Abstract

The late Frasnian Nisku Formation in subsurface Western Canada hosts the last known episode of carbonate buildup in the Cynthia-Winterburn basin below the Frasnian-Famennian boundary. The Zeta Lake Member is composed of dozens of carbonate buildups around the basin, although many compose a NE-SW oriented structure informally known as the Pembina Pinnacle Reef Trend. Four paleoecological communities are present in these late Devonian reefal environs: coral-pelmetazoan-microbial, coral-stromatoporoid-bivalve, coral-stromatoporoid-microbial, and stromatoporoid-microbial. Paleoecological communities differ principally by function and substrate colonization. The majority of buildups accreted in two growth phases under similar oligophotic to mesophotic conditions but different hydrodynamic regimes. Phase I accumulated during transgression and highstand as a mud-mound core with a low diversity coral motif. Phase II accumulated during falling sea level as a reef. Framework facies are composed of i) sub-cm scale rugose colonies with polymuds that approximate a bank meadow, or ii) carbonate crusts with synsedimentary cement and microbial biolithites with relatively minor contribution from metazoans that mimic interior reef strata. Fine-grained sediment that infills boundstones is grouped into four mud microfacies. Mud 1 and Mud 2 are reworked biogenic, resembling firmgrounds, with Mud 1 being microbial-enriched and low diversity while Mud 2 has highest skeletal diversity and terrigenous siliciclastics. Muds 3 and 4 are interpreted organic framework that could support stromatactis and create shelter cavities. Generally, Mud 3 has tubular calcimicrobes and is found in all coral-spongiostromate facies, whereas Mud 4 has dendritic calcimicrobes and increases within stromatoporoid facies relative to coral facies. These microfacies confirm a microbial-origin for fine-grained carbonate within late Frasnian buildups. Hyperspectral analysis in the short-wave infrared range is used to characterize four key buildup
components: micrite, microbial carbonate (*Renalcis*), skeletal carbonate and pore-filling cement. Segmentation by threshold method reveals that the absorption feature strength of water and calcite are sufficient to distinguish target components. *Renalcis* has very high raw reflectance attributed to very fine crystal size and is readily distinguishable from other carbonate components. This study demonstrates the feasibility of short-wave infrared reflectance spectroscopy to isolate and potentially quantify microbial carbonate in compositionally similar ancient reef strata.
Co-Authorship

The following is my own original work, supervised by Noel James and William Martindale.
Dedication

For my dad, Albert Wright, who passed into immortality while I was preparing this dissertation.

His faith and support, unwavering in life, are his legacy now.
Acknowledgements

In the course of my degree candidacy, I studied or conducted research at the following institutions: Queen’s University, Department of Geological Science and Geological Engineering (GEGE); the Bermuda Institute of Ocean Sciences (BIOS) in 2017 and 2018; and the Alberta Energy Regulator (AER) core facility, with support from the Alberta Geological Survey (AGS) in 2016 and 2017. In addition to those who nurtured my technical growth, there is a small, diverse cast of characters within these institutions who saw to my personal nourishment and progress, whether for a brief time or the duration of my studies. For their capable spirit and unwavering commitment to education I acknowledge Vicki Remenda, Kelly McCaugherty, and my teaching partner David Sask at Queen’s University, and Jane Burrows of BIOS.

This research was conducted with analytical support from the following: paleontological expertise provided by Stephen Kershaw (Brunel University), Paul Taylor (Natural History Museum, London), and Graham Young (Manitoba Museum); hyperspectral analysis and expertise provided by Jilu Feng and Benoit Rivard (University of Alberta); excitation spectroscopy analysis provided by Michael Robertson (Acadia University); and core facility research assistance provided by Meghan Zulian (Queen’s University). Nigel Watts provided provisional maps and a curated core database that were used to refine the scope of this study. Additionally, Hilary Corlett (AGS, MacEwan University) provided logistical support at the AER, generously shared her knowledge of the Western Canada Sedimentary Basin and carbonate sedimentology and has mentored me under many hats.

My supervisor Noel James and co-supervisor William (Bill) Martindale were invaluable to this project, each in his own way. Noel is fond of saying, “a PhD is a very personal thing.” It is a testament to his faith in students and in the scientific process that he can supervise with the
long-view and interfere little, while having uncompromising standards. I am ever grateful for the opportunity to study under one of greats! Noel saw me through real and metaphorical revisions without losing faith in the process or in me. Bill Martindale introduced me to the subsurface geology of western Canada and co-supervised my first field class in Bermuda. His years of work in the Canadian subsurface inspired a closer examination of the importance of mud in these late Devonian buildups.

While at Queen’s, my family and I made our home on Wolfe Island. I am especially thankful to the eclectic community of islanders who provided childcare and other support while I worked to complete this degree. They ensured we were never alone on a holiday.

Most importantly, I would like to acknowledge my family for demonstrating sacrificial love and sheer grit throughout my PhD studies. My parents and siblings were unfailing in their support of my work at Queen’s University and I am especially thankful for their many visits in year three of my program. My mother reminded me often to demonstrate self-care and to take care of my noggin. My children, Shawn and Celia, and my husband David gave me every support they could, often by allowing me space and time to work alone—a bittersweet gift. I am very grateful for my children’s daily self-reliance and gestures of thoughtful care; they sacrificed much and asked for little during the last four years. David’s iron-clad belief in me is the only gear that never stopped turning and this humbles me. Thank you, Heavenly Father, for these many blessings.
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Chapter 1

Introduction

General

The Nisku Formation (subsurface) and age-stratigraphic equivalent strata of the Winterburn group in the late Frasnian of western Laurentia host numerous carbonate slope buildups of peculiar origin in an otherwise shale-dominated basin, adjacent to a neighbouring carbonate platform. Zeta Lake Member buildups are a depositional environment paradox, characterized by skeletal metazoan-microbial boundstones, with biolithites and other mud-enriched facies, i.e., all three end-members of the carbonate buildup triad (Bosence and Bridges, 1995). This research addresses the origin of these buildups from the lens of late Devonian transitional periods using data from an area known as the Pembina Pinnacle Reef Trend (PPRT), in Nisku Formation core from the Cynthia-Winterburn Basin, a well-explored sub-basin of the Western Canadian Sedimentary Basin. Their isolated (slope) setting coupled with accretion primarily during regional transgression and their (current) subsurface location make it implausible to evaluate the carbonate factory through conventional facies and sequence stratigraphic techniques.

The main objectives of this thesis are to 1) determine the origin of off-platform upper Devonian reefs through a) conducting a paleoecological study with emphasis on the relationship between skeletal carbonate and non-skeletal carbonate, and b) documenting and interpreting the role of syndepositional carbonate and fine-grained carbonate, i.e., carbonate mud, in the genesis of the Pembina Pinnacle Reef Trend, and 2) progress the detection and documentation of various
carbonate volumes in fossilized reefs and mud-mounds by spectral characterization with an emphasis on calcimicrobial carbonate.

**Two Paleozoic Benthic Carbonate Buildups**

During the Paleozoic, the marine carbonate factory experienced numerous punctuated evolutionary changes that were fundamental to the increase of benthic carbonate factories, including the rise of metazoans and the decline of microbial reefs relative to their Precambrian abundance in normal marine environments. These evolutionary changes impacted the global volume and ecology of reefs (Copper, 1988, 1994), a form of benthic carbonate which are conservatively defined by Wood (2001) as “a discrete structure formed by in situ or bound organic components that develops topographic relief upon the seafloor.” Separately, mud-mounds that originated in the Proterozoic generally are regarded as a style of carbonate buildup distinct from reefs, formed primarily of carbonate mud and polymuds but which can incorporate metazoans (Bosence and Bridges, 1995), and occasionally display ecological zonation (Tosolini et al., 2012). A triad of depositional components—mud, metazoans, and microbes—can be found in either reef or mud-mound systems (see Wood, 2001 and references therein) and is joined by syndepositional carbonate cement, also appearing in both buildup systems. While managing overwhelming similarities, the siting of reefs vs. mud-mounds in various geologic settings and the physical arrangement of individual carbonate components within them is of profound importance to exploration for hard and soft mineral commodities, water, and chemical waste reservoirs.

Given their petrologic and to some extent biotic similarity, it makes sense that initiation and material changes in these two benthic carbonate systems, reefs and mud-mounds, would be related, but a temporal link does not emerge from abundance patterns that are well-documented
(summarizing, e.g., Copper, 1994; Monty, 1995; Wood, 1998, 1999 and references therein, 2001) for the early to middle Paleozoic such as i) in the Cambrian where both mud-mounds and reef-building metazoans increased, nor ii) do a smaller series of metazoan diversification and extinction events throughout the Silurian and most of the early-middle Devonian appear in-phase with the muted presence of mud-mounds.

