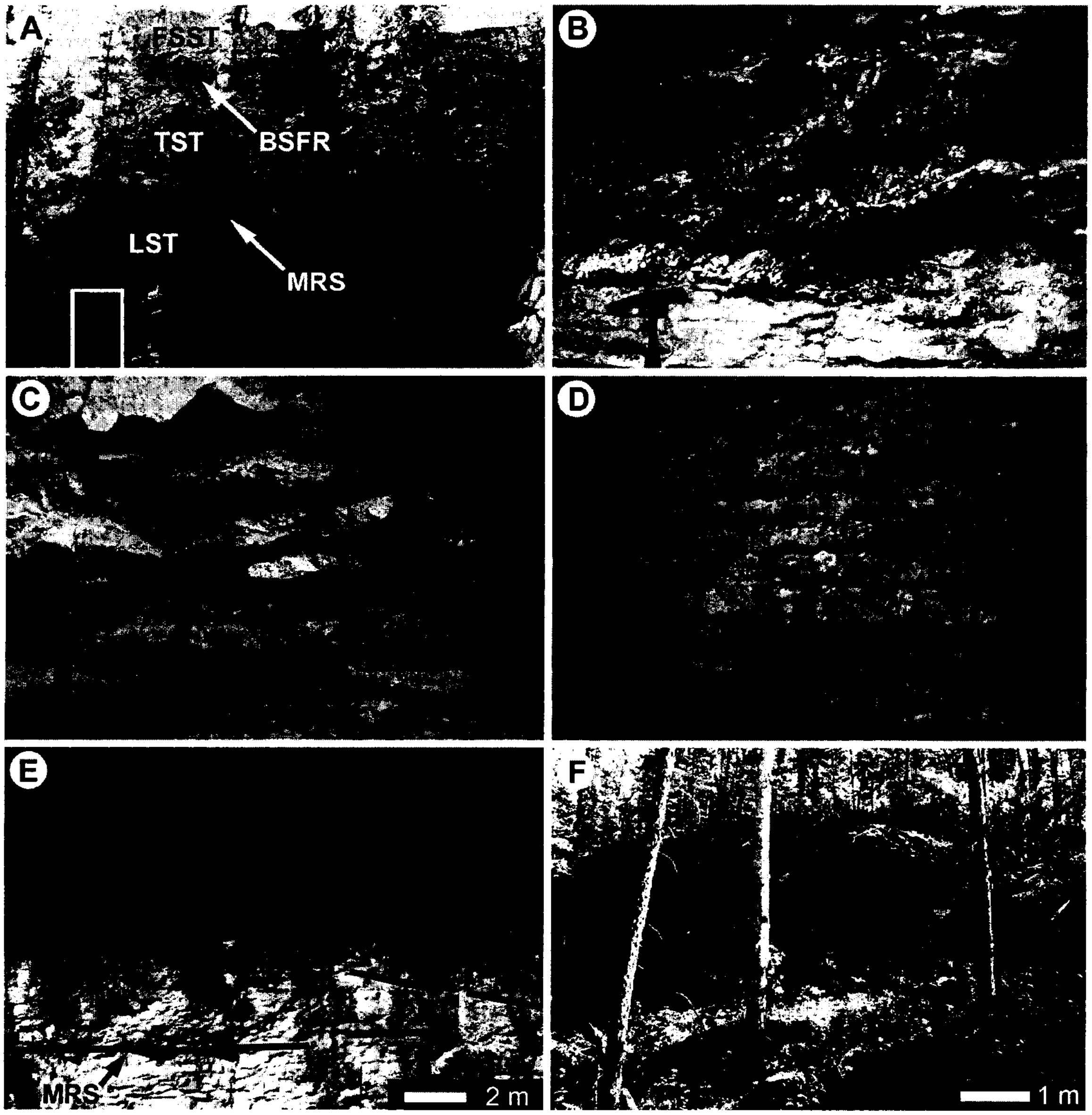


Figure 2-14. Representative facies of Reef Complex #2, transgressive systems tract. A–D=Locality AM16. **A)** Lowstand–transgressive–falling stage systems tract succession in reef-front valley. Bioherm of lowstand systems tract (LST) sharply overlain by discordant beds of dark mudstone of transgressive systems tract (TST). Top surface of bioherm is maximum regressive surface (MRS). Transgressive systems tract sharply overlain by unit of *Stachyodes* floatstones and rudstones that belongs to the falling stage systems tract (FSST). Basal surface of forced regression (BSFR) marks base of falling stage systems tract. Person in box for scale. **B)** *In situ Smithiphyllum* thicket. Located left of bioherm in A. **C)** Isolated, *in situ Smithiphyllum* in thin-bedded, sparsely fossiliferous mudstones. **D)** Thin-bedded, dark, organic-rich mudstones that bury coral thickets and fill reef-front valley. Person for scale. **E)** Broad bioherms overtop of massive reef-front. Maximum regressive surface (MRS) separates the two reefal architectures. Locality near AM100. **F)** Right-flank of bioherm on top of outer buildup. Locality AM15.

bioherms. In the back-reef area, light-coloured *Amphipora*-wackestones that contain calcispheres, typical of very shallow lagoon environments (e.g. Klovan, 1964; Playford,

1980) are sharply overlain by dark, organic-rich mudstones, bound by laminar and thin tabular (e.g. < 1 cm thick) anastamosing stromatoporoids into mud-dominated bioherms with flanks that dipped up to 50° (Figs. 2-15B and 2-16B). Horn corals and fragmented pieces of fasciculate rugosans (*Smithiphyllum*) are locally common. The common occurrence of cricoconarids in these organic-rich mudstones, and the mudstones-wackestones deposited elsewhere across the flooded expanse of Reef Complex #2, is consistent with deposition in deep marine conditions (cf. Leavitt, 1968; Noble, 1970; Krebs, 1974; Whalen *et al.*, 2000b).

The magnitude of sea-level rise was sufficient that the coastal plain above the top of Reef Complex #1 also eventually flooded. Its flooding, however, was highly diachronous, as indicated by a short-lived marine incursion that preceded the main event. The short-lived marine incursion deposited a unit of *Amphipora* floatstone, ≈ 35 cm thick, with fragmented and abraded corals, stromatoporoids, and brachiopods, interpreted as storm debris transported from an area basinward of the ramp step. Subsequent retreat of the shoreline and subaerial exposure of the unit is indicated by a number of pedogenic features that include root traces, rhizocretions, authigenic clays, and intense black and red staining (MacNeil and Jones, 2006). As sea-level rose above the top of Reef Complex #1 for the second time, permanent flooding of the coastal plain established an expansive region of peritidal flats (Figs. 2-9A and 2-15C). Along Hay River, these deposits are characterized by repeated shallowing-upward successions, 0.5 – 1 m thick, and desiccation cracks on several bedding planes (Fig. 2-15D) attest to repeated subaerial exposure, probably in the supratidal zone (cf. Shinn, 1983). At locality 79-10, peritidal deposits characterized by intertidal to shallow-restricted, thin-bedded stromatolitic deposits with fenestral fabrics sharply overlie reef facies of Reef Complex #1. Presumably these deposits graded basinward into shallow, open marine deposits, that extended down the ramp step into the flooded back-reef area of Reef Complex #2 (Fig. 2-11E). Unfortunately, deposits from this transition zone are not preserved at the surface.

Sequence Stratigraphic Interpretations

Flood-related deposits and corresponding changes in reef architecture, across Reef Complex #2, constitute a transgressive systems tract (Fig. 2-11E). The surface between

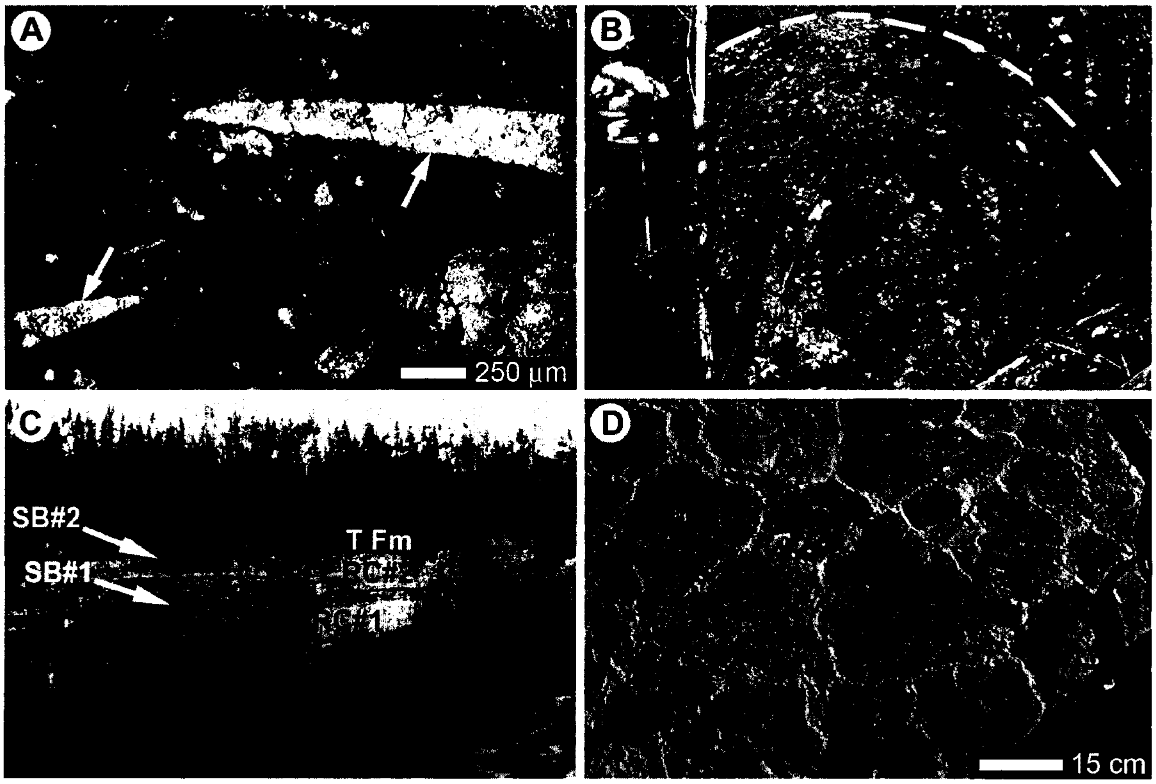


Figure 2-15. Representative facies of Reef Complex #2, transgressive systems tract. **A)** Thin-section photomicrograph of dark, organic-rich muddy wackestone with cricoconarids (arrows). Locality AM23. **B)** One of several steep-flanked, mud-dominated bioherms that developed in flooded back-reef of Reef Complex #2. Differential erosion of less-resistant surrounding muds exhumed bioherm. Person for scale. Locality AM02. **C)** Section along Hay River near Alexandra Falls. Reef Complex #1 (RC#1) forms most of lower part of section. Coastal plain succession marks Sequence Boundary #1 (SB#1). Peritidal deposits of Reef Complex #2 (RC#2) overlie Sequence Boundary #1. Upper part of peritidal deposits probably belong to highstand systems tract. Sequence Boundary #2 (SB#2) caps top of Alexandra Formation, and is overlain by the Twin Falls Formation (T Fm). Total cliff height ≈ 35 m. **D)** Mudcracks exposed on supratidal-intertidal bedding plane. Alexandra Falls Section.

the underlying reef complex and these deposits is the maximum regressive surface, and the different depositional responses to flooding are reflected in its character.

At the distal reef-front and fore-reef (ARC-3, Fig. 2-16A), and in the reef-front valley (Fig. 2-14A), intra-buildup low, and back-reef (Fig. 2-16B), the maximum regressive surface is located at the base of the dark mudstones. Where the reef-front developed up into bioherms, the maximum regressive surface occurs at the base of the bioherms (Fig. 2-14E). Where the biostrome developed above the outer buildup, the gradational change from sediment to tabular stromatoporoid framestone is interpreted to reflect the flooding event. A distinct surface, however, was not developed.

The base of the bioherms on the top and inner flanks of the outer buildup is considered to mark maximum regression. As the bioherms consist of *in situ* stromatoporoid-dominated deposits overtop of rubbly intraclastic deposits, the facies contrast is prominent and the maximum regressive surface is distinct. In the inner buildup, the maximum regressive surface is placed at the sharp surface that separates stromatoporoid–coral deposits from lower-energy, muddy deposits that filled depressions and *Stachyodes* floatstones and stromatoporoid-dominated framestones that were deposited on top. Above Reef Complex #1, the top of the short-lived marine incursion marks the top of the coastal plain succession (Fig. 2-9A) and the sequence boundary. The overlying peritidal succession is assigned to the TST, and its sharp base, which shows evidence of scour, is labeled as a ravinement surface (Fig. 2-11E). The upper part of the peritidal succession above Reef Complex #1 probably belongs to the ensuing highstand systems tract, but the cyclical nature of these deposits renders distinction of the HST from the TST difficult.

Regional Shallowing and Termination of Reef Complex #2 – Facies Framework

Extensive regional shallowing, high rates of carbonate sedimentation, and subaerial exposure followed the regional flooding event (Fig. 2-11F). Dark muddy bioherms in the back-reef of Reef Complex #2 are sharply overlain by light-coloured *Amphipora*-dominated wackestones with abundant calcispheres, interbedded with well-sorted calcisphere-dominated wackestones (Fig. 2-16C). Over the inner buildup, stromatoporoids maintained development of bioherms and biostromes, but began to incorporate clean, high-energy carbonate grainstones and packstones. Up-section, over 3–5 m, *Amphipora*-dominated wackestones and oncolitic floatstones (Fig. 2-16E) replace the stromatoporoid-dominated frameworks. These deposits, in turn, grade up into, and are interbedded with, stromatolitic horizons and fenestral mudstones (Fig. 2-16F). Vadose cements in these deposits attest to subaerial exposure.

Over the outer areas of Reef Complex #2, poorly-sorted *Stachyodes* floatstones are common (Fig. 2-16G) and bulbous, spherical, and irregular stromatoporoids formed irregular frameworks, similar to the patch reef facies of Reef Complex #1. These deposits (6–8 m thick) buried the outer buildup and supplied coarse bioclastic sediment towards the basin, over the reef-front and into the reef-front valley. At many localities,

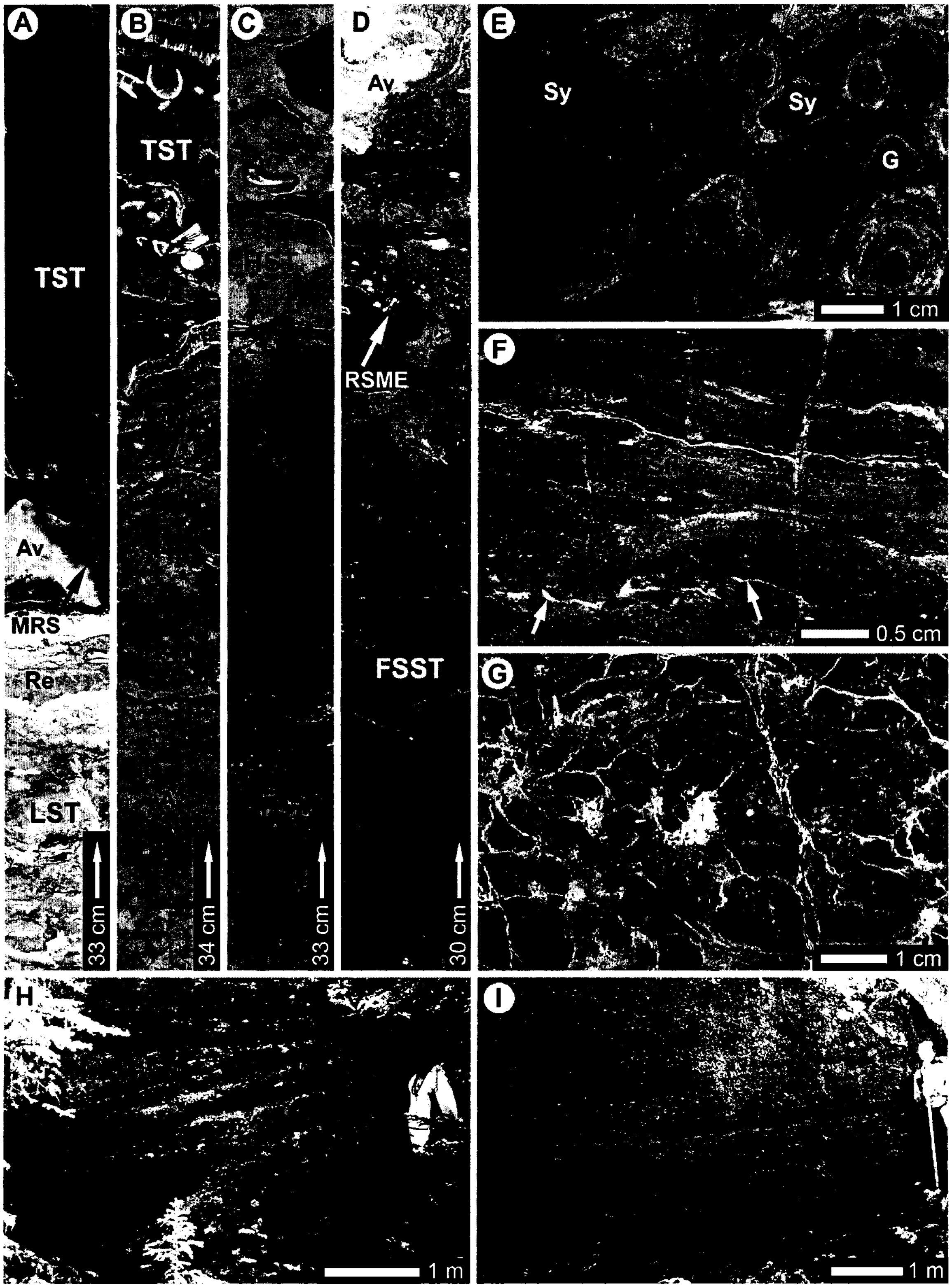


Figure 2-16. Representative facies and surfaces in Reef Complex #2. **A)** Distal reef-front facies in ARC-3 with framebuilders (e.g. *Alveolites*; Av) and renalcids (Re) of lowstand systems tract (LST) sharply overlain by dark, sparsely fossiliferous bioturbated mudstones of transgressive systems tract (TST). Surface is maximum regressive surface (MRS). **B)** Interval through back-reef of Reef Complex #2.

Maximum regressive surface (MRS) sharply separates *Amphipora* wackestones (A) in lowstand systems tract (LST) from laminar stromatoporoids that bind dark mudstones into bioherms of transgressive systems tract (TST). Core ARC-5. **C)** Top of transgressive systems tract in back-reef. Irregular stromatoporoid buried in *Amphipora*–calcisphere wackestone interpreted to have been shed from ramp step area and is assigned to the highstand systems tract (HST). Maximum flooding surface (MFS) placed at top-surface of stromatoporoid. Core ARC-5. **D)** Regressive surface of marine erosion (RSME) within falling stage systems tract (FSST). Well-sorted, bioturbated packstones and grainstones eroded and capped by the surface before deposition of overlying grainstones and rudstones of debris apron. *Alveolites* (Av) fragment at top. Core ARC-3. Length of each core interval indicated at its bottom right. **E)** Oncolitic floatstone. Nuclei of *Stachyodes* (Sy) fragments and gastropods (G). Note renalcid laminations (arrows) in some oncolites. Locality AM34. **F)** *Amphipora*-wackestone overlain by stromatolite with partly preserved fenestral fabric. Pendant vadose cements partly fill fenestrae and shelter cavities (arrows). Locality AM34. **G)** *Stachyodes* (Sy) floatstone–rudstone in prograding deposits of falling stage systems tract. Locality AM15. **H)** Foresets of subaqueous dune. Sediment consists of *Stachyodes* floatstone-rudstone. Locality AM37. **I)** Gently dipping beds of *Stachyodes* floatstones with fragments of laminar stromatoporoids. Locality near AM16.

Stachyodes-dominated detritus formed medium- to thick-bedded subaqueous dunes with foresets that dip up to 30° (Fig. 2-16H and I). These dunes, and thickly cross-bedded floatstones and rudstones, truncate and downlap onto deeper water deposits assigned to the transgressive systems tract (Fig. 2-17A). At AM03, a distinctly concave-up scoured area of the reef-front is filled with densely-packed floatstones (Fig. 2-17B). These may be part of a fan-like deposit into the fore-reef.

As found over the inner buildup, facies deposited as far north as AM15 shallow-up into thin–medium bedded lagoon deposits (4–6 m thick). At AM15 these deposits contain small subspherical stromatoporoids, an increasing abundance of *Amphipora*, and vadose cements (Fig. 2-17C and D). In the deepest part of the study area (core ARC-3), muddy facies of the preceding transgressive systems tract grade up into packstones and grainstones. These, in turn, are sharply overlain by grainstones and rudstones (Fig. 2-16D) formed of well-rounded fragments of corals, stromatoporoids, and crinoid debris (Fig. 2-17E and F). Encrustation of the rubble by large stromatoporoids, and intermittent deposition of muddy floatstones, suggests these deposits represent a colonized debris apron in the proximal fore-reef.

Sequence Stratigraphic Interpretations

Sequence stratigraphic interpretation of the shallow marine facies that were deposited at the top of Reef Complex #2, basinward of the ramp step, is based on the paleogeographic context and sedimentology of these deposits. The *Amphipora*-dominated wackestones

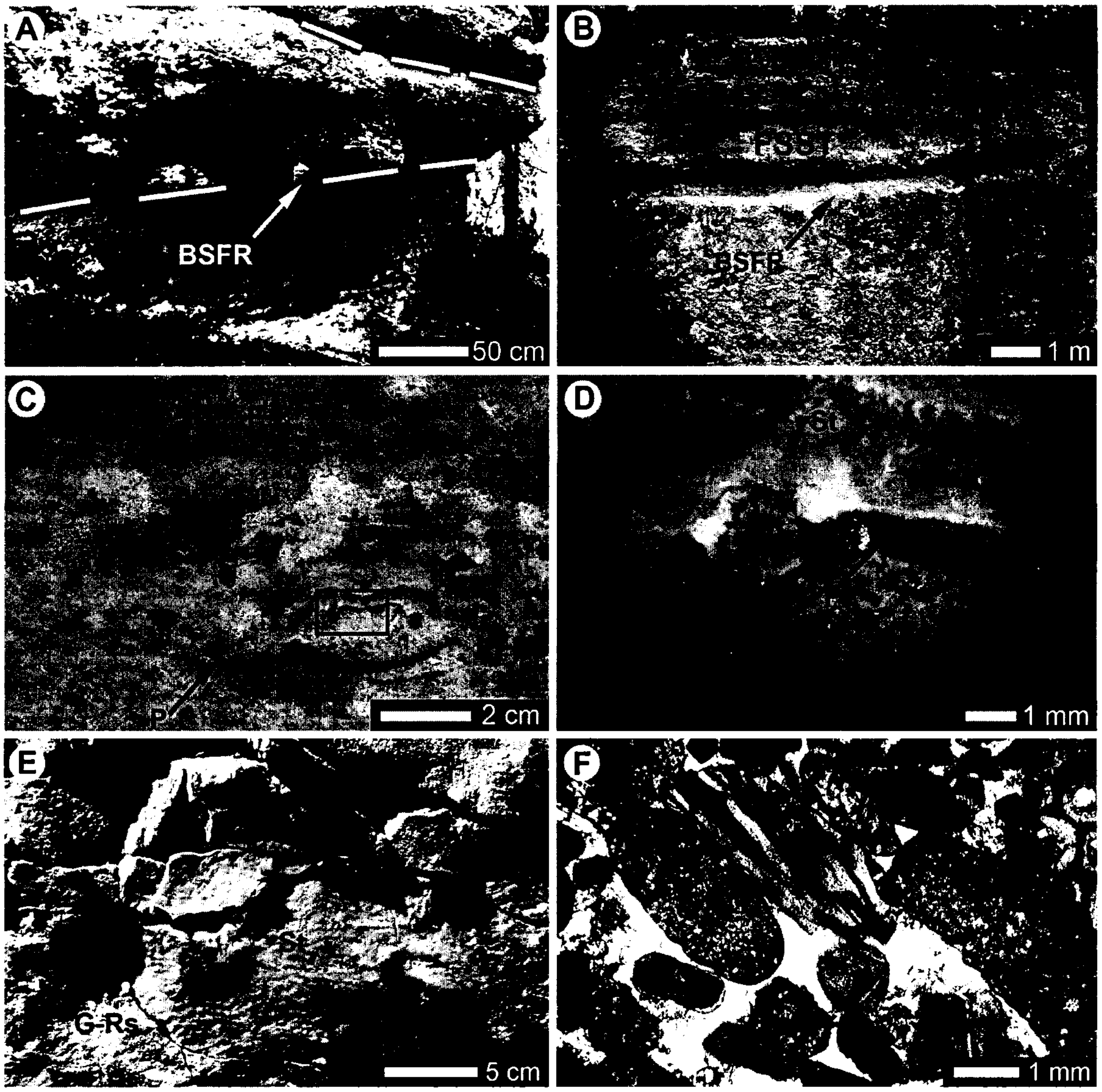


Figure 2-17. Facies of falling stage systems tract in distal part of Reef Complex #2. **A)** Thin-bedded mudstones in transgressive systems tract (± HST) truncated by medium–thick cross-bedded (dashed white lines) floatstones and rudstones in falling stage systems tract. Surface at base of cross-bedded deposits is basal surface of forced regression (BSFR). Locality AM16. **B)** Sharp, concave-up basal surface of forced regression (BSFR) separates reef-front deposits from overlying packstones-grainstones in falling stage systems tract (FSST). Locality AM03. **C)** *Amphipora* wackestone. Note fenestral fabric (F) in upper part of photograph and pendant (P) vadose cements. Boxed area figured in D. Locality AM15. **D)** Pendant (P) cements on underside of stromatoporoid (St) fragment. **E)** Toppled domal stromatoporoid (St) in crinoid-dominated grainstone and rudstone (G-Rs), in fore-reef debris apron, above regressive surface of marine erosion. Locality AM04. **F)** Photomicrograph of grainstone-rudstone in debris apron with exceptionally well-rounded bioclasts. Core ARC-2.

deposited near the ramp step (e.g. ARC-5), above the mud-dominated bioherms in the back-reef, could be toe-of-slope slope deposits that belong to the highstand systems tract, as this area would have been proximal to any shallow marine environment developed at the ramp step in the transgressive-highstand systems tracts (Fig. 2-11E). The interbedded deposits of well-sorted calcisphere-dominated wackestones are consistent with the sedimentology of sediments shed from shallow marine environments and redeposited in deeper waters (e.g. Hine *et al.*, 1981; Kenter *et al.*, 2001). As such, these deposits are interpreted as representing a component of highstand shedding, and assigned to the HST (Fig. 2-11F). Their basal contact with underlying muddy deposits, bound by stromatoporoids, is assigned as the maximum flooding surface (Fig. 2-16C).

Between ARC-5 and the inner buildup, the highstand deposits are interpreted to have pinched-out, such that remaining deposits over Reef Complex #2 are assigned to the following falling stage systems tract (Fig. 2-11F). A distinct HST cannot be documented in these deposits although the inner and outer buildup successions probably include at least a thin component of the HST. The lack of distinct breaks or changes in the sedimentation patterns, however, preclude distinction of the HST. This was the case at the base of the ramp step at the top of the Basal Onlapping Succession, where continuous muddy sedimentation precluded development of the maximum flooding surface and the HST cannot therefore be clearly distinguished from the underlying TST. Likewise, some of the dark mudstones with cricoconarids in Reef Complex #2, assigned to the TST, probably belong to the HST, but the paucity of any surfaces or marked changes in sedimentation through these successions precludes its distinction.

The possibility that the regressive deposits assigned to the FSST actually belong to the HST, or that they include a significant component of the HST, with only forced regression in their upper parts, is unlikely on the basis of several stratigraphic and sedimentary features. These include:

- The lack of deep to shallow water transitional deposits, and interbedded mudstones deposited from suspension (cf. Hine *et al.*, 1981; Westphal *et al.*, 1999). In many areas, the TST (± HST) is abruptly overlain by the regressive facies, without transitional deposits (Fig. 2-17A). Likewise, the bioherms that developed over the inner buildup, which represent *in situ* deposits and should therefore reflect water depth, lack fasciculate rugosans or other deep-water biota, indicating that they probably did not develop in a deeper-water environment.

- The direction of storm transport in the Alexandra Reef System. Progradation of deposits in the HST may be largely facilitated by shedding of sediment from the platform top to the slopes and basin by storm events (cf. Hine *et al.*, 1981). Redeposition of sediment to outer ramp environments by storms can also be an important mechanism of building-up the outer ramp profile (Aurell *et al.*, 1995; Beavington-Penney *et al.*, 2005). Although blackened lithoclasts in Reef Complex #2, and some mixing of shallow marine sediments with the transgressive deposits (±HST) in the outer parts of Reef Complex #2, indicate some basinward transport of sediment by storms, the lack of storm-derived sediment in the off-reef of Reef Complex #1, accretion of the outer buildup in Reef Complex #2 by sediment pruned and transported from the outer reef-front, and transport of reef debris several kilometers inland onto the coastal plain (hosted in the "marine incursion" deposit), indicate that the predominant direction of storm transport in the Alexandra Reef System was landwards, not basinwards. There is no evidence that the important mechanism of "building-up" the deeper water region with storm deposits shed from shallower environments (e.g. highstand shedding), was present.
- The regressive deposits, characterized by floatstones and rudstones (Figs. 2-16E and G and 2-17E and F), are coarser than sediment deposited by highstand shedding. Most sediments shed in the highstand systems tract are fine-grained (< 250 μm) and form wackestones-packstones (Hine *et al.*, 1981; Aurell *et al.*, 1995; Li *et al.*, 1997; Westphal *et al.*, 1999; Kenter *et al.*, 2001). Emplacement of coarse, and in some cases poorly sorted deposits directly over the muddy transgressive deposits in the outer parts of Reef Complex #2 (Fig. 2-17A), for example, is therefore not consistent with the sedimentology of highstand shedding. Likewise, a process that could deposit these types of depositional textures in deep water on a low-angle platform, several kilometers from their source, is not known (e.g. storms would have winnowed the sediment; turbidites, if possible at all, would have deposited sorted and normally-graded sediment).
- The distance covered by the regressive deposits, ≈ 18 km (distance corrected for oblique orientation of profile), is probably too vast for progradation associated with normal regression in high-frequency cycles (e.g. fourth- and fifth-orders), especially

without a significant component of highstand shedding. Sediments in the HST must fill significant and progressively increasing amounts of accommodation, before significant progradation can take place, and the deposition of regressive deposits over vast regions is more aptly facilitated by falling sea-level and forced regression, than normal regression associated with a HST (Posamentier and Morris, 2000).

- The stratigraphic position of shallow marine and intertidal facies at the top of Reef Complex #2 indicates that these deposits accumulated in the deeper submarine realm (Fig. 2-18), if assigned to the HST, which is not possible. This stratigraphic conundrum, in which the thickness of regressive strata above transgressive strata implies deposition in unrealistic water depths, if their strata are considered to be normal regressive and assigned to a HST, has been described as a feature of "foreshortened stratigraphy" by Posamentier and Morris (2000), and identified as a fundamental indicator of forced regression. Otherwise stated, the only mechanism to explain the occurrence of shallow marine and/or intertidal deposits (Fig. 2-18A), at a stratigraphic thickness above transgressive deposits that is insufficient relative to the magnitude of sea-level rise (Fig. 2-18B), is by invoking sea-level fall and forced regression.

As such, accepting that deposits located near the ramp step probably represent gently-dipping slope deposits that belong to the HST, the remaining regressive deposits over Reef Complex #2 are assigned to the FSST. The sedimentology of these deposits precludes the possibility that they are highstand deposits shed from the shallow marine environments that existed atop of Reef Complex #1 and in the region of the ramp step. They do not show sedimentary features typical of turbidites (cf. Droxler and Schlager, 1985), and could not have been shed from the inner and outer buildups because they overlie these buildups. In all probability, flooding of the coastal plain and sea-level highstand was short-lived and followed closely by sea-level fall. Rapid shallowing of marine environments below the ramp step, as sea-level fell, deposited a high-energy, shallowing-upwards succession, comparable to the forced-regressive autochthonous wedge of Hunt and Tucker (1993).

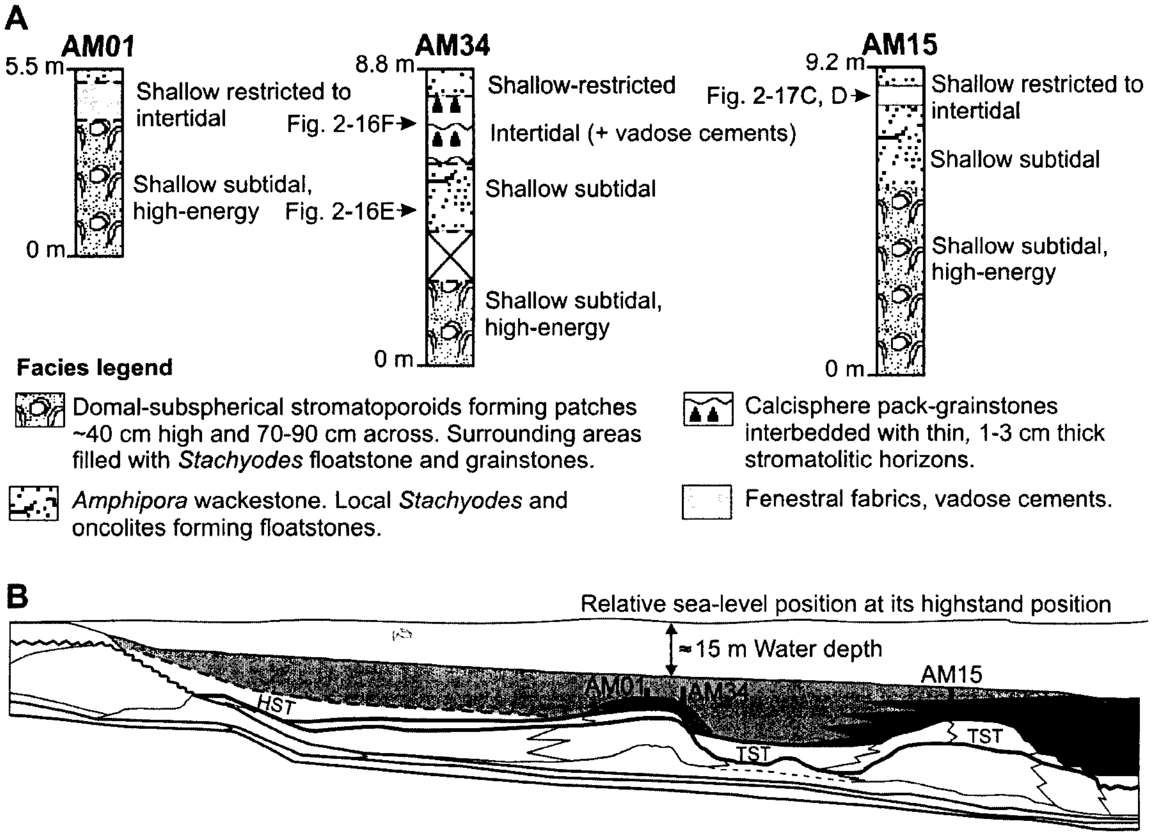


Figure 2-18. Foreshortened stratigraphy of Reef Complex #2. **A)** Sections through falling stage systems tract at localities AM01, AM34, and AM15, with facies and interpretations of depositional environments. Photographs of certain facies in AM34 and AM15 indicated by arrows. **B)** Simplified stratigraphic framework of Reef Complex #2, with falling stage systems tract shaded and positions of AM01, AM34, and AM15 indicated. Plotted sea-level position in highstand systems tract, based on top of peritidal succession above coastal plain at top of Reef Complex #1, indicates deposition of facies in sections AM01, AM34, AM15, and surrounding strata, in water depths of ≈ 15 m and greater, if assigned to the highstand systems tract.

In the intra-buildup low and in front of the outer buildup, where coarse bioclastic deposits downlap onto and truncate muddy facies, the base of the shallow marine and high-energy deposits is labeled the basal surface of forced regression (Figs. 2-14A and 2-17A). In ARC-3, gradation from dark, muddy deposits of the TST (± HST) to packstones and grainstones of the FSST precludes recognition of the basal surface of forced regression. The sharp surface at the base of the coarse debris, however, is assigned as a regressive surface of marine erosion (Figs. 2-11F and 2-16D). Termination of Reef Complex #2 is attributed to eventual subaerial exposure, and a second Type I sequence boundary (Sequence Boundary #2) is placed at its top.

SEQUENCE STRATIGRAPHIC FRAMEWORK

The Alexandra Reef System contains two reef complexes that belong to two depositional sequences (Sequence #1 and Sequence #2; Figs. 2-19 and 2-20A). Each depositional sequence is treated as a fourth-order sequence stemming from relatively high-frequency sea-level fluctuations, given the thin (<40 m) nature of the formation, its conodont zonation that indicates deposition in a time frame ≤ 1 Ma (Sandberg and Ziegler, 1996), and the magnitude of the sea-level fluctuations (cf. Lehrmann and Goldhammer, 1999).

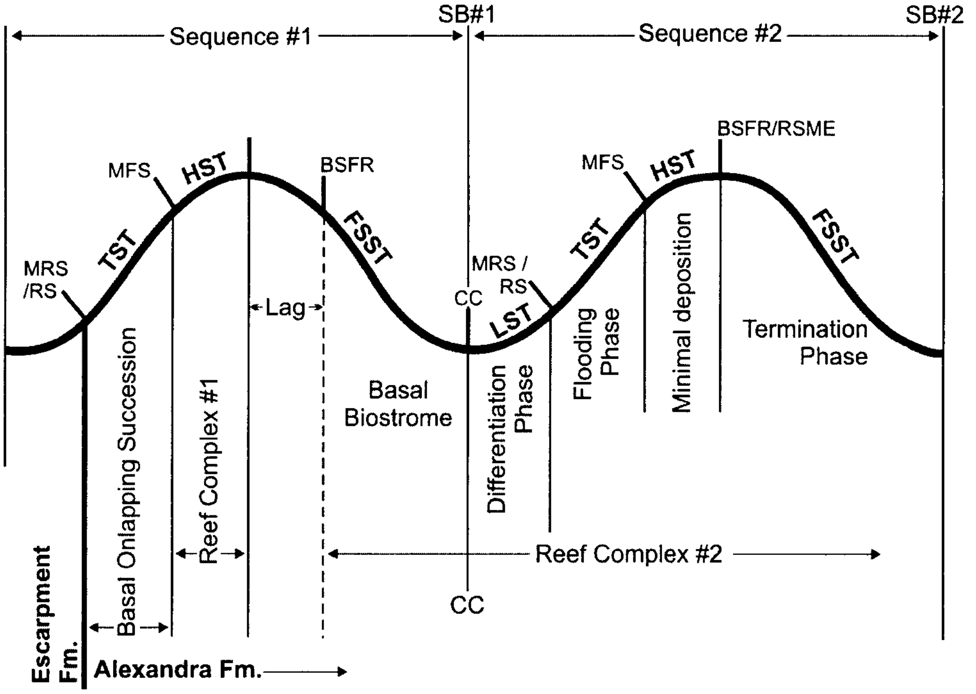


Figure 2-19. Sequence stratigraphic framework of Alexandra Formation plotted against base-level curve. Correlative conformity to Sequence Boundary #1 is in Reef Complex #2, rather than at its base, illustrating disconnect between this reef complex and base of Sequence #2.