Still, the most significant mud-mound formation in the early Carboniferous (Wilson, 1975) was preceded by end-Devonian extinction and decimation of highly skeletonized marine framework organisms. Fagerstrom (1994) has investigated biodiversity within and style of carbonate buildups from the Frasnian-Famennian reefs to Tournasian mud-mounds and characterized the transition as a loss of constructor guilds and subsequent replacement in the baffler and binder reef populations (essentially validating ecological succession postulated by Copper, 1988). It is toward the colloquial twilight of Devonian reefs that this thesis focuses with the premise that restricted buildups, i.e., those that are not connected to a platform, from this time are important process analogues and conjectural archives of intermediate reef—mud-mound systems.

The Pembina Pinnacle Reef Trend (PPRT) is a small, discrete reef trend buried 2.5-3.2 km in the subsurface of Western Canada that represents one of the last, if not the final episode of off-platform carbonate-buildups in the late Frasnian of western Laurentia. The reef trend is lithostratigraphically defined as the Zeta Lake Member of the Nisku Formation (Winterburn Group) and is sandwiched between the Frasnian Kellwasser and the end Famennian Hangenberg extinction events. The reefs range from 40m to ~120 m in thickness and are stratigraphically bound by organic-rich shales and fine-grained carbonate sediments with a low-energy motif. At their thickest, the reefs are analogous to the combined thickness of off-reef Nisku Formation
strata but are still only one-third the size of the nearest underlying Frasnian reefs (Leduc Formation).

This exploration of intermediate reef—mud-mound system in western Laurentia relies on foundational knowledge of calcimicrobes and carbonate mud in marine settings, buildups on carbonate slopes, and subsurface geology of the Winterburn Group, each addressed below.

**Calcimicrobes in Reef Systems**

Cyanobacteria are an extant group of photosynthesizing prokaryotes that appeared during the Archean, with a filamentous or coccoid form, and are included in the functional group “microalgae” (Steneck and Dethier, 1994). Calcified cyanobacteria are colloquially referred to as "calcimicrobes," (James and Gravestock, 1990) the term used throughout this volume.

Calcification is not a straightforward process. What we apply to the Paleozoic geologic record is largely based on our understanding of recent and modern cyanobacteria, and there is a great deal of uncertainty around the taxonomic affinity and ecology of Paleozoic and older cyanobacteria (Riding and Toomey, 1972; Feng et al., 2010). Most simply, the calcification of cyanobacteria is an extracellular process defined by two key features: 1) a sheath outside of the cell serves as the site of calcification either within (impregnation) or outside (encrustation) of the sheath, and 2) calcification occurs only when precipitation of CaCO3 is thermodynamically favoured (Riding, 1990, 2012).

Although sheaths are a key feature, Riding also indicates that these may be poorly developed or not develop at all, leaving some ambiguity around whether the lack of a sheath constrains the development of certain growth forms. Additionally, calcification does not always lead to the development of a skeletal form, but when it does then one of three growth forms
emerge—tubiform, micritic, or hollow. Thus, the classification of ancient calcified cyanobacteria (calcimicrobes) is based on growth form and direction (Table 1.1).

Recent research on calcification of modern marine cyanobacteria from Highborne Cay (Bahamas) indicates that under favourable conditions, the development of a sheath, i.e., an envelope, is only a requirement for initial calcification of cyanobacteria, and that cyanobacteria can subsequently form laminar structures without developing individual sheaths. This might have also been the case for ancient cyanobacteria (Planavsky et al., 2009).

While all cyanobacteria form calcareous mineralogy, additional factors may—and likely do—govern the calcification process, such as: 1) the constraint of calcite saturation need only be localized at the site of nucleation, 2) other physiochemical factors, e.g., increased sulfate concentration or pH, may favour the development of one microbialite group or species over another, 3) the extracellular polymeric substance (EPS) of certain cyanobacteria can also have a positive or negative impact on sheath growth as well as the diagenetic potential of sheaths. These factors are best understood from the study of modern marine and freshwater cyanobacteria, and may be impossible to observe even indirectly (or by proxy) in ancient carbonates given the microenvironment that calcification occurs in.

In terms of sedimentological role, cyanobacteria are typically described in terms of organized structures such as stromatolites and thrombolites where cyanobacteria play a unique functional role, e.g., help fix community structure with other prokaryotes (Yannarell et al., 2006). While some organized microbial structures are present in Nisku reef strata, calcimicrobes are more frequently disseminated in the matrix of wackestones and floatstones, or framework boundstones. Where calcimicrobes do not form organized structures, their functional role is ambiguous.
Table 1.1: Classification of calcified cyanobacteria. Form genera after Riding (1991), excluding the groups Garwoodia/Mitcheldeania and Microproblematica which are poorly defined.

<table>
<thead>
<tr>
<th>Group</th>
<th>Features</th>
<th>Appearance in Devonian</th>
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<tr>
<td>Angulocellularia</td>
<td>Micritic, solid, bush-like form. Growth form is erect or pendant.</td>
<td>Uncommon</td>
</tr>
<tr>
<td>Epiphyton</td>
<td>Micritic, narrow and branching filaments. Filaments occur as rod-like, chambered, or tubular. Growth is erect or pendant.</td>
<td>Prominent</td>
</tr>
<tr>
<td>Girvanella</td>
<td>Thin walled tubes are tangled, coiled or aligned. Growth is prostrate.</td>
<td>Prominent</td>
</tr>
<tr>
<td>Hedstroemia</td>
<td>Filamentous and branching clusters of tubes; adjacent tubes may share common walls. Growth form is radial erect.</td>
<td>Uncommon</td>
</tr>
<tr>
<td>Renalcis</td>
<td>Hollow reniform bodies form in clusters, typically with (micritic) thick walls. Growth form is erect or irregular.</td>
<td>Prominent</td>
</tr>
<tr>
<td>Rothpletzella</td>
<td>Sheets of juxtaposed (pseudo-parallel) branching tubes; sheets may be flat, curved or encrusting.</td>
<td>Prominent</td>
</tr>
</tbody>
</table>

**Carbonate Mud**

In the lexicon of carbonate sedimentology, mud refers to carbonate particles of mud-size, or to micrite specifically. Micrite is a fine-grained limestone with particle size of clay, in the range of 0.004-0.03 mm (Folk, 1962), or alternatively with an upper size limit of 0.02 mm (Dunham, 1962). Micrite can be ooze or consolidated and is used to refer to the matrix of microcrystalline calcite produced by chemical (abiotic), biotically-induced, or mechanical reworking processes.

Initially, micrites devolved into two descriptive types: microclastic, which has a dull luster and muddy appearance, and microcrystalline, which has a high luster and interlocking
crystals (Folk, 1962). Recently, micrite textures were classified according to their shape under SEM using a process-based interpretation (Lambert et al., 2006) as follows: 1) early mineral stabilization of micrite through a pathway of high-magnesium calcite (HMC) → low-mg calcite (LMC) or of aragonite → LMC produces a micro-rhombic texture, 2) pressure dissolution related to the presence of clay produces compact anhedral micrite, and 3) rounded micrite is produced by chemical dissolution and commonly occurs in the burial realm.

Where possible, attention is given to the differentiation of micrite originating through chemical or biotically-induced processes and micrite that is mechanically-derived from the breakdown of larger carbonate grains to mud-sized carbonate particles that are later sedimented and lithified. The former might be referred to as “autochthonous micrite” or “automicrite” (Keim and Schlager, 1999) which necessitates in-situ production. The term “micrite” is used herein more broadly as a descriptive, non-genetic term when the origin is not germane or cannot be determined.

**Slope Buildup Dynamics**

Shelf-margin carbonate slopes are a depositional environment for knoll-, pinnacle-, and barrier-type reefs. Pinnacle reefs develop isolated from a platform or margin and can reflect current-driven hydrodynamics more than normal-wave influence, or only current-driven hydrodynamics if the reef is below storm-weather wave base. Because of their physical isolation, a pinnacle reef’s bathymetric relief and its relationship to sea level are difficult to interpret using traditional stratigraphic techniques, e.g., systems tracts and sequence stratigraphic boundaries. Typically, aggradation of ancient reefs toward sea level and into the wave zone is empirically evidenced by (i) biological and physical change including development of a reef crest and lower-energy lagoon in a progression similar to that of a patch reef (Tucker et al., 1990, p57); (ii)
overall sediment coarsening; (iii) increased microbial influence; and (iv) biological changes such as an increase in skeletal organisms having a broader seafloor footprint and wave-tolerance, suggestive of increased hydrodynamic energy. At several points in this thesis, I challenge that an increased microbial influence is evidence for shallowing.

**Winterburn Group Setting**

The Nisku Formation of the Winterburn Group occurs in the subsurface of Alberta (see Fig. 2.1) in the Western Canadian Sedimentary Basin (WCSB). The WCSB in its contemporary form evolved as a foreland basin beginning in the mid-Jurassic with initiation and eastward propagation of the Cordillera Margin. For most of the Devonian, the proto-WCSB, otherwise known as the Alberta Basin, was a generally passive western Laurentian margin in southern tropical to sub-tropical latitudes (Miall, 2008). The middle- to late Devonian was a tectonically active time for this region. The West Alberta Arch and the Peace River Arch are large intracratonic arches which developed in succession, subparallel to the margin, intermittently cutting off the basin from open marine circulation and shedding large amounts of basement-sourced volcaniclastic and fluvial-clastic sediment into the Alberta Basin to the east (Potma et al., 2001; Miall, 2008).

Mid- to late Devonian carbonate sedimentation commenced in the Alberta Basin and reached its maximum lateral extent with deposition of the Beaverhill Lake Group in a single intracratonic basin (Potma et al., 2001).

Subsequent to Beaverhill Lake Group deposition, intrabasinal geometry was governed by the rise of local highs resulting from prominent reef development and was divided into a series of mini-basins with alternating siliciclastic and carbonate deposition in the Beaverhill Lake Group and overlying Woodbend Group (Stoakes, 1979, via Anderson, 1985). In early Late Devonian,
during deposition of the Woodbend Group, the Alberta Basin had a broad carbonate shelf, the Grosmont, in the east; prominent carbonate platforms in the southeast (Cooking Lake, Leduc); and isolated platforms in the southwest (e.g., Ancient Wall, Miette) (Mountjoy and Jull, 1978; Potma et al., 2001).

Paleogeographic reconstructions indicate only slight regional changes in the basin between deposition of the Woodbend Group and the Winterburn Group. Namely, a distinct siliciclastic shelf developed in the northeast of the Grosmont Shelf. Literature addressing the Winterburn Group specifically may refer to this area of the Alberta Basin as the West Shale Basin, Cynthia Basin, Winterburn Basin (Wierzbicki et al., 2008; Atchley et al., 2006; Bingham-Koslowski, 2010), or as the Cynthia-Winterburn Basin. The latter is adopted herein.

In addition to its importance to carbonate sedimentology and our knowledge of ancient reefs, the Pembina Reef Trend has in excess of $79 \times 10^6$ m$^3$ (500 million bbl) of oil and $1.4 \times 10^{10}$ m$^3$ (500 billion ft$^3$) of gas recoverable reserves (Watts et al., 1994), and is the focus of numerous feasibility studies for acid-gas injection and carbon sequestration (Machel, 2005; Bachu et al., 2008; Michael et al., 2009; Eisinger and Jensen, 2011). Investigations into regional facies and (largely) burial diagenesis of the Nisku Formation were completed by Anderson (1985) and Machel (1985), where the presence of syndepositional carbonate was established (Anderson, 1985) and interpreted as an environment where the movement of carbonate—either physically or through dissolution and (re)precipitation—is very similar to that of framework reefs with abundant framework porosity.
This thesis is structured in manuscript style and presents original research on two disparate topics, both focused on the late Devonian.

Chapters 2 and 3 are related entities concerning depositional dynamics of the Nisku carbonate slope buildups within the Pembina Reef Trend and using sedimentology to generate a paleoecological framework. Chapter 2 establishes the paleoecological context for the slope buildups by looking at the variety of boundstones present in the Zeta Lake Member and their stratigraphic distribution. All reefs and mud-mounds have some fraction of reworked sediment—indeed some might be composed entirely of reworked particles of the host—but the boundstone is the building block traditionally responsible for creating syndepositional relief and is a seafloor relic. Internal variation of a taxonomic or textural nature among these building blocks speaks to a changing benthic environment, thus documentation is key to understanding both the origin and demise of ancient reefs.

In Chapter 3 the focus shifts from individual boundstones to the source of carbonate throughout the carbonate buildup. The scale of inquiry ranges from petrographic to paleogeographic. The approach is to treat depositional and syndepositional carbonate equally in facies analysis of several buildups in the Pembina Pinnacle Reef Trend, and then evaluate the spatial distribution of facies and fine-grained carbonate material across the slope, as key to understanding the nature of the Zeta Lake Member and similar slope-carbonate buildups.

Chapter 4 presents the results of a standalone imaging experiment aimed at the recognition of microbial carbonate in drill core. Early in the core-description phase of this research, it became clear to me that calcimicrobes are an intricate component of the Pembina Reef Trend and, absent exhaustive and cost-prohibitive petrographic analysis, there really is no way to quantitatively characterize the distribution of microscopic organisms when working at the
core scale. I have observed in my own core work and in teaching that an unintentional bias toward larger skeletal organisms and microbial accumulations visible to the naked eye, e.g., stromatolites or oncolites, is established early on in semi-quantitative workflows, and this bias is inevitably carried through the working data set. Webb (1996) also theorized that a gap exists in our understanding of Paleozoic reef evolution, as we tend to focus on the metazoan components in classifying reefs, even if that bias is implicit.

To begin overcoming these biases, we need to invoke data capture tools that can overcome the restrictions of performing and upscaling standard petrography while being cost-efficient, quantitative, and objective. Toward that end, hyperspectral image analysis in the short-wave infrared (SWIR) range of the electromagnetic (EM) spectrum is applied to the recognition of calcimicrobes in core samples. Chapter 4 presents the results of SWIR discrimination of calcimicrobes from other carbonate phases including micrite, skeletal carbonate, and pore-filling cement that are the main constituents of many Paleozoic reef strata.

**Major Findings**

**Overview**

Documentation and interpretation of these critical rocks has taken two different approaches: 1) paleoecological analysis of the evolving benthic communities through time and the controls on change, and 2) determination of the evolving facies changes during growth as determined by integrated sedimentology, paleoecology and paleoceanography.

**Paleoecology of Zeta Lake Member**

Seven types of boundstones are identified based on relative abundance of skeletal metazoans, primarily coral and stromatoporoids, and a variety of calcimicrobes. The spatial distribution of boundstones suggests there were as many as four paleoecological communities in
the buildup environment that were oligophotic to mesophotic. Zeta Lake Member buildups display incipient ecological succession. While previous research has focused on broad interpretations of Nisku Formation reef facies relative to platform and basin, this work is the first examination of Nisku reef paleoecology. By suspending the conventional thinking that typical Paleozoic reef-building metazoans had high photic demands, this interpretation relies on sedimentological evidence after the manner of Pomar (2001) and a strong microbial imprint to interpret reef paleoecology.

**Origin of Zeta Lake Member**

Focused examination of fine-grained sediment infilling boundstones, together with syndepositional products and processes, are integrated into a facies analysis of carbonate buildups from the proximal-, mid-, and distal slope. Three of the four mud-dominated microfacies have a microbial origin defined by microclastic micrite, *Renalcis*, and *Rothpletzella*, thus the source of carbonate mud in the PPRT buildups is reworked biogenic and microbial particles, with ancillary peloids and nontrivial molds of siliceous spicules. Through facies analysis and applying modern (present) oceanographic principles, the Zeta Lake Member is re-interpreted as a hybrid mud-mound to reef system with the implication that framework metazoans occupied a subsidiary role in buildup origin, and a shift in carbonate factory from benthic mud-dominated to benthic skeletal-dominated can be linked to a change in the direction of relative sea level from rising to falling.

**Spectral Analysis**

The spectral signature of various carbonate phases in petrographic-sized slabs are explored in the short-wave infrared (SWIR) range of the electromagnetic spectrum. Using supervised classification guided by mirrored petrographic thin sections and sample slabs, unique
spectral signatures are identified for pore-filling calcite cement, skeletal calcite, micrite, and calcimicrobial calcite. Classes are defined by the strength of absorption features in water and calcite wavelengths that occur in continuum-removed spectra. As a result of internal variation among reflectance intensity, skeletal calcite requires sub-classification into three sub-classes. Skeletal calcite sub-classes are not taxonomically controlled, and their origin is unknown; at least one seems to result from spectral similarity of intra-skeletal (meso-) pores and macro-crystalline pore-filling cement. This study is the first of its kind in examining carbonate phases through mineralogically similar samples. The value of this work in its validation of an objective, and repeatable technique for the discernment of carbonate phases in core samples, particularly in the ancient geologic record where diagenetic overprinting complicates more traditional image analysis.