Whereas the ideal situation of relating Reef Complex #1 and Reef Complex #2 to Sequence #1 and Sequence #2, respectively, is facilitated by Sequence Boundary #1, problems arise when its adjoining correlative conformity is considered. Following Hunt and Tucker (1992), the correlative conformity should be placed at the top of the falling stage systems tract, which in this case is the top of the basal biostrome in Reef Complex #2. The problem with such a placement is that the basal biostrome of Reef Complex #2 thereby belongs to Sequence #1 and in conventional sequence stratigraphy, implies that it is genetically related to Reef Complex #1. This is not logical because the basal biostrome is the initiation phase of Reef Complex #2 and developed as/after Reef Complex #1 was terminated. The alternative solution of placing the correlative conformity below the basal biostrome, at the base of the FSST (cf. Kolla *et al.*, 1995; Posamentier and Morris, 2000), although practical, raises the issue then of whether the FSST at the top of Reef Complex #2 should equally have its base considered as a correlative conformity. This is problematic because it implies that it belongs to a third sequence, but it is capped by Sequence Boundary #2.

To rectify this situation, placement of the correlative conformity is maintained at the top of the FSST, but with the caveat that because it is a conformable contact, underlying strata can be genetically related to overlying strata of Reef Complex #2 more so than to underlying strata of Reef Complex #1. This can be rationalized by considering the autochthonous, biological nature of reef deposits, and emphasizes many of the academic problems with placement of the correlative conformity (e.g. Hunt and Tucker, 1995; Catuneanu, 2002). The result is that where the base of Sequence #2 is defined by the correlative conformity, the base of Reef Complex #2 actually lies below this surface (Fig. 2-19).

Stratigraphic relationships and sedimentary features indicate that Reef Complex #2 developed after Reef Complex #1, and argue against the notion that the two reef complexes form one contiguous back-stepping succession in which Reef Complex #2 actually developed first. Evidence that Reef Complex #1 developed first, after transgression of the inner ramp, includes 1) the deepening upward succession on the outer ramp in the Basal Onlapping Succession, that correlates to flooding of the inner ramp, 2) the thick, indivisible succession of dark bioturbated muds on the outer ramp, at the base of the ramp step, where the top of the Basal Onlapping Succession cannot be identified – these would have been higher energy deposits associated with a shallowing environment if Reef Complex #2 developed before Reef Complex #1, 3) the facies interpreted as off-reef deposits to Reef Complex #1 is consistent with a relatively deeper, open marine environment, not one conformable shallowing-upward succession, 4) the reef-front of Reef Complex #1 at AM08 is overlain by lagoon deposits of Reef Complex #2, providing unequivocal evidence that Reef Complex #2 developed after Reef Complex #1, 5) the coastal plain succession precludes the possibility that the Alexandra Formation contains

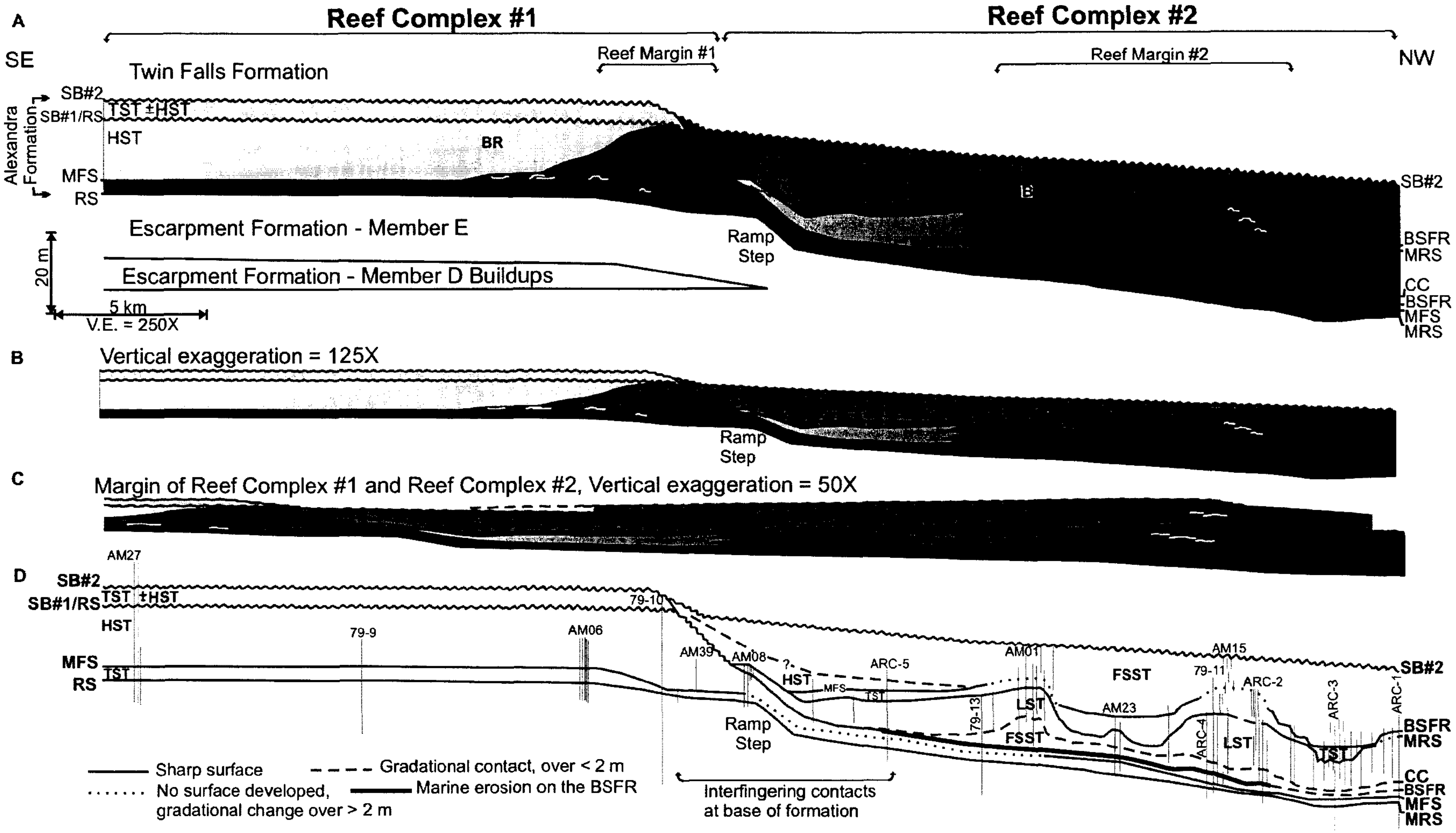


Figure 2- 20. Stratigraphic framework of Alexandra Formation. **A)** Sequence stratigraphic framework. **B)** Alexandra Reef System with vertical exaggeration reduced to 125X. **C)** Broad, low-relief nature of buildups in Alexandra Reef System increasingly apparent with reduction of vertical exaggeration to 50X. **D)** Variability in nature of sequence stratigraphic surfaces in Alexandra Formation. Sections (to same scale as in A) demonstrate data control; for clarity, 14 of 80 sections not figured.

only one sequence, and the deposition of peritidal facies above the coastal plain succession cannot be explained if only one sequence is recognized, and 6) blackened lithoclasts, conspicuous in the basal strata of Reef Complex #2, were probably sourced from the subaerially weathered top of Reef Complex #1, where they are also found.

DISCUSSION

Application of high-resolution (e.g. fourth and fifth-order cycles) sequence stratigraphy to the study of ancient carbonate ramps and associated reef systems can be used to elucidate complex stratigraphic relationships and enhance understanding of spatial and temporal variations. The Alexandra Formation has historically been described as a single reef complex (e.g. Jamieson, 1967; Jamieson, 1971; Magathan, 1987; McLean *et al.*, 1987; Bellow, 1993), or divided into two members in the area between the escarpment and Hay River (Douglas, 1973). Its growth-phases were attributed to pulses of relative sea-level rise and highstand (e.g. Jamieson, 1967), which is the control on reef development that underpins the interpretation of most Devonian reefs in western Canada (e.g. Jamieson, 1971; Mountjoy, 1980; Cutler, 1983; Walls and Burrowes, 1985; McLean and Mountjoy, 1993; Whalen *et al.,* 2000a; Potma *et al.,* 2001). Application of high-resolution sequence stratigraphic methods and concepts to the study of the Alexandra Formation, however, has determined that it encompasses two reef complexes, and demonstrates that the second reef complex developed basinward of the first, as part of a regressive depositional system. Important aspects of this system include:

1) Reef Complex #1 developed only in a highstand systems tract before being terminated by relative sea-level fall.
2) Reef Complex #2, which developed through an entire cycle of sea-level change, includes a series of systems tracts and is thereby stratigraphically more complex than Reef Complex #1 (Fig. 2-20A).
3) These reef complexes form a basinward-jumping reef system. The margin of Reef Complex #2 developed independent of the margin of Reef Complex #1, and the two reef complexes are separated by a Type I sequence boundary. This pattern of reef development is fundamentally different from that of a progradational reef system, in which the margin develops, in response to sea-level changes, as one continuous body.

4) As Reef Complex #2 developed, Reef Complex #1 was subaerially exposed and subject to physical and chemical erosion.
5) The transgressive systems tract in Reef Complex #2 onlapped Reef Complex #1 and deposited a thin peritidal succession overtop of Sequence Boundary #1. As such, the two sequence boundaries exposed along Hay River only bound a thin package of peritidal deposits (Fig. 2-15C). Basinward, however, the same two surfaces (with the correlative conformity to Sequence Boundary #1) diverge to encompass an entire reef complex (Fig. 2-20A).

Fundamental controls on the development of the Alexandra Reef System, that are reflected in its sequence stratigraphic framework, included the 1) inherited platform geometry of a very gently sloping ramp, 2) antecedent topography at the ramp step that divided the elevated, inner ramp from the lower, outer ramp, and 3) rates and trends of relative sea-level change. These were supplemented by various extrinsic factors (e.g. climate, basin configuration, minimal siliciclastic influx) that affect the nature of any carbonate depositional system (cf. Wilson, 1975). Development of Reef Complex #2 was possible because the magnitude of sea-level fall did not restrict the basin, environmental conditions remained favourable for reef initiation, and the outer ramp provided a broad region of shallow marine environments suitable for establishment of a carbonate factory.

The geometry of ramp-type carbonate platforms is a fundamental control on the nature of their depositional systems (cf. Ahr, 1973; Burchette and Wright, 1992; Aurell *et al.*, 1995), as found in the Alexandra Formation. Because they are different from carbonate shelves, it can be expected that their sequence stratigraphic frameworks will reflect some of these differences. One of the most significant processes predictable for carbonate shelves and isolated platforms is that of highstand shedding (Mullins, 1983; Schlager *et al.*, 1994). On carbonate ramps, high-rates of sediment production, shedding, and strong progradational geometries, however, are not unique to their highstand systems tracts, because their gentle slopes allow facies belts to shift in response to fluctuations in sea-level (cf. Burchette and Wright, 1992; Schlager *et al.*, 1994; Westphal *et al.*, 1999). Sarg (1988) and Hunt and Tucker (1993), for example, described autochthonous deposits of carbonate grainstones that may develop on gently sloping margins (or ramps) during periods of falling sea-level and in the lowstand systems tract.

In the Alexandra Reef System, with its ramp-type geometry, the highstand systems tracts were not characterized by high rates of carbonate sediment production and shedding, or strongly progradational geometries. The HST in Sequence #1 was characterized by reef development and gradual shallowing-upwards on the inner ramp. Time-equivalent deposits in the off-reef (outer ramp) consist of dark mudstones and wackestones with isolated corals and stromatoporoids, reflecting the low production rates to be expected in deeper water environments (cf. Schlager, 1981). In Sequence #2, a distinct HST cannot be documented in the relatively deep water part of Reef Complex #2. Short duration of the sea-level highstand, minimal storm transport of sediment from the shallow environments, and the lack of any significant environmental change in the deeper realms of the flooded complex, as rising sea-level passed to sea-level highstand, can explain this situation. Higher-frequency sea-level fluctuations, below the resolution of this study, may have also been important.

Facies shifts in the ramp setting of the Alexandra Reef System, in response to sea-level fluctuations, were also not simple and uniform, because the ramp step broke the regularity of its depositional gradient. The margin of Reef Complex #1, situated at the top of the ramp step, maintained the topographic break as the system evolved. As a result, facies contrasts were well-developed in this area, as indicated by the contrasts in the Basal Onlapping Succession, on the basinward face of Reef Complex #1, and in the TST (± HST) – FSST succession in Reef Complex #2. These contrasts, and the limited development of a HST in Reef Complex #2, demonstrate the potential variability in ramp systems and that their facies shifts are not always uniform as sea-level fluctuates. Indeed, the 'ramp slope crests' noted in seismic sections of other ancient carbonate ramp systems by Burchette and Wright (1992), and modeled by Aurell *et al.* (1995), may have been significant controls on the evolution of these ramps and their depositional systems.

Differences between the falling stage systems tract in Sequence #1 and the falling stage systems tract in Sequence #2 probably reflect different rates of sea-level fall and possibly the maturity of the overall system. In the first FSST, the basal biostrome to Reef Complex #2 developed. It was characterized by a stromatoporoid-microbial framework and lacks high-energy facies or evidence of high-rates of carbonate sediment production. In contrast, the second FSST was characterized by high-rates of carbonate production, mainly in the form of coarse, grainy sediments, and strong progradation. These differences between the two FSST's can be explained by a faster rate of sea-level fall in Sequence #2. It is also possible that although Reef Complex #2 had reduced carbonate productivity when flooded, it was "primed" for establishment of a highly productive carbonate system, and sea-level did not have to fall far before this was realized. This is similar in principle to the concept of "incipient drowning" of a carbonate platform, followed by high-rates of carbonate production as the system catches-up (cf. Kendall and Schlager, 1981). The basal biostrome in the first FSST, in contrast, represented new colonization in an area of the ramp that had not previously experienced reef development.

Given that many ancient stromatoporoid-dominated reef-complexes were characterized by knoll-reef belts on gently sloping, ramp-like platforms, and lacked elevated, steep rims (Wilson, 1975; Mountjoy, 1980; Walls and Burrowes, 1985; McLean and Mountjoy, 1993; Nestor, 1995; Kershaw, 1998; da Silva and Boulvain, 2004), the style of regressive reef development in the Alexandra Formation may be more common in these systems than generally realized. Elucidation of such stratigraphic relationships, however, can be complicated by the commonly broad nature of the buildups in these reef systems (e.g. Wilson, 1975; Walls and Burrowes, 1985; Nestor, 1995), and the development of buildups that belong to different depositional sequences in laterally adjacent positions. The margin of Reef Complex #2, for example, slightly below the margin of Reef Complex #1 (Fig. 2-20B), could be misinterpreted as the only reef margin in the formation (which has historically been the case), if the database was more limited in scope, the preservation of facies was poor, or the study was limited to seismic data. Reduction of the vertical exaggeration of Reef Complex #2 (Fig. 2-20C) exemplifies its broad, low-relief nature. As the low-gradient of ramp systems, in general, complicates their analysis (Burchette and Wright, 1992), recognition of sequence stratigraphic surfaces in these types of systems, and ramp-situated reef systems, is therefore absolutely critical to establishing accurate chronostratigraphic frameworks and interpreting their depositional histories.

The sedimentary nature and expression of sequence stratigraphic surfaces in the Alexandra Formation is not uniform. Some surfaces are consistently well-developed, whereas others are highly variable between areas (Fig. 2-20D). In Sequence #1, for example, the maximum flooding surface, well-developed in all areas except the ramp step, has very different attributes between the inner and outer ramp areas (e.g. contrast Fig. 2-5G and H with Figs. 2-5I and 2-6H). In Sequence #2, the maximum flooding surface is not clearly defined in most areas, and the HST cannot be clearly documented. In this case, the basal surface of forced regression overprints the top of the TST-HST succession, and the facies contrasts in most areas facilitate easy identification of this surface. The maximum regressive surface at the base of the formation was well-developed in most areas due to marine erosion (e.g. ravinement on the inner ramp). In Sequence #2, identification of this surface in the reef-front valley, intra-buildup low, inner buildup, and back-reef of Reef Complex #2 is fairly straightforward, because the relatively sudden rise in sea-level diminished carbonate productivity (cf. Schlager, 1981; Hunt and Tucker, 1993; Brett, 1995), resulting in obvious facies contrasts (e.g. Fig. 2-16A).

It is also important to note that not all changes in reef architecture reflect sea-level change or indicate a new systems tract. This is evident in 1) Reef Complex #1, where the biostrome at its base was sharply overlain by patch reefs, within the highstand systems tract, and 2) the basal part of Reef Complex #2, with the local development of bioherms above the biostrome at its base, within the falling stage systems tract. In both cases, reef architecture changed without a shift from transgressive or regressive conditions. Care must therefore be taken when interpreting sea-level fluctuations in ancient reefs, and there does not appear to be any direct correlation between the type of reefal buildup (e.g. biostromes, bioherms) and specific systems tracts (cf. Kershaw, 1998). Biostromes, for example, developed in both transgressive and regressive parts of the Alexandra Reef System, and in various depositional settings.

In considering the regional context of the Alexandra Reef System, the fourth-order sea-level fluctuations recorded in its stratigraphic framework partly correlate to the broader, continent-scale, third-order sea-level fluctuations (cf. Johnson *et al.*, 1985) that controlled overall evolution of the Late Devonian carbonate platforms on the western margin of Laurussia. This is supported by close correlation between its sequence stratigraphic framework and sea-level fluctuations recorded in lower-resolution, third-order sequence stratigraphic frameworks established for time-equivalent strata in Alberta (cf. Whalen *et al.*, 2000a; Potma *et al.*, 2001). Available biostratigraphic data (McLean and Klapper, 1998; Whalen *et al.*, 2000a; Potma *et al.*, 2001) indicate that the Alexandra Formation is most likely equivalent to 1) the uppermost part of Sequence 3 and part of Sequence 4 of Whalen *et al.* (2000a), formed of strata that belong to the Peechee Member of the Southesk Formation, and 2) the basal part of Sequence WD2 of Potma *et al.* (2001). Sequence Boundary #1 in the Alexandra Formation, characterized by a long-period of exposure and accumulation of palustrine deposits (MacNeil and Jones, 2006) after sea-level fell ≈ 17 m, appears to correlate to the sequence boundary at the top of Sequence 3 identified by Whalen *et al.* (2000a), which is marked by karst and soils (Whalen *et al.*, 2000a), and the sequence boundary at the base of Sequence WD2 of Potma *et al.* (2001; Weissenberger, pers. comm. 2004). More biostratigraphic data, with higher resolution, is required to confirm these correlations, but they are at least based on comparable rates and trends of sea-level change, in the upper part of T-R cycle IIc. The second sea-level fall recorded in the Alexandra Formation, represented by Sequence Boundary #2 at the top of the formation, has not been recognized in the lower-resolution frameworks of Whalen *et al.* (2000a) and Potma *et al.* (2001). Thus, the fluctuations recorded in the Alexandra Formation must be considered to indicate that the history of sea-level change in the Frasnian succession of western Canada is more complex than generally realized. Deposition of the Twin Falls Formation overtop of the Alexandra Formation followed a significant sea-level rise that almost certainly corresponds to the base of T-R cycle IId, and the third-order transgressive systems tract in the lower part of Sequence WD2, that was defined by Potma *et al.* (2001).

Finally, it should be noted that the magnitude of sea-level fluctuations recorded in the Alexandra Formation are greater than that generally predicted for higher-frequency sea-level cycles in greenhouse climates (e.g. cycle amplitudes ≤10 m), which characterized most of the Devonian (e.g. Copper, 2002; Joachimski *et al.*, 2004). They are, however, reasonable for a fluctuating climate between greenhouse and icehouse conditions (e.g. Tucker *et al.*, 1993; Lehrmann and Goldhammer, 1999), and consistent with evidence from the fossil record and stable isotopes that global cooling events punctuated the Frasnian, prior to the mass extinction events at the Frasnian – Famennian boundary (cf. Stanley, 1988; Buggisch, 1991; Copper, 2002; Joachimski *et al.*, 2004).

CONCLUSIONS

High-resolution sequence stratigraphic analysis of the Alexandra Formation has shown that it consists of two distinct reef complexes that formed in a regressive depositional system. Important conclusions from this include the following.

- High-resolution sequence stratigraphy can be used to establish the chronostratigraphy of stromatoporoid-dominated reef systems. From this framework, complex stratigraphic relationships and controls on reef development may be determined.
- Sea-level change over gently sloping carbonate platforms may be an important control on stratigraphic complexity within reef systems, determined predominantly by the rate and magnitude of sea-level change and the surface area of the platform. In the Alexandra Reef System, the second reef complex was stratigraphically complex because it initiated during a period of falling sea-level, developed through a complete cycle of relative sea-level rise, and was terminated by subaerial exposure in the following falling stage systems tract – as opposed to being initiated after only a transgressive event (e.g. Reef Complex #1).
- Significant falls in relative sea-level on gently sloping platforms favour basinward-jumping reef complexes, each separated by a Type I sequence boundary. Placement of the correlative conformity, however, may be problematic if it lies within the initiation phase of the new reef complex. Buildups in these regressive systems may be in laterally adjacent positions, and may onlap older reef sequences. This type of reef system is not likely to be developed on high-relief carbonate shelves with narrow margins and steep slopes.
- On carbonate ramps, relative sea-level fall may favour healthy rates of carbonate production and shedding from the platform (cf. Westphal et al. 1999). As such, significant carbonate deposits may characterize the falling stage and lowstand systems tracts, in addition to the highstand systems tract (cf. Schlager *et al.*, 1994). Platform orientation with respect to storms, water depth, and duration of sea-level

highstand, however, may also preclude significant carbonate production and shedding in the highstand systems tract, reiterating the complex nature of these systems.

- Different types of responses within carbonate environments to sea-level change are a fundamental control on the sedimentary expression of sequence stratigraphic surfaces. Variability in surface development must therefore be treated as one of the many inherent complexities associated with these depositional systems.
- The mid-Frasnian of western Canada was punctuated by a relative sea-level fall of ≈ 17 m that should have subaerially exposed most platform tops for a significant period. High-resolution sequence stratigraphy indicates that a second sea-level fall also took place, and these types of stratigraphic analyses are key to further defining the controls on carbonate platform development in this basin and its overall evolution.

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CHAPTER 3 – PALUSTRINE CARBONATES AT SEQUENCE BOUNDARY #1 IN THE ALEXANDRA REEF SYSTEM[1]

INTRODUCTION

Palustrine carbonates are fresh- to brackish-water deposits, with evidence of pedogenesis, that are typically deposited around the margins of lakes (Freytet 1973; Freytet and Plaziat 1982; Alonso-Zarza 2003). If climate permits, they can also form in shallow, carbonate-rich, fresh- to brackish-water marshes established on coastal plains and supratidal flats (Monty and Hardie 1976; Shinn 1983; Platt and Wright 1992). In these marginal marine settings, palustrine deposits can cover thousands of square kilometers, and may co-occur with karst and calcrete (Platt and Wright 1992). As such, the presence of palustrine deposits in successions of ancient marine limestones has important stratigraphic utility because they may indicate shifts in the shoreline position (cf. Monty and Hardie 1976) and the position of a sequence boundary. Nevertheless, few examples of such deposits have been documented from ancient marine limestone successions, possibly because they have been mistaken for marine deposits or calcrete (cf. Monty and Hardie 1976; Wright 1985). As a result, their potential importance to sequence stratigraphy has been overlooked.

The Late Devonian Alexandra Formation (< 40 m thick), located in the Northwest Territories of Canada (Fig. 3-1), is formed of two reef complexes that developed on an epicontinental ramp (MacNeil and Jones 2006 and Chapter 2). The second reef complex developed on the outer ramp after development of the first reef complex, located on the inner ramp, was terminated by a drop in sea-level. The top of the limestones that had been deposited on the inner ramp formed the base of the coastal plain to the second reef complex, and through subaerial weathering became stained black and red. Subsequent establishment of fresh- to brackish-water marshes on the coastal plain led to deposition of palustrine carbonates that are dominated by charophytes and skeletal stromatolites. Pedogenic features in these deposits include root traces partly filled with vadose silts and authigenic kaolinite, complex crack networks that impart a nodular texture, and zoned

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calcite fabrics that resemble the alpha fabrics found in some calcretes (Wright 1988; Wright and Peeters 1989). The palustrine carbonate was then buried by a marine limestone derived from a short-lived marine incursion. Following retreat of the shoreline, these deposits were also subjected to subaerial exposure and pedogenesis. Weathering of these deposits was terminated by retrogradation of peritidal environments of the second reef complex. As such, marine limestone deposits of the two reef complexes are separated by a succession of unconformable coastal-plain deposits that is ~ 50 cm thick.

In contrast to the development of well-defined karst features or pedogenic calcrete profiles, regarded as typical indicators of subaerial unconformities and sequence boundaries (e.g., James 1972; Esteban and Klappa 1983; Sarg 1988; Handford and Loucks 1993), the coastal-plain deposits in the Alexandra Formation, and their evidence of subaerial exposure and pedogenesis, are subtle. Nonetheless, they represent a Type I sequence boundary, and its recognition is critical to understanding the depositional evolution and stratigraphic framework of the entire reef system. This chapter examines the sedimentology of the coastal-plain deposits and the evidence of pedogenesis, and presents an enhanced set of criteria for the recognition of ancient palustrine deposits. These deposits in successions of marine limestones should be considered indicative of subaerial unconformities and sequence boundaries in the same manner as calcrete and karst, underscoring their importance to carbonate sequence stratigraphy.

GEOLOGICAL SETTING

The Alexandra Formation is exposed along a southwest–northeast gorge system cut by Hay River and in a southeast–northwest trending escarpment (Fig. 3-1A). Regional biostratigraphy indicates that these deposits are mid-Frasnian in age (Klapper and Lane 1985; McLean and Klapper 1998). Strata along Hay River were deposited at the landward extent of an epicontinental ramp and show little lateral variation because the exposure trend is nearly parallel to depositional strike. In contrast, the escarpment is oblique relative to depositional strike, providing a nearly continuous section through strata deposited in back-reef, reef, and fore-reef environments (e.g., Jamieson 1967).

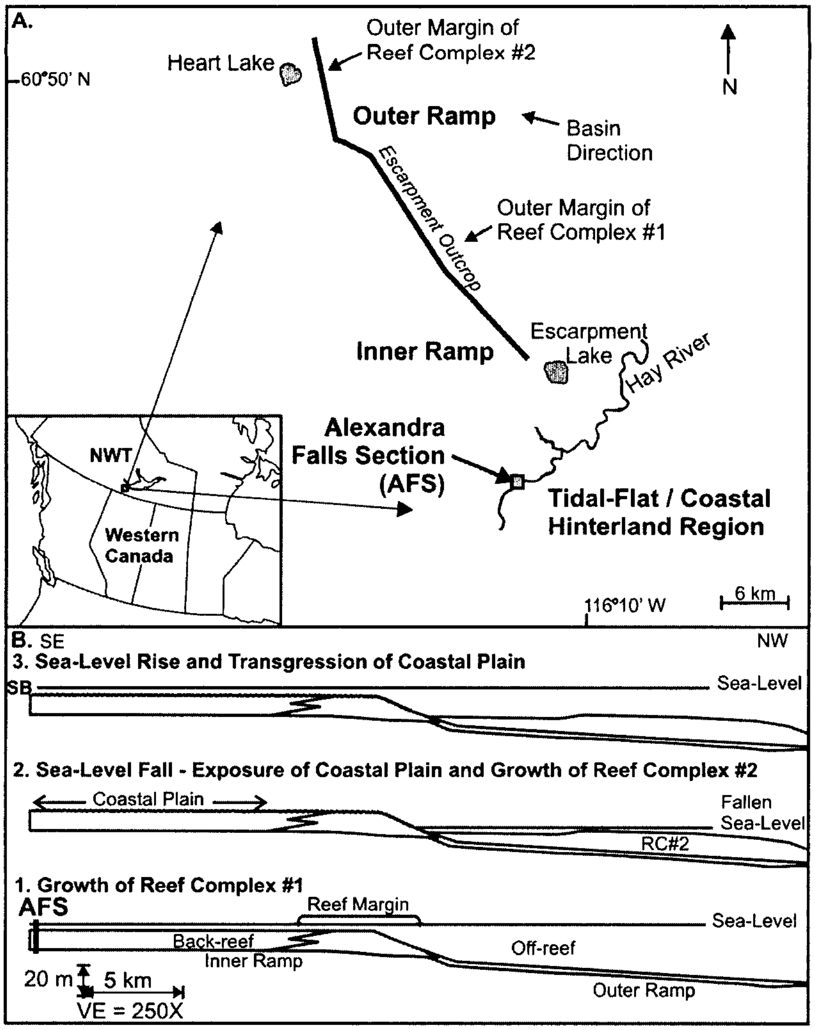

Figure 3-1. Study area and simplified stratigraphic evolution of Alexandra Formation. **A)** Locality map of Alexandra Formation. **B)** Three-stage evolution of reef system in Alexandra Formation. Section orientation from Alexandra Falls at left to Heart Lake at right. AFS = Alexandra Falls Section; SB = Sequence Boundary.

Detailed study of the formation over the summers of 2002 and 2003 determined that these deposits belong to two separate reef complexes (Chapter 2). The first Reef Complex (RC#1) developed on the inner ramp in a highstand systems tract, after an initial transgression, whereas the second, younger Reef Complex (RC#2) developed basinward of RC#1, after sea-level fell (Fig. 3-1B). Deposition of shallow restricted subtidal and intertidal facies on the outer ramp, directly above fore-reef deposits of the first reef complex, indicate that (1) a fall in sea-level terminated development of RC#1 on the inner ramp, and (2) the magnitude of sea-level fall, based on stratigraphic correlation, was ~ 17 m. As such, development of RC#2 in a lowstand systems tract was fringed by a low-relief coastal plain developed at the top of RC#1 (Fig. 3-1B #2). The coastal-plain succession at the top of RC#1, and a subtidal correlative conformity at the base of RC#2, separates deposits of the two reef complexes and defines a Type I sequence boundary (following definition of Posamentier and Vail (1988), whereby the subaerial unconformity formed due to a fall in relative sea-level). Exposure of the boundary is continuous for at least 500 m in the cliff faces below Alexandra Falls along Hay River (Fig. 3-2A), although previous study failed to recognize its unconformable nature (e.g., Belyea and McLaren 1962; Jamieson 1967; Bellow 1993). A subsequent sea-level rise flooded RC#2 and led to transgression of the coastal plain and deposition of peritidal facies (Fig. 3-1B #3).

METHODS

The sequence boundary exposed in the cliff faces below Alexandra Falls is difficult to access because the vertical cliffs are ~ 35 m high. Only one locality (Alexandra Falls Section; AFS) was found where the boundary could be safely accessed (Fig. 3-2A). Two profiles through the boundary, CS1 and CS2, ~ 15 m apart, were measured at this locality (Fig. 3-2B, C). Large samples (n = 12) were collected from these sections, and large (5 cm x 7.5 cm) thin sections (n = 15) were prepared from these for transmitted-light microscopic examination. In addition, small pieces fractured from selected samples (n = 4), polished thin sections (n = 2) etched for 45 s in 50% acetic acid, and polished and etched chip samples (n = 3) were coated with Au and examined with a JEOL 6301 field emission scanning electron microscope (SEM). Each of these sample preparation methods facilitated a different, but complementary, perspective of the features examined with the SEM. A Princeton Gamma-Tech Energy Dispersive X-ray Analyzer, operated at an accelerating voltage of 20 kV, was used with the SEM to identify calcite, feldspar, gypsum, and clay minerals. X-ray diffraction (XRD) analysis of powdered samples (n = 6) was used to confirm mineral identifications. Back-scattered electron (BSE) images of selected samples were collected with a JEOL 8900R electron microprobe operated at 15 kV accelerating voltage. The classification scheme of Folk (1959) for the size of micrite (1-4 μm), microspar (5-15 μm), and sparite (> 15 μm) is utilized.

STRATIGRAPHIC SUCCESSION

Sections CS1 and CS2 contain the same stratigraphic units with no discernible difference in bed thickness, with exception of the palustrine deposit, which varies from 10 to 20 cm thick. Four units have been recognized (Fig. 3-2B, C). The lowest, termed the host limestone, is the succession (13.6 m thick) of shallow marine and peritidal deposits from the lagoon and tidal-flat region of RC#1. The top of this unit marks the top of RC#1. Unit 2 is the palustrine deposit. Unit 3 is the short-lived marine incursion deposit, ~ 35 cm thick. Unit 4 is the overlying succession (7 m thick) of peritidal deposits that belong to RC#2.

PRIMARY SEDIMENTOLOGY OF UNITS 1 – 4

Unit 1 – Host Limestone

The lagoonal and peritidal deposits of RC#1 include bedded *Amphipora* deposits, peloidal packstones, laminated mudstones, and intertidal stromatolites, commonly in shallowing-upward cycles. Cloudy rhombs (~ 20 μm) of dolomite are found locally.

The top of Unit 1 is a thick bed of *Amphipora*-dominated floatstone-rudstone with a wackestone matrix. Its uppermost ~ 40 cm is irregularly stained black and red by Fe-sulfides, Fe-oxides, and derived pigments. Clotted and disseminated finely crystalline Fe-oxides are common in freshly broken samples, imparting a distinct red color to many *Amphipora* (Fig. 3-2D). Other *Amphipora* are partly impregnated with Fe-sulfides, resulting in a blackened stain to their appearance.

Unit 2 – The Palustrine Deposit

Sharply overlying Unit 1 is a recessive, brown wackestone with a nodular-chalky texture (Fig. 3-2E). Variably calcified charophyte stems, gyrogonites, and hollow calcite spheres are common throughout this unit. Distinct amber-colored laminated microbial calcite precipitates that form shrub-like masses, up to 2 mm thick, are found locally. Blackened lithoclasts and abraded, poorly preserved fragments of *Amphipora*, always with some degree of Fe-sulfide impregnation, are present in minor amounts (Fig. 3-3A, B). These are most probably derived from weathering of the underlying blackened *Amphipora*

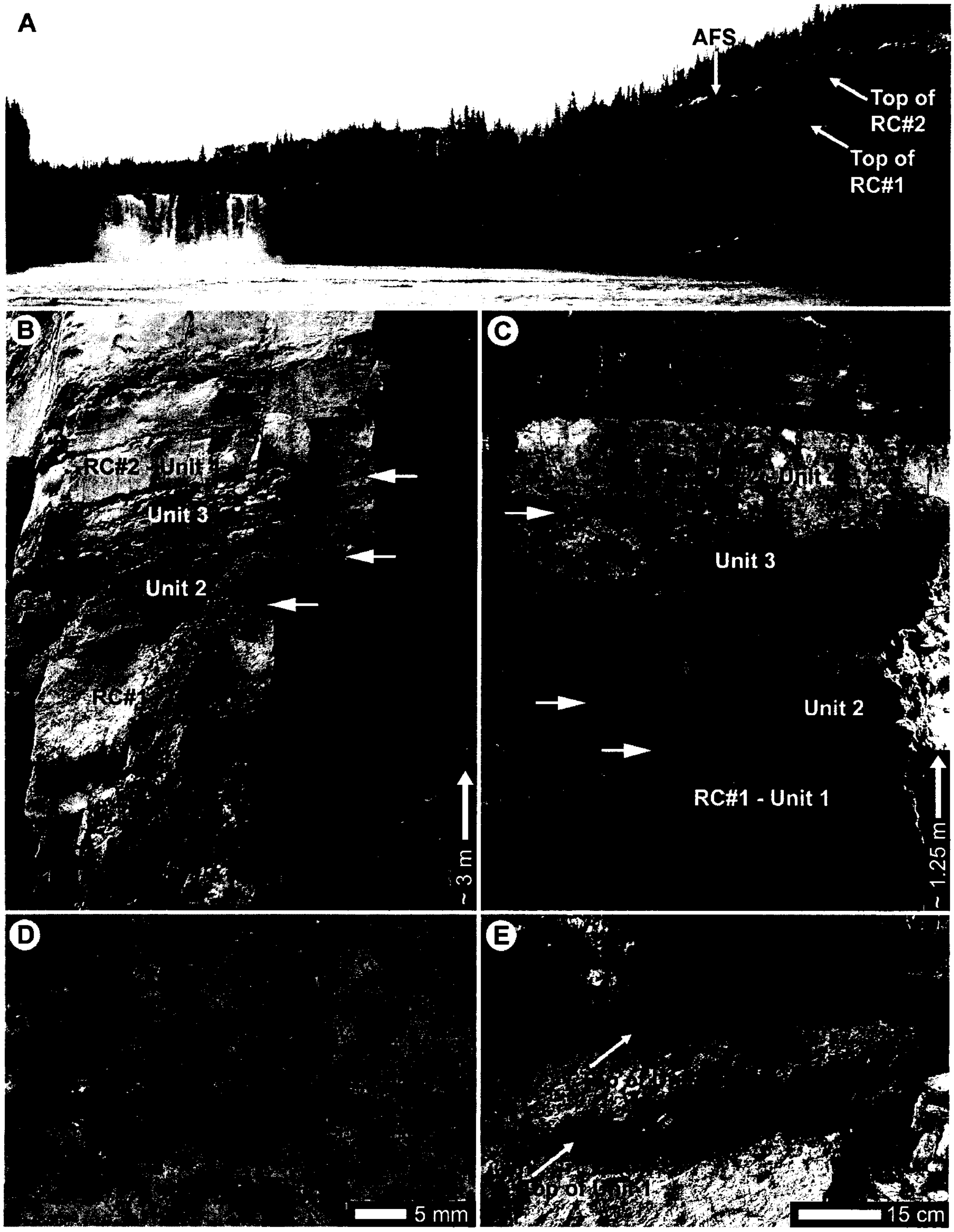

Figure 3-2. Exposure of coastal-plain succession in Alexandra Formation along Hay River. A-C and E = field photographs; D = photograph of polished surface. **A)** Alexandra Formation exposed in cliff below Alexandra Falls. Top contacts of RC#1 and RC#2 are sharp and traceable across field of view. AFS = Alexandra Falls Section. Cliff height ~ 35 m, view to southwest. **B)** CS1 at AFS. Arrows indicate contacts between units. Note recessive nature of Units 2 and 3, relative to Units 1 and 4. **C)** CS2 at AFS. Arrows indicate contacts between units. **D)** *Amphipora* floatstone from top of Unit 1 at CS2. *Amphipora* stained red and matrix partly stained (S). **E)** Sharp contact at base and top of Unit 2 at CS1.

floatstone-rudstone. Detrital quartz is present in minor (< 5%) amounts. No dolomite was found in this unit.

The charophytes (Fig. 3-3C) are characterized by brown-amber colored, inclusion-rich crystals, commonly with lamellar growth structure. Some charophytes were recrystallized and their primary morphological features are nearly indiscernible (Fig. 3-3D). Micrite in the deposit is characterized by inclusion-rich calcite comparable to the calcified charophytes, suggesting that much of it may have originated from charophyte degradation. The hollow calcite spheres include small spheres with outer diameters ≤ 10 μm and large spheres with inner diameters of 15–20 μm and outer diameters of 25–40 μm (Fig. 3-3D–F). Wall structure of the small spheres is characterized by a layer of blocky, anhedral calcite. Wall structure of the larger spheres is characterized by either a layer of blocky, anhedral calcite, or a radial arrangement of bladed crystals. Unfortunately, because hollow calcitic spheres have several possible origins (e.g., Jones 1992; Guo and Riding 1992), the affinity of these spheres is unknown.