References

Anderson, J.H., 1985, Depositional Facies and Carbonate Diagenesis of the Downslope Reefs in the Nisku Formation (upper Devonian), Central Alberta, Canada (sedimentology, Dolomite, Isotopes) [Ph.D.]: The University of Texas at Austin, 412 p.


Chapter 2
Paleoecology of deep-water calcimicrobe communities near the Frasnian-Famennian boundary, Western Canada

Abstract

Late Frasnian pinnacle reefs from the western margin of Laurentia (Nisku Formation, Western Canadian Sedimentary Basin) record ~100 m of base-of-slope reef aggradation without drowning. The Pembina reef trend of the Cynthia-Winterburn Basin is the putative last episode of off-platform reef deposition in the region prior to the Frasnian-Famennian boundary. Despite a 3-20 km range in distance from the Nisku platform margin, over a dozen km-scale reefs across the slope exhibit surprising decameter-scale homogeneity in taxonomic composition together with an overall shallowing upward trend. Four paleoecological communities are present in these late Devonian reefal environs: 1) coral-pelmetazoan-microbial, 2) coral-stromatoporoid-bivalve, 3) coral-stromatoporoid-microbial, and 4) stromatoporoid-microbial. Communities differ principally by substrate (interpreted preference) and morphological (skeletal) diversity, which are interpreted to indicate local bathymetric relief and periods of relative hydrodynamic activity, juxtaposed against broad ecological succession. In paleoecological communities 1, 3, and 4, reefs demonstrate a close in-situ association between metazoans and calcimicrobial growth without other euphotic sediments. The persistence of this association from reef origin through a full cycle of off-platform deepening and shallowing leads to an oligophotic-mesophotic interpretation of communities with a coral-microbial association. The metazoan-microbial association does not necessarily imply community replacement of metazoans by microbes at the reef-scale but does
support the expansion of microbes into deeper water environments that is observed in other late Frasnian reefs globally.

**Introduction**

Latest Devonian tropical reefs worldwide underwent a major shift in framework biota from stromatoporoid-coral (skeletal metazoan)-dominated to microbial-dominated just prior to the Frasnian-Famennian (F-F) boundary (Stearn, 1987; Stearn et al., 1987; Webb, 1996; Wood, 1999; Copper, 2002; George and Chow, 2002; Whalen et al., 2017). In a global review paper, Copper (2002) demonstrated that the cosmopolitan Devonian reef declined substantially by the *rhenana-linguiformis* conodont zones, to be replaced by bryozoan and stromatolitic units. Where sections enable comparison across the F-F boundary, reef evolution from primarily metazoan- to primarily microbially-produced carbonate is especially distinctive such as in barrier and fringing reefs of the Lennard Shelf (Australia; Playford, 1980; Copper, 1994, 2002) and forereef and slope environments (George and Chow, 2002). In his review, Copper (2002) offers numerous, well-studied reefs of Givetian-Frasnian age with co-occurring metazoans and calcimicrobes on large (100s kms long) carbonate platforms, succeeded upward by Famennian microbial reefs with subordinate bryozoans, and reduced families of stromatoporoids and corals. This is the late-Devonian reef narrative many are familiar with. In contrast, among off-platform settings there was a preponderance of early- and mid-Frasnian microbial mudmound-type reefs in Europe (Belgium, Germany) and Russia that diminished by (rarely *in*) the late Frasnian due to regional factors, e.g., tectonic-related sea level rise, siliciclastic influx, anoxia—with no later (Frasnian) reefs in the record. This contrast highlights the gradual shift with “dominant*ly* metazoan” and “dominant*ly* calcimicrobial” associations as evolutionary end-members rooted in the Givetian and Famennian, and that ecological end-members exist as a function of reef restriction, leaving
the question: what is the nature of off-platform reefs near the F-F boundary, and do they appear ecologically driven?

Our study is confined to the off-platform carbonate environment in the late Frasnian Nisku Formation in central regions of the Western Canadian Sedimentary Basin (WCSB) (Mossop and Shetsen, 1994). The sedimentary record indicates a period of pinnacle reef building along multiple margins of the seaway that bordered western Laurentia (Whalen et al., 2002) during the regressive phase (Switzer et al., 1994) of Devonian transgressive-regressive (T-R) cycle IIId (Johnson et al., 1985 and references therein). Pinnacle reefs typically developed on remnant bathymetric highs produced by underlying, large Givetian and early Frasnian reef complexes, and coincide with a period of closure of multiple intracratonic basins in Western Canada due to increased siliciclastic sedimentation at tectonic arches (Miall, 2008).

Integrated conodont and coral biostratigraphy place the Nisku Formation within uppermost Montagne Noir (MN) Zone 11 through all of MN Zone 12 (McLean and Klapper, 1998; McLean, 2005). Copper (2002) interpreted “MNCZ 12-13 [with] approximately upper *rhenana-linguiformis* CZ.” Accepting that the Nisku Formation is correlative to global cycle IIId, and MNCZ 11-12, then this episode of pinnacle reef building in Western Canada most likely occurred, at least partially, within the *rhenana-linguiformis* conodont zones. Thus the origin of Nisku Formation reefs is a necessary addition to the record of end-Devonian reef demise in terms of its timing and slope setting.

The purpose of this investigation is to expand the record for the Devonian twilight of reefs by examining the sedimentology and ecology of over a dozen isolated reefs in the WCSB. Limestone and partially dolomitized cores examined herein average 80-100 m thickness by ~1-4 km estimated diameter. Their subsurface depths range from 1440 m to 3098 m measured depth.
Our approach is to examine paleocology and sedimentology at the boundstone-scale and how these translate to paleoecological communities. In many cases, boundstones are composed of more than one genus and their organization can give further insight into paleoenvironmental conditions than individual species. We examined core from 14 pinnacle reefs to 1) assess whether the Nisku reefs are metazoan or microbial in nature, and 2) determine how reef communities were structured in the slope environment. Paleoecological communities are defined using a combination of boundstone petrology and elements of Pomar’s 2001 genetic approach to classification of carbonate—in particular the nature of off-reef strata and hydrodynamic regime. One goal of our paleoecological study is to avoid the implication of shared specific resources, given the uncertain trophism of many Paleozoic metazoans and calcimicrobes. This paper does not abandon functional “reef guild” concepts by Fagerstrom (1988, 1991), which rely heavily on skeletal form and are commonly used to interpret ancient reefs but uses guilds as a step to bolster our understanding of observed reef sedimentology in off-platform reefs.

**Geological Setting**

The Nisku Formation is part of the carbonate and basinal shale Winterburn Group (Fig. 2.1A). Carbonate platform and reef complexes of the Nisku Formation are found in the subsurface of Saskatchewan and Alberta, and outcrop in the Front Ranges of the Canadian Rocky Mountains, Alberta, and British Columbia (Fig. 2.1B). This study concerns carbonate deposited near the margins of the Cynthia-Winterburn Basin (a sub-basin of WCSV, Fig. 2.1C). Downslope pinnacle reefs termed the Pembina reef trend (PRT) in the southeast margin (Fig. 2.2) are the focus of the study. Intraformational carbonate buildups deposited on the northeastern Meekwap Shelf and one Nisku reef on the eastern shelf are used as regional comparison data points to aid our interpretation of paleoecology. The paleogeographic elements in Figure 2.1C
are a compilation of surface and subsurface data published in the region (Switzer et al., 1994; Wendte et al., 1995; Potma et al., 2001; McLean, 2005; Bachu et al., 2008). Herein, “the basin” will refer to the Cynthia-Winterburn Basin unless noted otherwise.

For most of the Devonian, the WCSB was a generally passive western Laurentian margin in southern tropic to sub-tropic latitudes (Miall, 2008), composed of the Alberta and Williston basins. Today the WCSB is bounded by the eastern limit of deformation from the Cordilleran Front (Mossop and Shetsen, 1994; Bachu et al., 2008). The Peace River Arch (PRA) developed subparallel to the cratonic margin, shedding large amounts of basement-sourced volcaniclastic and fluvial-clastic sediment into the basin from the west (Potma et al., 2001; Miall, 2008) for much of the mid-Paleozoic. The result of sedimentation westward from the PRA and eastward from the continent was a filling of the narrow seaway between these two elements and eventual separation of the Alberta basin into distinct northern and southern sub-basins during the late Devonian, with the Cynthia-Winterburn Basin included in the latter.

Reef Architecture

The offshore pinnacle reef zone is roughly parallel to depositional strike, trending northeast-southwest in a belt ~80 km long and 10 km wide. Most of the pinnacles used in this study are situated 10-25 km basinward of the Nisku platform margin; two are <10 km. Individual pinnacles range <1 km to >4 km in diameter. The largest reefs exhibit slight elongation in the dip-direction, although the majority of pinnacle reefs appear roughly circular in areal extent. Underlying ramp sediments are typically argillaceous limestone interbedded with calcareous siltstones and nodular, bioclastic argillaceous wackestones. Where the base of the reef interval is cored, the underlying ramp deposits are thinly-bedded oncoid floatstones and mottled marl. The lowest reef sediments are coral-crinoidal facies. Closest to the platform margin (<2 km), ramp
and reef sediments broadly intertongue, but this is from a single core. The contacts between these systems here range from gradational to sharp but not scoured.

The pinnacle reefs display a two-part vertical sequence at the scale of tens of meters (Fig. 2.3). A complete vertical succession within the distal Zeta Lake Member consists of:

1. A ~40-60 m thick interval of tabulate and rugose coral bafflestones intercalated with coral-pelmatozoan floatstones.

2. A ~20-40 m thick unit composed of 0.5-1.2 m couplets of coral-microbial floatstone; low-relief, mixed stromatoporoid-coral boundstone; and microbial-skeletal boundstone.

The reef sequence grades without evidence of exposure into a locally absent or poorly developed cap ~2-10 m thick of reworked, biofragmental packstones-rudstones and faintly-laminated to mottled mudstone. In-situ biota of this interval have a restricted paleoenvironmental motif, e.g., poorly developed thrombolites and stromatolites with gastropods and local fenestrae. This unit is interpreted as Wolf Lake Member.

Notably, a discrete (singular) ~1-4 m thick accumulation of megalodont bivalves (superfamily: *Megalodontoidea*, Morris, 1853) is present in many reefs and broadly correlates with the transition from coral-dominated to coral-stromatoporoid fauna (Fig 2.3). On the shelf, megalodont bivalves are rare and occur in skeletal floatstone to mud-dominated packstone.
Figure 2.1: Stratigraphy and paleogeography of late Frasnian Nisku Formation. A) Internal stratigraphy of the Winterburn Group in the Alberta Basin, with the base of the Nisku in global context using (a) biostratigraphy (McLean and Klapper, 1998; McLean, 2005) or (b) Paleozoic sea level transgressive-regressive (T-R) cycles (Johnson et al., 1985). B) Present subsurface location of the Cynthia Basin in context of the Western Canada Sedimentary Basin (WCSB) of Alberta, and the regional paleo-shelf edge for Nisku-aged carbonate, modified from Bachu et al., 2008. C) Key depositional elements of the Cynthia Basin during deposition of late Frasnian pinnacle reefs (compiled from Switzer et al., 1994;
Figure 2.2: Location map, Cynthia-Winterburn Basin, subsurface Alberta. Carbonate buildups of the Zeta Lake Member (ellipses) form a trend downdip and subparallel to the Nisku platform margin. Dolomitization increases toward the southwest, therefore most cores selected for the study are from buildups located in the limestone-dominated region. Surface location and well formation data comes through the Alberta Energy Regulator and is in the public domain. R=Range, T=Township, M=meridian.

Sampling & Methods

This study is a semi-quantitative investigation of limestone paleoecology and boundstone sedimentology using core analysis, digital photography, and optical petrography. All data comes from the analysis of cores penetrating the Winterburn Group in the Western Canada Sedimentary Basin in subsurface Alberta.
Sampling Constraints

Several factors affect the availability of reef material for this study, including dolomitization, sampling regulations, and general constraints related to working in the subsurface on km-scale to m-scale geologic features.

Pervasive and fabric-destructive burial dolomitization and biomoldic porosity are extensive, especially in the southwest (structural downdip) portion of the pinnacle reef trend (Machel and Anderson, 1989; Machel et al., 2009) and renders nearly all core from the area incompatible with the stated objectives of this study. In contrast, the northeast portion of the buildup trend is only locally impacted by fabric-retentive dolomitization or meter-scale intervals of fabric-destructive dolomitization evident in density measurements from routine core analysis.

Lastly, in contrast to outcrop studies wherein spatial relationships and dimensions are determined by tracing beds visually or direct measurement, such level of detail is impossible in this subsurface study. The lateral distribution of samples is in all cases controlled by hydrocarbon well spacing which far exceeds the scale of lateral facies change that is expected in a reef environment. The philosophy applied here is that lateral distribution of drilled, producing wells yields a minimum approximation of the depositional environment boundaries.

Methodology

Regional investigation began with a physical review from the Nisku Formation cores in the southeast and eastern Cynthia Basin. Review of wireline logs and routine core analysis data screened out wells in the limestone area that had thick intervals of dolomite. Wireline log data was used to separate wells with reef carbonates from those having only basin or ramp carbonates. Cores were visually examined to gain a general understanding of the facies representing reef and off-reef environments (Fig. 2.3).
A subset of cores (n=18; a total of 1,325 meters) were high-graded largely based on textural preservation and thickness of the cored interval. Core (BR-1320) from the dolomitized reef trend was incorporated into the study owing to surprisingly good textural preservation. BR-1320 is further significant to this study because it provides coverage closest to the slope margin. Most cored depths range from 2194-3003 m measured depth at the top of core to 2297-3098 m measured depth at the base of the core. Figure 2.2 illustrates the location of the cores and a conservative outline of the pinnacles inferred from well penetrations. Detailed well locations and measured depths of each core are documented in Appendix A.

Stratigraphic sections were produced for eight wells (Appendix B). Boundstones were initially classified according to their primary biota and matrix sediment, using a binocular microscope when necessary. Core box photos and >900 high-resolution feature photographs were taken with a Canon DSLR using a fluorescent-lit sampling box with mounted camera stand built by geologist W. Martindale (Queen’s University).

Core sampling was obtained in conjunction with a separate study of the Nisku Formation addressing microfacies and spectral properties of fine-grained carbonate in the Nisku Formation (this thesis, Chapters 3 and 4). Targeted sampling for petrography was completed over two work seasons.

Initially, one well each from the southeastern and the eastern margins were systematically sampled for petrography at approximately every meter to record the observed range of boundstones and other Dunham rock textures. Subsequently, 21 samples were collected from six different wells to target fine-grained carbonate. Petrographic sample locations and depth are tabled in Appendix C.
Digital core logging was completed using EasyCore® software. Optical petrography was conducted on Leica DM750 and Labrolux Pol 12S microscopes. All drill cores, wireline log data, and routine core analyses used to prepare for and conduct this study are part of the public domain, in the stewardship of the Alberta provincial government by the Alberta Energy Regulator, with physical materials housed at the Core Research Centre (Calgary, Alberta).

Figure 2.3: Generalized pinnacle reef structure. The illustrated change in fauna and microbial reef-building organisms draws from a composite of cores (see Appendix A, B) analyzed for this study and includes cores that penetrate forereef, inner reef, and backreef locations in the northeastern, mid- to distal slope of the Pembina Reef Trend. Dashed lines are gradational lithologic boundaries.
Results

**Nisku Formation stratigraphy**

Johnson et al. (1985) interpreted three “depohases,” or groups of multiple, smaller transgressive-regressive (T-R) cycles in the Devonian geologic record in Euramerica (inclusive of Laurentia). Switzer et al. (1994) interpreted Johnson’s smaller T-R cycles in the subsurface of Western Canada as records of distinct carbonate ramps. Cycles composed of alternating shale and carbonate deposition were noted in Frasnian basinal strata underlying the Winterburn Group by Stoakes (1980, and references therein), who argued that the cycles arise after the manner of reciprocal sedimentation.

In the global record, the base of the Nisku Formation is tied to the base of Devonian transgressive-regressive (T-R) cycle IIId (Fig. 2.1A) (Johnson et al., 1985). This interpretation indicates that Nisku strata fit within *Rhenana* to *Linguiformis* standard conodont zones, although as yet these zones are undefined in the paleo-Alberta basin, owing to the paucity of pelagic, deeper-water conodonts in the Winterburn Group (Drees et al., 1998). Biostratigraphy integrating shallow-water conodont and rugose coral faunal zones from Western Canada with the Montagne Noir (MN) conodont zonation places the Nisku Formation in uppermost MN Zone 11 (Fig. 2.1A), extending through all of MN Zone 12 (McLean and Klapper, 1998; McLean, 2005).