The amber-colored laminated calcitic precipitates are characterized by lensoid to hemispherical shrub-like shapes in longitudinal section, up to 2 mm high, or fragmented pieces of these masses (Fig. 3-4). Parallel to slightly curved branching tubules, ~ 10 μm in diameter, are well defined in these structures (Fig. 3-4A, B). The calcite between the tubules is thinly (submicron – micron scale) laminated with light and dark layers and very fine inclusions (Fig. 3-4C). Branching of the tubules always takes place near the terminal surface of the precipitates (Fig. 3-4D). In transverse section, the precipitates have a honeycomb-like appearance (Fig. 3-4E). These features are consistent with microbial precipitates (e.g., Riding 2000) but are not similar to any known marine microbial precipitate from the Paleozoic (cf. Pratt 1984; Riding 1991, 2000). Rather, they are directly comparable to modern freshwater skeletal stromatolites (Freytet and Plet 1996; Freytet and Verrecchia 1998) and, in particular, *Rivularia* skeletal stromatolites, which have a fossil record extending back to the Precambrian (Bertrand-Sarfati 1976; Golubic et al. 2000). Modern examples of freshwater *Rivularia haematites* stromatolites, for example, are characterized by (1) masses of calcified, nearly parallel filaments of comparable diameters, (2) synchronous events of false branching at the outer margins of colonies, (3) thinly laminated sparitic calcite between filaments, and (4) a honeycomb

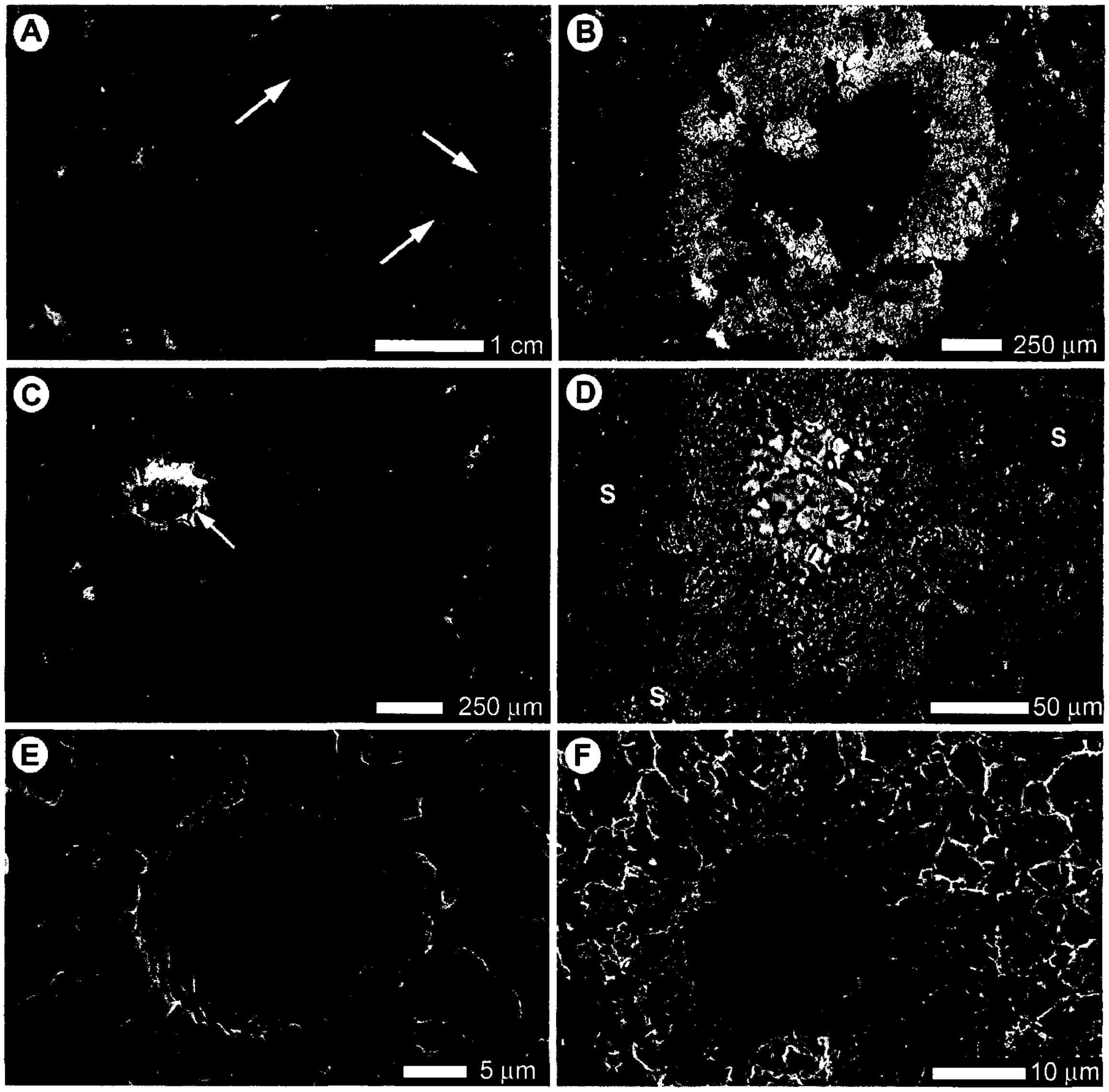

Figure 3-3. Depositional features in Unit 2. A = photograph of polished surface; B-D = thin section photomicrographs; E, F = SEM photomicrographs. **A)** Blackened lithoclasts (arrows) in Unit 2 that were derived from top of Unit 1. **B)** Poorly preserved *Amphipora* fragment with clotted Fe-sulfides that was derived from top of Unit 1. **C)** Charophyte gyrogonite (arrow). Abundant small pieces of fragmented charophytes impart speckled appearance to matrix. **D)** Intensely recrystallized charophyte with lamellar crystal structure. Note hollow spheres (S) in matrix. **E)** Hollow sphere with wall formed of blocky micrite. **F)** Hollow sphere with wall constructed of bladed calcite crystals (etched sample).

appearance of colonies in transverse section (e.g., Monty 1976; Pentecost 1978, 1987; Freytet and Verrecchia 1998; Caudwell et al. 2001; Pentecost and Edwards 2003). The microbial precipitates in Unit 2 display these characteristics. Fragmented pieces of these microbial precipitates and disarticulated, fragmented charophytes are abundant throughout the matrix of Unit 2 (Fig. 3-4B, F).

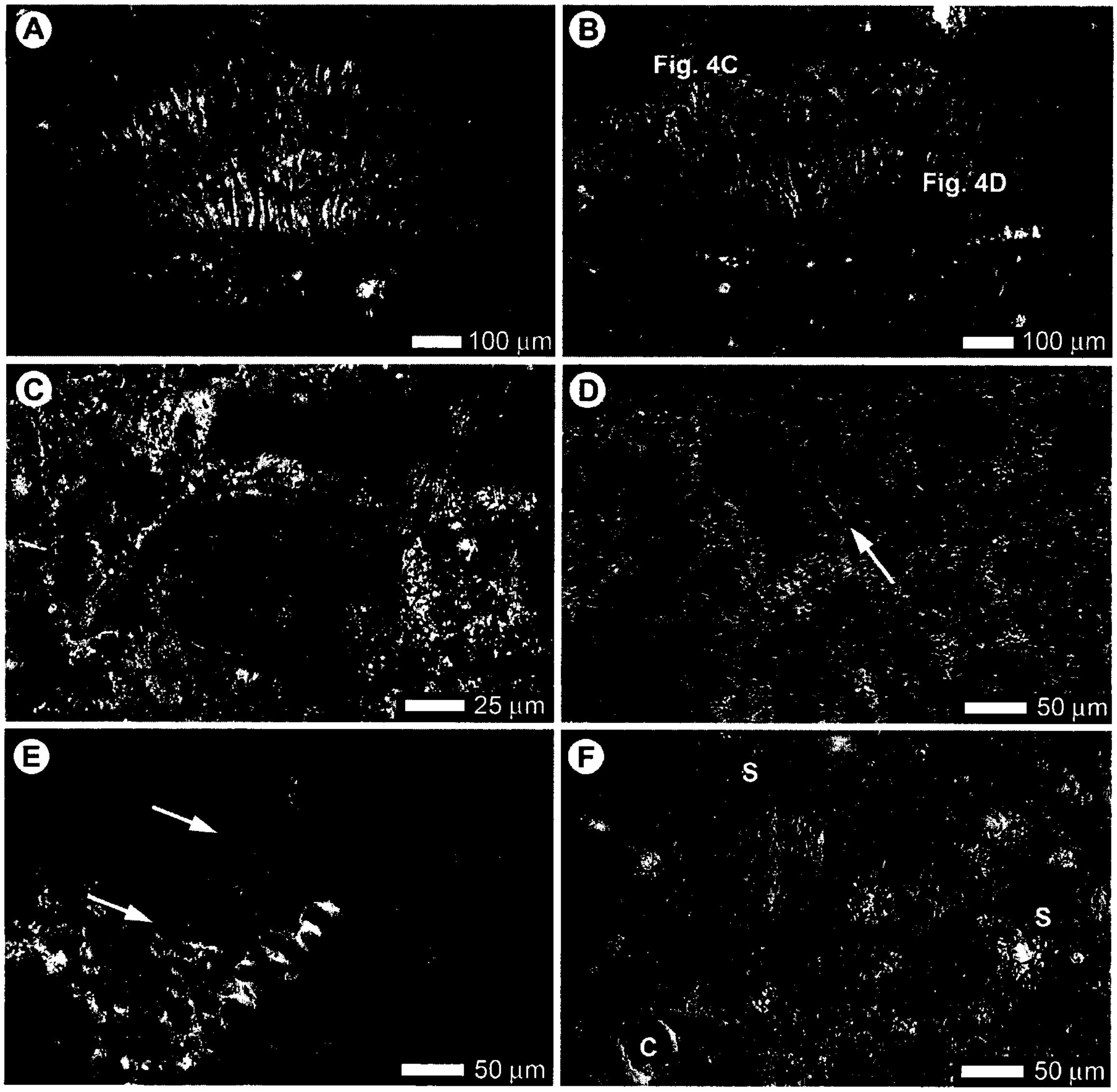

Figure 3-4. Thin-section photomicrographs of skeletal stromatolites in Unit 2. **A, B)** Well-preserved skeletal stromatolites in matrix. Boxes in Fig. 4B indicate positions of Fig. Parts C and D. **C)** Laminated light and dark spar between tubules, near terminal growth surface. **D)** Falsely branched tubule (arrow) near terminal growth surface. **E)** Transverse surface of skeletal stromatolite with honeycomb appearance. Two tubules are indicated with arrows. **F)** Matrix with numerous hollow spheres (S) and fragmented pieces of charophytes (C) and skeletal stromatolites (M).

Charophytes in modern freshwater environments are closely associated with microbes and their precipitates (e.g., Freytet and Plaziat 1982; Platt and Wright 1992), and in particular *Rivularia* (Whitton 1987). Thus, interpretation of these microbial precipitates as *Rivularia* skeletal stromatolites is consistent with the abundance of charophytes in the unit. The combination of charophytes and microbial precipitates, without any associated marine biota (e.g., *Amphipora* that do not occur as detrital, Fe-stained clasts derived from the top of Unit 1, calcispheres *sensu* Williamson (1880), foraminifera, marine algae, or *Stachyodes* – all of which are abundant in the underlying and overlying marine limestones) indicates that Unit 2 was deposited in a shallow, fresh- to brackish-water environment. The absence of any dolomite, which is unlikely to be formed from fresh and brackish waters (Hardie 1987), but is a common primary precipitate in peritidal facies throughout the formation, supports this interpretation. The lack of marine sediment mixed in with Unit 2, or laminated alternations between fresh-water-derived and marine-water-derived sediment, further indicates that these deposits were disconnected from the marine realm (cf. Monty and Hardie 1976).

Unit 3 – The Marine-Incursion Deposit

The boundary between Unit 2 and overlying Unit 3 is well defined but irregular (Fig. 3-2E). Unit 3 is a dark gray limestone with numerous *Amphipora* along with fewer ostracods and scattered fragments of corals, stromatoporoids, and brachiopods. Detrital quartz is present in the matrix in minor (< 5%) amounts, along with ripped-up clasts of Unit 2 (Fig. 3-5A). The latter indicates partial erosion of the palustrine deposit prior to (or during) deposition of Unit 3. The biota of this unit is consistent with a shallow marine facies that was periodically supplied with storm-derived detritus. The fragments of corals and stromatoporoids show evidence of extensive transport and abrasion, relative to the *Amphipora*, indicating they were not locally derived. The deposit probably represents a marine incursion over the coastal plain with periodic storm transport of allochthonous reef-derived detritus.

Unit 4 – Peritidal deposits of RC#2

Unit 3 is sharply overlain (Fig. 3-2B) by well-bedded deposits (0.2 – 1.1 m thick) of Unit 4 that extend to the top of the Alexandra Formation (Fig. 3-2A). The basal deposit is a burrowed, light tan algal mudstone – wackestone with numerous palaeoberesellids, *Vermiporella*, and ostracods. *Amphipora* are less common. Yellowish primary dolomite is common throughout the matrix (Fig. 3-5B). Spar-filled vertical tubes, analogous to those described from Ordovician, Cretaceous, and modern supratidal storm deposits by Shinn (1983), are conspicuous (Fig. 3-5C). This bed, and overlying beds, characterized by mudstones and shallowing-upward peritidal deposits, lack evidence of pedogenesis, although many bedding planes display mudcracks and desiccation breccias (Fig. 3-5D). The deposits in Unit 4 are interpreted as peritidal deposits that belong to RC#2.

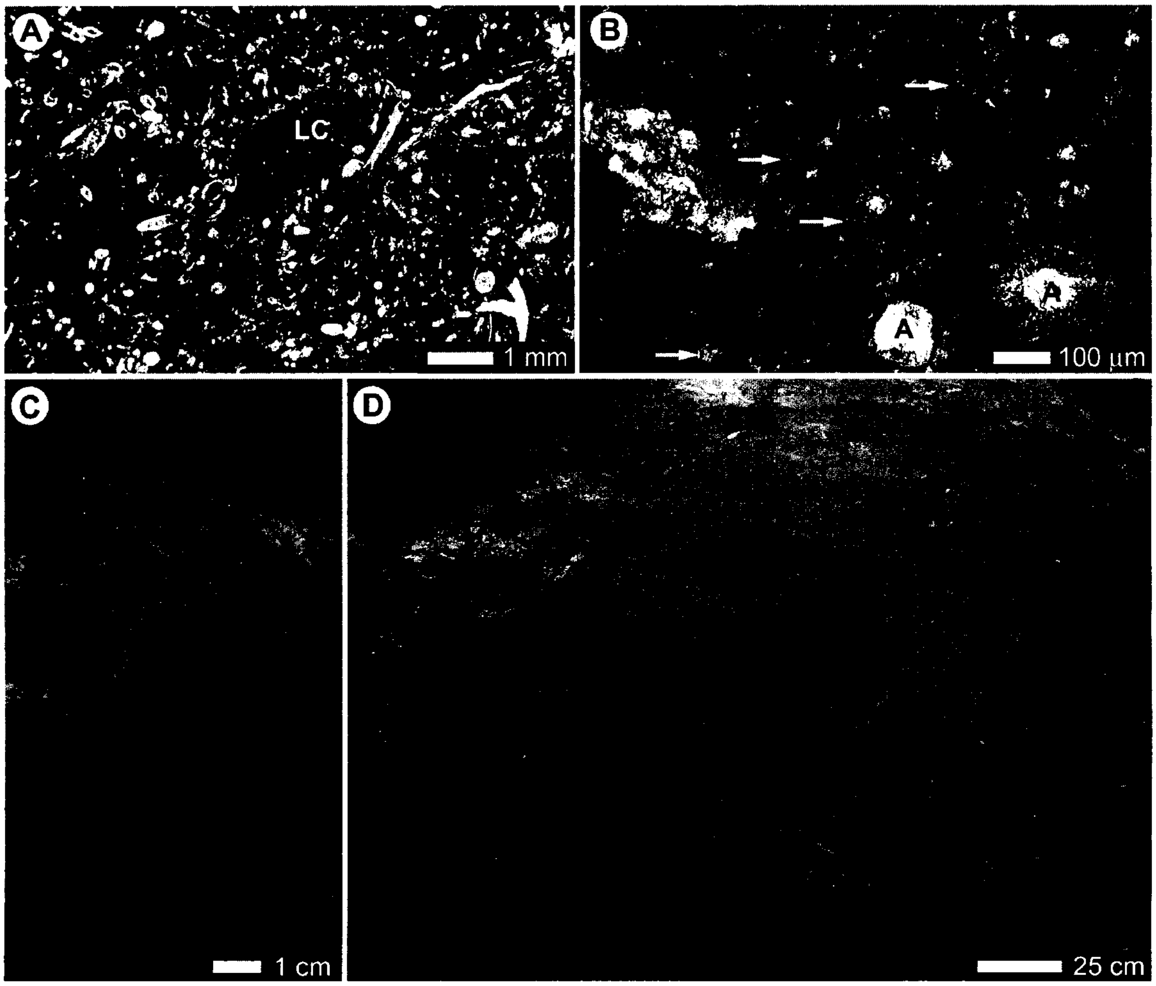

Figure 3-5. Depositional features of Unit 3 and Unit 4. A, B = thin-section photomicrographs; C = photograph of polished surface; D = field photograph. **A)** Unit 3 matrix with abundant algal fragments and ripped-up Unit 2 lithoclast (LC). **B)** Wackestone in Unit 4 with algal fragments (A) and yellowish rhombs of syndepositional dolomite scattered throughout (some indicated with arrows). **C)** Sample from bed at base of Unit 4 showing spar-filled vertically elongated tubules (T). *Amphipora* fragments at base of sample (arrows). **D)** Exposed bedding plane in Unit 4 with well-preserved mudcracks.

FEATURES OF SUBAERIAL EXPOSURE AND PEDOGENESIS

Unit 1 – The Host Limestone

Evidence of subaerial exposure and pedogenesis in Unit 1 is limited because karst features such as vuggy porosity, or calcrete deposits, are not found. The only evidence of subaerial exposure is the Fe-staining in its uppermost ~ 40 cm, and the impregnation of

Amphipora with clotted Fe-sulfides and Fe-oxides (Fig. 3-2D). Because blackened lithoclasts and stained *Amphipora* fragments were incorporated into Unit 2, the cause of staining must have pre-dated establishment of marsh-like conditions on the coastal plain.

Although blackened limestones may be produced in anoxic subtidal environments (Strasser 1984), this mechanism is discounted for explaining the staining at the top of Unit 1 because (1) the same depositional facies, without staining, is common lower in the unit, (2) it lacks mudstone, vertical fenestrae, or dark muddy deposits, which may indicate the deposit underwent a period of subtidal stagnation, (3) similar facies are found in Unit 4, without staining, and (4) the staining at the top of Unit 1 directly underlies an unconformity. The staining, therefore, is attributed to subaerial exposure and a series of diagenetic processes similar to those documented from recent and Cretaceous coastal plains by Strasser (1984), Shinn and Lidz (1988), and Vera and de Cisneros (1993). Blackening of exposed limestones on coastal plains, through processes that may include adsorption of organics, staining by Fe-sulfides, and fires (Shinn and Lidz 1988), is characterized by irregular patterns of staining and blackened intraclasts (Strasser 1984), like those present at the top of Unit 1. Extensive black and red staining has also been documented as an alteration feature found at the subaerial unconformity that defines the top of the Mississippian Monteagle Limestone Formation, in the United States (Driese et al. 1994). The preferential staining of *Amphipora* fragments at the top of Unit 1 is akin to the preferential blackening of Pleistocene corals in Florida, attributed by Strasser (1984) to the percolation of staining fluids through their porous skeletons.

Unit 2 – The Palustrine Deposit

Features in Unit 2 indicative of subaerial exposure and pedogenesis include complex horizontal, vertical, and curved crack networks and root traces lined and filled with various materials. Other features, including zoned neomorphic calcite crystals, calcite crystals with matrix embayments and authigenic clay inclusions, and spherulites, are more enigmatic but comparable to pedogenic features found in calcretes.

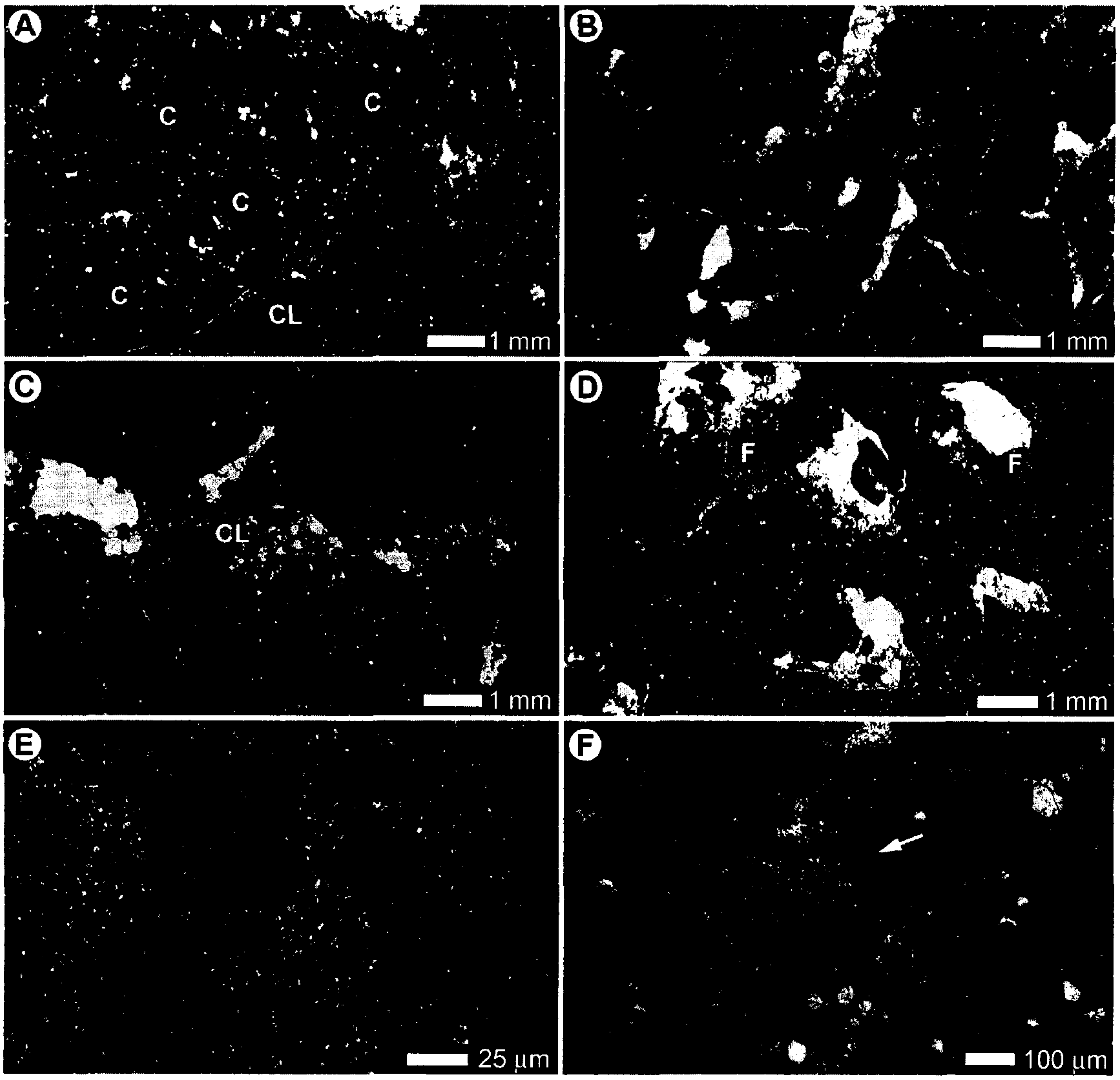

Figure 3-6. Thin-section photomicrographs of subaerial exposure and pedogenesis features in Unit 2. **A)** Matrix brecciation. Clasts (C) separated by cavities filled with clay-rich micrite and laminated clays (CL). **B)** Subvertical sinuous rootlets filled by micrite-clay mixtures and coarse calcite spar. **C)** Brecciated root trace partly filled by illite and kaolinite clays (CL) mixed with micrite. **D)** Fractured root traces partly filled by clay-micrite mixtures and vadose silt (F). Remaining space is filled by coarse calcite spar. **E)** Vadose silt. **F)** Rootlet (black outline) lined by micritic cutan with spherulite (white arrow) and filled with vadose silt (VS) that contains a branching segmented fungal hyphae or root hair (black arrow).

Crack Networks and Development of a Nodular Texture

Throughout Unit 2 there are submillimetric horizontal, vertical, and curved cracks. Some of the horizontal and vertical crack networks are associated with small-scale brecciation (Fig. 3-6A), and the curved crack networks give the rock a nodular texture which is evident in outcrop and thin section. Micrite, authigenic kaolinite, illite, and/or calcite cement fill or partly fill the cracks and brecciated zones. Similar crack networks in palustrine carbonates and calcretes have been attributed to drying of soft but cohesive sediment, presumably repeated numerous times before lithification took place (e.g., Freytet 1973; Freytet and Plaziat 1982; Braithwaite 1983; Platt 1989; Tandon and Friend 1989; Alonso-Zarza 2003).

Root Traces

Root traces in Unit 2 are characterized by vertical and subhorizontal sinuous tubes, 1-2 mm in diameter, generally < 2 cm in length, that bifurcate locally (Fig. 3-6B-D). Where these traces are intersected by crack networks, they have become brecciated into irregular fractures and vugs (Fig. 3-6D).

The voids formed by the root traces and their brecciated equivalents are filled by various materials. Many voids contain calcitic vadose silt (Fig. 3-6D-F), characterized by micrite and microspar grade anhedral, clear calcite crystals (cf. Dunham 1969; Freytet and Plaziat 1982; Platt 1989; Jones and Kahle 1995). Calcite silt is also found in some voids at constrictions, and in rare cases contain bifurcating segmented root hairs or fungal hyphae (mycorrhizae?) that are preserved by iron oxides (Fig. 3-6F).

Clay cutans and dense micritic coatings, of variable thickness, also partly line many voids (Fig. 3-7A-D). The micritic coatings appear to be calcitic cutans or the products of void-lining biofilms (Fig. 3-7A). Many are formed of micrite-clay mixtures (Fig. 3-7B), and many coatings have partly or completely spalled off, forming clasts (Fig. 3-7C). Some linings include calcite spherulites (Fig. 3-6F), which are common in void-lining cutans (Brewer 1964). Spalling of the linings is attributed to expansion and constriction of the surrounding matrix due to periodic of wetting and drying, akin to the generation of the crack networks.

Some voids also contain coarse, inclusion-rich calcite rhombs (comparable with the intercalary crystals of Brewer (1964)) mixed in with vadose silt (Fig. 3-7C, D), and books of authigenic kaolinite arranged into vermiform patterns (Fig. 3-7D-F). Root traces and brecciated, modified root traces, partly lined and filled with vadose silt, authigenic clays, cutans, and coarse calcite crystals, have been well documented as pedogenic indicators in other palustrine carbonate deposits (e.g., Freytet 1973; Freytet and Plaziat 1982; Platt

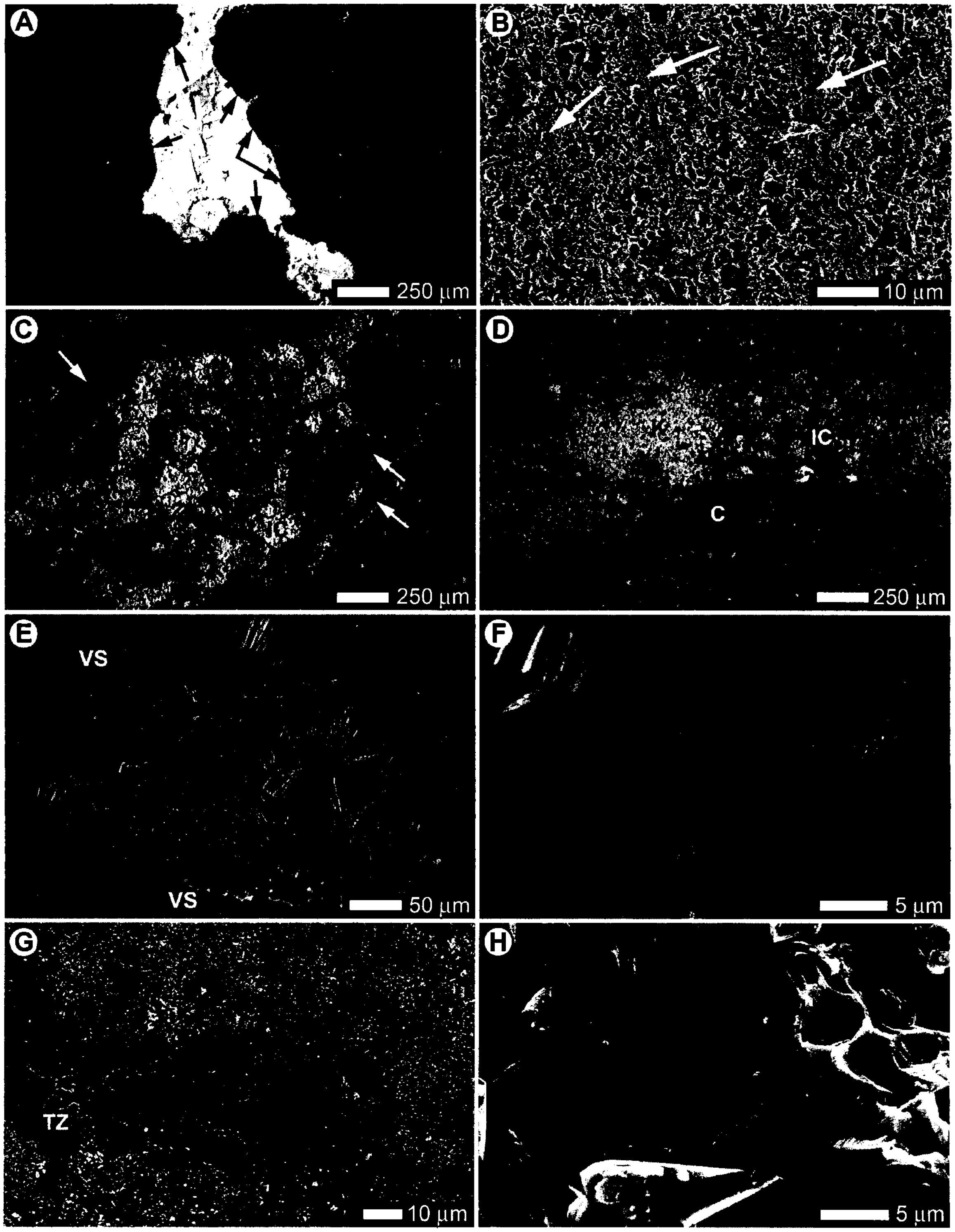

Figure 3-7. Pedogenic features in Unit 2. A and C-E = thin-section photomicrographs; B and F-H = SEM photomicrographs. **A)** Irregular rootlet lined by laminated micrite and laminated micrite-clay features (arrows). **B)** Polished and etched clay-micrite lining. Clay laminations (arrows) are well defined, but etching removed most micrite, leaving epoxy. **C)** Rootlet with micrite-clay linings on walls (arrows) that spalled off at bottom right. Rootlet is filled by mix of vadose silt (VS) and coarse, inclusion-rich calcite rhombs (IC). **D)** Rootlet lined at base by discontinuous clay cutan (C) and filled by pockets of authigenic kaolinite (K), clay-micrite mixtures, and coarse inclusion-rich calcite (IC) crystals. **E)**

Authigenic kaolinite booklets embedded in vadose silt (VS) in rootlet. **F)** Authigenic kaolinite booklets in rootlet arranged in vermiform patterns. **G)** Spar patch surrounded by transition zones (TZ) into surrounding micritic matrix. Etched sample. **H)** Concentrically zoned calcite in spar patch. Fractured sample.

1989; Dunagan and Driese 1999; Alonso-Zarza 2003) and in many calcretes (e.g., Bal 1975; Wieder and Yaalon 1974, 1982; Braithwaite 1983; Esteban and Klappa 1983; Drees and Wilding 1987).

Spar Patches, Neomorphic Calcite, and Authigenic Minerals

Randomly distributed throughout Unit 2 are small (< 1 mm), irregular-shaped patches of spar that in some parts appear transitional with the surrounding micritic matrix (Fig. 3-7G). The transition zones appear to be aggradationally recrystallized micrite with the degree of aggradation increasing towards the spar patch (cf. Folk 1959). Inclusions of matrix in the crystals and matrix embayments are common. These patches are similar to crystallaria, nodules, and crystal tubes described from other palustrine carbonates, calcretes, and soils (e.g., Brewer 1964; Freytet 1973; Wieder and Yaalon 1974, 1982; Braithwaite 1983; Tandon and Friend 1989; Purvis and Wright 1991), which are generally attributed to complex neomorphic processes involving dissolution of micrite in the matrix at the expense of the precipitating spar (cf. Brewer 1964; Sehgal and Stoops 1972; Freytet 1973; Tandon and Friend 1989; Purvis and Wright 1991). Similar neomorphic processes in Unit 2 may explain these patches that are at least partly transitional with the surrounding matrix.

Light-colored zoned calcite crystals are found in and around the spar patches, and in the matrix of Unit 2, in some cases as overgrowths on micrite (Figs. 3-7H, 3-8A-D). In many cases, micrite and clays, some of which were authigenic, have been trapped as inclusions in the crystals (Fig. 3-8B, D). The crystals in the matrix, generally of microspar grade, vary in shape from rhombic with planar faces and straight edges to anhedral forms with curved faces and irregular boundaries. Concentric growth zones are well defined. Some crystals intersect each other or grow in jagged forms. Many zoned crystals also have fine tubule inclusions (Fig. 3-8A), consistent with precipitation or neomorphism in the presence of filamentous microbes. The size range of tubule inclusions is variable, indicating that more than one taxon of microbe was present (e.g.,

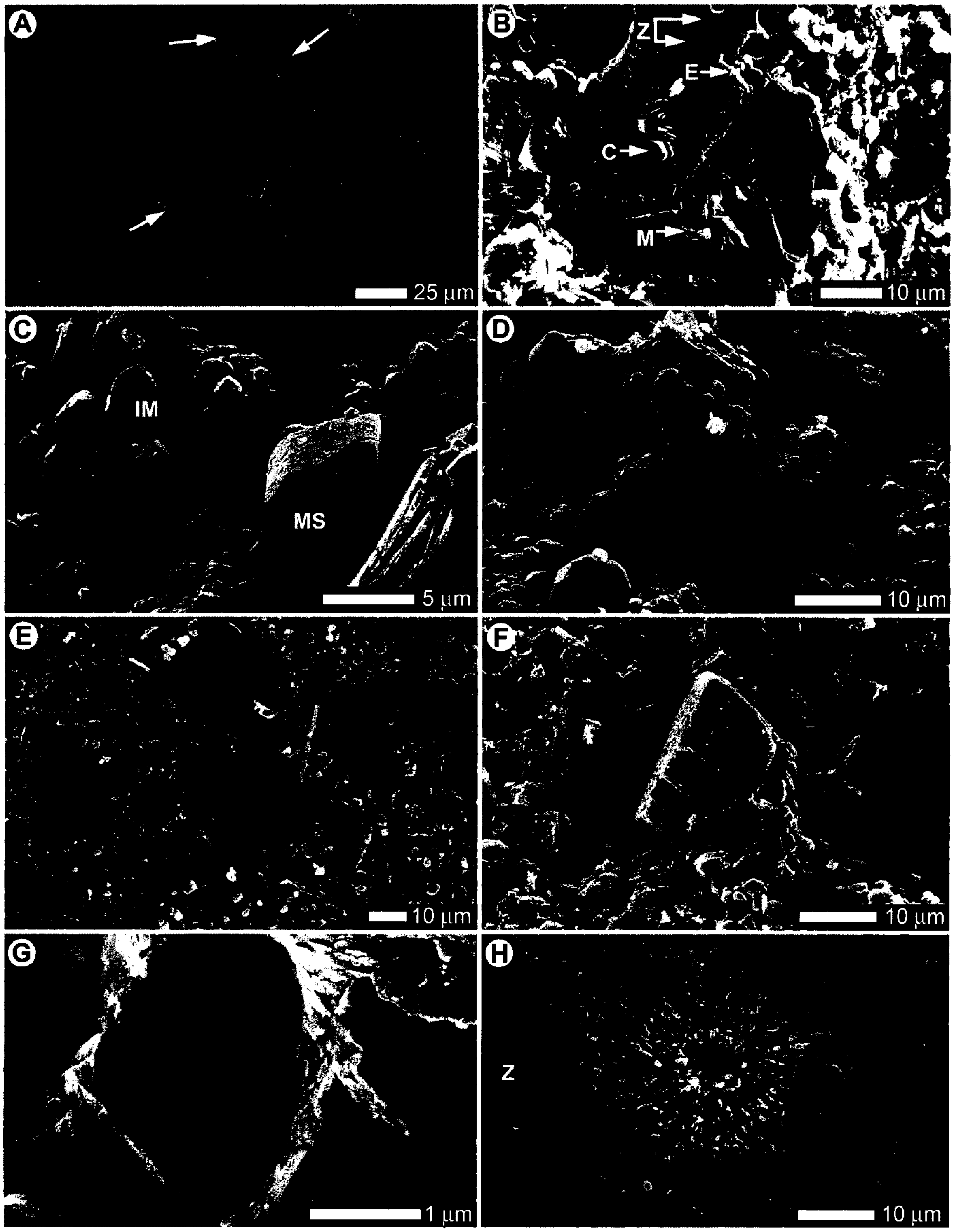

Figure 3-8. Pedogenic-diagenetic features in Unit 2. A = Thin-section photomicrograph; B-H = SEM photomicrographs. **A)** Zoned spar crystal in matrix with tubule inclusions at outer edges (arrows). **B)** Spar crystal in matrix with growth zonations (Z) and matrix embayments (E), authigenic kaolinite inclusions (C), and matrix inclusions (M). Matrix inclusions presumably formed after diagenetic overgrowth of matrix embayments. **C)** Interlocking micrite (IM) and zoned microspar (MS) growing on surface of authigenic kaolinite booklet. **D)** Microspar overgrowths of micrite, trapping some micritic matrix as inclusions. **E)** Crystal with filament extending from its edge (arrow). It is not clear if the

filament penetrated the crystal or the crystal grew around the filament. F) Partly dissolved authigenic feldspar (F). G) Tubule lined by clays. H) Spherulite surrounded by zoned (Z) spar. Irregular edges of the zoned spar against the spherulite suggest that it grew against the preexisting spherulite.

cyanobacteria, fungi). In rare cases, filaments extending from crystals are still preserved (Fig. 3-8E).

The variation in size and shape of the zoned calcite crystals, presence of authigenic clay inclusions, growth of some crystals from micrite in the matrix, and presence of the zoned crystals in some spar patches indicates that these crystals are diagenetic products. They may have formed through dissolution and recrystallization of carbonate in the matrix, including fragmented pieces of charophytes and skeletal stromatolites. The crystals in the matrix are similar to zoned calcite fabrics in alpha-type calcretes (Wright 1988; Wright and Peeters 1989), although alpha fabrics tend to lack evidence of biogenic influences and were interpreted by Wright (1988) to represent an abiogenic end member of calcrete fabrics. The differences between the neomorphic calcite crystals in Unit 2 and alpha fabrics in calcretes, however, may simply reflect the same types of processes taking place in a palustrine context as opposed to a calcrete context.

Authigenic feldspar and clays (illite and kaolinite) are dispersed throughout the matrix of Unit 2. Some feldspar crystals show evidence of partial dissolution (Fig. 3-8F), but the timing of dissolution is not known. Clay minerals are also found randomly in the matrix and wrapped around some tubules (Fig. 3-8C, G). It is not always clear if these clays were deposited as sediment or are authigenic. Clays have not, however, been found as inclusions in charophytes or in any of the skeletal stromatolites.