Radiometric dating of the Muskwa Formation—a WCSB unit that is stratigraphically correlative to the Duvernay Formation of the Woodbend Group underlying the Winterburn Group—yields an Re-Os isochron age of 376.0 ±2.4 Ma (Pana et al., 2018).

The Nisku Formation (Fig. 2.1A) is composed of four off-reef members (Lobstick, Bigoray, Cynthia, and Wolf Lake) and one reef member (Zeta Lake) (Chevron Standard Exploration Staff, 1979; Stoakes, 1992; Switzer et al., 1994; Wendte et al., 1995).
Lithostratigraphic names used herein for members of the Nisku Formation are those proposed by Chevron Standard Exploration Staff (1979).

The internal stratigraphy and timing of reef growth is complex. The authors propose three regional transitions in carbonate sedimentation during deposition of the Nisku Formation. These transitions are interpreted using lithologic data and findings from the aforementioned sources and our own observations; they are presented here from oldest to youngest.

**Transition 1: Basin shallowing, carbonate ramp development coincides with a reduction in shale**

Ireton Formation shale in the underlying Woodbend Group shallows upward to inner- to mid-ramp carbonates of the Nisku Formation. Two ramp units totaling ~51 m, the Lobstick Member and Bigoray Member successively, are composed of argillaceous, bioclastic limestone, and decreasing upward calcareous siltstone. Oncolites and an open marine fauna characterize both ramp units. There is little if any distinction between the fossil components and mineralogy of the Lobstick Member and Bigoray Member, and thus the lower Nisku Formation represents an increase in open-marine carbonate in response to a regional decline of siliciclastic sediment and relative sea level fall at the end of deposition of the Woodbend Group.

Reefs of the Zeta Lake Member are locally underlain by ramp strata, and in rare cases overlay Woodbend Group basinal strata, which in turn is condensed. Therefore it is unclear if pinnacle reefs initiated during or after the period of relative sea level fall. Chevron Standard (1979) concluded that patch reefs developed during deposition of the initial (Lobstick Member) ramp, forming the base of some pinnacle reefs. In their scenario, Nisku Formation reefs accumulated in a growth/hiatus cycle that reflects changing relative sea level, largely driven by
subsidence. This interpretation of the Zeta Lake Member is lithostratigraphic and refers to all reef growth in the fairway.

**Transition 2: Basin deepening and downslope reef aggradation**

Bigoray Member strata are succeeded by Cynthia Member deeper water sediment and Zeta Lake Member pinnacle reefs. At the basin margins, the Cynthia Member is a ~45 m unit characterized by a basal calcareous, silty shale that grades upward into coral rudstone-floatstones, and interbedded argillaceous peloidal-bioclastic limestone and marl. In the basin center, Cynthia Member shale overlies shale from the Ireton Formation. Intertonguing of the Zeta Lake Member and Cynthia Member occurs locally at some reef margins, but there are no known occurrences of reefs fully covered by Cynthia Shale. There is no regional conformity to indicate the Cynthia Member was eroded. This spatial relationship indicates that part of the reef and basinal sediment accumulated synchronously, or in a reciprocal fashion.

**Transition 3: Shallowing, reef demise, and return to ramp carbonate**

Zeta Lake reefs and Cynthia basinal sedimentation were both terminated by an advancing shallow carbonate ramp referred to as Wolf Lake Member strata. Interfingering of Zeta Lake and Wolf Lake is reported (Chevron Standard Exploration Staff, 1979; Anderson, 1985) but was not observed in cores evaluated in this study. Peritidal to shallow subtidal limestone and dolostone of the Wolf Lake Member cover both reef and basinal strata. In a study focused on the Wolf Lake Member, Watts (1987) observed distinctions in lithofacies that suggest the peritidal environment overlying Zeta Lake reefs was more restricted than the peritidal environment overlying basinal sediments, and concluded that reefs were slightly topographically higher than the basin floor.
**Boundstone Sedimentology**

The term boundstone is used following Dunham (1962) to define reef rocks. Boundstones exert a strong control on the macrotexture of any pinnacle reef. Seven types of boundstones emerge using 1) the observed variety of framework metazoans, 2) skeletal morphology, and 3) the interpreted process of binding as indicated by the presence of calcimicrobes and algae. The rocks are further subdivided following the commonly used classification of Embry and Klovan (1971). This classification utilizes the principles described for autochthonous carbonate rock texture such as bafflestone, framestone, and bindstone that reflect the process by which organisms interact with reef sediment and the substrate, to baffle sediment, produce topographic relief, or enhance cementation.

Boundstone types are characterized (Table 2.1) in detail according to:

1. The taxonomy of principal and subsidiary framework metazoans, and their relative abundance.
2. Range of observed skeletal morphology of framework metazoans, i.e., growth forms. Although a paleontological trait, the growth form of framework organisms directly describes the spatial arrangement of skeletons to the seafloor and subsequent distribution of matrix material.
3. Other distinguishing features, e.g., association with other boundstone types.
4. Boundstone occurrence and abundance in pinnacle reef or shelf environments; distribution does not impact how boundstone types were defined but is necessary for paleontological interpretation.
<table>
<thead>
<tr>
<th>Boundstone Type</th>
<th>Setting and Abundance</th>
<th>Framework Metazoan(s)(^1)</th>
<th>Observed Skeletal Morphology of Principal Metazoan(s)(^1)</th>
<th>Other distinguishing features</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1. Coral bafflestone</td>
<td>PR-abundant, S-rare</td>
<td>1) <em>Thamnophyllum</em> (Penecke 1894)(^2) aff. Julli; 2) <em>Disphylia</em> sp. (de Fromentel, 1861; Hill 1939); 3) <em>Peneckielia</em> sp. (Soshkina, 1939); 4) <em>Macgaea</em> sp. (Webster, 1889); 5) <em>Syringopora</em> sp. (Goldfuss 1826)</td>
<td>All fasciculate phaceloid and dendroid</td>
<td>Frequent association with pelmetaozans and subsidiary open marine fauna; spongiostromate texture and grumeleuse structures are very common in matrix between coral colonies</td>
</tr>
<tr>
<td>B2. Coral framestone</td>
<td>PR-common, S-rare</td>
<td>1) <em>Alveolites</em> (Nicholson &amp; Etheridge, 1877, Duncan, 1972) or <em>Coenites</em> sp. (Stumm, 1960); 2) <em>Aulopora</em> cf. <em>Thecostegites</em> (Edwards &amp; Haime, 1849); <em>Thamnopora</em> sp. (Steininger, 1831); <em>Thamnophyllum</em> Sp.,</td>
<td>1) Massive, 2) massive and/or encrusting basal surface with space between corallites</td>
<td>Massive corals occur locally in a mud-dominated matrix; corals observed upright and inclined</td>
</tr>
<tr>
<td>B3. Coral-stromatoporoid framestone</td>
<td>PR-rare, S-rare</td>
<td>1) <em>Aulopora</em> (Goldfuss, 1826); 2) <em>Stachyodes</em> sp. (Stearn et al. 1999); <em>Labechia</em> Sp. (Milne- Edwards and Haime 1851); <em>Stromatoporella</em> sp. (Nicholson 1886)</td>
<td>1) Obligate encrusters, generally subramose; 2) tabular to irregular, locally dendroid</td>
<td>An intergrowth of coral and stromatoporoids; routinely interbedded with packstone or rare rudstone; encrustation of corals and stromatoporoids is observed but arrangement varies; B3 intercalated with B4 Thamnopora, Cladopora, and Coenites are coarse-sand to gravel-sized skeletons that are intact but frequently rotated; if not for presence of binding calcimicrobes, this would properly be a floatstone-rudstone</td>
</tr>
<tr>
<td>B4. Coral framestone - microbial bindstone</td>
<td>PR-rare, S-rare</td>
<td>1) <em>Thamnophora</em> sp.; 2) <em>Cladopora</em> Sp. (Stumm, 1960); 3) <em>Coenites</em> sp., or same assemblage as for type B1</td>
<td>1) Robust fasciculate; 2) phaceloid, locally dendroid or reticulate; 3) locally encrusting, locally dendroid</td>
<td>On the shelf, the matrix is dark brown; in the reef tract, the matrix is usually light brown to light grey</td>
</tr>
<tr>
<td>B5. Stromatoporoid framestone - microbial bindstone</td>
<td>PR-common, S-abundant</td>
<td>1) <em>Stachyodes</em> sp. (Bargatzky, 1881); 2) <em>Amphipora</em> Sp. (Shulz, 1883; Stearn et al., 1999); <em>Thamnopora</em> sp.; <em>Aulopora</em> Sp.; <em>Syringopora</em> Sp.</td>
<td>1) Tabular to irregular-anastomosing; 2) dendroid</td>
<td>NA</td>
</tr>
<tr>
<td>B6. Non-laminated microbial bindstones</td>
<td>PR-rare, S-common</td>
<td>None</td>
<td>NA</td>
<td>Massive Renalcis-mdstn, and thrombolites with diverse calcimicrobes; hosts stromatactis and irregular-shaped pores Stromatolite, cryptagal and microbial oncolites in grain- or mud-dominated matrices; rare large (&gt;3 cm) polytaxic oncolites and macroids,</td>
</tr>
<tr>
<td>B7. Laminated microbial bindstone and oncolites</td>
<td>PR-rare, S-rare</td>
<td>(Rarely) syringoporids with one or very few corallites, and very thin stromatoporoids and bryozoans of unknown taxonomy</td>
<td>Encrusting</td>
<td></td>
</tr>
</tbody>
</table>