Spherulites

Spherulites (15-40 μm diameter) formed of irregular bladed calcite crystals that radiate from a sometimes hollow center are common throughout Unit 2 (Fig. 3-8H). Locally, they appear to be joined into composite structures. In contrast to the hollow spheres, which are abundant but randomly dispersed, the spherulites are, in some areas, closely associated with void systems and cutans (Figs. 3-6F, 3-8H). The origin of the spherulites is not clearly understood, but they may be pedogenic (e.g., Brewer 1964; Verrecchia et al. 1995).

Unit 3 – The Marine-Incursion Deposit

Evidence of pedogenesis in Unit 3 includes small rhizocretions, poorly preserved root traces, irregular fracture patterns, and irregular patterns of staining by organics, Fe-sulfides, and Fe-oxides. Unlike the marine deposits in Unit 1 and Unit 4, Unit 3 is characterized at the outcrop scale by an irregular nodular texture formed from the variable alteration of the limestone, such that areas of hard limestone are separated by friable, chalky areas of soft limestone (Fig. 3-2B, C). This is similar to the subaerial alteration of Pleistocene limestones on Barbados (James 1972), in which remnants of the host limestone float in an intensely altered matrix, and Palustrine Facies #6 of Freytet (1973), attributed to oscillation of the water table.

Rhizocretions, Root Traces, and Fractures

Rhizocretions, root traces, and irregular fracture networks, in some cases associated with brecciation, are variably preserved in Unit 3. The rhizocretions, formed of concentric micritic laminae, have small diameters (~ 1 mm) with variably stained outer margins and contain amorphous organic material and vadose silt (Fig. 3-9A). Root traces and irregular fracture networks intersect each other and are partly filled with brecciated clasts of matrix material, calcitic vadose silt, mixtures of calcitic vadose silt with illite, books of authigenic kaolinite arranged in vermiform patterns, Fe-oxide pigments, gypsum, and coarse calcite spar (Fig. 3-9B-D). Fine (~ 10 μm diameter), orange-brown segmented sinuous tubules that resemble fungal hyphae or root hairs are preserved locally in these voids (Fig. 3-9E), and in rare cases can be traced for lengths that exceed 1 mm.

Staining Patterns and Clots

Throughout Unit 3 there are irregular nodular and stringer-like patterns of red and black staining caused by Fe-oxides and related pigments, very finely crystalline Fe-sulfides, and organics. Nodular stain patterns in the matrix, up to ~ 2 cm in diameter, are characterized by irregular, sharply defined to diffuse margins and variably stained interiors (Fig. 3-9F). *Amphipora* and other fossil fragments are variably stained, like those at the top of Unit 1. As such, the staining is treated as a subaerial alteration feature, like the staining at the top of Unit 1.

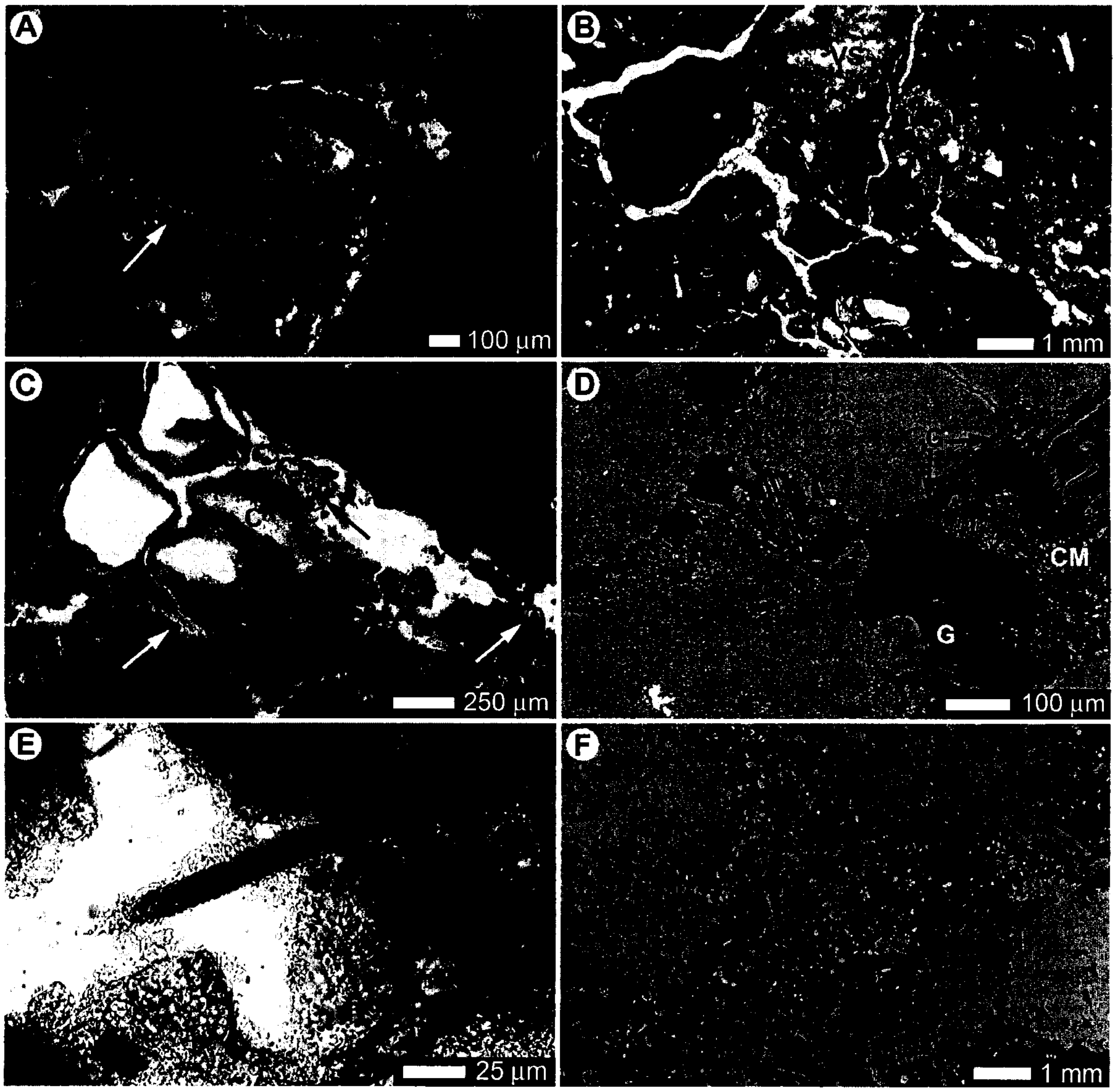

Figure 3-9. Pedogenic features in Unit 3. A-C, E, and F = thin section photomicrographs; D = BSE image. **A)** Rhizocretion with micritic laminae and partly stained outer edge (arrow). Central part of rhizocretion partly filled with organics and micrite. **B)** Complex crack and root-trace network. Root trace filled with vadose silt (VS). Crack network filled with mix of clays, micrite, gypsum, and spar. **C)** Close-up of irregular clay-micrite (C) material filling part of crack network. Clays are a mix of illite and kaolinite. Gypsum (arrows) partly filled remaining space. **D)** Crack network partly lined and filled with clays (C) and filled with clay-micrite mixtures (CM), quartz (Q), and gypsum (G). Black = pore space. **E)** Orange-brown hollow, segmented tube in crack network. **F)** Nodular stain pattern in matrix defined by concentrated halo of black staining and lesser staining of interior.

EVOLUTION OF THE COASTAL-PLAIN SUCCESSION

Deposits in the Alexandra Formation at the top of RC#1 record the evolution of a dynamic coastal-plain environment concurrent with fluctuating sea-level and the offshore development of RC#2. Periods of subaerial exposure, weathering, and pedogenesis alternated with periods of fresh-water to brackish-water deposition and marine deposition. The cumulative succession, ~ 50 cm thick, represents a Type I sequence boundary that separates the marine deposits of RC#1 (Unit 1) from marine deposits of RC#2 (Unit 4). Five stages (1 – 5) in its evolution are evident (Fig. 10).

Stage 1: Initiation of Coastal Plain

RC#1 formed the limestone substrate to the coastal plain after sea level fell ~ 17 m (Fig. 3-10 #1). Whereas the reef-margin facies, several kilometers away, contain vadose cements in 1–3 cm solution vugs (Chapter 2), the peritidal deposits in the Alexandra Falls region were stained by weathering processes. Storms transported blackened intraclasts from the coastal plain to the outer ramp, where they became common constituents of storm beds in the basal part of RC#2 (Chapter 2).

Stage 2: Deposition of Palustrine Carbonate

In the Alexandra Falls area, establishment of shallow, carbonate-rich marshlands on the weathered limestones at the top of Unit 1 led to deposition of palustrine carbonate (Fig. 3-10 #2). Blackened intraclasts and stained *Amphipora* fragments from the top of Unit 1 were incorporated into these deposits. Root traces, crack networks, complex crystal fabrics, and authigenic mineral growth attest to exposure of the marsh deposits and pedogenesis on a vegetated coastal plain in an intermediate to semiarid climate (cf. Platt and Wright 1992).

Stage 3: Deposition of Sediment from Marine Incursion

Deposition and weathering of the palustrine carbonate was terminated by the incursion of marine waters onto the coastal plain. Shallow lagoon sediments dominated by *Amphipora* and algae were deposited along with storm detritus that may have been derived from the reef situated on the outer ramp (Fig. 3-10 #3).

Stage 4: Subaerial Exposure and Pedogenesis

Following retreat of the shoreline, subaerial exposure, weathering, and pedogenesis of Unit 3 produced features similar to those found in Unit 2 (Fig. 3-10 #4). The presence of gypsum in cavities indicates percolation of saline waters through the unit. Periodic establishment of saline ponds on the coastal plain, or sea spray, which may travel several kilometers inland (e.g., James 1972), may have provided this water.

Stage 5: Transgression and Deposition of Peritidal Facies

Subaerial weathering and pedogenesis at the top of Unit 3 was terminated by permanent flooding of the coastal plain that established an inland peritidal region to RC#2 (Fig. 3-10 #5). These deposits form the upper part of the Alexandra Formation.

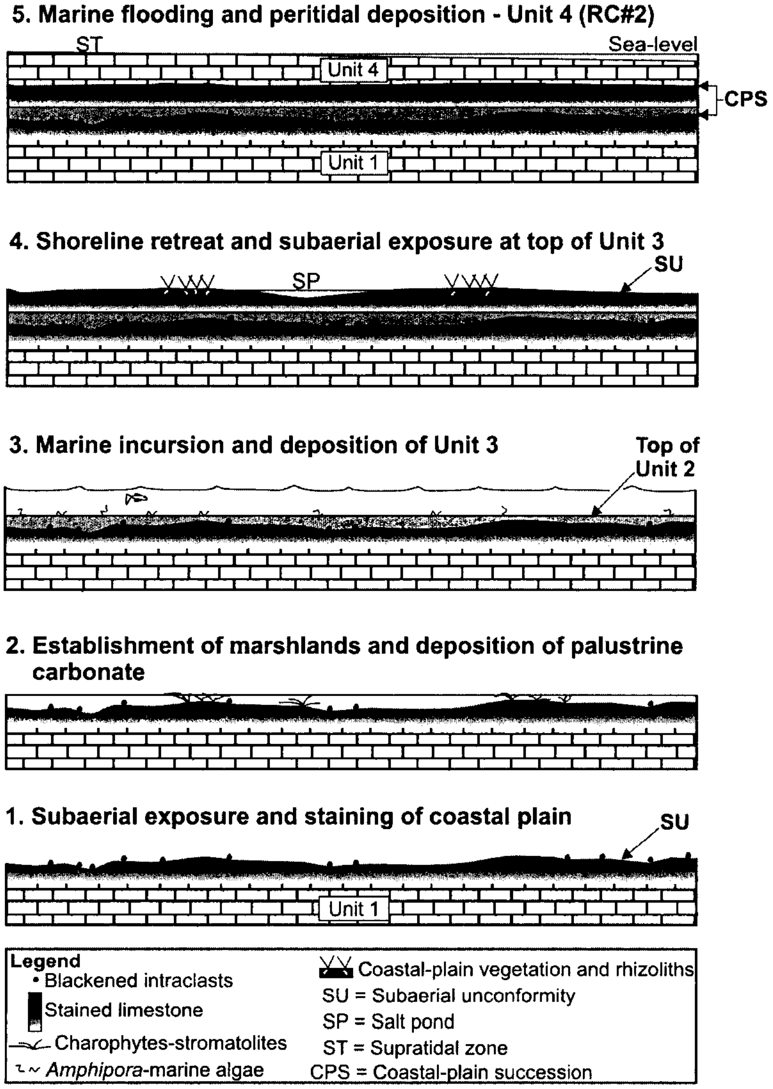

Figure 3-10. Evolution of coastal-plain succession in Alexandra Formation after sea-level fall terminated development of RC#1 and exposed its top. Stages 1-4 took place while RC#2 developed on outer ramp. Final stratigraphic succession is illustrated in #5. Not to scale.

DISCUSSION

Features at the top of Unit 1 and in Unit 2 and Unit 3 (Table 3-1) are interpreted to collectively reflect events of subaerial exposure and pedogenesis that took place on the coastal plain after falling sea-level exposed the top of Reef Complex #1. Features of the palustrine deposit are comparable with those documented from other palustrine deposits and calcretes (e.g., Brewer 1964; Freytet 1973; Bal 1975; Freytet and Plaziat 1982; Wieder and Yaalon 1974, 1982; Braithwaite 1983; Esteban and Klappa 1983; Platt 1989; Tandon and Friend 1989; Platt and Wright 1992; Dunagan and Driese 1999; Alonso-Zarza 2003). Features in Unit 3 are comparable with alteration features found in limestones at subaerial unconformities and below calcrete profiles (e.g., James 1972; Driese et al. 1994).

Table 3-1. Features indicative of subaerial exposure and pedogenesis found in coastal-plain succession at top of RC#1 in Alexandra Formation along Hay River.

Unit 1	Unit 2	Unit 3
Blackened/ reddened	Nodular texture	Chalky differentiation of outcrop
Fe-staining	Crack networks	Crack networks
	Root traces	Root traces
	Brecciated root traces	Rhizocretions
	Vadose silt	Vadose silt
	Authigenic kaolinite, feldspar, illite	Authigenic kaolinite, illite
		Fracture-filling gypsum
	Spar patches with diffusive margins	Blackened/ reddened
	Clay cutans and micrite and micrite-clay cutans or biofilms	Fe-staining
	Neomorphic calcite	
	Neomorphic calcite with siliciclastic inclusions, matrix embayments	
	Spherulites	

Although it is reasonable to assume that subaerial alteration of Unit 2 and Unit 3 reached depths below their bases and may have imparted pedogenic or diagenetic features onto the underlying deposits, there is limited evidence for this possibility having taken place. Blackened intraclasts in Unit 2, derived from the top of Unit 1, indicate that staining at the top of Unit 1 took place before Unit 2 was deposited and is distinct from the staining of Unit 3. Likewise, ripped-up lithoclasts of Unit 2 with zoned neomorphic calcite in Unit 3 indicate that these features developed prior to deposition of Unit 3. The root traces in Unit 2 probably formed close to the surface of that unit, rather than at depth from the top of Unit 3, because they are delicate forms (e.g., ≤ 2 mm diameter) and robust (e.g., > 2 mm diameter), deeply penetrative root traces are not present in Unit 3. The authigenic kaolinite that fills some voids in Unit 2 may be genetically related to the kaolinite in Unit 3, but the absence of gypsum in the voids of Unit 2, which is common in the voids of Unit 3, suggests that downward percolation of waters was minimal and that the kaolinite in each unit is probably distinct. Neither authigenic kaolinite nor gypsum have been found in Unit 1, Unit 4, or any other part of the Alexandra Formation.

The coastal-plain succession has regional stratigraphic significance because it marks the termination of RC#1 and separates RC#1 from RC#2. The amount of time represented by the succession, however, is unknown because of the lack of precise biostratigraphic controls due to the absence of age-diagnostic fossils (McLean and Klapper 1998) and deposits suitable for absolute age dating. Comparison of the magnitude of sea-level fall (~ 17 m) to sea-level fluctuations (third – fifth order cycles) for greenhouse and transitional climates, which characterized the Late Devonian (e.g., Copper 2002), however, suggests that the boundary between RC#1 and RC#2 is a relatively high-frequency boundary, with even higher-frequency superimposed shoreline shifts. The latter is indicated by the deposition of Unit 3, which probably took place at the top of the lowstand systems tract in which RC#2 was developing. Given the magnitude of sea-level fall, it seems reasonable that the coastal-plain succession represents a fourth-order sequence boundary with a hiatus of 0.1-1 Myr. The higher-frequency deposits that form Unit 3 may be of 0.01-0.1 Myr duration (cf. Tucker et al. 1993; Lehrmann and Goldhammer 1999). The amount of time represented by Unit 2 is unknown.

The significance of palustrine deposits, which can cover thousands of square kilometers in coastal regions (Platt and Wright 1992), to the sequence stratigraphic analysis of marine limestone successions, has yet to be fully realized. There are two end-member contexts in marine coastal environments where palustrine deposits can be found (Fig. 3-11A), with each conveying different stratigraphic implications.

At one end of the spectrum (where climate permits) are fresh- to brackish-water marshes situated in supratidal environments, subject to periodic flooding by seawater during spring tides and storm events (e.g., Monty and Hardie 1976; Shinn 1983). In this context, the marshes represent marginal depositional systems to the surrounding marine system, thereby acting as a connect, or transition zone, between conformable deposits in the marine realm and the adjacent subaerial unconformity (Fig. 3-11A). Deposits in these marshes have distinct sedimentary features (Table 3-2) that unequivocally point to their location in the peritidal realm (Monty and Hardie 1976; Shinn 1983). Because peritidal facies associations track sea-level fluctuations, the stratigraphic implications of these deposits are well known; supratidal palustrine deposits can be predicted to cap normal regressive peritidal systems (Fig. 3-11B) or be found at the bases of transgressive peritidal systems (Monty and Hardie 1976; Wright 1985). The top of supratidal palustrine deposits in normal regressive deposits indicates therefore the point of maximum regression and will be overlain by transgressive deposits if sea-level rises (Fig. 3-11B), or by a sequence boundary if relative sea-level falls. In contrast, supratidal palustrine deposits at the base of a transgressive peritidal system are subject to intense erosion as the tidal flat retrogrades and are not likely to be preserved (Wright 1985).

At the opposite end of the spectrum are palustrine deposits that form in marshes that are not associated with the peritidal realm but are juxtaposed onto subaerial unconformities (Fig. 3-11A). These deposits may be directly associated with karst and/or calcrete (e.g., Monty and Hardie 1976; Esteban and Klappa 1983; Platt and Wright 1992). Described herein as "disconnected" palustrine deposits, the marshes in which these deposits originate are isolated from direct marine influence and form part of the exposed landscape (Fig. 3-11A-C). As such, disconnected palustrine deposits are distinguishable from supratidal palustrine deposits (Table 3-2; cf. Monty and Hardie 1976) and should be considered a sedimentary component of subaerial unconformities and sequence boundaries. Modern examples of disconnected palustrine deposits include marshes in the interior eastern half of Andros Island in the Bahamas (e.g., Monty and Hardie 1976) and marshes in the interiors of the Cayman Islands (personal observations). Palustrine deposits in the Florida Everglades (e.g., Platt and Wright 1992) cover a continuum from those that are disconnected from marine influence to those that are deposited proximal to

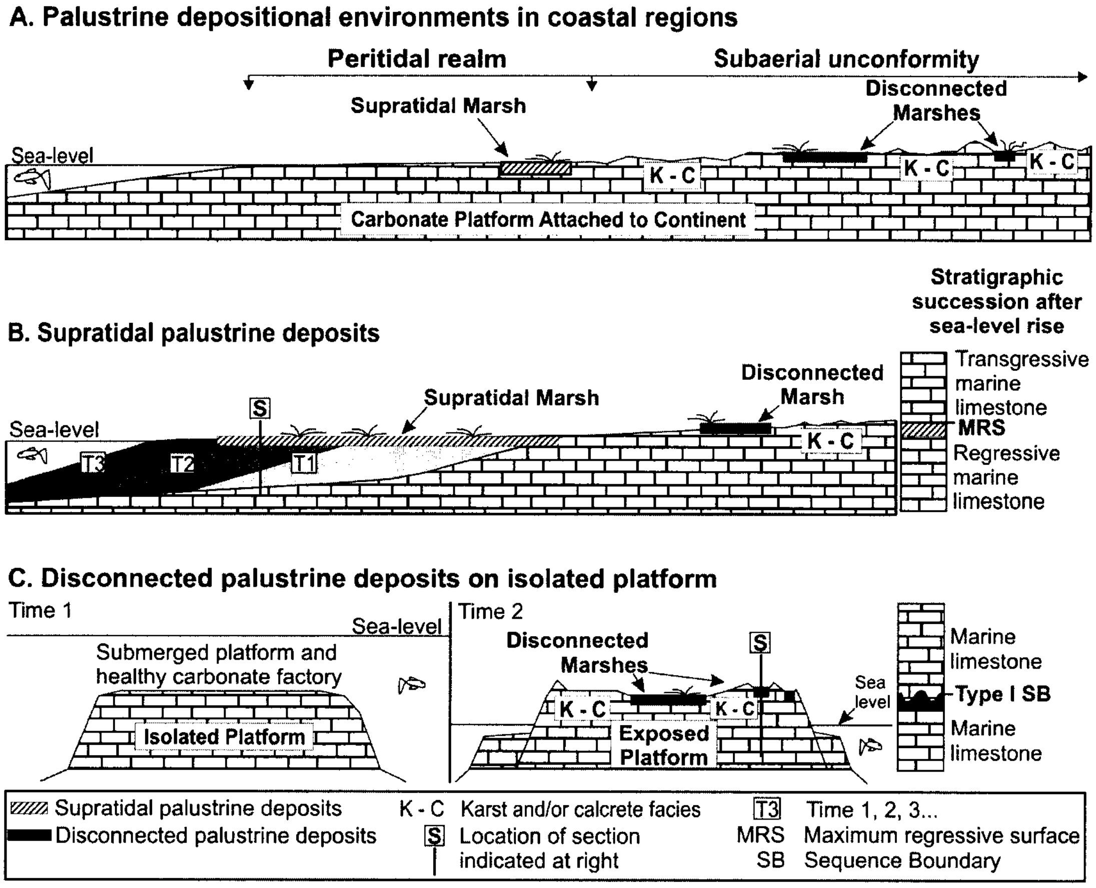

Figure 3-11. Context of palustrine deposits in marine coastal environments (not to scale). **A)** Spectrum of palustrine deposits in coastal regions defined by supratidal and disconnected end members. **B)** Supratidal deposits capping progradational, normal regressive system. Note that supratidal palustrine deposits connect landwards with subaerial unconformity, which may include disconnected palustrine deposits. Sea-level rise and transgression would result in a regressive-transgressive marine limestone succession (column at right), divided by supratidal palustrine deposits. Top of supratidal palustrine deposits marks maximum regressive surface. **C)** Disconnected palustrine deposits on isolated oceanic platform. Carbonate sediment deposited when platform is submerged (Time 1) will be subaerially exposed upon relative sea-level fall of sufficient magnitude (Time 2). The subaerial unconformity may be marked by karst, calcrete, and/or disconnected palustrine deposits. Subsequent relative sea-level rise may deposit new sequence of marine limestone. The two marine limestone sequences (column at right) are separated by a Type I sequence boundary marked by disconnected palustrine deposits.

the mangrove swamps and salt marshes. In all of these examples, the palustrine deposits are characterized by very thin (< 1 m) deposits surrounded by elevated (centimeter to decimeter scale) areas with concurrently developing karst and/or calcrete (cf. Monty and Hardie 1976; Platt and Wright 1992). After a relative sea-level rise that leads to permanent marine flooding, these deposits, in addition to the karst and/or calcrete, mark the sequence boundary (Fig. 3-11C). They are distinct from overlying transgressive deposits because (1) they are not conformable with these deposits, as shown by their inherent evidence of exposure and pedogenesis (cf. Freytet 1973; Freytet and Plaziat 1982; Esteban and Klappa 1983; Platt and Wright 1992; Dunagan and Driese 1999; Alonso-Zarza 2003), (2) they were deposited, and altered, concurrently with surrounding calcrete and/or karst, which constitute the other criteria for identifying the sequence boundary (cf. James 1972; Esteban and Klappa 1983; Sarg 1988; Handford and Loucks 1993; Hunt and Tucker 1993), and (3) transgression in carbonate systems is usually characterized by a lag between the initial flooding event and subsequent onset of deposition (e.g., mangrove peat), during which physical and biological erosion takes place (Enos 1977; Harris 1979; Hardie and Shinn 1986; Desrochers and James 1988; Jones and Hunter 1989; Jones and Desrochers 1992; Gischler 2003). As such, the base of the transgressive deposits is the erosional surface (e.g., a ravinement surface) that is found at the top of the palustrine deposit (cf. Jones and Desrochers 1992).

The importance of revising the criteria for recognizing subaerial unconformities and defining sequence boundaries in marine limestone successions (Table 3-2, Fig. 3-11) is exemplified in the Alexandra Formation, where karst features and calcrete profiles are not found at the boundary between RC#1 and RC#2. In this case, the coastal-plain deposits in Unit 2 originated in marshlands situated on the subaerial unconformity developed at the top of Unit 1, which is notable only for its stained appearance. The sedimentology of the marshlands indicates that they were isolated from the marine realm in which RC#2 was developing, and were not part of a supratidal depositional environment. Given that overlying Unit 3 also includes evidence of subaerial exposure and pedogenesis, the hiatus at its top is identified as the physical surface that defines the top of the coastal-plain succession and separates the depositional sequence of RC#1 from that of RC#2. Deposition of Unit 3 was probably a prelude to the more permanent flooding that deposited Unit 4, as part of RC#2.

Recognition of ancient disconnected palustrine deposits is important because of their stratigraphic implications. Successful recognition of these deposits, however, may be difficult because (1) root traces may be mistaken for animal burrows, (2) the deposits may be structureless (Wright 1985) or nodular, which is not solely diagnostic, (3) fossil content may be sparse and the ecology of many ancient microfossils remains poorly understood, and (4) calcrete and/or karst features, which would suggest a terrestrial origin

Table 3-2. Criteria for recognition and distinction of supratidal palustrine deposits, disconnected palustrine deposits, karst, and pedogenic calcrete.

	Supratidal Palustrine Deposits	**Disconnected Palustrine Deposits**	**Karst**	**Pedogenic Calcrete**
Sedimentary setting	Marshes in supratidal realm	Marshes on subaerially exposed platform	Subaerially exposed platform	Subaerially exposed platform
Sedimentary nature	Fresh-brackish water deposits; periodic exposure and pedogenesis	Fresh-brackish water deposits; periodic exposure and pedogenesis	Subaerial erosion of limestone by meteoric diagenesis	Erosion of limestone substrate and pedogenesis
Distinctive features	Sediment-binding stromatolites dominant; fenestral porosity; skeletal stromatolites	Charophytes and skeletal stromatolites (e.g., *Rivularia haematites*) abundant	Sink holes, caverns, speleothems, solution vugs, phytokarst	Nodular, platy, laminar, chalky pedogenic horizons; possibly colour (e.g., red, green)
	Contain storm-derived marine sediment and may appear to be cyclical marine deposits	No marine sediment. May contain peat and occur with lacustrine facies, karst, and/or calcrete		Do not contain primary charophyte-skeletal stromatolite associations
Important attributes	Rhizoliths, desiccation cracks, brecciation, circumgranular cracks, blackened intraclasts, vadose silt, cutans, spar patches, *Microcodium*, neomorphic calcite, authigenic clays and feldspar, spherulites	Rhizoliths, desiccation cracks, brecciation, circumgranular cracks, blackened intraclasts, vadose silt, cutans, spar patches, *Microcodium*, neomorphic calcite, authigenic clays and feldspar, spherulites	Rhizoliths, collapse breccias, blackened intraclasts, terra rossa, vadose silt and cements	Rhizoliths, desiccation cracks, brecciation, circumgranular cracks, blackened intraclasts, vadose silt, cutans, spar patches, *Microcodium*, calcite tubules, authigenic clays and feldspar, alpha fabrics, lichen, pisoids, spherulites
Indicates subaerial unconformity	NO	YES	YES	YES

Lists compiled from features identified in this paper and in Monty and Hardie (1976), Shinn (1983), Esteban and Klappa (1983), and Platt and Wright (1992).

to the deposit, may not be co-developed, as seen in the Alexandra Formation. Wright (1985) noted that failure to recognize these deposits, when they do occur, must partly explain their limited record. Palustrine deposits may also be easily mistaken for calcrete, given that a number of features are common to both types of deposits (Freytet and Plaziat 1982; Esteban and Klappa 1983; Alonso-Zarza 2003). The association of charophytes with *Rivularia* skeletal stromatolites, therefore, is an important depositional feature that should aid in the recognition of ancient palustrine deposits. In modern marshlands, calcareous streams, and rice fields, charophyte-microbe, and in particular, charophyte-*Rivularia* associations, are well documented (e.g., Freytet and Plaziat 1982; Whitton 1987). Monty (1976), for example, noted that colonies of *Rivularia haematites* are commonly found in the splash zones of lakes, which is where palustrine deposits would be accumulating. As such, inclusion of charophyte – skeletal stromatolite associations with sedimentary and pedogenic features (Table 3-2) provides an enhanced set of criteria for the identification of ancient, disconnected palustrine deposits, and distinction of these deposits from supratidal palustrine deposits and calcrete. Although a few examples of calcified *Rivularia* are known from marine environments (e.g., Golubic and Campbell 1981), these precipitates are distinct from freshwater *Rivularia* precipitates and are likely to be associated with marine biota, thereby allowing distinction from those in palustrine deposits.

CONCLUSIONS

The unconformable nature of the coastal-plain succession in the Alexandra Formation is deceptive because it lacks karst features and calcrete profiles. The palustrine deposits, however, which are distinct from all other facies in the Alexandra Formation, provide unequivocal evidence that a fresh- to brackish-water environment, disconnected from the marine realm, existed at this stratigraphic level. Conclusions from this study include:

- RC#2 was fringed by a coastal plain developed at the top of RC#1, on which a series of unconformable deposits were deposited in an intermediate to semiarid climate. The most distinct were the palustrine deposits, and the succession represents a Type I sequence boundary.

- The sequence boundary probably represents a hiatus of 0.1 – 1.0 Myr, with higher-frequency sea-level fluctuations superimposed.
- Disconnected palustrine deposits should be considered important criteria for recognizing subaerial unconformities in marine limestone successions.
- Disconnected palustrine deposits, calcrete profiles, and/or karst are the criteria for defining sequence boundaries in successions of marine limestones.
- Ancient palustrine deposits can be recognized through a set of depositional and pedogenic criteria that include charophyte – skeletal stromatolite associations. This association distinguishes palustrine deposits from calcrete, which share a number of the same pedogenic features.

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CHAPTER 4 -ECOLOGICAL/ENVIRONMENTAL CONTROLS ON THE TYPES OF REEF FACIES IN THE ALEXANDRA REEF SYSTEM[1]

INTRODUCTION

Devonian reef systems and associated carbonate platforms, especially of the Givetian-Frasnian, represent the most significant phase of global reef development in the Phanerozoic (Copper 1989, 2002). Although numerous studies have catalogued the gross fossil composition of Devonian reefs (e.g., stromatoporoids, corals, calcimicrobes), the relative lack of detailed studies has limited our understanding of Devonian reef paleoecology (Moore 1989; Wood 1993; Kiessling et al. 1999). As ecological dynamics control the composition of any carbonate-producing community (Wood 1999), and thereby the types of carbonate facies that are deposited, this lack of information fundamentally limits our understanding of the controls on Devonian carbonate systems. Nutrients (e.g., nitrogen, phosphate, iron), in particular, are an important control on carbonate systems (Hallock 1987; Mutti and Hallock 2003), and yet their role in the development of Devonian reef systems has been investigated in only a few studies (e.g., Wood 1993; Eliuk 1998; Whalen et al. 2002), and they are not addressed in existing facies models for these systems (Machel and Hunter 1994).

With the perspective that carbonate depositional systems and platform evolution are controlled by the interaction of several dynamic variables, this study examines the relationship between platform geometry, sea-level change, and nutrification, on the development of the Late Devonian (Frasnian) Alexandra Reef System. Located in the Western Canada Sedimentary Basin, a fall in relative sea-level caused a basinward-jump of reef development in this ramp-situated system and facilitated a combination of nutrient-enrichment (= nutrification) mechanisms that caused a shift from metazoan-dominated to metazoan-microbial dominated reef facies. The mechanisms of nutrient enrichment included terrestrial run-off, groundwater seepage, storm disturbance of offshore nutrient reservoirs, and possibly seasonal nutrification events that were triggered

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by climate change. Although not detrimental to the evolving reef system, nutrient enrichment changed the nature of reef-framework, and the types of carbonate deposits that accumulated. Rising sea-level eventually diminished the synergy of nutrification mechanisms and the reef facies returned to being metazoan-dominated.

The sequence stratigraphic context of nutrification in the Alexandra Reef System demonstrates some important mechanisms of nutrient enrichment that apply to forced regressive and lowstand systems on carbonate ramps, and that nutrient-enrichment is not necessarily detrimental to reef-building communities and platform evolution. The study also demonstrates that the common assumption (cf. Wood 1998a) that microbial carbonates were ubiquitous in Devonian reefs is not accurate. A nutrient-gradient model, developed to explain the contrasting facies types in the Alexandra Reef System, is proposed as a new approach for understanding variations in Devonian reef facies, with significant implications for how these systems are evaluated. In particular, the nutrient-gradient model indicates that Devonian reef systems were not limited to oligotrophic (nutrient deficient) environments and their platforms were not highly susceptible to nutrient-invoked drowning. This, and the ability of stromatoporoids to grow over different types of substrates (Wood 1995; Kershaw 1998), may partly explain the global expansiveness of these systems, and the preponderance of these reefs to form broad, gently sloping platforms (cf. Wilson 1975), quite different from the geometries of modern carbonate platforms constructed by coralgal reefs in oligotrophic realms.

METHODOLOGY

Strata that belong to the Alexandra Reef System (= Alexandra Formation, ~35 m thick), which is located in the southern part of the Northwest Territories of Canada (Fig. 4-1), are exposed along a southwest–northeast gorge system cut by Hay River and in a southeast–northwest trending escarpment. Strata along Hay River show little lateral variation because the exposure trend is nearly parallel to depositional strike. In contrast, the escarpment trend is oblique to depositional strike, providing a nearly continuous section across different parts of the reef system. Eighty stratigraphic sections, measured from 47 localities along the escarpment edge, 5 road-cuts on the escarpment top, a quarry,

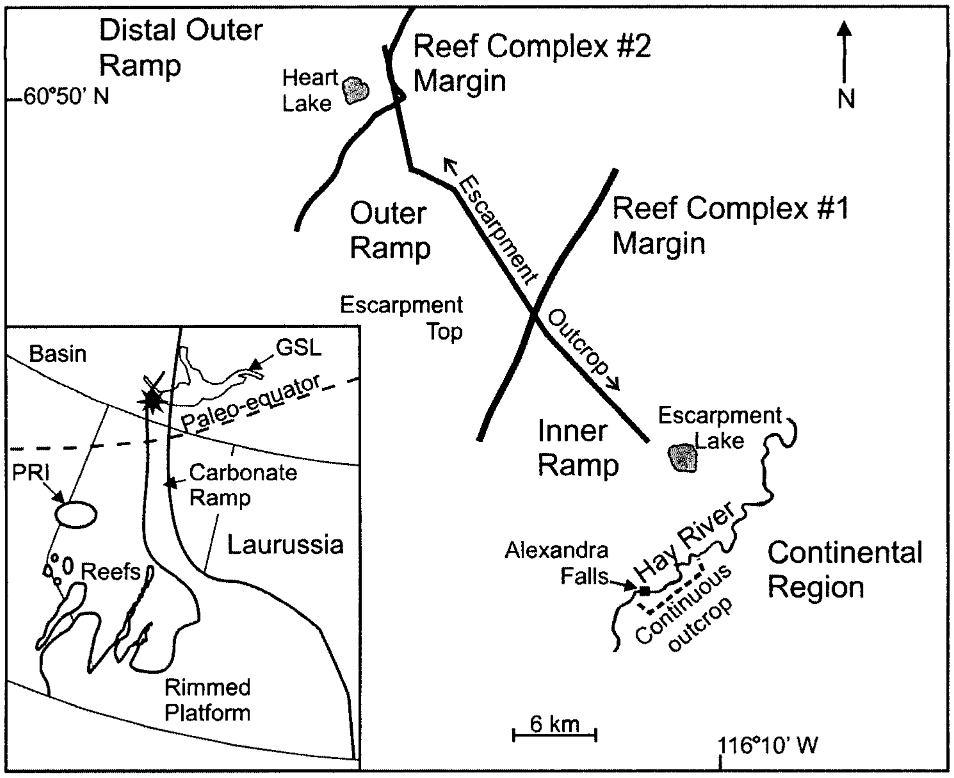

Figure 4-1. Map of study area in southern part of Northwest Territories and Alexandra Reef System paleogeography. Inset shows study area (star) relative to Late Devonian paleogeography of western Canada, overlain on geopolitical boundaries. Paleoequator position from Scotese (2004). GSL = Great Slave Lake; PRI = Peace River Island.

and 3 localities along Hay River, combined with 11 continuous cores, provided the database for this study. Detailed aspects of the section localities and sequence stratigraphic correlation are given in Chapter 2. Most (> 90%) of the oriented samples (n =827) collected from the measured sections, at ~ 1 m intervals, were slabbed and etched in dilute HCl for study of macroscopic features. Large (5 x 7·5 cm) thin-sections were made from outcrop (n = 134) and core (n = 160) samples for detailed petrography.

GEOLOGICAL SETTING OF THE ALEXANDRA REEF SYSTEM

The Alexandra Reef System developed during the mid-Frasnian (Klapper and Lane 1989; McLean and Klapper 1998) on an epicontinental ramp that was situated near the equator on the western edge of Laurussia (Fig. 4-1 inset; cf. Kiessling et al., 1999; Scotese, 2004). The continental margin was located to the north and west and continental hinterland lay to the east. To the south, inundation of western Canada through a series of sea-level rises

(Johnson et al. 1985) had formed a long and narrow intracratonic basin in which extensive, warm-water carbonate platforms existed (Moore 1989; Whalen 1995).

The Alexandra Reef System lies on top of regressive, mixed siliciclastic-carbonate ramp deposits that belong to Member E of the Escarpment Formation (Fig. 4-2A; Hadley and Jones 1990). These include green shales in deeper depositional environments, marls and sparsely fossiliferous quartzose limestones in shallower environments, and quartz siltstones in the shallowest environments (Hadley and Jones 1990). The ramp formed by these deposits, in the area of the Alexandra Reef System, had a very gentle slope (< 0.1°) and is divided into an *inner ramp* and *outer ramp* on the basis of a step in the ramp profile, termed the *ramp step* (Chapter 2). Whereas the inner ramp and ramp step entirely underlie the Alexandra Reef System, the outer ramp extends beyond the Alexandra Reef System, probably several 10s to 100s of kilometers. Most of the Alexandra Reef System therefore developed above the shallow marine quartz siltstones and sparsely fossiliferous quartzose limestones that had been deposited in the inner to proximal outer ramp regions, with marls, green shales, and deeper basinal shales deposited abroad of the study area.

The Alexandra Reef System is formed of two stromatoporoid-dominated reef complexes (Reef Complex #1 and Reef Complex #2), separated by a sequence boundary and its correlative conformity (Fig. 4-2B-E). Conodont zonations, and the magnitude of sea-level change recorded in these deposits, indicate that these reefs were deposited during two relatively high-frequency fourth-order sea-level cycles (Chapter 2) in the upper part of T-R cycle IIc of Johnson et al. (1985). The second reef complex developed basinwards of Reef Complex #1, on the outer ramp, after a sea-level fall of ~ 17 m terminated development of Reef Complex #1 (Fig. 4-2C). This sea-level fall appears to correlate with a sea-level fall identified by Whalen et al. (2000) and Potma et al. (2001) in other parts of the Western Canada Sedimentary Basin, indicating a basin-scale fluctuation in sea-level position. Punctuated global cooling in the Frasnian, the existence of which has been suggested based on biodiversity trends and fossil assemblages (Stanley 1988; Copper 2002), and indicated by stable isotopes (Joachimski et al. 2004), could account for the magnitude of this sea-level fall and its subsequent rise (Chapter 2). As sea-level fell, the gentle slope of the ramp was a primary control on development of Reef Complex #2 because it provided a broad region of shallow marine environments, in front

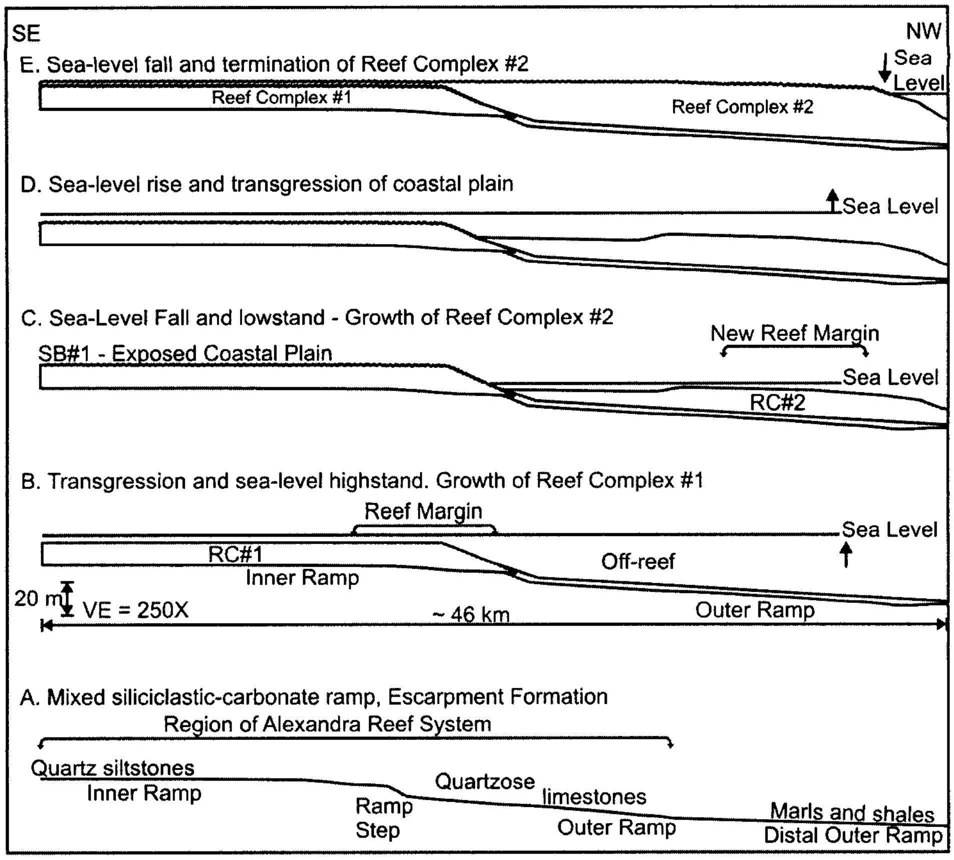

Figure 4-2. Simplified stratigraphic evolution of Alexandra Reef System. **A)** General ramp profile and distribution of mixed carbonate-siliciclastic facies at top of Escarpment Formation. **B-E)** Evolution of Alexandra Reef System. Scale at base of part B. Note Reef Complex #2 (RC#2) developed basinward of Reef Complex #1 (RC#1), after sea-level fall. Final succession (part E) consists of two depositional sequences separated by sequence boundary #1 (SB#1). A second sequence boundary caps top of formation.

of Reef Complex #1, that were conducive to new colonization by carbonate-producing communities (Chapter 2). The stratigraphy of Reef Complex #2 is complex relative to that of Reef Complex #1 because it subsequently developed through an entire cycle of sea-level rise (Fig. 4-2D), and a second sea-level fall (Fig. 4-2E), before being terminated by subaerial exposure. Bioclastic limestones of the Twin Falls Formation unconformably overlie the Alexandra Reef System.

SEQUENCE STRATIGRAPHIC FRAMEWORK OF REEF FACIES IN THE ALEXANDRA REEF SYSTEM

Reef facies in the Alexandra Reef System can be divided into stromatoporoid dominated facies, stromatoporoid-coral dominated facies, and stromatoporoid-coral-microbial dominated facies. Variations in the spatial-temporal distribution of these reef facies are delineated by the sequence stratigraphic framework of the Alexandra Reef System.

Reef Complex #1

Reef Complex #1 developed on the inner ramp in a transgressive and highstand systems tract (Fig. 4-3A), above Member E of the Escarpment Formation. The transgressive systems tract (= Basal Onlapping Succession in Chapter 2) comprises muddy carbonate deposits with scattered stromatoporoids and corals on the outer ramp (off-reef), and a stromatoporoid-coral biostrome (~ 3.5 m thick) on the inner ramp, where shallow marine conditions conducive to reef development existed. The biostrome is dominated by laminar, tabular, and domal stromatoporoids, and corals (Fig. 4-3B, C) that include solitary and colonial rugosans (*Macgeea*, *Phillipsastrea*, *Thamnophyllum*, *Disphyllum*, *Smithiphyllum*) and tabulates (*Alveolites*, *Thamnopora*).

Passage from the transgressive systems tract into the highstand systems tract was accompanied by the main stage of reef development (~ 21 m thick). Reef development took place at the outer edge of the inner ramp, at the top of the ramp step, with the *in situ* accumulation of a broad, stromatoporoid-dominated buildup (Fig. 4-3A). Parts of this buildup were dominated by stromatoporoid-dominated patch reefs laden with *Stachyodes*-dominated floatstones and rudstones, whereas other parts were characterized by a more massive framework of densely packed domal and tabular stromatoporoids (Fig. 4-3D-H). Tabulate and rugose corals (e.g., *Phillipsastrea*, *Alveolites*) were present locally in the reef-front to fore-reef area, but the reef core, with the exception of *Thamnopora*, lacks colonial corals. Back-reef deposits include small stromatoporoid-dominated patch reefs and thin- to medium-bedded *Amphipora*-dominated wackestones and floatstones that contain calcispheres and small bulbous stromatoporoids.

In the off-reef direction, the reef-front of Reef Complex #1 passes into thin-bedded, gently dipping, rubbly recessive-weathering fore-reef wackestones and floatstones that contain numerous peloids, brachiopods, and crinoids. In deeper water on the outer ramp, solitary and colonial corals and stromatoporoids grew in scattered, isolated positions. Locally, low-profile bioherms developed. Most of the outer ramp was blanketed by brown, muddy (carbonate mud) wackestones and floatstones.

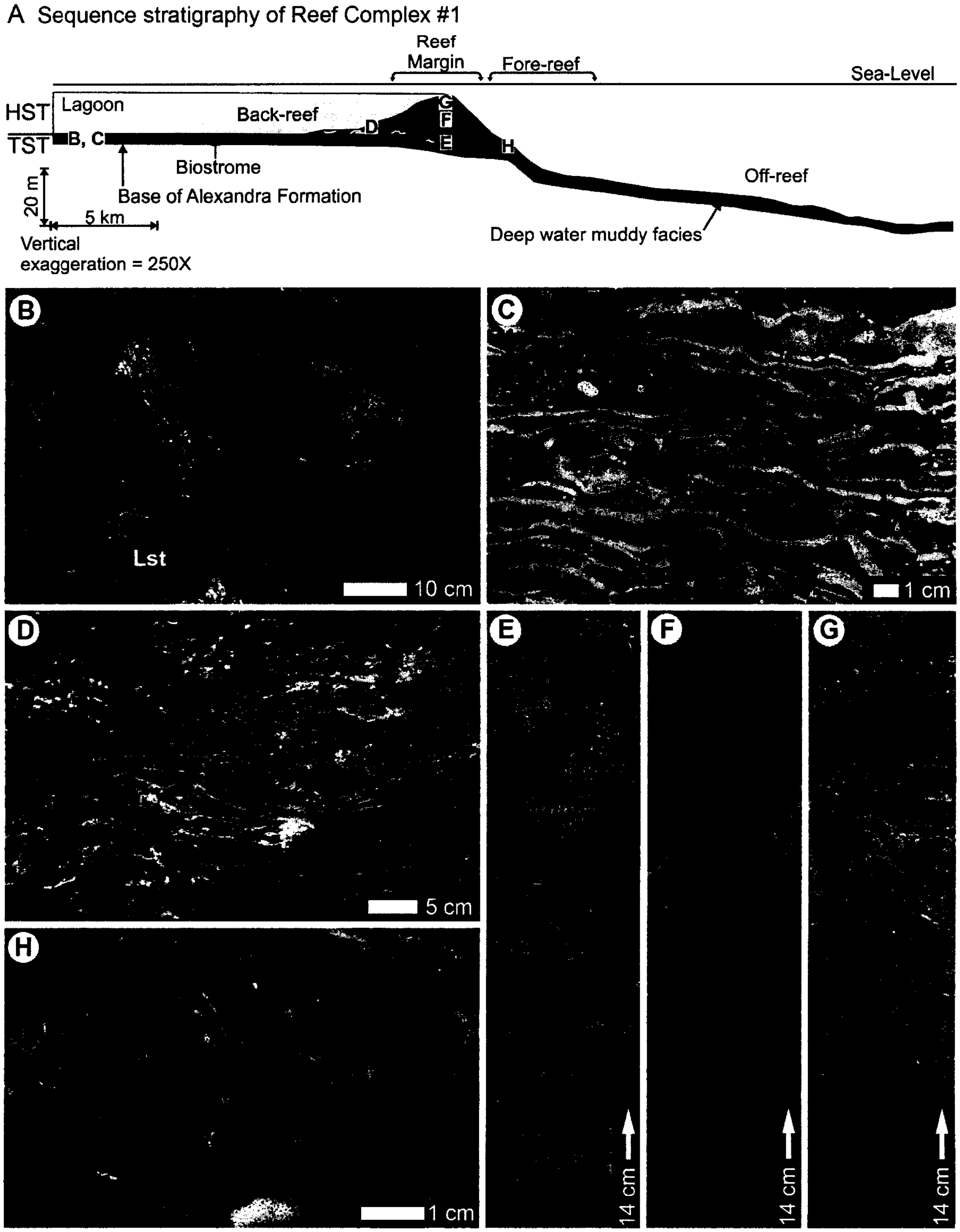

Figure 4-3. Metazoan-dominated reef facies of Reef Complex #1. B, C = transgressive systems tract. D-H = highstand systems tract. **A)** Reef Complex #1 sequence stratigraphy and environment zonations (modified from Chapter 2). TST = transgressive systems tract; HST = highstand systems tract. Positions of photos B-H indicated. **B)** Outcrop photograph of laminar stromatoporoid-coral bindstone facies in biostrome on inner ramp. P = *Phillipsastrea*; Lst = laminar stromatoporoids. **C)** Cut and polished laminar stromatoporoid bindstone with dark *Amphipora* wackestone bound between plates. **D)** Outcrop photograph of laminar stromatoporoid bindstone. Cryptic spaces filled with mudstone-wackestone. E-

G) Core photographs; interval lengths in bottom right corners. **E)** Stromatoporoid-dominated reef facies with toppled domal stromatoporoid (Strm). Note caunopores (arrows) in stromatoporoid. **F)** *Stachyodes*-dominated floatstone-rudstone capped by tabular stromatoporoid (Strm). **G)** Stromatoporoid rubble mixed with *Stachyodes*-dominated floatstone and capped by laminar stromatoporoids. **H)** Cut and polished laminar stromatoporoid bindstone-floatstone with wackestone matrix from reef-front.

Apart from rare specimens (e.g., a few scattered pieces in a couple of thin sections) of *Renalcis* in the reef deposits, and minor clots of *Girvanella* on stromatoporoids in the reef and on corals and stromatoporoids situated off-reef, in the outer ramp deposits, no microbial deposits have been found in the reef facies of Reef Complex #1. The calcimicrobes are so rare that they do not form visible clots in cut and polished hand samples, and did not contribute to development of the reef framework. Rather, the reef developed through stromatoporoid-coral (transgressive systems tract) and stromatoporoid-stromatoporoid associations (highstand systems tract), and the trapping of significant amounts of *Stachyodes*-dominated sediment beneath tabular and irregular stromatoporoids (Fig. 4-3F). As such, the reef-building communities in Reef Complex #1 were metazoan-dominated (for brevity, stromatoporoids and corals are collectively referred to as metazoans). Falling sea-level terminated Reef Complex #1.

Reef Complex #2

Reef Complex #2 was initiated as sea-level fell, and subsequently developed through an entire cycle of sea-level rise and fall. Its development involved 1) initiation and differentiation stages, which took place in a falling stage systems tract and lowstand systems tract, respectively, 2) a flooding stage, which consists of a transgressive systems tract and highstand systems tract, and 3) shallowing and termination stages, which took place in a second falling stage systems tract, as relative sea-level started to drop from its highest position.

Initiation and Differentiation Stages

Sea-level fall and termination of Reef Complex #1 coincided with shallowing of the marine conditions over the outer ramp. In this falling stage systems tract (Fig. 4-4A), an expansive stromatoporoid-microbial biostrome (maximum of ~ 4 m thick) developed, which forms the basal part of Reef Complex #2. Stromatolites capped the top surfaces of

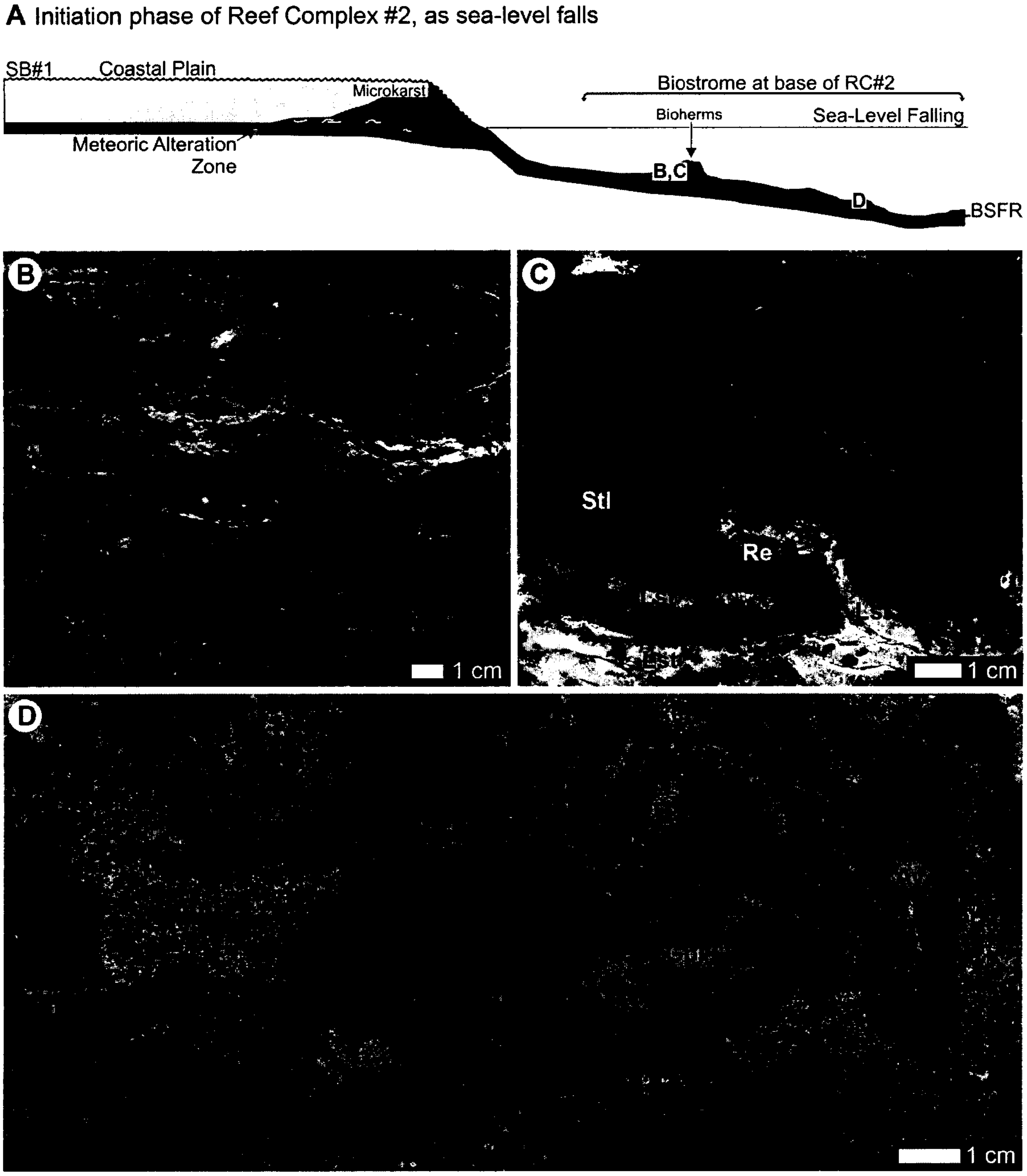

Figure 4-4. Metazoan-microbial reef facies in initiation phase of Reef Complex #2. **A)** Sequence stratigraphy of Alexandra Reef System at time of Reef Complex #2 (RC#2) initiation phase (modified from Chapter 2). Scale as in Fig. 4-3A. BSFR = basal surface of forced regression at base of falling stage systems tract. Positions of photos B-D indicated. **B)** Outcrop photograph of laminar stromatoporoid bindstone with *Thamnopora* fragments in basal biostrome. Note stromatolite (Stl) capping laminar stromatoporoid. **C)** Cut and polished sample of laminar stromatoporoids (Lst) with minor clots of *Renalcis* (Re), capped by domal stromatolites (Stl) that grade up into columnar stromatolites (CStl). Top of stromatolites outlined (black dashed line). **D)** Cut and polished laminar stromatoporoid-coral-*Renalcis* boundstone. Branch of *Alveolites* (Av) and thin, delicate laminar stromatoporoids (Lst) bound into rigid framework by thick renalcid (Re) masses. Renalcids encrust under stromatoporoid plates, entire skeleton of *Alveolites*, and bridge between these elements,

dominating framework. Stromatolites (Stl) cap some tops of laminar stromatoporoids. Geopetal mudstone (Gpl) and calcite cement fill remaining cavity spaces.

stromatoporoids (Fig. 4-4B and C), whereas renalcid boundstone accumulated in cavities under and between framebuilders (Fig. 4-4D). Encrusting of stromatoporoid and coral fragments by *Girvanella* and *Rothpletzella* was common but less significant. Whereas stromatolites were present across the extent of biostrome development, renalcid boundstone was most common in the more basinward areas of biostrome development.

In the middle region of the biostrome, broad bioherms 300–400 m across with 5–7 m of synoptic relief subsequently developed on top of the biostrome (Fig. 4-4A). Laminar stromatoporoids, commonly only 2-3 mm thick, capped by laminar and domal stromatolites, generally ~ 2 cm thick, are a conspicuous part of these bioherms. Growth of an inner buildup above these bioherms, and an outer buildup in a slightly basinwards position, defined a margin to the evolving reef complex and marked the start of its environmental differentiation (Fig. 4-5A). This took place when relative sea-level reached its lowest position and the falling stage systems tract passed into the lowstand systems tract (Chapter 2). Concurrent with growth of the inner and outer buildups, a broad reef-front developed in front of the outer buildup, and a back-reef region and shallow lagoon developed landwards of the inner buildup (Fig. 4-5A). Between the inner and outer buildups was a low area, termed the intra-buildup low, where bioherms developed. Microbial reef deposits are a volumetrically significant part, and in some cases dominate, the intra-buildup low, outer buildup, and reef-front facies, but are less significant in the inner-buildup facies.

The inner buildup (~ 8 m thick) is characterized by stromatoporoid–coral deposits (Fig. 4-5B). Stromatolites on top of stromatoporoids, and renalcid boundstone, are common in some areas, but less prevalent in other areas. Bioherms in the intra-buildup low were dominated by laminar stromatoporoids and laminar stromatoporoids that amalgamated into outward- and upward-growing platy complexes. Thick (up to 4 cm) masses of renalcid boundstone accumulated on the undersides of these plates, in crypts between vertically stacked plates, and between laterally adjacent plates (Fig. 4-5C).

The outer buildup (maximum of ~ 14 m thick) is formed of stromatoporoid rubble and intraclastic wackestones-packstones. Large (up to ~ 1 m) fragmented pieces of

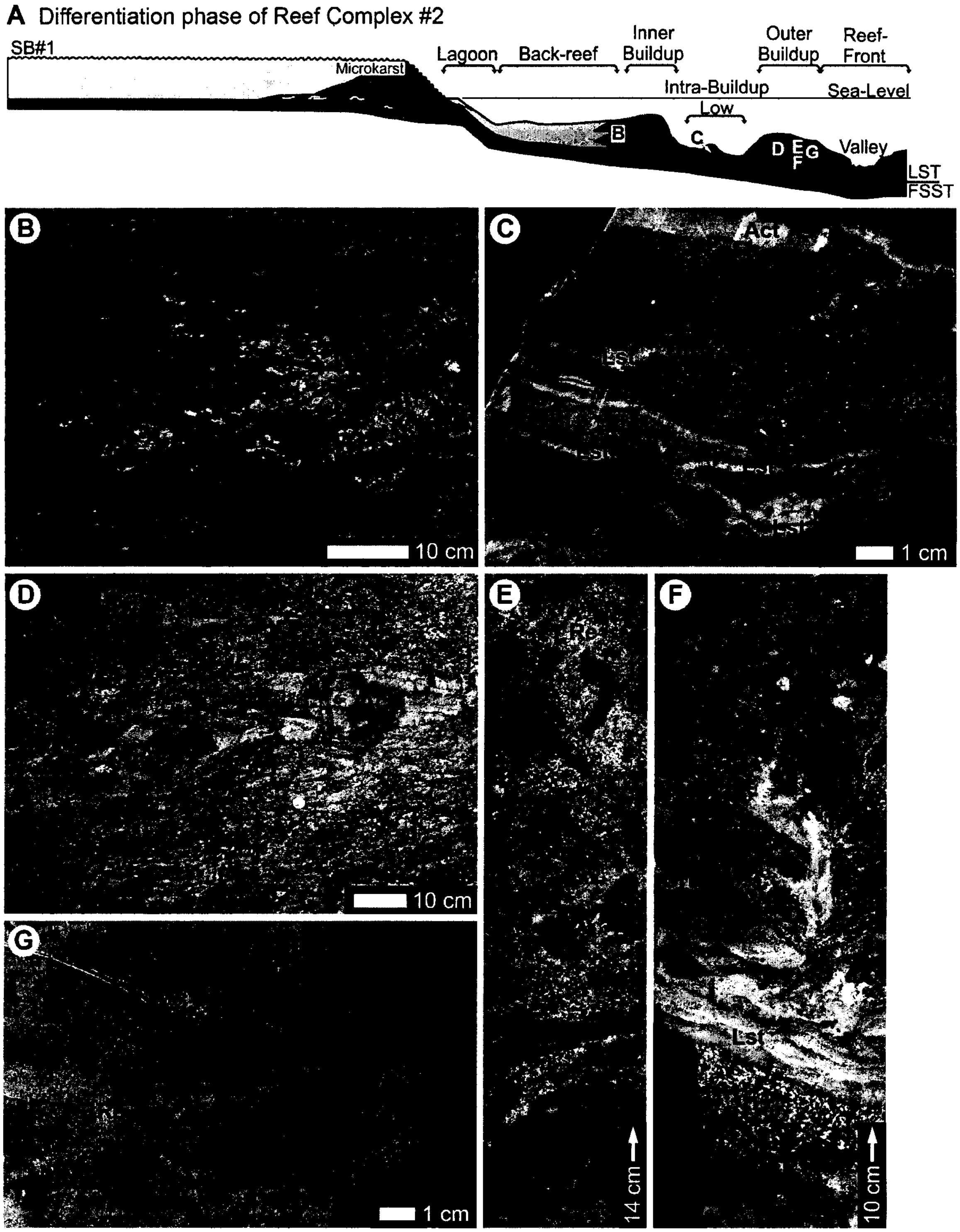

Figure 4-5. Metazoan-microbial reef facies in differentiation phase of Reef Complex #2. **A)** Sequence stratigraphy of Alexandra Reef System at time of Reef Complex #2 (RC#2) differentiation (lowstand systems tract; modified from Chapter 2). Scale as in Fig. 4-3A. LST = lowstand systems tract; FSST = falling stage systems tract. Positions of photos B-G indicated. **B)** Outcrop photograph of laminar stromatoporoid bindstone characteristic of inner buildup. Partly encrusted coral (Cr) present. **C)** Cut and polished framework of amalgamated laminar stromatoporoid plates (Lst) with thick renalcid (Re) encrustations. Thin tabular *Actinostroma* (Act) present. Remaining cavity spaces in platy complex

infilled (If) by muds and wackestone. **D)** Outcrop photograph of rubble deposit of outer buildup. Large, fractured actinostromids (Act) hosted in renalcid-bound intraclastic packstones-rudstones with fragmented pieces of corals and stromatoporoids. **E)** Core photograph of renalcid (Re)-bound laminar-stromatoporoid floatstone of outer buildup. Drill location near outcrop shown in part D. **F)** Core photograph of laminar stromatoporoid-stromatolite-renalcid boundstone of outer buildup, capped by intraclastic wackestone-packstone. Crypt (Crt) beneath laminar stromatoporoid filled by geopetal mud and cement. **G)** Cut and polished renalcid (Re) boundstone from outer buildup with horn corals (C) capped by small domal stromatolites. Syndepositional fracture (edge marked by arrows) filled with intraclastic (Ic) packstone indicating renalcid accumulation formed lithified mass in depositional realm.

Actinostroma, in all possible orientations relative to their original growth position, are common, but *in situ* stromatoporoids and corals are minor (Fig. 4-5D). As *in situ* actinostromids are commonly found in the reef-front, their occurrence as fragmented pieces in the outer buildup, with the intraclastic-rubble dominated sediment, is interpreted to indicate that the outer buildup accumulated through intense storm activity that included pruning of skeletal framebuilders in the reef-front. This mechanism of reef development, whereby storms devastate thriving reef-front environments and build-up a rubble-dominated ridge in a landwards location, is well known from numerous modern reef systems (Longman 1981; Blanchon et al. 1997; Blanchon and Perry 2004).

In the outer buildup, stromatolites cap stromatoporoid fragments and renalcid boundstone is ubiquitous (Fig. 4-5E-G). In some cases, stromatolites developed upwards from renalcid boundstone, which locally forms > 75% of the framework (Fig. 4-5E and G). Syn-depositional fractures in these deposits (Fig. 4-5G), filled with intraclastic sediment, support the interpretation that renalcid boundstone formed hard, lithified masses. Marine cements are common throughout the outer buildup.

The reef-front is dominated by massive (up to 2.2 m across), *in situ* stromatoporoids that grew in tabular, concave-up tabular, expanding-conical, laminar, and anastamosing-laminar growth forms (Fig. 4-6A, B). Colonial corals, including *Alveolites*, *Phillipsastrea*, and *Thamnopora*, are also present. The stromatoporoids did not coalesce into a rigid framework, but rather, existed as densely packed individual entities. Floatstones and rudstones of intensely fragmented laminar stromatoporoids that contain large, overturned coral heads (Fig. 4-6C), attest to the periodic storm activity that led to the formation of the outer buildup. Thin (≤ 2 cm thick) beds of green siliciclastic mud that periodically cover the tops of the reef-front stromatoporoids (Figs. 4-6D and 4-7) were probably deposited from suspension as the storms waned. Renalcid boundstone and

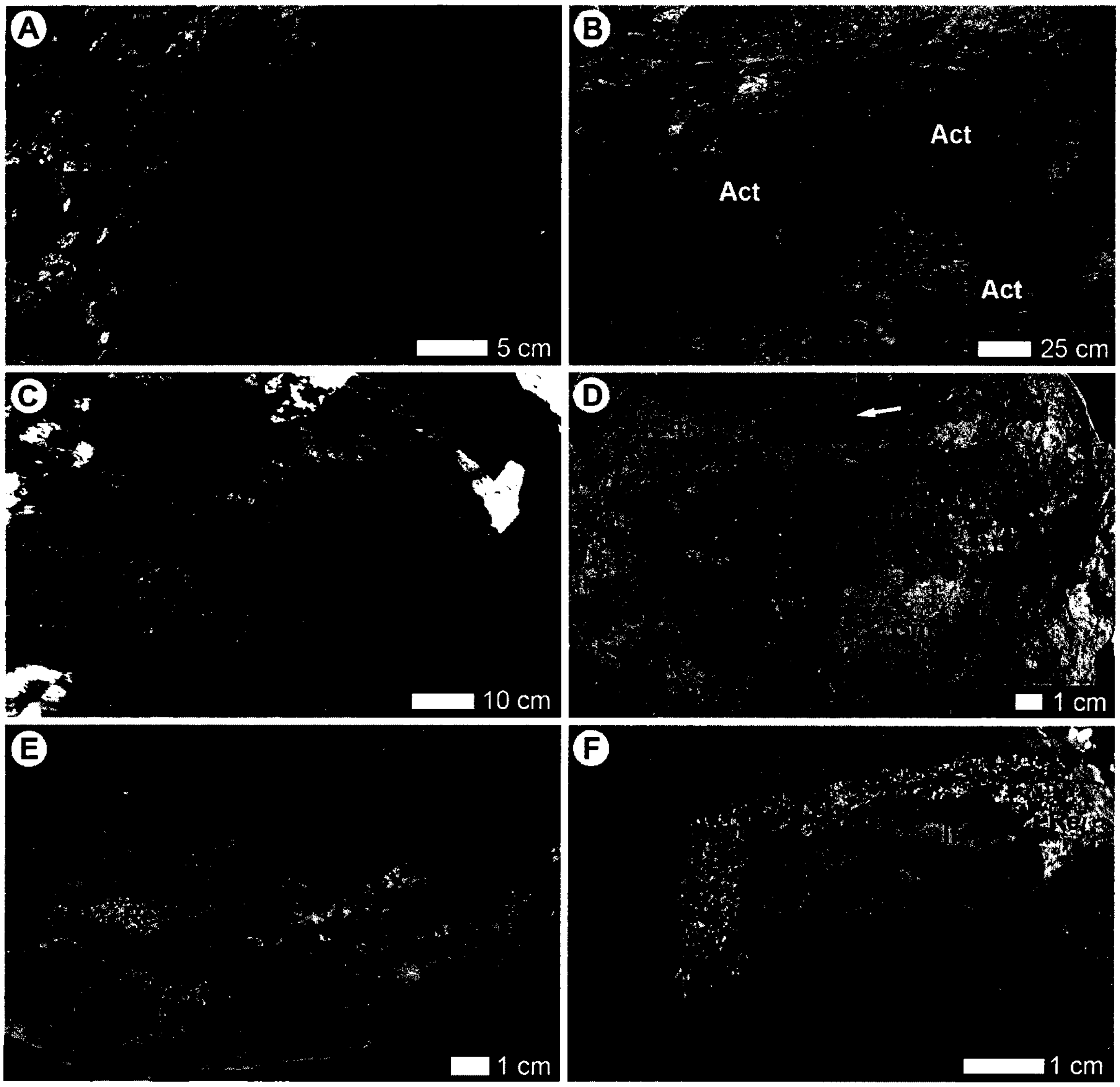

Figure 4-6. Metazoan-microbial reef-front facies in differentiation phase of Reef Complex #2. **A)** Outcrop photograph of densely packed tabular stromatoporoids. Note each stromatoporoid is individual entity; they do not coalesce into framestone. **B)** Outcrop photograph of massive tabular and concave-up *Actinostroma* (Act) and thinner tabular stromatoporoids. Each stromatoporoid is individual entity. **C)** Outcrop photograph of laminar stromatoporoid rudstone with large toppled head of fasciculate rugosan. Top of toppled coral encrusted by stromatoporoid (St). **D)** Bedding-plane view of laminar stromatoporoid (strm)-coral (Crl) facies. Thin deposit of green mud (Gm), partly weathered away, covered top surface of skeletons and filled physical compaction cracks (arrow at top centre). **E)** Cut and polished laminar stromatoporoid (Lst)-*Renalcis* (Re)-stromatolite (Stl) reef facies with >50% of framework of microbial origin, buried by intraclastic (Ic) packstone. **F)** Growth cavity in cut and polished stromatoporoid partly lined by renalcid boundstone (Re). A thin stromatolite (Stl) developed on cavity floor before buried by infilling (If) mud.

stromatolites are common in the lower part of the reef-front succession, especially in crypts and between stromatoporoids and corals (Fig. 4-6E, F). Upwards through the reef-

Figure 4-7. Core photograph of storm deposit in reef-front of Reef Complex #2. ~ 2 cm thick deposit of green mud covers fractured, upside-down stromatoporoid (St 1)-stromatolite (Fr stl) association. Note sharp edge of fracture (arrow) at top of stromatolite. Three latilaminae (a, b, c) of new stromatoporoid growth (St 2) subsequently overgrew green mud. Stromatolite (Stl) caps second stromatoporiod, in partly sheltered cavity formed by *Alveolites* (Av).

front facies, the renalcid component significantly decreases. Only near the top of the succession, however, does the abundance of stromatolites start to decrease.

Due to limited data, less is known about the deeper reef-front and fore-reef environments. A ‘valley’ that divides the continuity of the reef-front and opens into the fore-reef (Fig. 4-5A), however, offers some insight. It appears that transition of the reef-front into deeper water of the valley was marked by the development of stromatoporoid-coral bioherms, with stromatolites and lesser renalcid boundstone.

Flooding Stage

An acceleration in the rate of rising sea-level flooded Reef Complex #2, marking its passage into a transgressive systems tract (Fig. 4-8A; Chapter 2). Some areas of the reef

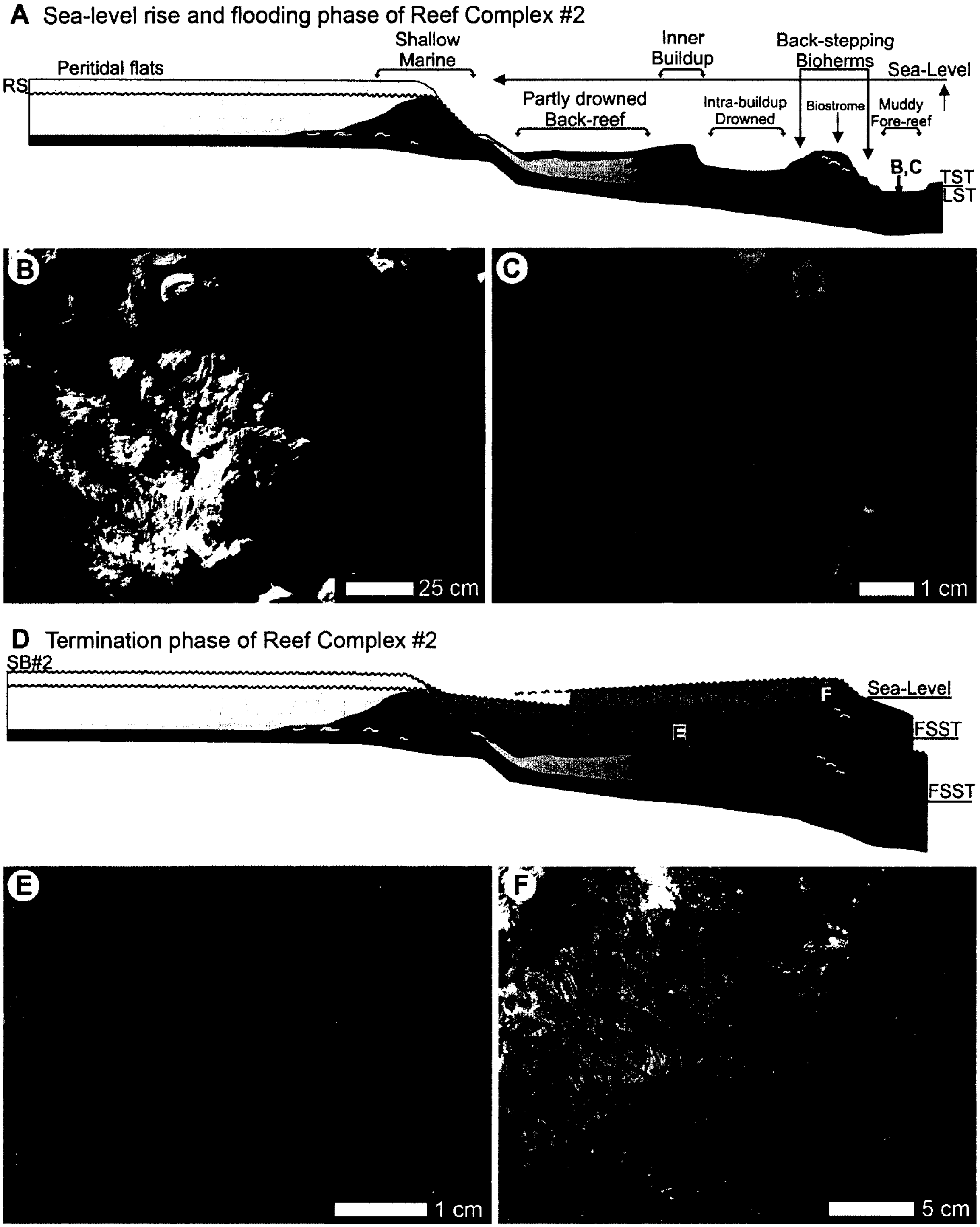

Figure 4-8. Metazoan-dominated reef facies in flooding phase and termination phase of Reef Complex #2. **A)** Sequence stratigraphy of Reef Complex #2 flooding (transgressive systems tract), with significant facies changes across reef complex and flooding of coastal plain on top of Reef Complex #1 (modified from Chapter 2). Microbial reef facies not present. Scale as in Fig. 4-3A. LST = lowstand systems tract; TST = transgressive systems tract; RS = ravinement surface. Positions of photographs B and C indicated. **B)** Outcrop photograph of *Smithiphyllum* thicket in reef-front. **C)** Photograph of cut and polished sample of *Smithiphyllum*. Dark mudstone, without microbial constituents, fills area between coral stalks. **D)** Sequence stratigraphy of Reef Complex #2 termination phase (modified from Chapter

2). Scale as in Fig. 4-3A. FSST = Falling stage systems tract; SB#2 = sequence boundary #2. Positions of photographs E and F indicated. **E)** Cut and polished intraclastic-peloidal grainstone (Grs) bound by irregular laminar stromatoporoids in patch reef facies. No microbial constituents present. **F)** Outcrop photograph of domal – irregular stromatoporoid patch reef, akin to reef facies in Reef Complex #1, with no microbial constituents. Outlines of individual stromatoporoids drawn with black marker. Wackestone fills cavities between stromatoporoids.

complex were able to maintain growth whereas other areas drowned. Associated with passage into the transgressive systems tract was disappearance of the stromatolites in the reef framework and near-disappearance of all renalcid components. Only in some areas of the outer buildup did minor clots of *Renalcis* and related calcimicrobes form. These were not, however, significant, and did not contribute to framework development. Likewise, *Girvanella* and *Rothpletzella* encrusted some stromatoporoids and corals, but only as minor elements. Most of the deeper reef-front (Fig. 4-8B, C) was dominated by decimeter to meter-scale thickets of fasciculate rugosans *(Smithiphyllum)* whereas the outer buildup was dominated by laminar stromatoporoids. Over the outer part of the outer buildup, stromatoporoids coalesced to form dense framestone intermittently divided by large (e.g., 1-2 m across, 1 m high) thickets of fasciculate rugosans; no microbial components have been found in this framestone or bafflestone. In drowned and near-drowned areas of the reef-front, intra-buildup low, and back-reef, dark, thin-bedded carbonate mudstones and wackestones with cricoconarids and other deep water biota were deposited (Fig. 4-8C; Chapter 2). As such, passage from the lowstand systems tract to the transgressive systems tract corresponded with loss of calcimicrobial contribution to framework development, complete loss of peri-reefal stromatolites, and domination of framework development, in those parts that did not drown, by stromatoporoids and corals. As sea-level position peaked in the highstand systems tract, there were no significant facies changes and highstand shedding was not significant (Chapter 2). As such, most of Reef Complex #2 remained "underproductive".