\(^{1}\) Metazoan(s): Thamnophyllum (Penecke 1894), Disphylia sp., Peneckielia sp., Macgaea sp., Syringopora sp.

Table 2.1: Boundstone types identified in Nisku reefal environments and their faunal associations. Settings include pinnacle reef (PR), and Meekwap Shelf (S). 1) All fauna and flora in the table are listed at the lowest taxonomic level resolved and are ordered from most to least relatively abundant. Only the first occurrence of a taxa in the table includes its citation. 2) Several workers report *Phacellophyllum* and *Smithiphyllum* from the Zeta Lake Member as principal framework builders. *Thamnophyllum* and *Phacellophyllum* have disputed placement with respect to each other (Hill, 1981; McLean, 1989). This study applies the classification of Mclean, treating *Phacellophyllum* as a junior synonym of *Thamnophyllum*. See Zhen, 1995 for additional discussion on this point. 3) Skeletal morphology nomenclature after Hill (1981).

Boundstones with a skeletal framework are coral bafflestone (B1) (Fig. 2.4), coral framestone (B2) (Fig. 2.5A), coral-stromatoporoid framestone (B3) (Fig. 2.5B), coral framestone-microbial bindstone (B4) (Fig. 2.6A), and stromatoporoid framestone–microbial bindstone (B5) (Fig. 2.6B). Boundstones without a metazoan skeletal framework are non-laminated microbial bindstone (B6), and laminated microbial bindstone and oncolites (B7) (Fig. 2.7).

Calcimicrobes are major contributors to the overall reef system functionally and as producers of reef biomass. The phylogeny and trophism of Paleozoic calcimicrobes remains unresolved at the time of this publication (Riding and Toomey, 1972; Surge et al., 1997; Feng et al., 2010; Zhang et al., 2019). The contribution of calcimicrobes to each type of boundstone is detailed in Table 2.2 along with suggestions for photic demand.

In coral bafflestone-floatstone strata of the lower reef unit, some coral clasts have encrustations of tubular-form microbes, typically, *Rothpletzella*, *Girvanella*, and *Wetherdella* (Fig. 2.7A). This microbial association also forms laminated boundstones and oncolite coatings (Fig. 2.7B), although organized boundstones or microbial structures such as these are rare. Tubular microbial coatings are present in both mud-dominated and grain-dominated rocks, although they are largely absent from the *Renalcis*-dominated boundstones. Clotted or bush-like microbes of *Renalcis* and *Epiphyton* are the most common types among both reefs and shelf...
**Figure 2.4: Boundstone type 1.** A) Type B1 coral bafflestone with fasciculate dendroid corals in a wackestone calcimicrobe *Renalcis* (Rn); framework cavity (Cv) lined with isopachous calcite cement (IC) and partially filled with geopetal internal sediment (IS) Location PBT-1112, wet slab photo. B) Bafflestone (bottom) contact with skeletal floatstone (top) bearing reworked brachiopods (B), colonial coral fragments (CC), *Coenites* sp., and solitary horn corals (SC). C) Inset from image B, bafflestone matrix has is *Renalcis*-mudstone (Rn) with a locally grumeleuse (Gm) texture. Location PBT-0612, slab photo. D) Grumeleuse structure (Gm) in the matrix of coral bafflestone has a distinctly clotted appearance in contrast to laminated (IS). Location SC-1402, wet slab photo.

Buildups and rarely form organized structures; their interpreted depositional function was to source sediment to and perform binding in the matrix of coral and stromatoporoid boundstones (Fig. 2.7C). Locally in association with *Epiphyton*, the calcimicrobe *Renalcis* lines cavity walls and forms encrustations on both the upper and lower surfaces of laminar stromatoporoids and, locally, tabulate corals.

**Figure 2.5: Boundstone types 2 and 3.** A) Type B2 coral framestone composed of several auloporid tabulate coral (TC) colonies separated by internal sediment (IS), overlying colonial rugose coral (CC)
wackestone with subsidiary auloprids. Location BGD-1404, wet slab photo. B) Type B3 coral-stromatoporoid framestone from a proximal-slope reef is a composite boundstone with two genera of tabulate corals favositid and ramose alveolotid (TC1, TC2), encrusting laminar stromatoporoids (St) and laminar auloporid coral (TC3). These are stacked in repetition with reworked carbonate grains and cavities rimmed with isopachous calcite cement (IC). Location BGC-0612, wet slab photo.

Figure 2.6: Boundstone types 4 and 5. A) A typical Type B4 coral framestone-microbial bindstone has massive coral colonies (CC), smaller tabulate corals (TC) *Thamnopora* (shown) accompanied by *Coenites* (not shown). This colony has large volumes of intercoral space which is occluded by *Renalcis*-mudstone also capable of hosting cavities (Cv). Cavities can be partly to wholly occluded with internal sediment (IS) and isopachous calcite (IC) cement. Location PBT-1112, wet slab photo. B) Type B5 stromatoporoid framestone–microbial bindstone has anastomosing wafer stromatoporoid (St) *Stachyodes* sp. that forms shelter cavities occluded with pendant *Renalcis* and subsequent isopachous calcite cement (IC) The metazoan succession appears overlain by micrite cement (MC) although this cement could be infilling framework space between stromatoporoids, as in the lower right of photo. Location MN-0222, wet slab photo. Note size and shape of cavities is determined by adjacent skeletal metazoans, e.g., Type B5 yields small, irregular cavities between coral colonies whereas Type B5 cavities produced by stromatoporoids are larger and elongated.
Table 2.2: Autotrophic Presence and Role in Boundstone Construction

<table>
<thead>
<tr>
<th>Boundstone Type</th>
<th>Autotroph(s)</th>
<th>Spatial Occurrence of Autotroph</th>
<th>Most Conservative Photic Environment of Autotrophs Inferred from Spatial Occurrence</th>
<th>Depositional Significance of Autotrophs</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2. Coral framestone</td>
<td><em>Girvanella</em> <em>Cladogirvanella</em> (Ott, 1966), <em>Epiphyton</em> (Bornemann, 1886) (Ep)</td>
<td>(All) Encrusting on heterotrophs and disaggregated in matrix; Grv and Ep pore-filling in zooecia</td>
<td>Photic and adapted to low light</td>
<td>Subordinate: sediment stabilizing is locally abundant, cavity-filling more common</td>
</tr>
<tr>
<td>B3. Coral-stromatoporoid framestone</td>
<td><em>Renalcis</em></td>
<td>Pendant in cavities, disaggregated in matrix</td>
<td>Adapted to low light</td>
<td>Subordinate: disaggregated in matrix or thin pendant encrustations in cavities</td>
</tr>
<tr>
<td>B4. Coral framestone - microbial bindstone</td>
<td><em>Renalcis, Epiphyton</em></td>
<td>Encrusting on heterotroph top, sides; aggregated in matrix</td>
<td>Adapted to low light</td>
<td>Prominent: binds carbonate mud between metazoan skeletal particles and cavity filling</td>
</tr>
<tr>
<td>B5. Stromatoporoid framestone - microbial bindstone</td>
<td><em>Renalcis, Epiphyton</em></td>
<td>Opportunistic, cryptic filler--pendant</td>
<td>Adapted to low light</td>
<td>Prominent: binds carbonate mud between metazoan skeletal particles and produces thick (&gt; 1cm) cavity linings</td>
</tr>
<tr>
<td>B6. Non-laminated microbial bindstones</td>
<td><em>Renalcis, Epiphyton, Solenopora</em> (Dybowski, 1977) (So)</td>
<td>Rn clotted binder in wackestone; So encrusting laminar</td>
<td>Dominant: binding and trapping</td>
<td></td>
</tr>
<tr>
<td>B7. Laminated microbial bindstones and oncolites</td>
<td><em>Rothpletzella, Girvanella, Sphaerocodium</em> (Rothpletz, 1908)</td>
<td>Encrusting and binding in crypalgal layers and stromatolites, and oncolite-bearing wackestones</td>
<td>Photic</td>
<td>Dominant: binding and trapping</td>
</tr>
</tbody>
</table>