Regional Shallowing and Termination Stages

As sea-level began falling, which marks the beginning of the second falling stage systems tract (Fig. 4-8D), extensive carbonate sedimentation over Reef Complex #2 resumed. The falling stage systems tract was characterized by strongly progradational "clean" carbonate deposits of *Amphipora* and *Stachyodes* floatstones and rudstones (Fig. 4-8E), and growth of stromatoporoid-dominated patch reefs (Fig. 4-8F) and bioherms, like the reef facies that characterized Reef Complex #1. Corals are minor in these deposits, except in the outer fore-reef location, where stromatoporoid-coral deposits accumulated. Microbial components were not significant in these deposits; framework in the bioherms and patch reefs was not built through any microbial contributions, and unlike the outer buildup in the lowstand systems tract, rubbly deposits were not bound by renalcids (Fig. 4-8E). Termination of Reef Complex #2 is attributed to subaerial exposure (Chapter 2).

NUTRIENTS AS A CONTROL ON THE DIFFERENT TYPES OF REEF FACIES IN THE ALEXANDRA REEF SYSTEM

Contrasting types of reef framework are conspicuously demonstrated in the Alexandra Reef System (Fig. 4-9A). Given that seawater chemistry in the Late Devonian was markedly conducive to the calcification of microbial communities (Riding 1992; Riding and Liang 2005), these facies contrasts must be linked to ecological and environmental controls on the composition of the reef-building communities. Indeed, traces of *Renalcis*, *Girvanella*, and *Rothpletzella* in Reef Complex #1, and the upper parts of Reef Complex #2, indicate that physicochemical conditions were conducive to the calcification of these microbes throughout the evolution of the Alexandra Reef System, if they were present. Likewise, the high-frequency, low-order of these depositional sequences, and their systems tracts, requires the control(s) on their facies composition to fit within a time-frame of < 1 million years, well-below a likely time-frame for significant shifts in seawater chemistry.

The shift to the metazoan-microbe dominated reef framework in Reef Complex #2 is attributed to elevated nutrients in the ambient environment of the reef system, for a number of reasons. First, physiological requirements limit most types of algae and microbes to environments with available nitrogen, phosphate, and/or iron (Lobban et al. 1985). If required nutrients are not available, these organisms will not be present. Second, community-structure models for modern reefs predict algal-microbial blooms to be positively correlated with increasing nutrients (Littler and Littler 1984). Third, numerous studies have documented that nutrification results in coral-algal phase shifts and algal-

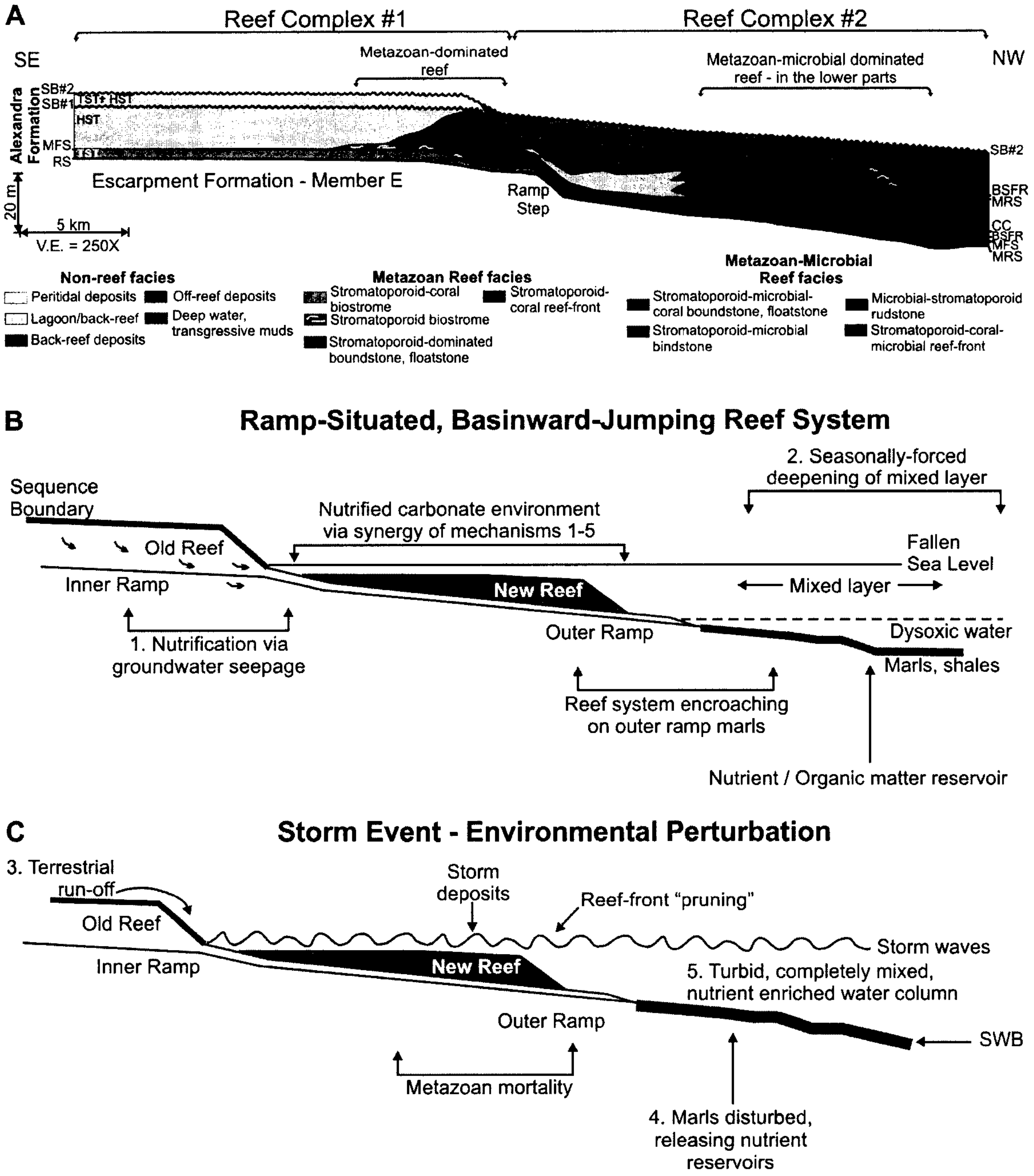

Figure 4-9. Summary of reef facies in Alexandra Reef System and models for nutrification on carbonate ramps. **A)** Sequence stratigraphic distribution of metazoan-dominated and metazoan-microbial dominated reef facies in Alexandra Reef System. Metazoan-microbial reef facies only found in lower parts of Reef Complex #2. **B and C)** Nutrification mechanisms on a carbonate ramp as sea-level falls and in lowstand systems tracts. Note deposits of new carbonate complex, in this case a reef, separated from old reef by sequence boundary and its correlative conformity. Synergy of potential nutrification mechanisms 1-5 bathe new carbonate complex in nutrient-enriched seawater, with potential implications for types of carbonates produced. No scale provided, but affected area, because of low depositional gradient of ramp, may cover several thousand square kilometers. **B)** Basinward-jumping reef system encroaches on distal outer ramp deposits as sea-level falls. Potential nutrification mechanisms include 1. nutrification via groundwater seepage through porous, now exposed old reef deposits, and 2. seasonally-forced deepening of mixed layer. **C)** Storm event perturbs reef complex and metazoans experience significant mortality. Concurrent with metazoan mortality environment may be

nutrified by mechanisms (continued from part B) including 3. terrestrial run-off, 4. release of nutrient reservoirs hosted in marls and shales on outer ramp, and 5. mixing of surface layer with nutrient-rich parts of water column at depth. Nutrified water that bathes post-storm carbonate complex, as metazoans begin to recover, may have long residence time. SWB = storm wave base.

microbial blooms, on the scale of days, months, and years, (e.g., Smith et al. 1981; D'Elia and Wiebe 1990; Hallock et al. 1993; Genin et al. 1995; Lapointe 1997; Miller et al. 1999; Costa et al. 2000; Lapointe et al. 2004; Hallock 2005; Paul et al. 2005). Relating the shift from metazoan-dominated to metazoan-microbe dominated reef facies to increased nutrient levels is therefore consistent with the physiological needs of algae and microbes, models of reef-community structure, and the conclusions of numerous modern reef studies. Increased trophic resources was also invoked to explain the same types of shifts from metazoan-dominated to metazoan-microbial dominated reef facies in Jurassic reef systems (Dupraz and Strasser 2002), and similar conclusions have been made for these types of shifts in Quaternary (Camoin et al. 1999) and modern reef facies (Sprachta et al. 2001).

Alternative ecological/environmental controls to explain the microbial components in Reef Complex #2, such as the availability of preferred habitat-types (e.g., cryptic spaces for the renalcids, hard substrates for the stromatolites), changes in salinity levels or temperature ranges, or the degree of wave-energy, can all be precluded. Reasons include:

- The environmental conditions did not preclude the growth of stromatoporoids, corals, and brachiopods, indicating that temperature and salinity values fell within ideal, normal marine ranges.
- All systems tracts of both reef complexes contained habitats of the same composition (e.g., laminar stromatoporoids – hard substrates – with sheltered cavities underneath) in comparable spatial arrangements, and yet these habitats were not exploited by microbial constituents.
- A range of water depths and depositional conditions also existed in Reef Complex #1 and in the later stages of Reef Complex #2 development, without favouring the growth of microbial constituents.

- There is no evidence in any part of the Alexandra Reef System for mass terrigeneous influx, which is often accompanied by a detrimental reduction in salinity (Hallock and Schlager 1986).

Thus, a state of elevated nutrient levels is the only reasonable explanation for the microbial framework constituents in the lower parts of Reef Complex #2. The lack of algal laminates in the reef deposits (as in soft, non-calcified organic matter from planktonic blooms), which would be expected with nutrient enrichment, can be attributed to scavengers (e.g., gastropods), grazing and scavenging fish, and the generally poor preservation potential of non-mineralized organic matter in shallow marine, well-oxygenated environments.

NUTRIFICATION ON CARBONATE RAMPS

Carbonate depositional systems are controlled by the interaction of dynamic variables such as climate, platform geometry, water depth, temperature, and sea-level change. In the Alexandra Reef System, Reef Complex #2 was only able to develop because the gentle slope of the inherited ramp-type platform provided a broad region of shallow marine environments that were suitable for colonization by carbonate-producing communities, as and after sea-level fell (Chapter 3). The magnitude of sea-level fall (~ 17 m) determined the location of new reef development, and this new reef complex was distinct from the older Reef Complex #1. This type of basinward-jumping reef system, however, would be precluded from developing on a high-relief, steep-sided carbonate shelf, or isolated platform, because of the different platform geometry (Sarg 1988; Hunt and Tucker 1993).

Just as several variables interact to control the depositional nature of carbonate systems and platform evolution, it is to be expected that these interactions and changes will also carry implications for potential nutrification mechanisms. The result of falling sea-level on carbonate ramps is that (1) their depositional systems encroach upon potential sediment-hosted nutrient reservoirs situated in distal ramp positions, (2) new carbonate-producing communities are increasingly susceptible to nutrification via terrestrial runoff, aeolian transport of sediment with nutrients, and groundwater seepage from older, exposed deposits, and (3) decreasing water volume in the basin (assuming that sea-level fall is either basin-scale or eustatic), as the system encroaches basinward, increases the likelihood that storm- and/or seasonal-deepening of the mixed layer will impinge upon nutrient reservoirs in deeper waters, and these nutrient-enriched waters may be advected onto the region of carbonate production (Fig. 4-9B and C). If the basin becomes significantly restricted, eutrophication and a shift to evaporite-dominated facies (James and Kendall 1992) may take place. In contrast, rising sea-level and transgression will diminish many of these nutrification mechanisms because (1) increasing water volume in the basin dilutes and expands the water column and nutrient reservoirs may be sequestered to greater depths, (2) terrestrial nutrient resources will have been relatively depleted by the preceding sea-level fall, (3) terrestrial erosion decreases as base-level rises, and (4) weathering profiles/soils, that are sources of nutrients, may not be mature and their transgressive erosion in the coastal zone is likely to be highly diachronous (Catuneanu 2002; MacNeil and Jones 2006a), which limits their nutrient-deliverability at any specific time. Thus, transgressive shifts on carbonate ramps may not be balanced by the same degree of nutrification.

Relating Reef Complex #2 to a model for basinward-jumping reef systems (Fig. 4-9B, C) reveals that nutrient enrichment of its initiation and differentiation stages was most probably caused by a combination of (1) terrestrial run-off from the coastal plain on top of Reef Complex #1, (2) groundwater seepage through recently exposed deposits of Reef Complex #1, (3) storm disturbance of the offshore oceanographic system, and possibly (4) seasonally-forced deepening of the mixed layer. Not all of these mechanisms were active at the same time, and the punctuated events (storms and terrestrial runoff) probably supplemented longer-term events (groundwater seepage) and seasonal-climate events. Thus, it was likely the synergy of mechanisms, rather than one specific mechanism, that facilitated the microbial contribution to reef framework development. It should also be noted that different mechanisms likely supplied different types and concentrations of nutrients, and nutrient variability, in itself, can be an important control on the composition of algal-microbial blooms (e.g., Kuffner and Paul 2001). Passage into the transgressive systems tract probably diminished and turned-off nutrification as the top of Reef Complex #1 flooded (turning off direct terrestrial runoff and reducing groundwater seepage through Reef Complex #1), the climate warmed, and storm events either became less frequent or with rising sea-level, no longer impinged upon nutrient reservoirs at depth. Erosion of soils as the coastal plain flooded probably contributed nutrients, but not in the supply needed to facilitate blooms in the reef framework.

Terrestrial Run-off

Terrestrial run-off from the coastal plain that developed on top of Reef Complex #1 (Fig. 4-9C), as sea-level fell, may have delivered nutrients and organic matter to the outer ramp where Reef Complex #2 was developing. An indication that run-off took place are blackened lithoclasts in storm beds in the basal parts of Reef Complex #2 that are also found in the coastal plain deposits above Reef Complex #1 (Chapter 2). Consideration, however, that the climate appears to have been semi-arid (Golonka et al. 1994; MacNeil and Jones 2006b) suggests that nutrification due to terrestrial run-off was probably sporadic and short-lived. This mechanism also would have been present for the growth of Reef Complex #1, which lacks peri-reefal microbial components, suggesting that it was probably an insignificant mechanism on its own.

Groundwater Seepage

The geographic position of Reef Complex #2 made it particularly susceptible to nutrification via groundwater seepage through the recently exposed deposits of Reef Complex #1 (Fig. 4-9B). As sea-level fell below the margin of Reef Complex #1, this was the first time that these deposits, which were probably a rich source of decaying organic matter and trapped nutrients, were subject to groundwater percolation and a shifting water-table. Groundwater seepage is a well-documented mechanism of nutrification on modern carbonate platforms (Marsh 1977; Johannes 1980; D'Elia et al. 1981; Lewis 1987; Cuet et al. 1988; Lapointe 1997), and in some cases is of significantly greater magnitude than terrestrial runoff (Johannes 1980; Lapointe 1997).

A distinct horizon of vuggy porosity in the lower parts of Reef Complex #1 (Fig. 4-4A), due to extensive dissolution of stromatoporoid and coral skeletons, at the approximate level of sea-level position after its fall, was interpreted in Chapter 2 to be the result of mixing-zone diagenesis in an aquifer established during/after the fall in sea-level. The development of such aquifers are predictable with falls in sea-level (Sarg

1988) and will effectively discharge nutrient-enriched groundwater into the environs of attached platforms. Even though the climate was semi-arid, this mechanism of nutrification would not have been limited by precipitation levels in the same manner that terrestrial run-off was limited, because sea-level (and thereby the water table) did not fall below the base of Reef Complex #1.

Groundwater seepage from Reef Complex #1 probably supplied significant amounts of nutrients in the form of ammonia and nitrate, derived from the decay of organic matter trapped in the deposits of Reef Complex #1, and in ephemeral marshes at its top (cf. Chapter 3). Nitrogen-fixing microbes in these deposits would also have enriched the nitrogen content in percolating water, and consistent with this, skeletal stromatolites of *Rivularia sp.*, an efficient nitrogen-fixing cyanobacteria, are found in the marsh deposits at the top of Reef Complex #1 (Chapter 3).

Storm-Disturbance of the Offshore Oceanographic System

Storms are a viable, potentially high-impact mechanism of nutrient enrichment (Fig. 4-9C). Storm-induced vertical mixing of the oceanic surface layer, such that normally nutrient-depleted surface water is mixed with deeper, nutrient-rich seawater, can lead to a short-term (e.g., 1 – 3 weeks) but significant enrichment in the seawater and rapid blooms of algae and microbes (Holloway et al. 1985; Ostrander et al. 2000; Shiah et al. 2000; Subrahmanyam et al. 2002; Lin et al. 2003; Babin et al. 2004). The impact of storm-induced enrichment is magnified for seasonal storm activity, when repeated storm events compound the extent of nutrient-enrichment (e.g., Holloway et al. 1985; Babin et al. 2004). In addition to deepening the mixed surface layer, storms may also disturb sediment-hosted nutrient reservoirs on the platform and in off-reef locations, especially if they lie above storm wave-base (Fig. 4-9C). In addition to dissolved and particulate organic matter and nitrogen, clay-rich sediments may contain large volumes of iron, in a variety of states (e.g., reduced, colloidal) that can be utilized by microbes (Entsch et al. 1983), facilitating significant microbial blooms.

In the lowstand systems tract of Reef Complex #2, the rubble deposits of fragmented stromatoporoids, toppled and fragmented corals, and intraclastic sediment that form the outer buildup attest to intense storm (hurricanes?) activity. Stromatoporoid and coral rubble in the inner buildup and reef-front support the interpretation that storms affected development of the lowstand systems tract, and the green clays that cover stromatoporoids in the reef-front were probably deposited from suspension as storm activity waned (Chapter 2). The most likely source for these muds are green marls and shales situated on the ramp basinwards of Reef Complex #2, in deeper water, that were put into suspension by storm wave-energy (Fig. 4-9C). Such deposits characterize deeper water deposits of Member E in the underlying Escarpment Formation, which may have been exposed or only thinly covered, as the Alexandra Reef System developed. Fluvial input of the mud is discounted because it is not found in landward portions of the lowstand systems tract, including the protected area of the intra-buildup low, or in the coastal plain deposits at the top of Reef Complex #1 (Chapter 3).

Storm disturbance of the offshore oceanic system therefore may have caused significant nutrient enrichment of the seawater circulating over the lowstand systems tract by (1) mixing of the surface layer with stratified layers of nutrient-enriched seawater at depth, and advection of these waters onto the reef complex, and (2) release of nutrient reservoirs (e.g., iron) hosted in the marls and green shales situated further out on the ramp (Fig. 4-9C). With respect to the latter, the gentle slope (<0.1°) of the ramp was particularly important because the sea-level fall of ~ 17 m may have facilitated the raising of several thousand square kilometers of deeper, outer ramp marls and shales to above storm wave base, especially if the lowstand systems tract was characterized by exceptionally intense storms with deeper-than-average wave bases.

The synergy of storms with other mechanisms was also probably important. Heavy rains associated with the storms would have increased the volume of terrestrial run-off and groundwater seepage, thereby increasing nutrient delivery from these mechanisms. In addition, the havoc that was wreaked upon the reef-building communities in the lowstand systems tract must have caused significant stromatoporoid and coral mortality. It would have taken several weeks to months for new stromatoporoids and corals to start colonizing the decimated reef complex, and to start developing new framework. It is in this post-storm window of significant metazoan mortality, positively correlated with nutrient enrichment from the different sources that microbial blooms would have flourished in the reefal environs (e.g., renalcid boundstone lithifying new rubble-dominated deposits at the outer buildup). From modern reefs, this type of post-storm shift to algae and microbes (for a period of weeks to several months), because of coral mortality and the slow-speed of new coral growth, relative to the fast growth-rates of algae and microbes, is well-documented (e.g., Stoddart 1969; Woodley et al. 1981; Ostrander et al. 2000; McManus and Polsenberg 2004).

Seasonally-Forced Deepening of the Mixed Layer

Advection of seawater that has been enriched in nutrients through seasonally-forced deepening of the mixed layer is a mechanism of nutrient supply that carbonate ramps located in intracratonic basins and marginal seas, with weakly stratified water columns, may be particularly susceptible to. This is especially true for periods of sea-level lowstand, when water depth is relatively low and the basins may be increasingly restricted. A modern example is the arid, partly-restricted Gulf of Aqaba, where vertical stratification of the water column, because of warm water inflow from the Red Sea and minimal seasonal variations in salinity, is weak (Reiss and Hottinger 1984; Genin et al. 1995). As a result, vertical variations in water density are primarily determined by temperature, and the mixed-layer deepens in the winter when the sea-surface temperature cools by ~ 5° C and surface waters sink. The sinking, oxygenated waters mix with relatively nutrient-rich waters below the euphotic zone, and nutrients are transported upwards into the photic zone (Genin et al. 1995). This process in the Gulf of Aqaba deepens the mixed-layer every winter to depths of 500-600 m and causes significant nutrient enrichment in the spring. Demonstrating the potential impact of this mechanism, an unusually cool winter in 1991-1992 resulted in a deepening of the mixed-layer to ~850 m. The level of nutrification that resulted, when the nutrient-rich seawater was advected onto reefs along the northern margin of the gulf in March of 1992, caused significant algal blooms that blanketed the reefs with algal mats that exceeded 15 cm in thickness and caused notable coral death (Genin et al. 1995).

Relating this type of mechanism to the region that contained the Alexandra Reef System is speculative, but not unreasonable, given that a number of parallels can be drawn between the inland sea on the western margin of Laurussia with the Gulf of Aqaba. First, like the partly-restricted Gulf of Aqaba, Whalen (1995) argued that tectonic barriers along the western margin of Laurussia partly restricted its inland sea from open-ocean circulation, such that contrary to its eastern-ocean position, vast carbonate platforms were able to develop. An implication of this interpretation is that the oceanic water flowing into the basin, compensating for evaporative draw-down, would have been limited to less-dense waters closest to the ocean's surface (because of barriers at depth). Second, similar to the arid climate of the Gulf of Aqaba, this region of Laurussia, within 0-10° of the equator, was hot and semi-arid (Golonka et al. 1994). Third, akin to the Gulf of Aqaba, the basin configuration was long, narrow, and deep. Whalen (1995) argued that such configurations do not favour intrabasin gyral circulation, which may have limited the strength of its stratification. Weak stratification, such that cooling of sea-surface temperature by only a few degrees Celsius results in significant vertical mixing, is integral to this mechanism of nutrient enrichment.

The punctuated global cooling in the Frasnian (cf. Stanley 1988; Copper 2002; Joachimski et al. 2004), that probably caused the sea-level fall that terminated Reef Complex #1 and exposed platforms throughout the basin (Chapter 2) may have perturbed the climate such that a seasonally-forced mechanism of nutrification, similar to the one that operates in the Gulf of Aqaba, was activated. This may have been particularly important in the falling stage systems tract, when storm events appear to have been less important. It should be noted that this mechanism does not require the surface layer to mix with waters at hundreds of meters of depth. The nutricline in inland and marginal seas can be < 100 m deep (e.g., Tyson and Pearson 1991; Wignall and Newton 2001) and Chow et al. (1995) interpreted dysoxic-anoxic, presumably nutrient-rich water masses in the Late Devonian of western Canada at depths as shallow as 39 m (Fig. 4-9B). Such water masses are easily within the range of seasonally-forced mixing (and storm events), especially when sea-level position is lowered.

DISCUSSION

Carbonate platforms and reef systems from the Devonian have been extensively studied, but as Kiessling et al. (1999) demonstrated, consistent with the opinions of Moore (1989) and Wood (1993), there are few Devonian reef systems with "good data". Although some specific reef systems (e.g., the Lennard Shelf in the Canning Basin, Australia) have been extensively studied, the paleoecology of Devonian reef-building communities remains scarcely investigated and largely enigmatic (Moore 1989; Wood 1993; Kershaw 1998). In this regard, our understanding of the controls on Devonian reefs and carbonate platforms, despite their global significance, is largely based on assumptions (cf. Mountjoy 1980).

A common, prevalent assumption (Wood 1998a), exemplified by existing facies models (e.g., Machel and Hunter 1994), is that stromatoporoid-microbe reef facies were the norm in pre-Famennian Devonian reefs (e.g., Kershaw 1998; Wood 1999). This may be partly the result of a bias towards the well-studied and famous Canning Basin reef systems in Australia, from which numerous types and fabrics of microbial carbonates have been documented (e.g., Wray 1967; Playford et al. 1976; Playford 1980; George 1999; Wood 1998b, 2000, 2004; Chow and George 2004). With the advent of sequence stratigraphy, attempts have also been made to correlate specific microbial facies, assumed to be the norm, with specific systems tracts (cf. George 1999). Whalen et al. (2002), for example, concluded that Late Devonian highstand systems tracts in Devonian reefs of western Canada are characterized by stromatoporoid-*Renalcis* associations. Although this may apply to highstand systems tracts in the Ancient Wall and Miette reef systems of Alberta, it is incorrect to apply this conclusion across the basin to all platforms, as indicated by the lack of *Renalcis* in the highstand systems tract of Reef Complex #1 in the Alexandra Reef System. Indeed, the general assumption that stromatoporoid-microbe associations characterize Devonian reef facies ignores early observations that the prevalence of microbes in Devonian reefs is highly variable between geographic regions (Wray 1967; Krebs 1974; Burchette 1981). Krebs (1974), for example, noted that *Renalcis* and related microbes (referred to algae in that paper) are rarely found in Devonian reef complexes in Germany. Similarly, various studies of Devonian reefs in the Western Canada Sedimentary Basin (e.g., Fischbuch 1968; Leavitt 1968; Noble 1970; Dolphin and Klovan 1970; Vopni and Lerbekmo 1972) have not identified *Renalcis*, and related forms, as being present.

The lack of microbial constituents in some Devonian reefs is exemplified by the sharp facies contrasts in the Alexandra Reef System (Fig. 4-9A). The significant accumulations of renalcid boundstone and peri-reefal stromatolites found in the lower parts of Reef Complex #2 disappear upwards and are not found in any part of Reef Complex #1.

Consistent with the complex ecology of modern reefs, such variations cannot represent random coincidences. Rather, they offer valuable insight into how different ecological and environmental variables controlled these carbonate systems. The interpretation that the metazoan-microbe reef facies in Reef Complex #2 represent mesotrophic conditions therefore forms the premise for a new, nutrient-gradient model that explains variations in the biotic compositions of Devonian reef facies (Fig. 4-10). The use of changes in reef-facies composition to identify fluctuating nutrient levels in these systems, if integrated with potential mechanisms for such fluctuations, may be a powerful tool for interpreting the significance of lateral and vertical facies changes in these systems and understanding aspects of the local climate, sea-level change, and the surrounding oceanographic system (e.g., seasonality, importance of storm events). As part of this, other variables that may accompany nutrification, such as changes in salinity and temperature, also need to be considered. The nutrient-gradient model supports the first-order conclusion of Kiessling et al. (1999) that Givetian-Frasnian reefs lived in environments with high nutrient concentrations. This was based on their continent reconstruction maps that placed most studied reefs in regions with >70% probability of upwelling.

Nutrient-Gradient Model

Increasing nutrient levels →			
	Oligotrophic	Mesotrophic	Eutrophic
Biotic composition of framework facies	Stromatoporoid-dominated reef facies Stromatoporoid-tabulate coral reef facies Stromatoporoid-tabulate-rugose coral reef facies	Stromatoporoid-microbe[1] reef facies Stromatoporoid-coral[2]-microbe[1] reef facies	Megalodont-microbe[3] facies (replace reef facies)

[1] *Renalcis*, *Shuguria*, *Izhella*, stromatolites
[2] Tabulate and/or rugose corals
[3] Calcimicrobes, stromatolites, thrombolites

Figure 4-10. Nutrient-gradient model for Devonian reef systems. Devonian reef communities capable of inhabiting oligotrophic and mesotrophic environments. Only in eutrophic environments does platform demise take place, marked by replacement of reef facies with megalodont-microbe associations (cf. Eliuk 1998).

The breadth of oligotrophic to eutrophic environments in the nutrient-gradient model (see Hallock 1987 for a detailed review of the trophic resource continuum) is based on consideration of the nutritional mode (e.g., phototrophic, heterotrophic) of the different reef-building constituents, and consideration of the resources that are needed to fulfill the nutritional needs of the constituents in the reef-building community. Reef-building metazoans in the Alexandra Reef System, like many other Devonian reefs, include stromatoporoids, tabulate corals, and rugose corals. The nutritional mode of these fossil metazoans is debatable, but the general consensus is that stromatoporoids and tabulate corals were probably mixotrophs (Coates and Jackson 1987; Wood 1993, 1995). Rugose corals are generally treated as heterotrophs (Coates and Jackson 1987; Wood 1993, Wood 1995), although it should be noted that this interpretation is biased towards solitary and pseudocolonial morphologies (Coates and Jackson 1987). Stromatoporoid-tabulate coral associations are therefore generally associated with oligotrophic environments (Hallock and Schlager 1986; Hallock 1987; Wood 1993, 1995; Kershaw 1998; Whalen et al. 2002), whereas rugose corals are generally treated as indicative of mesotrophic environments (Wood 1993, 1995).

The common occurrence of stromatoporoid-tabulate-rugose coral associations, however, clearly indicates that the ecological niches of these organisms overlapped, and it is entirely possible that rugose corals, because of their ability to grow in soft substrates, were specially-adapted to oligotrophic environments. In particular, rugose corals are well-documented from the soft-substrate reef-front and fore-reef environments of Devonian reefs (Klovan 1964; Embry and Klovan 1972; Burchette 1981; MacNeil and Jones 2006a), where they presumably did not compete with stromatoporoids and corals located in shallower environments that are conventionally treated as having been oligotrophic (Hallock and Schlager 1986; Wood 1995). On this basis, the occurrence of rugose corals in transgressive systems should not be interpreted as unequivocal indicators of mesotrophic environments (e.g., Mallamo and Geldsetzer 1991). Consistent with Hallock and Schlager (1986), Hallock (1987), and Wood (1993, 1995), stromatoporoid-tabulate coral associations in the nutrient-gradient model are therefore considered indicative of oligotrophic environments (Fig. 4-10; Table 4-1). In contrast, rugose corals are treated as having been adapted to mesotrophic *and* oligotrophic environments (Table 4-1), and stromatoporoid-tabulate-rugose coral associations are treated by the model as indicative of oligotrophic conditions. It should be noted that within oligotrophic environments, the nutrient-gradient model does not preclude lateral variations between different types of metazoans (e.g., as may be expected between different reef zones) or community succession. In Reef Complex #1, for example, stromatoporoid-coral dominated frameworks are vertically succeeded by stromatoporoid-dominated frameworks and this succession took place within a continual state of oligotrophy.

Table 4-1. Trophic range of biota found in Devonian reef-building communities.

	Oligotrophic	**Mesotrophic**	**Eutrophic**
Stromatoporoids	X	X	
Tabulate Corals	X	X	
Rugose Corals	X	X	
Renalcis		X	X?
Shuguria		X	X?
Izhella		X	X?
Girvanella	X	X	X
Rothpletzella	X?	X	X?
Stromatolites		X	X
Megalodonts	X?	X	X

Microbial components and deposits that contributed to reef framework development in Reef Complex #2 include *Renalcis*, *Shuguria*, *Izhella*, a clotted form of *Renalcis*, and stromatolites with a micro-peloidal fabric. *Epiphyton* is not found in the Alexandra Reef System (with the exception of possibly one specimen), and *Rothpletzella* and *Girvanella* are minor, but with a broad distribution. Although the microbial affinity of the renalcids remains debatable, these and the stromatolite-producing microbial communities required nutrient levels characteristic of mesotrophic conditions (Table 4-1). In contrast, the broad distribution of *Rothpletzella* and *Girvanella* may suggest that these microbes are not good indicators of fluctuating nutrient levels. Certainly, *Girvanella* is well-known throughout most of the Paleozoic (Pratt 2001), and *Girvanella*-oncolites, characteristic of low-light, deeper water environments with low sedimentation rates, are common deposits in the Paleozoic (Peryt 1981; Riding 1983).

The nutrient-gradient model indicates that stromatoporoids, tabulate corals, and rugose corals lived in a broader range of nutrient levels than traditionally considered and broader ranges than modern reef-building corals, which are restricted to oligotrophic environments (Hallock and Schlager 1986; D'Elia and Wiebe 1990; Mutti and Hallock 2003). In addition to the ability of stromatoporoids to live in both oligotrophic and mesotrophic environments, many stromatoporoids also appear to have been capable of colonizing and developing over soft substrates (e.g., Fig. 4-7) as individual entities (Wood 1995; Kershaw 1998). This was the case in the initiation and differentiation stages of Reef Complex #2, in which the stromatoporoids did not coalesce to form framestone (Chapter 2). Rather, each skeleton existed as an individual entity, commonly bound together by microbial elements. This ability of stromatoporoids to colonize a wider range of substrates than modern scleractinian corals, which are restricted to areas where hard substrates are available (Wood 1993), may explain why many Devonian reefs, akin to the Alexandra Reef System, have low-profile, ramp-like geometries with reef development spread over a broad region (Wilson 1975; Mountjoy 1980; Walls and Burrowes 1985; Eliuk 1998; Kershaw 1998; da Silva and Boulvain 2004). This type of platform geometry is very different from that of modern coralgal-reef platforms with narrow reef zones and steep marginal slopes (Wilson 1975; James and Ginsburg 1976; Enos and Moore 1983).

A broad implication of the nutrient-gradient model is that Devonian reefs and their platforms were not highly susceptible to nutrient-invoked drowning (cf. Kiessling et al. 1999). As metazoan-dominated reef communities in these systems could be replaced by metazoan-microbial communities as nutrients became more available (Fig. 4-10), elevated nutrient levels should not have caused reef demise or platform drowning, except in cases of extreme nutrification. This supports the idea of Eliuk (1998) that replacement of Devonian reef facies by megalodont-microbe associations (a non-reef building phase) reflects significant eutrophication. Accordingly, replacement of reef facies by megalodont-microbe deposits is treated as an end-member in the nutrient-gradient model, indicative of nutrient-invoked platform drowning. The broad range of trophic resources that Devonian reef-building communities could utilize may also partly account for the global expansiveness of these systems, including their ability to develop in regions of upwelling (Kiessling et al. 1999) that normally preclude reefs.

The prediction that Devonian reefs were expansive and resilient to nutrification because of the wide range of trophic resources that could be exploited finds support in the extensively studied Canning Basin reef systems of northwestern Australia. These reef systems, with siltstones to pebble conglomerates periodically deposited across the span of back-reef to fore-reef environments (Read 1973; Playford et al. 1989; George 1999; Wood 2000), must have been nutrified (also suggested by Wood 2000) because this magnitude of terrestrial input is a well-established cause of nutrification (Garrels and MacKenzie 1971; Hallock and Schlager 1986; Hallock 1987; Mutti and Hallock 2003; McManus and Polsenberg 2004). Given the tectonically active extensional-setting of the Canning Basin in the Devonian, it is also possible that many of the neptunian dykes in these reefs were connected with deeper-seated fractures and faults, spewing nutrients as subsurface fluids vented. Thus, it is unlikely that these reefs developed in oligotrophic conditions, which is consistent with the volume of siliciclastic-stromatoporoid-microbial carbonate facies (e.g., Wood 2000) that characterize these reef systems. Kiessling et al. (1999) also concluded that these reef systems developed in mesotrophic conditions, given their close proximity to a region that was susceptible to upwelling.

CONCLUSIONS

The Alexandra Reef System demonstrates that the interactions of platform geometry, sea-level change, and nutrient levels, were important controls on Devonian reefs. The nutrient-gradient model indicates that Devonian reefs and associated platforms were formed by dynamic carbonate-producing communities, and carries significant implications for interpreting Devonian reef facies. Conclusions from this study include:

1) Ramp-situated carbonate systems – of any geological age – may be increasingly susceptible to nutrification as sea-level falls and in subsequent lowstand systems tracts. In contrast, transgressive systems on ramps may not be as susceptible to nutrification. As nutrients are a fundamental control on the types of carbonates deposited, different systems tracts on carbonate ramps may be characterized by different types of deposits (e.g., photozoan, heterozoan assemblages).
2) Stromatoporoids, tabulate corals, and rugose corals, lived in oligotrophic and mesotrophic environments. The occurrence of stromatolites and calcimicrobes in Devonian reef framework is not characteristic of all Devonian reefs, and is important because these types of deposits indicate that nutrients were not limited in the

environment. The mixed carbonate-siliciclastic Canning Basin reef systems were almost certainly nutrified (cf. Kiessling et al. 1999; Wood 2000), and the stromatoporoid-microbial reef facies in these systems may be relatively unique.

3) Devonian platforms were not highly susceptible to nutrient-invoked drowning because changes in community composition facilitated continued carbonate production and accumulation as nutrient levels increased. The wide range of environments and substrates that could be colonized by Devonian reef-builders may have been an important factor in the global expansiveness of these systems, and probably explains why these platforms were generally characterized by broad areas of reef-framework development with stratigraphic architectures that are markedly different from modern reef-rimmed carbonate platforms.
4) Use of the nutrient-gradient model to recognize fluctuating nutrient levels, and interpretation of the mechanisms causing such fluctuations, is a critical step towards understanding variations in Devonian reef-facies and local controls on the initiation, development, and demise of Devonian carbonate platforms.

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CHAPTER 5 – NEW MICROFOSSILS FOUND IN UPPER DEVONIAN STRATA OF THE HAY RIVER REGION[1]

INTRODUCTION

The Devonian succession of western Canada is renowned for its carbonate complexes that rimmed the continental edge of Laurussia and formed isolated buildups in the adjacent basin. The micropaleontology of these and associated depositional systems, however, has been poorly documented. This is because most studies of these deposits have been concerned with aspects related to petroleum exploration and exploitation (e.g., controls on porosity and permeability), rather than aspects of micropaleontology, and most of the reefs have been extensively dolomitized, destroying fossils and depositional textures. Upper Devonian strata (Escarpment Formation and Alexandra Formation) in the Hay River region of the Northwest Territories, however, are superbly preserved and contain a diverse array of microfossils from different types of marine depositional environments.

Enigmatic calcareous microfossils that belong to the family Ovummuridae Munnecke, Servais, and Vachard, 2000 are found throughout most of the upper Escarpment Formation – Alexandra Formation succession. These small (generally < 150 μm long) microfossils, which are known from Silurian, Carboniferous, and Permian strata (Munnecke et al., 2001), have not yet been described from Devonian strata. Although their biological affinity remains unknown, they have been allied to foraminifera, bryozoans, calcispheres, and algae (Munnecke et al., 2000). Based on the specimens found in the upper Escarpment Formation and Alexandra Formation, this chapter 1) documents the first Devonian specimens of the Ovummuridae, 2) describes *Minourella cameroni* n. sp., 3) demonstrates that like echinoderm fragments, these microfossils acted as cement magnets in the seafloor-marine burial realm, and 4) delineates their facies

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[1] Chapter is combination of papers:

MacNeil, A.J. and Jones, B. 2006. Ovummuridae (calcareous microfossils) from a Late Devonian ramp: their distribution, preservation potential, and paleoecological significance. Canadian Journal of Earth Sciences. **43**, 269-280.

MacNeil, A.J. and Jones, B. In review. The new genus and species *Devonoracemus cameroni* – an encrusting, reef-dwelling microorganism from the Late Devonian. Submitted for publication to Journal of Paleontology.

distribution. As a result, the stratigraphic range of *Minourella gotlandica* is extended from the Late Silurian to the Late Devonian (mid-Frasnian), and it becomes apparent that these microorganisms were minor background constituents in the reef ecosystem but an important element of the biota that lived in mixed carbonate-siliciclastic environments. Their abundance in mixed carbonate-siliciclastic ramp deposits indicates that they were capable of inhabiting marine environments unsuitable to most other carbonate-secreting organisms in the Paleozoic.

In contrast to the fairly broad environmental distribution of the ovummurids, a particularly distinct encrusting calcareous microfossil, *Devonoracemus cameroni* n. gen. and n. sp., is only found in high-energy reef facies in Reef Complex #2 of the Alexandra Reef System. Present in a variety of shapes, this microfossil shares a number of morphological and ecological similarities with *Shamovella obscura* (Maslov, 1956) Riding, 1993 (= *Tubiphytes obscurus* Maslov, 1956), which is known from Lower Carboniferous to Lower Cretaceous strata. *Shamovella*, the biological affinity of which remains debated (e.g., Riding and Guo, 1992; Vachard et al., 2001), was important in Permian and Triassic reef systems where it served as a significant contributor to reef framework development (e.g., Newell, 1955; Bradner and Resch, 1981; Flügel, 1981; Riding and Guo, 1992; Li and Mamet, 1993; Vennin et al., 1997). *Devonoracemus cameroni*, described in the latter part of this chapter, was most likely some type of tubiform cyanobacterium.

GEOLOGICAL SETTING

Well-preserved deposits of the Escarpment Formation (~ 106 m thick) and Alexandra Formation (~ 35 m thick) crop out in the southern part of the Northwest Territories (Fig. 5-1A). These Upper Devonian siliciclastic and limestone deposits accumulated in an epicontinental ramp setting near the equator on the western edge of Laurussia (Kiessling et al., 1999; Scotese, 2004). Continental hinterland lay to the east and the continental margin lay to the west and north (Moore, 1989; Switzer et al., 1994).

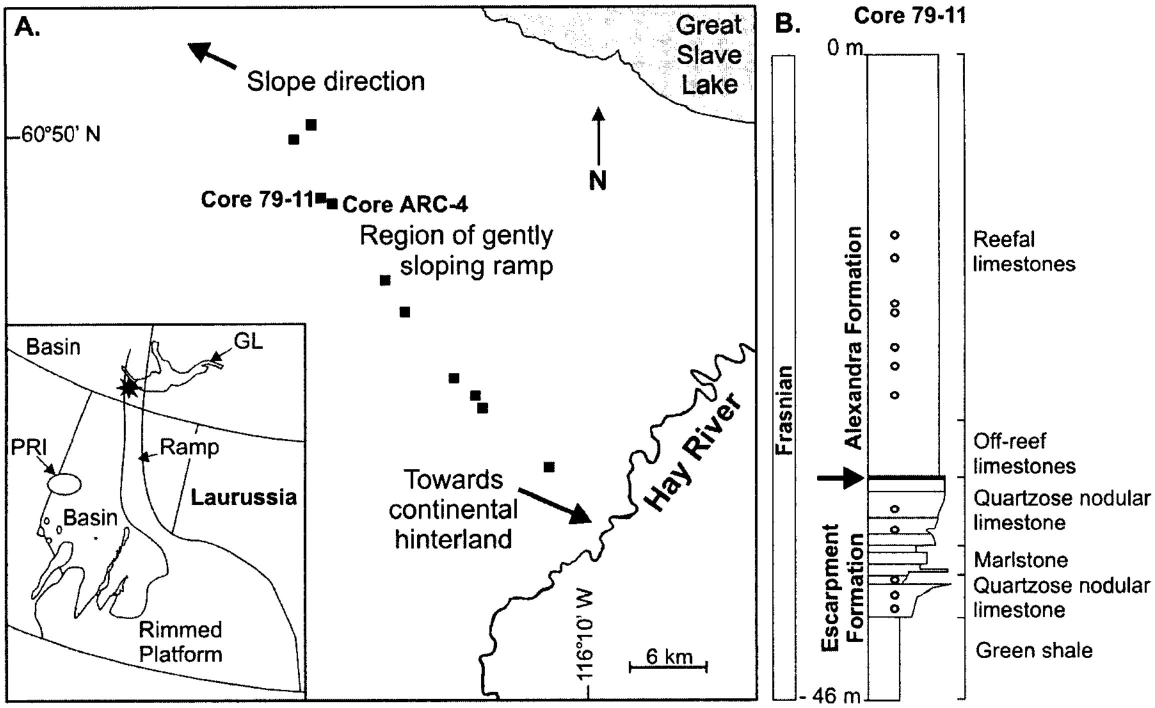

Figure 5-1. Map of study area and representative core (79-11) through upper Escarpment Formation – Alexandra Formation succession . **A)** Hay River area in southern Northwest Territories, Canada, with key elements of Late Devonian paleogeography and location of the ten cores (square symbols) indicated. *Devonoracemus cameroni* n. gen. and n. sp. studied from core ARC-4. Inset shows study area (star symbol) in relation to western Canada paleogeography in Late Devonian (Frasnian; simplified from Weissenberger and Potma, 2001). Political boundaries and Great Slave Lake included for geographical reference. PRI = Peace River Island; GL = Great Slave Lake. **B)** Core 79-11 through upper part of Escarpment Formation and Alexandra Formation showing facies succession. Arrow indicates position of change from mixed carbonate-siliciclastic ramp deposits with low biotic diversity to ramp-situated stromatoporoid-dominated reef system with negligible siliciclastics. Black circles indicate distribution of ovummurids.

The upper part of the Escarpment Formation (upper Member D and Member E; ~31 m thick) includes shallow marine regressive ramp deposits that are characterized by argillaceous, bioturbated quartzose-nodular limestones, green shales, marlstones (calcareous clays and silts intercalated with calcareous siltstones and quartzose limestones), and trough cross-bedded coarse quartz siltstones (Fig. 5-1B). The low diversity biota in these deposits includes crinoid ossicles, fragments of brachiopods, and thin-shelled molluscs (e.g., Hadley and Jones, 1990). The overlying Alexandra Formation (~ 35 m thick) is formed of limestones that developed in two stromatoporoid-dominated reef complexes (Chapter 2). Facies associations include those from coastal plain, peritidal, lagoon, back-reef, reef, and fore-reef/proximal off-reef environments. The siliciclastic content of these limestones is negligible. Conodont and rugose coral assemblages in the lower Escarpment Formation and Alexandra Formation constrain their age to the mid-Frasnian (Klapper and Lane, 1985; McLean and Klapper, 1998).

Ovummurids were found in large (5 x 7.5 cm) thin sections (n=67) prepared from samples collected from ten cores (Fig. 5-1A) that extend from the top of the Alexandra Formation into the upper parts of the underlying Escarpment Formation (Member E and upper part of Member D of Hadley and Jones (1990)). Green shales in the Escarpment Formation were not investigated. Microfossils were identified with transmitted-light under a Leica DMLP microscope and photographed with a Polaroid Digital Microscope Camera. Although no modification of the thin sections was required, the microfossils were more obvious when the thin section was stained with Alizarin Red-S (cf. Dickson, 1966). One sample (Escarpment Formation; Core 79-9, at a depth of 9.4 m) with abundant ovummurids was polished and etched (~5 % HCl for < 5 seconds), coated with Au, and examined with a JEOL 6301 field emission scanning electron microscope.

Devonoracemus cameroni n. gen. and n. sp. is common in deposits from the lower part of the reef in Reef Complex #2. These deposits (~ 14 m thick) are dominated by broken stromatoporoids and intraclastic debris that was redeposited from the reef-front by storms, and subsequently lithified by renalcid boundstone, stromatolites, and marine cements. Numerous specimens of *Devonoracemus cameroni*, found in seven large (5 x 7.5 cm) thin sections prepared from core ARC-4 (Fig. 5-1A), which penetrated this rubble-dominated reef facies, were examined with the same microscope setup used for study of the ovummurids. Specimens in two polished and etched (40 seconds in 50% acetic acid) thin sections were also coated with Au and examined with a JEOL 6301 field emission scanning electron microscope (SEM).

SYSTEMATIC PALEONTOLOGY

Thin sections that contain the illustrated specimens are stored in the collection of the authors in the Department of Earth and Atmospheric Sciences, University of Alberta, Canada. They are individually identified by their thin section number. Thin sections that contain type specimens are stored in the Type Collection of the Paleontology Museum in the Department of Earth and Atmospheric Sciences, University of Alberta, Canada. They are individually identified by their University of Alberta (UA) collection number.

Incertae sedis

Family OVUMMURIDAE Munnecke, Servais, and Vachard, 2000

Genera included.— *Ovummurus* Minoura and Chitoku, 1979; *Minourella* Munnecke, Servais, and Vachard, 2000; *Arouxina* Munnecke, Servais, and Vachard, 2000; and *Samtlebenella* Munnecke, Servais, and Vachard, 2000.

Original diagnosis (Summarized from Munnecke et al., 2000).— Small calcareous microfossils with two or more chambers, aperture in apex of chamber, wall formed of small calcite tablets regularly arranged into pseudo-concentric layers.

Original description (Summarized from Munnecke et al., 2000).— Spherical to ovoid or dolioform in shape, maximum diameter < 100 μm, wall composed of calcite tablets ~ 1 μm thick in roughly lamellar series, wall thickness variable in different parts of test. Wall similar to that described in bryozoans and tentaculitoids. Partition of internal cavity by subequatorial or equatorial pseudo-septum common. Apertures, invariably present, define axial plane of test.

Occurrence (From Munnecke et al., 2001).— Lower Silurian to Upper Permian. The Upper Permian occurrence is based on one poorly preserved specimen of *Ovummurus* (Munnecke et al., 2001) and it is not known if these microorganisms became extinct before or at the Permian-Triassic boundary. Well-preserved specimens of *Ovummurus* are known from Lower Permian strata (Minoura and Chitoku, 1979; Munnecke et al., 2001). The identification of partly preserved *Samtlebenella* in Upper Carboniferous samples by Munnecke et al. (2001) is not convincing because the specimen (fig. 2A of Munnecke et al., 2001) attributed to *Samtlebenella circumcamerata* is only moderately preserved, and the specimen attributed to *Samtlebenella sp.* (fig. 2B-D of Munnecke et al., 2001) not only lacks obvious chamberlets (as noted by Munnecke et al., 2001), but is also more than double the maximum size of the specimens that Munnecke et al. (2000) described from Gotland. On the basis of morphology, size, and wall microstructure, these specimens appear to be small bryozoans that have been misidentified. Identical specimens of bryozoan affinity are present in the Hay River material. As such, only *Ovummurus* has unequivocally been demonstrated from strata younger than Silurian. Ovummurids have not been described from strata of Devonian age, but Munnecke et al.

(2001) noted a personal communication from Kazmierczak (2001) that he had observed *Ovummurus* in Upper Devonian samples from Poland.

Remarks.— The size range of the Ovummuridae is greater than the maximum diameter of 100 µm given in the original description. Minoura and Chitoku (1979) gave maximum diameters of 120 µm for *Ovummurus* and dimensions for genera described by Munnecke et al. (2000) all exceed 100 µm. As such, this part of the original description appears to have referred to the size of individual chambers in the tests, rather than the maximum size of the test.

Numerous specimens of ovummurids in the Hay River material (Figs. 5-2G, 5-4A) contain 1-2 quartz grains in their chambers. Minoura and Chitoku (1979) noted the same feature in their specimens of *Ovummurus duoportius*, and incorporation of quartz into the septum of some specimens. These grains were probably trapped during life as the test developed, rather than after death, because the 1) tests generally appear to be intact and well-preserved, 2) apertures are generally too small to allow passage of the quartz grains, and 3) incorporation of quartz grains into the septal structure of some specimens (cf. Minoura and Chitoku, 1979) implies that the grains were present as the microorganisms grew. Minoura and Chitoku (1979) suggested that the trapped quartz grains may indicate an encrusting lifestyle, similar to encrusting algae.

Genus Ovummurus Minoura and Chitoku, 1979

Type species.— *Ovummurus duoportius* Minoura and Chitoku, 1979. Upper Pennsylvanian, Kansas, U.S.A., by original designation.

Original diagnosis (Modified from Minoura and Chitoku, 1979).— Free calcareous microorganism, ovoid to ellipsoidal shaped test, oval to elliptical internal chamber divided diagonally by septum-like structure into two equal spaces. Two narrow slit-like apertures extend nearly symmetrically about center, diagonally relative to long and short axes of test. Aperture length up to half of long axis of test. Test slightly elevated around aperture, may appear as slender lips.

Occurrence.— Lower Silurian to Upper Permian (Munnecke et al., 2001).

Remarks.— The shape of the apertures is difficult to discern from randomly oriented sections. Munnecke et al. (2000) did not find the slit-like shaped aperture described by

Minoura and Chitoku (1979) convincing, and suggested that it may, instead, be cylindrical.

Ovummurus duoportius Minoura and Chitoku, 1979

Fig. 5-2A-D

Description.— Ellipsoidal test. Aperture to each chamber visible in longitudinal cross-sections. One specimen (Fig. 5-2C) with flange-like features on outside wall of one aperture. Wall around other aperture slightly thickened. Test 160-230 μm long, 70-100 μm wide, 65-70 μm high, wall and septum-like structure 3-12 μm thick.

Material examined.— More than 100 specimens.

Remarks.— Ascertaining dimensions of *Ovummurus* is problematic when natural size variation is combined with the limitations of two-dimensional sections. Partly-flattened oval (ellipsoidal) tests have three dimensions, but Minoura and Chitoku (1979) only provided a long-diameter and short-diameter. The Hay River specimens are three-dimensional ellipsoidal tests, with axes (height, width, length) of different lengths. The test height, wall, and septum-thickness measurements of the Hay River specimens fall in the size ranges given in the original description by Minoura and Chitoku (1979). The test length, however, exceeds the maximum measurement (120 μm) of Minoura and Chitoku (1979). Munnecke et al. (2000) noted that specimens in their material (n=5) fell in the ranges of Minoura and Chitoku (1979), but they may have mistaken ellipsoidal width for maximum length. The specimen figured in plate 1, fig. 2 of Munnecke et al. (2000) may be a longitudinal cross-section (thereby same orientation as the test in their plate 1, fig.1), based on the mid-position and sharply-defined nature of the septum, which would be obliquely-cut in a longitudinal transverse section (cf. fig. 2 of Minoura and Chitoku, 1979). If so, the measurement of 121 μm given by Munnecke et al. (2000) as the maximum length of the test may, in fact, be the width. The Hay River specimens, and possibly the Gotland specimens, show that maximum size of *Ovummurus* (up to ~ 230 μm) is greater than that given in the original description of the taxa.

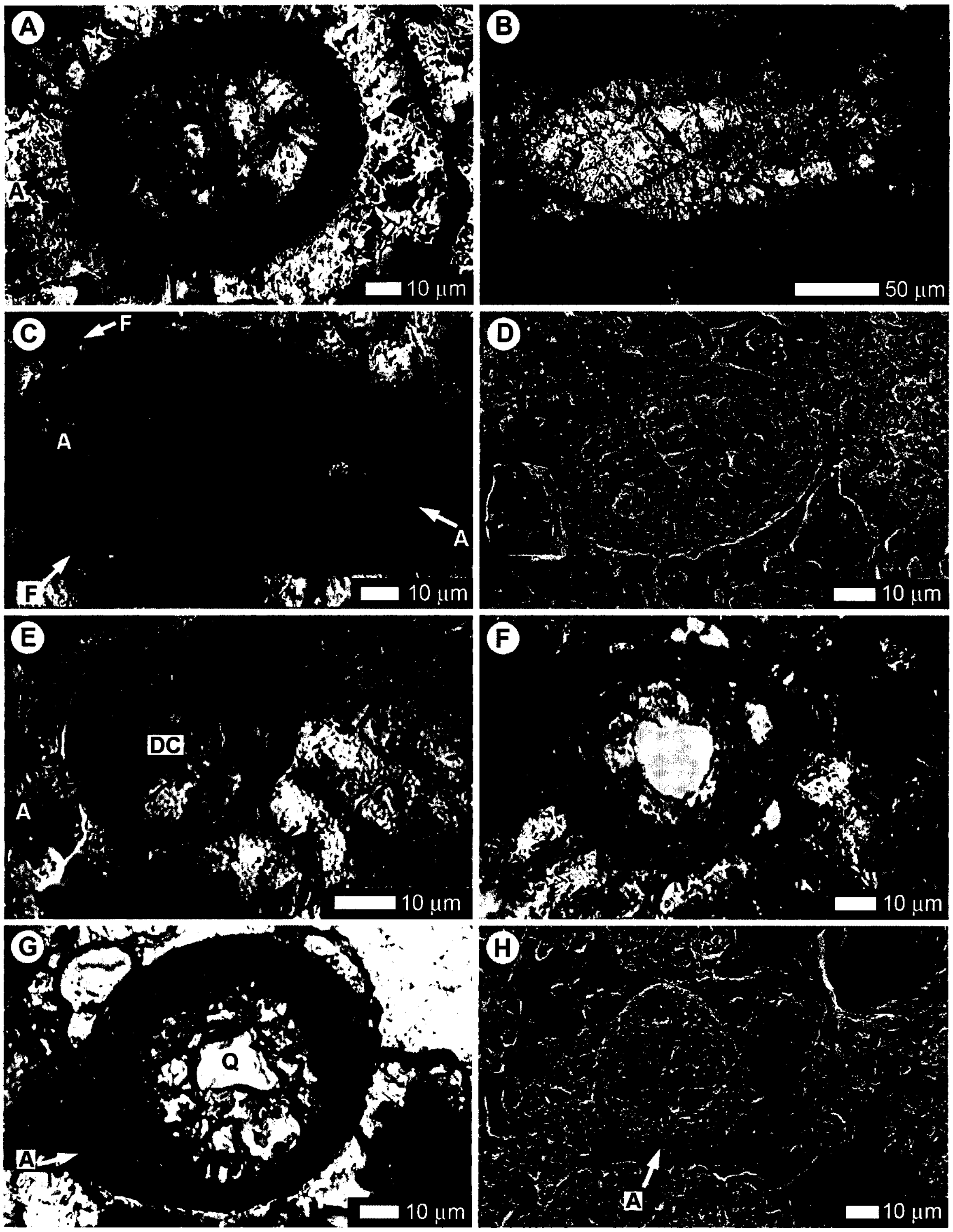

Figure 5-2. Thin section (A-C, E-G) and scanning electron microscope (D, H) photomicrographs of *Ovummurus duoportius* (A-D) and *Minourella gotlandica* (E-H). **A)** Longitudinal cross-section showing one aperture (A). Escarpment Formation, Core 79-9, 9.4 m depth. **B)** Equatorial transverse section showing diagonal septum-like structure (arrow) that divides two chambers. Escarpment Formation, Core 79-9, 34.4 m depth. **C)** Longitudinal cross-section showing two chambers, each with an aperture (A). Wall around right chamber aperture slightly thickened. Two flanges (F) surround outside of aperture of left chamber. Escarpment Formation, Core 79-9, 36.8 m depth. **D)** Oblique

longitudinal section of specimen with cement overgrowth (OG) around test. Escarpment Formation, Core 79-9, 9.4 m depth. **E)** Longitudinal section showing apical aperture (A) to dorsal chamber (DC). Note internal oval to rectangular shape of dorsal chamber. Escarpment Formation, Core 79-9, 32.2 m depth. **F)** Well-preserved specimen with thick wall with tablet-like microstructure. Alexandra Formation, Core 79-13, 13.55 m depth. **G)** Specimen with apical aperture (A) developed in ventral chamber. Quartz (Q) grain trapped in dorsal chamber. Alexandra Formation, Core 79-13, 13.55 m depth. **H)** Well-preserved specimen with aperture (A) visible. Test encased by thick cement overgrowth (OG). Escarpment Formation, Core 79-9, 9.4 m depth.

Genus Minourella Munnecke, Servais, and Vachard, 2000

Type species.— *Minourella gotlandica.*

Diagnosis (Modified from Munnecke et al., 2000).— Test bilocular, globular or conical, with one or more simple apertures. Dorsal part gently vaulted, with small apical aperture in central part. Ventral part corresponding to second chamber with or without aperture. External and internal surfaces smooth. Uniform wall thickness.

Occurrence.—Silurian to Upper Devonian.

Remarks.— Diagnosis amended to include form with conical test and possibility of aperture in ventral chamber, as found in two specimens of *Minourella gotlandica. Minourella cameroni* n. sp. has a conical test as opposed to the globular test of *M. gotlandica*, which was based on over 1000 specimens (Munnecke et al., 2000). Conceivably, *M. cameroni* could be placed in a new genus based on test shape. Given that *Minourella* has, up to now, been a monospecific genus with the full range of morphological variability yet to be established, *M. cameroni* is herein retained in this genus because 1) longitudinal cross-sections through the test of *M. cameroni* resemble *M. gotlandica*, 2) it has the same type of wall microstructure, and 3) the wall thickness falls in the range of *M. gotlandica.*

Minourella gotlandica Munnecke, Servais, and Vachard, 2000

Figs. 5-2E-H, 5-5B, D

Diagnosis.— One large and one small chamber, separated by flat septum-like structure. Rare specimens with apical aperture in smaller chamber.

Description.— Globular microorganism with two chambers separated by flat septum-like structure. Large chamber, oval to nearly rectangular with long-axis of rectangle parallel to septum. Small chamber triangular to elongate-oval with long-axis parallel to septum. Apical aperture in large chamber may or may not be visible. Two specimens with aperture at apex of small chamber. Test 40-100 μm high, 35-95 μm wide, height:width = 1.0-1.3, large chamber 20-80 μm high, 25-75 μm wide, wall around large chamber 5-15 μm thick, small chamber 5-10 μm high, 15-25 μm wide, wall 3-7 μm thick, septum 2-7 μm thick, aperture 3-6 μm in diameter (Table 5-1).

Material examined.— More than 1000 specimens.

Occurrence.— Lower Silurian to Upper Devonian.

Table 5-1. Dimensions (μm) of *Minourella gotlandica* in Hay River material, following measurement protocol of Munnecke et al. (2000).

	H	W	H/W	H1	W1	th1	H2	W2	th2	th3	ap
Minimum	40	35	1.0	20	25	5	5	15	3	2	3
Maximum	100	95	1.3	80	75	15	10	25	7	7	6
Average	71	61.5	1.1	47	49	7	6.5	18	5	4.5	5

Note: H = height of test; W = width of test; H1 = height of dorsal chamber; W1 = width of dorsal chamber; th1 = wall thickness around dorsal chamber; H2 = height of ventral chamber; W2 = width of ventral chamber; th2 = wall thickness around ventral chamber; th3 = thickness of septum; ap = width of aperture

Remarks.— Unlike the Gotland material described by Munnecke et al. (2000), two specimens in the Hay River material have an apical aperture in the ventral chamber. An aperture was not visible in the dorsal chamber of these specimens. Although comparable in size to the specimens described by Munnecke et al. (2000), the Hay River specimens have 1) a smaller ventral chamber, 2) slightly thicker walls around the smaller ventral chamber, and 3) a slightly smaller apical aperture in the dorsal chamber. It is important to note that measurements of *Minourella gotlandica* provided in columns H1 – W1 and H2 – W2 of table 1 in Munnecke et al. (2000) appear to have been reversed, based on their text-fig. 3 and the figured holotype (plate 1, fig. 3).

Rare specimens that resemble *M. gotlandica*, but contain three or four chambers (Fig. 5-3A, B), were found in the Hay River material. It is not clear if these are distinct species from *M. gotlandica*, or variants of the species, possibly reflecting different lifecycle stages. Munnecke et al. (2000) noted a specimen with three chambers (their plate 4, fig.

5) comparable to the specimen (Fig. 5-3A) found in the Hay River material. They, however, considered it to be an indetermined genus and species distinct from *M. gotlandica*, on the basis of the third chamber.

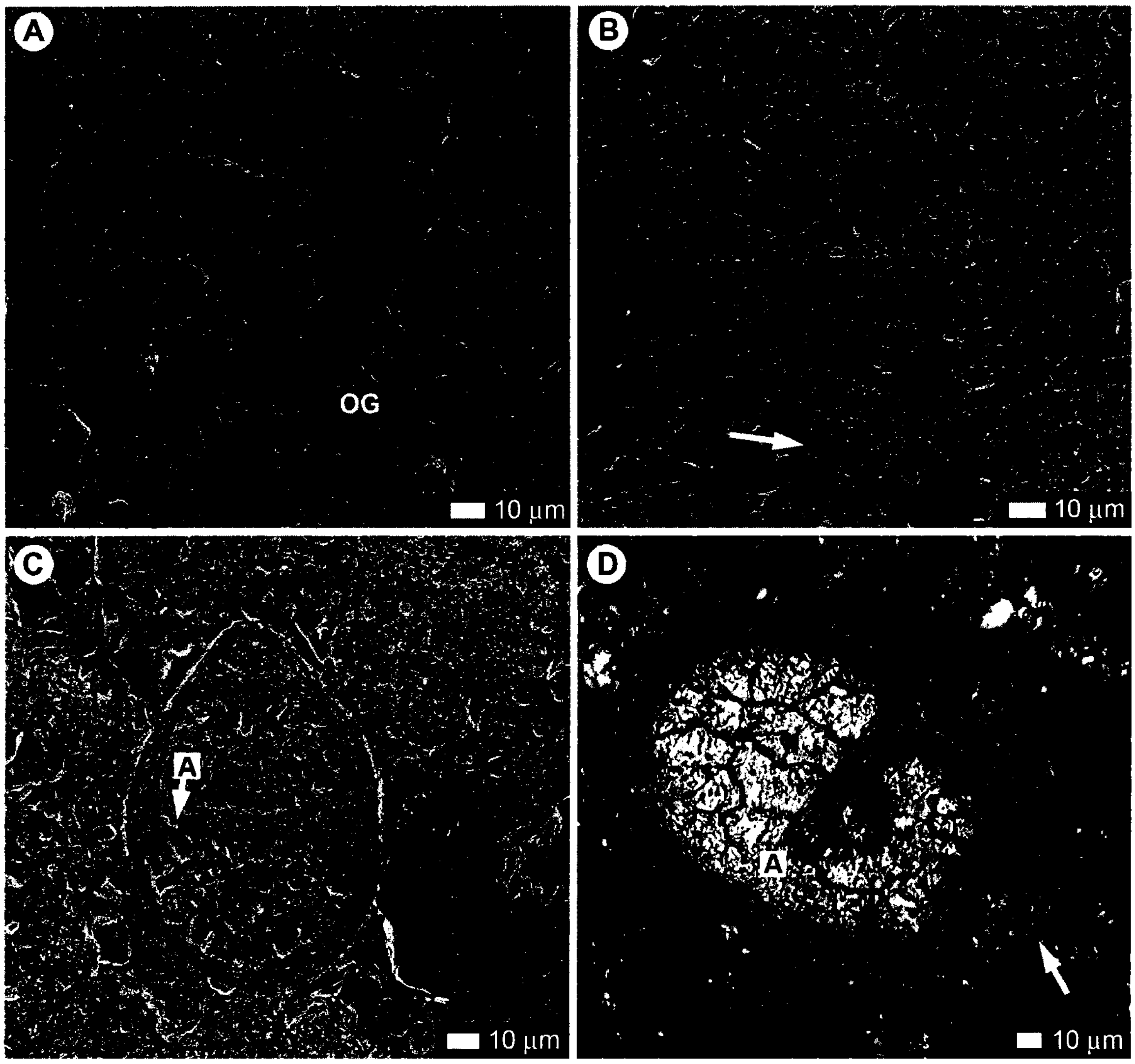

Figure 5-3. Scanning electron microscope (A-C) and thin section (D) photomicrographs of Ovummuridae variants, not formally named. **A)** Three-chambered specimen encased in cement overgrowth (OG). Escarpment Formation, Core 79-9, 9.4 m depth. **B)** Four-chambered specimen. Chamber at bottom (arrow) poorly preserved. Escarpment Formation, Core 79-9, 9.4 m depth. **C)** Two-chambered form with dorsal chamber partly divided by septum. Aperture (A) connects the two sub-chambers. Test encased in overgrowth cement (OG). Q = quartz grain. Escarpment Formation, Core 79-9, 9.4 m depth. **D)** Two-chambered form, with outer wall (arrow) of small chamber poorly preserved. A = aperture. Alexandra Formation, Core 79-13, 11.6 m depth.

Minourella cameroni new species

Figs. 5-4, 5-5C

Diagnosis.— Conical test, one large dorsal chamber and one small ventral chamber with apertures at anterior end of test and a dorsal secondary aperture.

Description.— Test conical, dominated by large, anteriorly expanding dorsal chamber. Septum partly divides dorsal chamber into large, posterior sub-chamber and small, anterior sub-chamber. Large, posterior dorsal sub-chamber contains secondary aperture, possibly slit-like, on dorsal side of test. Small sub-chamber with large simple aperture at anterior dorsal end of test, with or without lateral flanges. Small ventral chamber narrows over area of dorsal chamber that contains septum before opening into aperture at anterior end. Test 195-275 μm long, 70-115 μm high, length:height = 1.8-3.9, dorsal chamber 55-105 μm high, ventral chamber 0.5-13 μm high, wall 3-6 μm thick (Table 5-2).

Table 5-2. Dimensions (μm) of *Minourella cameroni* n. sp. (n=5).

	L	H	L/H	DCH	VCH Max/Min	WT
Holotype	240	115	2.1	105	9/3	3
Minimum	195	70	1.8	55	7/.5	3
Maximum	275	115	3.9	105	13/8	6
Average	235	95	2.6	79	8.2/2.7	3.8

Note: L = test length; H = test height; L/H = length:height; DCH = maximum dorsal chamber height; VCH Max/Min = maximum and minimum heights of ventral chamber; WT = wall thickness.

Etymology.— After A.E. Cameron, who conducted important geological and paleontological fieldwork along Hay River in 1917.

Types.— Holotype UA11087 – thin section prepared from core 79-9 at depth of 36.8 m; Escarpment Formation. Specimen circled. Paratype UA11088 – thin section prepared from core 79-9 at depth of 34.4 m; Escarpment Formation. Specimen circled. Both thin sections contain additional ovummurids.

Other Material Examined.— 30 specimens.

Occurrence.—Upper Devonian.

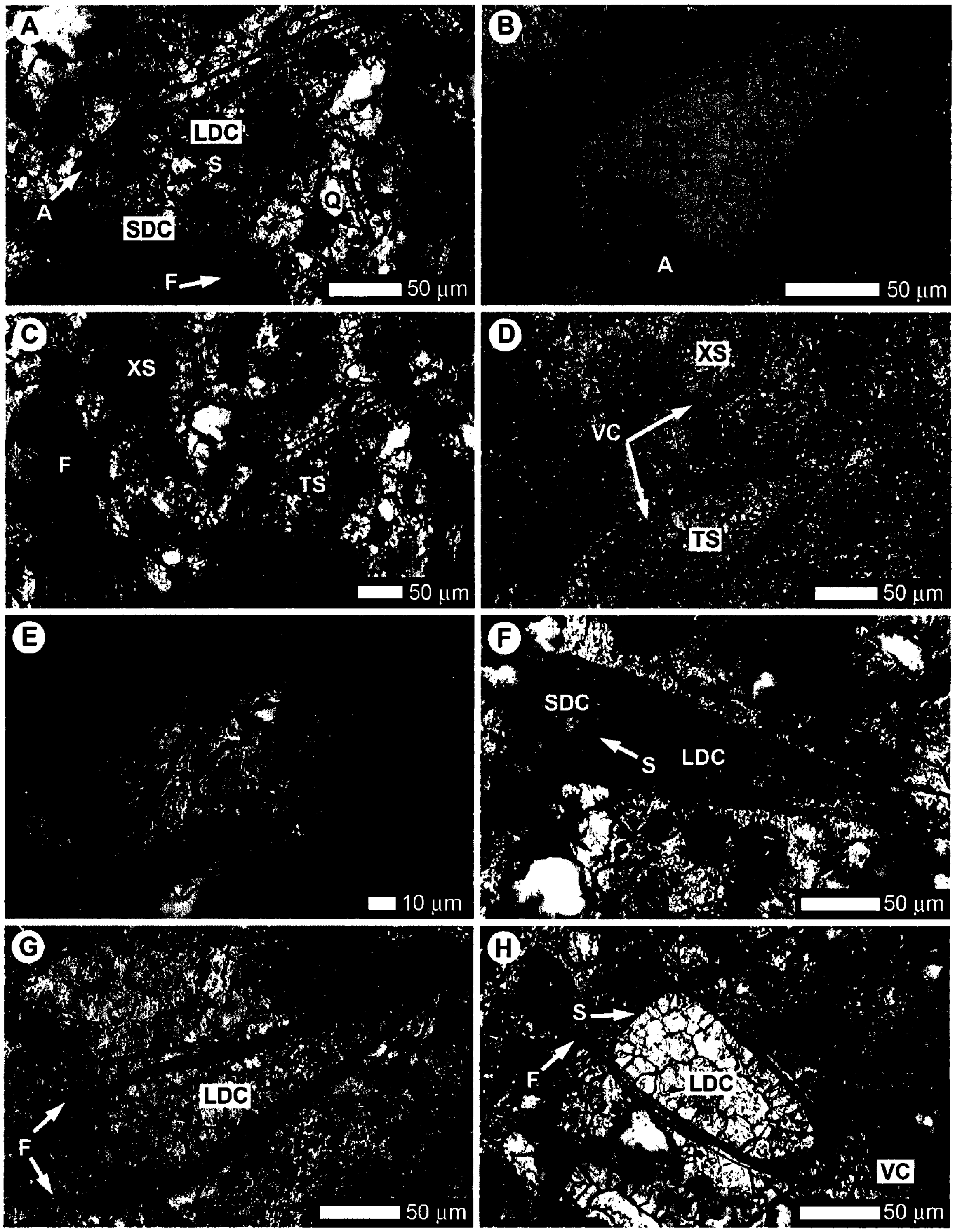

Figure 5-4. Thin section photomicrographs of *Minourella cameroni* n. sp. **A)** Longitudinal transverse section of holotype (UA11087) showing conical shape of test. Dorsal chamber partly divided into large dorsal sub-chamber (LDC) and small dorsal sub-chamber (SDC) by septum (S). Flange (F) present at dorsal anterior part of test. Ventral chamber (VC) runs along top of test and opens into a second aperture. Note quartz (Q) grains in test and surrounding matrix. **B)** Paratype (UA11088) showing aperture (A) at dorsal-anterior part of test. **C)** General view of holotype (TS) in longitudinal transverse section and adjacent specimen in longitudinal cross-section (XS) that resembles *Minourella gotlandica.*

Note partly preserved foram (F). **D)** Partly preserved specimens in transverse section (TS) and cross-section (XS). Ventral chamber of both tests (arrows) emphasized to show how the two sections relate to each other. Alexandra Formation, Core 79-11, 18.7 m depth. **E)** Longitudinal cross-section through anterior part of test with large aperture (A). Escarpment Formation, Core 79-9, 34.4 m depth. **F)** Equatorial transverse section through test showing large dorsal sub-chamber (LDC) partly separated from small dorsal sub-chamber by septum (S). Escarpment Formation, Core 79-13, 19.7 m depth. **G)** Oblique transverse section through test with flange-like protuberances from anterior end of large dorsal sub-chamber (LDC). Alexandra Formation, Core 79-11, 18.7 m depth. **H)** Oblique section through anterior end of test demonstrating ventral chamber (VC), large dorsal sub-chamber (LDC), septum (S), and protruding flanges. Escarpment Formation, Core 79-9, 34.4 m depth.

Remarks.— Separated from *M. gotlandica* by conical as opposed to globular test form. Morphological features akin to those in *M. gotlandica* render longitudinal cross-sections through *M. cameroni* difficult to distinguish from *M. gotlandica* without accessory longitudinal transverse sections or equatorial transverse sections.

Genus and Species Indetermined 1

Fig. 5-3C, D

Description.— Globular Ovummuridae characterized by one small ventral chamber and one large dorsal chamber. Septum partly divides the large dorsal chamber into two sub-chambers, connected by a simple aperture. Test 135-200 μm high, 85-130 μm wide, test height:width = 1.5-1.6, wall 9 – 14 μm thick, small chamber 15-25 μm high and 25-40 μm wide, large chamber 95-145 μm high and 70-105 μm wide, septum 50-75 μm long, septum length: test width = 0.5-0.6.

Material examined.— Two specimens; one from Escarpment Formation (Core 79-9, at depth of 9.4 m) and one from Alexandra Formation (Core 79-13, at depth of 11.6 m).

Remarks.— These specimens are distinct from *Minourella gotlandica* because of their larger test size and partial division of their dorsal chamber by a prominent septum. Their globular test shape distinguishes them from *Minourella cameroni*, which is conical. They have been left under open nomenclature because only two specimens were found and the full range of morphological variation therefore remains unknown.

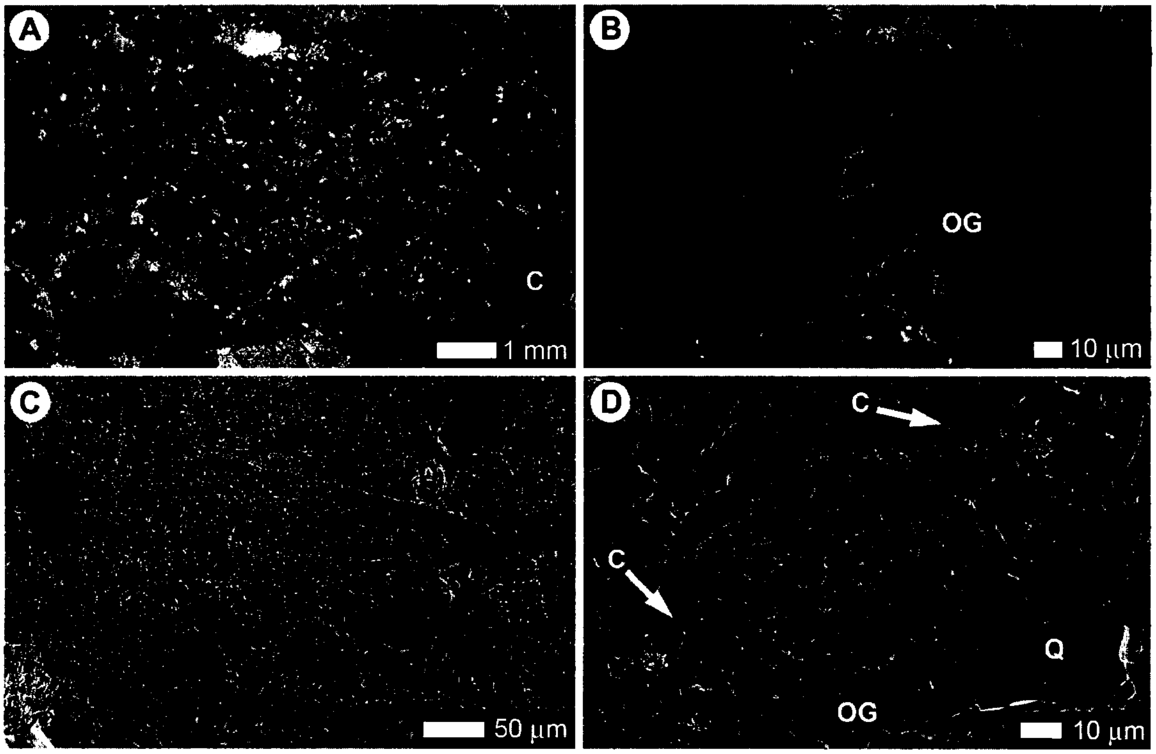

Figure 5-5. Thin section (A,B) and scanning electron microscope (C,D) photomicrographs of depositional textures and diagenetic features of ovummurids. A) General view of packstone with numerous ovummurids (fine black-coloured grains) and larger molluscs (cement-filled molds), and crinoid (C) fragments. Cement overgrowths around ovummurid tests common. Escarpment Formation, Core 79-11, -37.8 m. B) *Minourella gotlandica* encased by inclusion-rich cement overgrowth (OG). Cement has uniform extinction when Nichols are crossed. Escarpment Formation, Core 79-9, -9.4 m. C) *Minourella cameroni* sp. nov. partly encased by cement overgrowth (OG). Q = quartz grain. Escarpment Formation, Core 79-9, -9.4 m. D) Cement overgrowths (OG) around adjacent tests of *Minourella gotlandica* with planar compromise boundaries ('C' arrows). Q = quartz grain. Escarpment Formation, Core 79-9, -9.4 m.

Family NIGRIPORELLIDAE Rigby, 1958

Genera included.— Shamovella (Maslov, 1956) Riding, 1993; *Tubiphytes* Flügel, 1966; *Devonoracemus* n. gen..

Occurrence (amended from Riding and Guo, 1992).— Upper Devonian (Frasnian) to Lower Cretaceous (Albian).

Remarks.—Riding (1993) indicated that *Shamovella obscura* is the correct name for *Tubiphytes obscurus* Maslov, 1956. Use of "*Tubiphytes*" for *Tubiphytes obscurus*, however, is well-entrained in the literature and its usage continues (e.g., Stemmerik, 1997; Vennin et al., 1997). Wang et al. (1994) argued that more than one genus is included under "*Tubiphytes*". *Tubiphytes* Flügel, 1966 refers to *T. carinthiacus*.

Genus *Devonoracemus* new genus

Figs. 5-6 and 5-7

Type species.—Devonoracemus cameroni new species.

Diagnosis.—Elongate, circular, or globular bundle, 0.6 – 2.8 mm long, of one tube or coiled calcareous tubes, each 140 – 220 μm diameter. Tubes loosely or tightly packed with outer tubes totally or partly enveloping inner tubes (Fig. 5-6A, B). Tubes formed of anhedral micrite and fine anhedral microspar. Edges of loosely packed tubes sharp and dark. Tubes, especially when tightly packed, may amalgamate at contacts producing diffused boundaries and dark flocculent microstructure (Figs. 5-6A, D, E, and 5-7A, B). One or more circular or irregular-shaped holes in bundle filled by secondary calcite (Figs. 5-6 and 5-7C-E).

Description.—Fossil consists of one tube, or cluster of tubes, encrusted around foreign object (Fig. 5-6D) or as free carbonate grain (Fig. 5-7A-C) detached from host substrate. Calcite-filled circular or irregular-shaped holes appear to mark sites where encrusted objects used to be, and gaps between loosely packed tubes.

Etymology.—Latin *Devono* = after the Devonian Period; Latin *racemus* = cluster of grapes, similar to commonly clustered appearance of microfossil in thin section.

Occurrence.—Late Devonian (Frasnian). High-energy reef facies.

Remarks.—The biological affinity of *Devonoracemus* is not clear. Its simple structure of calcified tubes, in many cases clustered together, suggests it may be some form of cyanobacterium. Individual tubes may represent variable calcification of a cyanobacterium sheath and surrounding extracellular polymeric substances (EPS), around either individual or massed trichomes. Diffused boundaries between adjacent tubes may reflect calcification of EPS shared between adjacent packages of trichomes, or partial degradation of tubes concurrent with calcification. Specimens examined with the SEM show simple microstructure and no structural organization, consistent with microbial calcification (cf. Riding, 2000). Calcification of other types of microbes (e.g., bacteria, fungi), however, is ruled out for the origin of *Devonoracemus* because of its gross tubular morphology. With respect to the cyanobacterium interpretation, it should be noted that the diameter of tubes in *Devonoracemus* is one order of magnitude greater than the

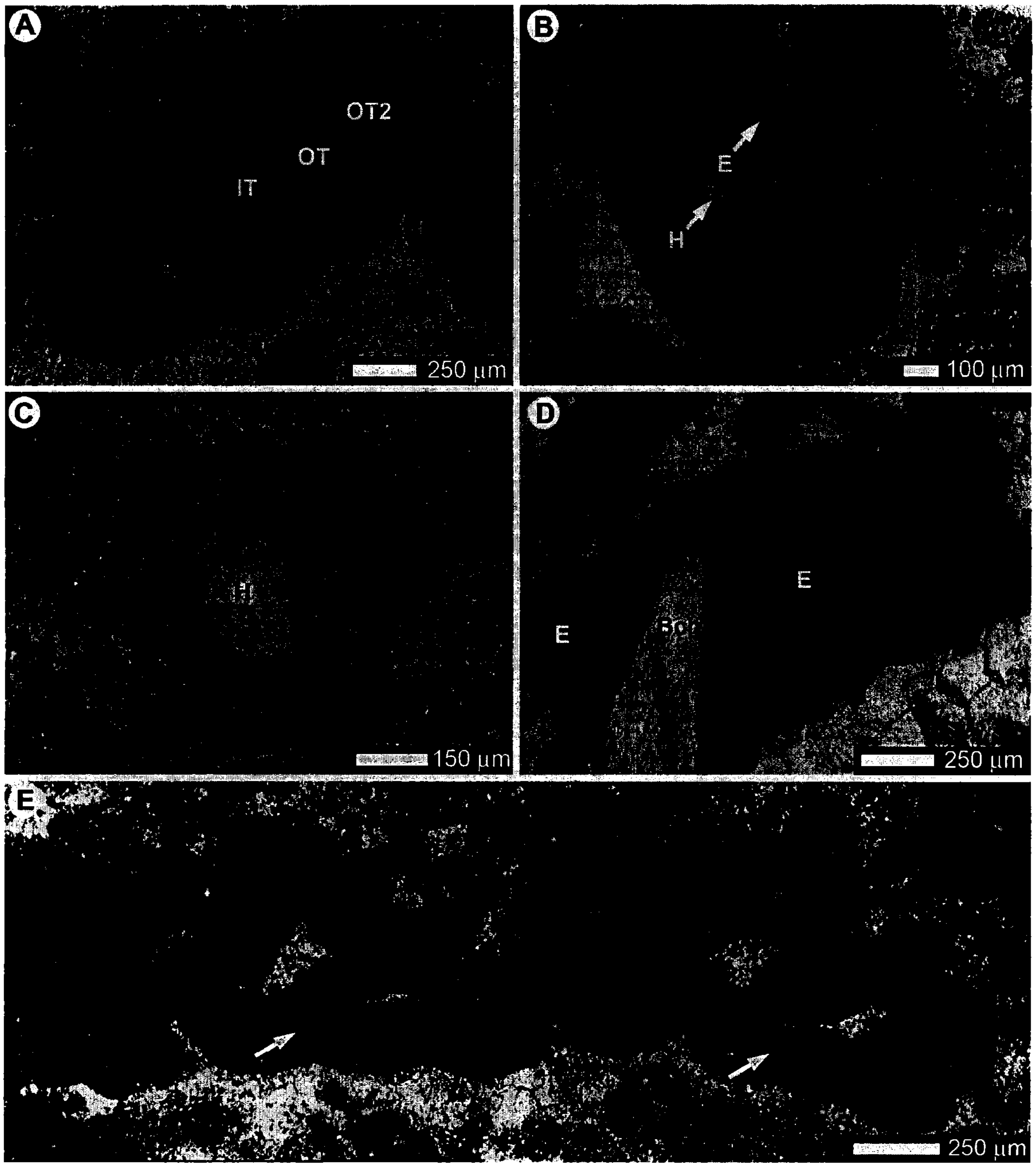

Figure 5-6. Thin section photomicrographs of *Devonoracemus cameroni*. **A)** Holotype UA11089. Bundle of successively layered partly enveloping tubes. Calcite-filled hole (H) in center of inner tubes (IT) marks where foreign object was located. Outer tube (OT) partly envelopes inner tubes. Second growth phase of outer tubes (OT2) with diffusive microstructure marks outermost part of bundle. **B)** Paratype UA11090. Concentric growth around object no longer preserved. Calcite cement fills hole (H) from object. Edge (E) between inner growth and second outer growth well-defined. **C)** Tube with micritic and microsparitic microstructure showing complete circumferential encrustation of object no longer present, marked by irregular hole (H) filled by calcite cement. Edge around hole irregular, not smooth. Core ARC-4, at depth of 6.2 m. **D)** Bundle encrusted (E) on brachiopod (Bch). Calcite cement filled cavities between tubes. Many tubes partly amalgamated producing flocculent microstructure. Core ARC-4, at depth of 5.9 m. **E)** Loosely packed tubes. Some tubes have dark centers and some tubes in contact with each other lost distinction of their walls (arrows) and amalgamated. Calcite cement fills cavities between tubes. Core ARC-4, at depth of 6.2 m.

diameter of other types of tubular calcareous microfossils known from the Paleozoic (e.g., *Girvanella* Nicholson and Etheridge, 1878) that have been allied to the cyanobacteria.

A green algae affinity for *Devonoracemus* does not seem likely because its tubes do not share morphological similarity with codiacean or dasycladacean algae. If the tubes are loosely packed, however, the fossils resemble a grain of codiacean algae in which the thallus is poorly preserved and the utricles have been filled with cryptocrystalline cement (cf. Milliman, 1974). Numerous specimens with tightly packed tubes and specimens that display circumferential encrustation habits, however, indicate that the apparent similarity of loosely packed bundles to diagenetically altered codiacean algae is coincidental. *Devonoracemus* does not resemble any known Devonian foraminifera, most of which are free-living forms.

Devonoracemus shares a number of morphological similarities with the problematic microfossil *Shamovella*. Published figures of *Shamovella obscura* (Newell, 1955 – pt. 6B; Flügel, 1981 – fig. 5B and 5C; Vennin et al., 1997 – fig. 5#7; Weidlich and Fagerstrom, 1999 – fig. 5F and 8D; Scholle and Ulmer-Scholle, 2003 – pg. 211), for example, are comparable to Fig. 5-6A-C of *Devonoracemus*. Simple morphotypes of *Shamovella obscura* in Mamet et al. (1987 – pt. 29 #4 and pt. 30 #7) and Scholle and Ulmer-Scholle (2003 – pg. 211, the specimen from Upper Permian of Tunisia), for example, are nearly indistinguishable, on the basis of morphology and approximate size, from the specimens of *Devonoracemus* in Fig. 5-6B and C.

From descriptions of *Shamovella* by Maslov (1956) and Riding and Guo (1992), morphological similarities with *Devonoracemus* include:

1) The size range of *Devonoracemus* (0.6 – 2.8 mm) overlaps with size range of *Shamovella* (< 1 mm to several mm).
2) Both organisms grew in successive, enveloping or partly enveloping layers. Although successive bands in *Shamovella* may develop asymmetrically, such that the fossil becomes elongated or conical in form, inner growth zones are generally concentric (see figures on p. 211 in Scholle and Ulmer-Scholle, 2003) and are morphologically indistinguishable from many circular bundles of *Devonoracemus*.

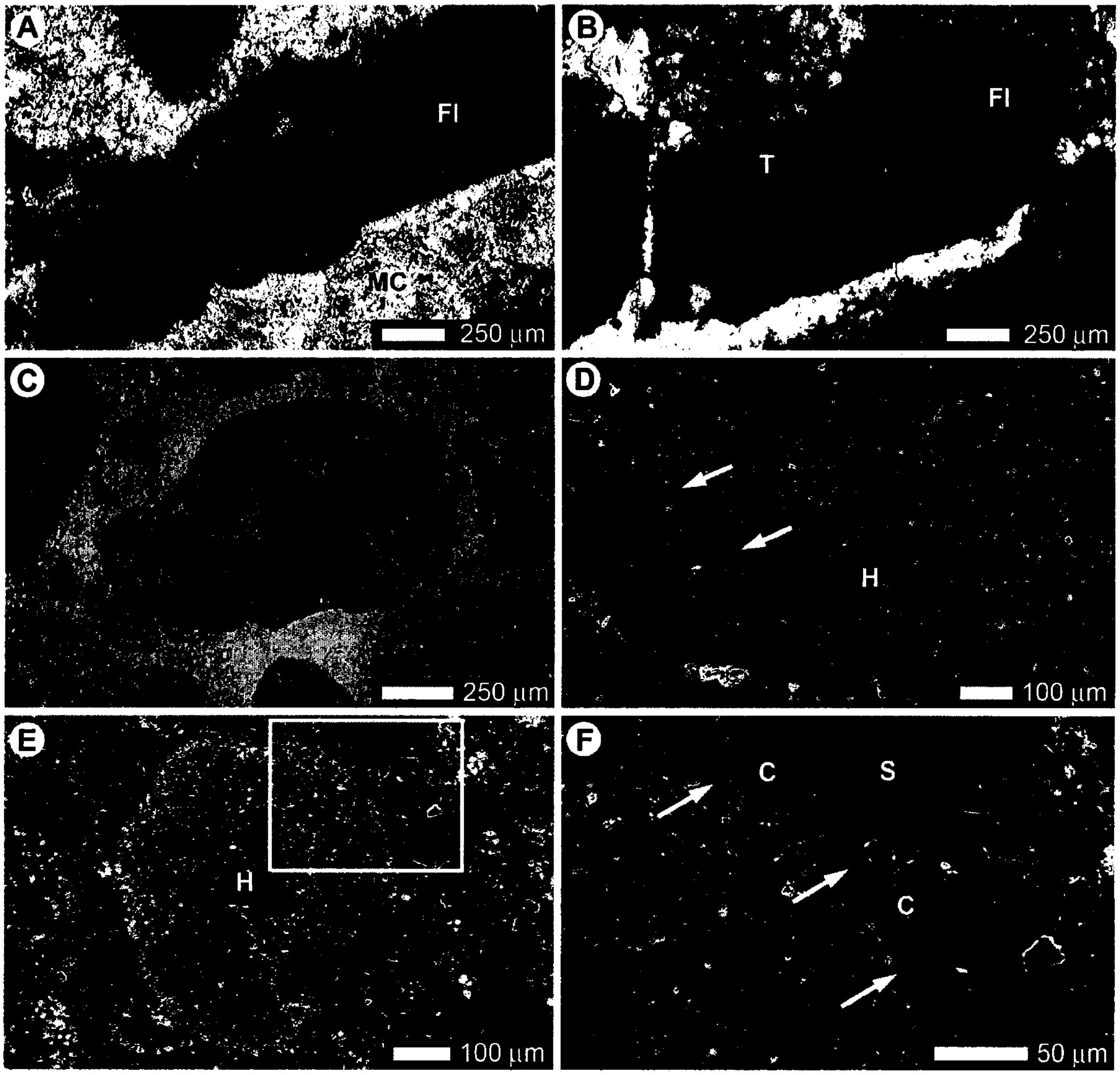

Figure 5-7. Specimens of *Devonoracemus cameroni.* A-C = thin section photomicrographs; D-F = SEM images. **A)** Elongate bundle in packstone cemented by marine cements (MC). Bundle forms carbonate grain. Some tightly packed tubes partly amalgamated to form dark, flocculent (Fl) microstructure. Core ARC-4, at depth of 6.2 m. **B)** Darkly flocculent (Fl) microstructure in bundle due to amalgamation of tightly packed tubes. Ghosts of some tubes (T) visible. Core ARC-4, at depth of 6.2 m. **C)** Grain of loosely packed tubes. Calcite filled spaces between tubes before it became detrital. Core ARC-4, at depth of 11.2 m. **D)** Globular bundle with spar-filled hole (H) where foreign object existed. Inner edges of two successive growth bands shown (arrows). Sharp edge around most of bundle. Core ARC-4, at depth of 6.2 m. **E)** Circular bundle of one tube with spar-filled hole (H) in center. White box indicates figure part F. Core ARC-4, at depth of 11.2 m. **F)** Close-up of bundle and bundle edge. Microstructure of bundle consists of randomly organized micrite and microspar. Edge of bundle (arrows) sharp and lined with radially-arranged bladed marine cement (C). Intergranular porosity filled with coarse, anhedral spar (S).

From descriptions of *Shamovella* by Maslov (1956) and Riding and Guo (1992), morphological similarities with *Devonoracemus* include:

4) The external surfaces of these fossils are smooth and well-defined.
5) The internal structure may be dark and micritic (cf. Maslov, 1956) or darkly flocculent and possibly containing a network of fibers (Riding and Guo, 1992). Although some specimens of *Devonoracemus* have a darkly flocculent microstructure (Figs. 5-6A, D, and 5-7A, B), and some specimens have a weakly heterogeneous internal microstructure of micrite and microspar (Figs. 5-6B, C and 5-7C, F), none displayed a fiber network.

SEM images of *Devonoracemus* (Fig. 5-7D-F) are also directly comparable to the SEM images of *Shamovella obscura* of Flügel (1981; his fig. 8). Both sets of SEM images show specimens with (1) a microstructure of micrite and fine microspar, (2) well-defined edges but no specific, distinct wall microstructure, (3) internal, spar-filled spaces (tubes), and (4) radial carbonate cements growing on their outer edges. Neither sets of images show organized, internal microstructures.

Given the number of shared morphological features between *Devonoracemus* and *Shamovella*, *Devonoracemus* is interpreted to be in the same family as *Shamovella*. In addition to the shared morphological features, both microorganisms thrived as encrusting constituents in shallow, agitated reef environments with strong illumination. *Devonoracemus*, however, is distinct from *Shamovella* because (1) *Devonoracemus* does not attain the larger sizes that *Shamovella* reaches, (2) tubes in the outer growth zones of *Devonoracemus* do not broaden into enveloping growth bands, and (3) specimens of *Devonoracemus* with internal fibers (a morphological feature of *Shamovella*) have not been found, although this could be a result of diagenetic alteration.

Devonoracemus cameroni new species

Figs. 5-6 and 5-7

Diagnosis.—As for genus.

Description.—As for genus with appearance in thin section depending on number of tubes, manner of coiling (e.g., tight, loose), and shape of hole produced by encrusted object.

Etymology.—Latin *cameroni*, after A.E. Cameron who conducted important geological and paleontological fieldwork in Hay River area in 1917.

Types.—Holotype UA11089 – thin section prepared from core ARC-4 at depth of 7.2 m; specimen circled. Paratype UA11090 – thin section prepared from core ARC-4 at depth of 7.35 m; specimen circled. Both thin sections contain numerous additional specimens.

Other Material Examined.—38 specimens.

Occurrence.—As for genus.

Remarks.—Fragmented pieces of *Ellesmerella* Mamet, Roux, and Nassichuk, 1987 resemble *Devonoracemus cameroni*, but tubes of *Ellesmerella* are non-uniform in diameter, bifurcate, and are one order of magnitude smaller in diameter (12 – 38 µm) than tubes of *Devonoracemus cameroni*. The encrusting, coiled nature of *Devonoracemus cameroni* is crudely comparable to the coiled nature of *Obruchevella* Reitlinger, 1948, known mostly from the Proterozoic and Cambrian. Tubes of *Obruchevella*, however, are helically-coiled and one order of magnitude smaller in diameter (generally <25 µm) than tubes of *Devonoracemus cameroni*. Furthermore, the tubes are mineralized with clear calcite and well-defined walls, in same manner as *Girvanella* (Mankiewicz, 1992). This mineralization is different from that of *Devonoracemus cameroni*, which is characterized by a micritic and microsparitic microstructure throughout the tube.

STRATIGRAPHIC DISTRIBUTION OF OVUMMURIDS

Escarpment Formation

Minourella gotlandica, *M. cameroni n. sp.*, and *Ovummurus duoportius* were found in argillaceous, bioturbated, quartzose-nodular limestones, but not in the marlstones or quartz siltstones (Fig. 5-1B, Table 5-3). The only possible exception to this is in one thin section of the quartz siltstones that contains poorly preserved carbonate grains that resemble ovummurids. Numerous specimens (e.g., one thin section contains ~ 1200 ovummurids) were found in lenses of quartzose packstones and grainstones that are considered to be storm-winnowed deposits.

Alexandra Formation

Low numbers of *Minourella gotlandica, M. cameroni*, and *Ovummurus duoportius* were found in back-reef, reef, and fore-reef facies (Fig. 5-1B, Table 5-3), but not in the peritidal or lagoonal facies. In general, < 20 specimens were found in each thin section. As such, ovummurids are not as abundant as in the Escarpment Formation. The percentage of thin sections with ovummurids increases from the back-reef through to the fore-reef/proximal off-reef facies (Table 5-3).

Table 5-3. Facies distribution of ovummurids in Hay River material.

Formation	**Facies**	**Ovummurids present Yes/No**	**Number of thin sections with/without ovummurids**	**Percentage of thin sections with ovummurids**
Alexandra Formation	Peritidal and lagoon limestones	No	0/17	0%
	Back-reef limestones	Yes	6/48	11%
	Reef limestones	Yes	21/84	20%
	Fore-reef/Off-reef limestones	Yes	11/29	28%
Escarpment Formation	Marlstone	No	0/4	0%
	Quartz siltstone	No[a]	0/2	0%
	Argillaceous, bioturbated, quartzose-nodular limestone	Yes	29/38	43%

[a] One thin section contains poorly preserved carbonate grains that resemble ovummurids.

DISCUSSION

Ovummuridae

The significance of ovummurids on Paleozoic platforms is poorly understood because they have only recently been described in detail and their biological affinity remains unknown. Previous studies have shown that some limestones, generally in marlstone successions, contain large numbers of these microfossils (Minoura and Chitoku, 1979; Munnecke et al., 2000, 2001). As a result, Munnecke et al. (2001) suggested that ovummurids may have been abundant on carbonate platforms throughout most of the Paleozoic, but that they escape detection because of their small size and the susceptibility of their skeletons to diagenetic obliteration. They are, however, readily identifiable in thin section (Figs. 5-2A-C, E-G, 5-3D, 5-4, and 5-5A-C), indicating that the small size of these microfossils does not inhibit their detection.

There is no evidence that ovummurids were ubiquitous on carbonate platforms throughout most of the Paleozoic. The distribution of the ovummurids in the upper Escarpment Formation and Alexandra Formation, and their preservation, is clearly the result of both environmental and taphonomic factors. In the Escarpment Formation, ovummurids are common in the variably argillaceous, bioturbated quartzose-nodular limestones, and are particularly abundant, along with peloids of unidentifiable skeletal origin, in quartzose packstones and grainstones of storm-winnowed deposits (Fig. 5-5A). Good preservation of these specimens has been facilitated by cement overgrowths around many of the tests (Figs. 5-2D, H, 5-3A, C, and 5-5B-D), that probably protected them from any further mechanical or diagenetic alteration. This cement, which must have precipitated relatively early in the marine realm, given that compacted tests and grains are not found (cf. Bathurst, 1975), is akin to the syntaxial overgrowth cement that is commonly found around Paleozoic crinoids (e.g., Meyers, 1974; Kerans et al., 1986). The overgrowths are characterized by inclusion-rich calcite with planar compromise growth boundaries (Fig. 5-5B, D). This style of overgrowth cementation of the tests indicates that the individual crystals of the test microstructure likely shared the same crystallographic orientation, and that the microfossils were originally composed of calcite and possibly low-Mg calcite (cf. Bathurst, 1975). Munnecke and Samtleben (1996) also concluded that these microfossils were likely calcitic, but on the basis of wall-microstructure preservation, which may not be expected if these microfossils were originally formed of aragonite.

The absence of ovummurids in the marlstones is surprising because Munnecke et al. (2001) noted numerous specimens of ovummurids in these types of deposits. Their absence from this facies in the Hay River material, however, may be due to poor cementation of these deposits and subsequent diagenetic destruction of the tests (cf. Munnecke and Samtleben, 1996; Munnecke et al., 2000). The absence of ovummurids in the quartzose siltstones may be due to mechanical or diagenetic degradation of the tests, and one thin section of this facies has poorly preserved carbonate grains that resemble ovummurids. Thus, it is possible that ovummurids were abundant over a widespread area of the ramp when the deposits that form the upper Escarpment Formation were accumulating (cf. Munnecke et al., 2001). A combination of mechanical degradation and diagenesis, however, may have destroyed most evidence of their existence in the marlstones and quartzose siltstones.

In contrast to the Escarpment Formation, ovummurids are rare in the limestones of the Alexandra Formation (Table 5-3). These limestones, which contain little siliciclastic material, are characterized by a diverse reef-building fossil assemblage that includes stromatoporoids, corals, and calcimicrobes. Microfossils, including a variety of foraminifera, calcispheres, and algae, in addition to ovummurids, when present, are well-preserved. The scarcity of ovummurids, therefore, cannot be attributed solely to mechanical degradation or diagenetic factors. Rather, it appears that the ovummurids were only minor constituents of the reef ecosystem, which is supported by the increasing percentage of thin sections with ovummurids in the off-reef direction. The general absence to low-abundance of the ovummurids in the reefal limestones is consistent with a review of other Devonian reef studies (Klovan, 1964; Toomey, 1965; Toomey et al., 1970; Kettenbrink and Toomey, 1975; Vachard, 1994) in which various micro-paleontological aspects were studied, but there was no description or illustration of specimens that could be attributed to the Ovummuridae.

The life mode and paleoecology of the Ovummuridae is open to debate. Minoura and Chitoku (1979) suggested, on the basis of trapped quartz grains in the test, that *Ovummurus duoportius* had an encrusting, presumably benthic mode of life. Munnecke et al. (2001) concluded that ovummurids probably had a planktonic mode of life. This was on the basis that ovummurids have been found in a number of different depositional environments (e.g., shallow lagoon to deep shelf facies) in Silurian strata of Gotland. If, however, these microorganisms were planktonic, their paucity from lagoon and peritidal deposits in the Alexandra Formation, where such microorganisms might be transported to and deposited after death, is unexpected. Rather, the facies distribution in the Alexandra Formation suggests that ovummurids were probably benthic and preferred off-reef environments. Storms may have transported these microfossils into the reefal environments of the Alexandra Formation, similar to the transport of modern fore-reef foraminifera into the back-reef environments of the Cayman Islands by hurricanes (Li et al., 1998). A benthic mode of life is also suggested by the quartz grains found in some tests, which appear to have been trapped during life, because a planktonic mode of life would require these grains to have been floating at the surface for their entrapment. Furthermore, the trapped grains would have decreased the buoyancy of the test, adding stress to a planktonic lifestyle. Significant storm redistribution may explain the wide distribution of ovummurids in the Silurian deposits of Gotland.

The difference between ovummurid abundance in the upper Escarpment Formation and Alexandra Formation also indicates that the partly siliciclastic open-ramp environment of the Escarpment Formation was the preferred habitat for these microorganisms. Regressive, siliciclastic input onto the ramp, likely accompanied by fluctuations in salinity, increased nutrient levels, and turbidity (cf. Hallock and Schlager, 1986; Mutti and Hallock, 2003), produced conditions on the ramp, below and above fairweather wave base, that were favoured by ovummurids but few other carbonate-secreting organisms. Much of the seafloor, where these microorganisms are interpreted to have lived, probably had a soft consistency during fairweather conditions, based on the argillaceous and muddy texture of the quartzose limestones and the sedimentary nature of marlstones. Periodic storms reworked these deposits and probably produced exceptionally murky conditions in the water column as fine material was winnowed from the inner ramp and muds that had settled on the outer ramp were disturbed. Ovummurids were apparently well-suited for these environmental conditions, given their abundance in the upper Escarpment Formation and in marlstones from Gotland (Munnecke et al., 2000).

Devonoracemus cameroni **n. gen. and n. sp.**

The interpretation that *Devonoracemus* n. gen. was some type of tubiform cyanobacterium, and that it was related to *Shamovella*, does not help to resolve the uncertain biological affinity of *Shamovella*. Many studies of *Shamovella*, for example, have concluded or suggested that it was some form of cyanobacterium (e.g., Maslov, 1956; Johnson, 1963; Toomey, 1969; Flügel, 1977; Flügel, 1981; Mamet et al., 1987; Li and Mamet, 1993; Shen and Xu, 2005), and Vennin et al. (1997) suggested that it may have been a cyanobacterium-foraminfera symbiosis. In contrast, Riding and Guo (1992) and Wang et al. (1994) concluded that *Shamovella* was some type of calcareous sponge. Vachard et al. (2001) proposed that *Shamovella* was a free-living cyanobacterium or alga, and that part of its life strategy included developing a symbiotic relationship with other organisms. As such, the biological affinity of these microorganisms remains debatable.

CONCLUSIONS

Superbly preserved Upper Devonian deposits in the Hay River region of the Northwest Territories, Canada, include a diverse array of microfossils. *Ovummurus duoportius, Minourella gotlandica, Minourella cameroni* n. sp., and related but indeterminate forms, are found in the mixed carbonate-siliciclastic deposits of the Escarpment Formation and limestones of the Alexandra Formation. These are the first described Devonian occurrences of these microorganisms and the stratigraphic range of *Minourella gotlandica* is extended by ~ 50 million years from the Late Silurian to the Late Devonian. Analysis of the variable distribution of ovummurids in the different facies indicates that these microorganisms 1) thrived in mixed carbonate-siliciclastic muddy marine environments, 2) were minor in limestones deposited in biologically diverse environments with minimal siliciclastic input, and 3) were capable of successfully inhabiting marine habitats characterized by conditions that were too stressful for most other carbonate-secreting organisms. They were not ubiquitous microorganisms on Paleozoic carbonate platforms, but when present, early cement overgrowth of their tests markedly enhanced their preservation potential.

Devonoracemus cameroni n. gen. and n. sp. is a distinct microfossil only found in Reef Complex #2 in the Alexandra Reef System. It was probably an encrusting tubiform cyanobacterium that thrived in high-energy, well-illuminated reef environments. *Devonoracemus cameroni* shares numerous morphological and paleoecological similarities with *Shamovella* and is probably related to this important reef-building organism of the Permian and Triassic. The lineage of *Shamovella* successfully survived the mass extinction events in the Late Devonian and at the end of the Permian, indicating a very generalized biology capable of surviving adverse marine conditions.

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CHAPTER 6 – CONCLUSIONS

The Alexandra Formation offers unique insight to the nature of a reef system in the Upper Devonian of the Western Canada Sedimentary Basin. To maximize its usefulness as an analogue for other Devonian reef systems – in western Canada and abroad – it is important that its stratigraphic framework is well-understood. Important conclusions about the stratigraphy of the Alexandra Formation from this study include:

1) It consists of two west-northwest facing ramp-situated reef complexes (Reef Complex #1 and Reef Complex #2). These were deposited during two fourth-order sea-level cycles in TR cycle IIc and each sequence probably represents a time span of 0.1 – 1 million years.
2) The complete stratigraphic succession of these two reef complexes is ~ 35 m thick.
3) Reef Complex #2 developed basinwards of Reef Complex #1, as a basinward-jumping reef system, after sea-level fell ~ 17 m.
4) Each reef complex had a margin of reef facies developed over a broad area of the ramp. These reef complexes had very low relief – they did not have narrow, high-relief, wave-resistant margins built to sea-level.
5) Deposits of Reef Complex #2 are separated from deposits of Reef Complex #1 by Sequence Boundary #1 and its correlative conformity. A second sequence boundary (Sequence Boundary #2) delineates the top of Reef Complex #2.
6) Sequence Boundary #1 is marked by a coastal plain succession that is well-exposed along Hay River. The thin bed of marine deposits in this succession, overprinted by various pedogenic features, indicates that higher-frequency shifts in sea-level position were important in the evolution of this reef system.

High-resolution sequence stratigraphic analysis of the Alexandra Reef System has provided a framework for evaluating facies associations from across the reef system at specific intervals of the system's evolution. This spatial-temporal context, integrated with sedimentology, paleontology, and paleoecology, has served as a powerful mechanism for elucidating important controls on the evolution of this carbonate system. Important conclusions about these controls include the following:

1) The inherited platform geometry of a gently-sloping ramp was absolutely critical for determining how the system responded to changing sea-level position. The ramp step, which was probably antecedent topography from biostrome development in the underlying Escarpment Formation, differentiated the ramp into an elevated, inner ramp area and a lower, outer ramp area. Reef Complex #2 developed because the outer ramp provided a broad region of shallow marine environments, conducive to reef initiation, as and after sea-level fell.
2) The rates and magnitude of sea-level change were important. The magnitude of sea-level fall (~ 17 m) that terminated Reef Complex #1 was important because it controlled where the location of reef initiation on the outer ramp took place. Highstand shedding was not an important component of Reef Complex #2 because the system did not have the time to recover from incipient drowning before sea-level started to fall. As such, high rates of carbonate production and redistribution characterized its falling stage systems tract rather than the preceding highstand systems tract.
3) The reef-building communities in the Alexandra Reef System were of dynamic composition. Stromatoporoids did not require hard substrates for growth, and grew in various forms and sizes. Microbial carbonates in reef framework were only present when suitable levels of nutrients (e.g., nitrogen, phosphate, and/or iron) were attained in the ambient environment.
4) Nutrient enrichment of the initiation and differentiation stages of Reef Complex #2 was the result of a synergy of groundwater seepage, terrestrial runoff, seasonally-forced deepening of the mixed layer, storm-induced mixing of the water column, and storm-induced disturbance of mud-hosted nutrient reservoirs on the outer ramp. Stromatoporoid-coral mortality due to storm events may have enhanced microbial blooms until new metazoans colonized the reef.

With regards to better understanding stromatoporoid-dominated reef systems, and the evolution of carbonate platforms in the Late Devonian of western Canada, the Alexandra Reef System highlights a number of important features. These include:

1) Concepts and methods of carbonate sequence stratigraphy can be used to establish high-resolution chronostratigraphic frameworks for stromatoporoid-dominated reef systems.
2) Sequence boundaries are fundamental to sequence stratigraphy and their recognition, as subaerial unconformities, is critical to establishing accurate chronostratigraphic frameworks and intrabasin correlation of sequences. In marine carbonate successions of any geological age, disconnected palustrine carbonates, karst, and calcrete are the criteria for recognizing sequence boundaries. The oldest coastal plain palustrine carbonates in the geological record are found in the Alexandra Formation at Sequence Boundary #1, and they are distinguished from calcrete by the presence of charophytes and skeletal stromatolites of *Rivularia* (*haematites*?).
3) Platform geometry is a critical element in determining how these reef systems responded to sea-level fluctuations. High-relief platforms with steep margins are not conducive to basinward-jumping reef systems. Most stromatoporoid-dominated reef systems, however, were not characterized by such geometries, and may actually consist of multiple depositional sequences in more or less laterally-adjacent positions. As such, these reef systems may be more stratigraphically complex than generally realized. Recognition of sequence stratigraphic surfaces in these low-relief buildups is therefore absolutely critical to establishing accurate stratigraphic frameworks.
4) There is no direct correlation between biostromes and bioherms with either transgressive or regressive systems. Biostromes and bioherms may form in both types of systems, at the same time, and are probably controlled by water depth and the biology of the sediment-contributing organisms.
5) Highstand shedding is not always an important aspect of carbonate platforms. Shedding associated with forced regression may be an important element on carbonate ramps and it should be realized that many studies that have interpreted highstand shedding did not differentiate the falling stage systems tract. Thus, they do not actually demonstrate that the process of sediment shedding took place when sea-level was actually at its highest position.

6) Regressive systems on carbonate ramps are increasingly susceptible to nutrification.
7) The mid-Frasnian of western Canada was punctuated by a relative sea-level fall of ~ 17 m. This should have been sufficient for subaerially exposing most platforms in the basin.
8) *Renalcis* and related microbial carbonates are not ubiquitous in Devonian reef frameworks. A nutrient-gradient model can be used to relate different types of Devonian reef facies to oligotrophic, mesotrophic, and eutrophic environments. Stromatoporoids and corals thrived in oligotrophic environments but could inhabit mesotrophic environments. Microbial carbonates with stromatoporoids and corals indicate mesotrophic conditions. Eutrophic conditions are marked by platform demise and a shift to heterozoan-microbe dominated accumulations.
9) Devonian carbonate platforms were not highly susceptible to nutrient-invoked drowning.
10) The magnitude of sea-level fluctuation recorded in the Alexandra Reef System is consistent with a period of global cooling in the Frasnian. This may be part of a larger climate-change event that was linked to the mass extinction events at the Frasnian-Famennian boundary.

Facies and fossils in the Alexandra Formation are exceptionally well-preserved. Fabrics in the palustrine deposits show no more alteration than fabrics in recent palustrine deposits, and good preservation of the original limestone in the formation has facilitated the identification of a number of new microfossils. Important conclusions about these include:

1) The first Devonian specimens of Ovummuridae are found in the Escarpment Formation and Alexandra Formation. Until this discovery, most of these calcareous microfossils were only known/ convincingly demonstrated from Silurian strata of Europe.
2) *Minourella cameroni* is a new species of Ovummuridae.
3) The distribution patterns of ovummurids in these deposits indicate that they thrived in mixed siliciclastic-carbonate environments that were unsuitable to most other

carbonate secreting organisms. They were only minor background elements in reef environments, and preferred off-reef environments.

4) The ovummurids were most likely benthic fauna similar to bryozoans.
5) The new genus and species *Devonoracemus cameroni* was an encrusting, reef-dwelling microorganism. *D. cameroni* shares a number of morphological and ecological similarities with *Shamovella obscura*, which was an important reef-building organism in the Permian and Triassic.
6) *D. cameroni* was related to *S. obscura* and these were probably cyanobacteria.

This study of the Alexandra Reef System has revealed more complexities in Devonian reef systems than was anticipated at its inception. A large part of this can be attributed to the large, high-quality database upon which the study was founded. It has become apparent that Devonian reef systems were formed of dynamic, carbonate-producing communities capable of adapting to a wide range of environmental parameters, and can not be studied from the perspective of a single facies model. It is also apparent that Frasnian reef systems of western Canada were subject to greater fluctuations in sea-level than traditionally perceived. It is possible that these fluctuations took place at a global scale, indicating that the period of time leading up to the global mass extinctions at the Frasnian-Famennian boundary was far more complex than currently realized. Future study of the Alexandra Reef System needs to integrate the stratigraphic framework established in this study with fabrics of marine and meteoric diagenesis and geochemistry (e.g., stable isotopes, strontium ratios). This line of study may provide valuable insight to links between the sedimentary and oceanographic system, including climate fluctuations and shifts in seawater chemistry. Likewise, analysis of the different types of stromatoporoid growth forms, at a generic or species level, may offer valuable insight to the paleobiology of these reef-building organisms. Such insight is warranted given that Middle and Late Devonian reef systems represent one of the greatest phases of reef evolution and biodiversity in the Phanerozoic.