Table 2.2: Microbial influence across boundstone types. The variety of microbial influence across boundstone types is summarized according to autotroph taxonomy (form genera), their spatial occurrence and depositional significance. Autotrophic demand for light is interpreted from spatial occurrence of *in-situ* autotrophs. Genera in bold type are most commonly observed. 1) *Sphaerocodium* reported from southwest, dolomitized end of pinnacle reef trend (Anderson, 1985) but not observed in cores from this study.
Figure 2.7: Microbial presence. A) Coral-microbial boundstone with floatstone matrix. Transverse sections of solitary rugose that are encrusted by syringoporids and tubular calcimicrobes, here
Rothpletzella (Rth). Local shelter cavities have radial-fibrous isopachous calcite (IC) followed by blocky calcite (BC) cement. The lack of internal sediment in corallites and in shelter cavities can reflect the early, potentially in-situ coating by calcimicrobes. Digital scan 16#RGB of thin section stained with alizarin-red. Location SC-1402. B) Unpolished slab photo type B7 boundstones. In a bioclastic wackestone-marl (Md) matrix, individual oncolites with multiple generations of tabulate corals (TC) and laminated Rothpletzella, coalesce around micrite cement (MC) with geopetal skeletal clasts to form a large, polytaxic macroid, sensu Denayer (2018). Location PBT-1112. C) Unpolished slab photo a (left) coral floatstone with massive Renalcis (Rn) grading upward to a skeletal-matrix with less abundant Renalcis, typical of boundstone Types 1 and 6. Abrupt contact (right) with coral framestone hosting isopachous cement. Location BGB-1209.

Boundstone Ecology

Characteristics used to describe and interpret the ecology of fossil boundstones include substrate, mechanical preservation, wave resistance, and photic zone. While not specifically interpreted herein, the term trophism is used occasionally; trophism is defined herein as the mechanism that a fossil organism used to acquire food, either by (1) synthesizing its own food (autotrophy) through uptake of light or chemicals, (2) predation and use of dissolved inorganic carbon (heterotrophy), or (3) a combination of the above mechanisms (mixotrophy) (Tittel et al., 2003). The trophism of many extinct, epibenthic invertebrate groups is an ongoing point of contention that is addressed in the discussion section under the heading Metazoan Photic Considerations. Table 2.3 provides a comparison of ecological characteristics and an explanation of each characteristic.

Substrate.—Substrate preference is inferred through observation of in-situ fossils. Of the metazoan boundstone types, coral-bafflestones were exclusively related to soft-muddy bottoms. Firm or rocky bottoms were most-utilized by stromatoporoid-microbial boundstones. All other metazoan-dominated boundstone types occur on a range of substrates. The substrate for non-laminated microbial bindstones is categorized as indeterminate. Rothpletzella and Girvanella encrust coral skeletons, presumably taking advantage of firm substrate.

Mechanical preservation.—Preservation is ranked according to the degree to which framework-forming fauna (or faunal communities if they are plainly intergrowths) is observed.
in-situ vs. reworked, as follows: almost always in-situ = high, sometimes in-situ = fair, rarely in-situ = poor. Both coral-microbial boundstones and stromatoporoid-microbial boundstones have a high volume of calcimicrobes in their matrix that presumably aided high preservation.

Wave resistance.—Wave resistance is not a directly observed trait in ancient reefs and can only be inferred. Insalaco (1998) cautioned that the attribute of wave resistance by an organism is only meaningful with respect to a particular hydrodynamic regime, i.e., resistance to normal waves vs. storm waves. This point is acknowledged here, however, Madin (2005) has demonstrated in a laboratory setting that coral morphologies are individually impacted by hydrodynamic disturbance. A combination of topographic relief and growth form, in consideration with mechanical preservation and maturity of sediment surrounding each boundstone is used to interpret either a low, fair, or high resistance to agitation by waves. Boundstones with laminar to bulbous growth forms are ranked more wave resistant than those with digitate, fasciculate growth.

Photic Zone.—Pomar (2001) considered three main zones of benthic carbonate production that modern and ancient carbonate environments could theoretically possess. On the joined premises that biotic distribution of mixotrophs and (photo)autotrophs is tied to light and that carbonate grain production is tied to biota, Pomar established euphotic, oligophotic, and aphyotic groups of biota. The former two form sediment occupied by phototrophs and mixotrophs in modern reefs. Heterotrophs characterize the upper aphyotic zone but are not confined there and might outcompete mixotrophs when in the other two zones. A fourth zone, the mesophotic, was additionally defined as a transition between euphotic and oligophotic, occurring between ~40-80 meters below sea level in modern, Halimeda zones. No ancient zones have specific depth ranges associated with them.
<table>
<thead>
<tr>
<th>Boundstone Type</th>
<th>Substrate</th>
<th>Mechanical Preservation</th>
<th>Wave Resistance</th>
<th>Interpreted Photic Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1. Coral bafflestone</td>
<td>soft, muddy bottom</td>
<td>high: in-situ colonies are abundant; entombed with marine cement, spongioscramate mud-matrix, or Renalcis mudstone</td>
<td>poor to fair</td>
<td>oligophotic</td>
</tr>
<tr>
<td>B2. Coral framestone</td>
<td>usually soft, muddy bottom; occasionally fine-sand sized, bioclastic wkstn-pkstn</td>
<td>fair</td>
<td>fair: highest topographic relief</td>
<td>oligophotic</td>
</tr>
<tr>
<td>B3. Coral-stromatoporoid framestone</td>
<td>firm to mixed; either another tabular, calcareous fossil or less commonly, a bioclastic floatstone</td>
<td>high</td>
<td>high: low-relief biostromes</td>
<td>oligophotic to mesophotic</td>
</tr>
<tr>
<td>B4. Coral framestone - microbial bindstone</td>
<td>soft, muddy bottom or occasionally fine-sand sized, bioclastic wkstn-pkstn</td>
<td>poor: frequent reworking</td>
<td>fair</td>
<td>too rare to determine</td>
</tr>
<tr>
<td>B5. Stromatoporoid framestone - microbial bindstone</td>
<td>bioclastic grainstone or other stromatoporoids</td>
<td>fair to high</td>
<td>high</td>
<td>mesophotic</td>
</tr>
<tr>
<td>B6. Non-laminated microbial bindstones</td>
<td>indeterminate</td>
<td>poor to fair</td>
<td>fair</td>
<td>oligophotic to euphotic</td>
</tr>
<tr>
<td>B7. Laminated microbial bindstone and oncolites</td>
<td>variable: soft, muddy bottom and skeletal packstone-grainstone</td>
<td>high</td>
<td>high</td>
<td>euphotic</td>
</tr>
</tbody>
</table>

Table 2.3 Boundstone ecological indicators. Substrate, mechanical preservation, and wave resistance are used in conjunction with matrix sediment (see Table 2.1) to interpret a likely photic zone for each boundstone type.
Formation of Paleoecological Communities

Boundstones are the most volumetrically significant rocks in the pinnacle reef environment. For reef framework organisms, the integration of observed skeletal morphology, their transport and preservation, and arrangement with non-framework sediments allows assignment to Fagerstrom’s (1988, 1991) reef guilds as Bafflers, Constructors, or Binders. Plotting individual biota and boundstone types on a ternary diagram (Fig. 2.8) permits visualization of the overall diversity and function of Nisku reefs. These plots indicate that individual guilds were occupied by multiple taxa. Additionally, several key fauna in the late Frasnian reef had the flexibility of filling more than one reef guild owing to morphological diversity (see Fig. 2.8A). When organisms are organized by boundstone type as previously defined (see Fig. 2.8B), we see that boundstone types 3-5 conform with Fagerstrom’s (1994) idea of “balanced guild structures,” which is interpreted here to mean that the relative taxonomic diversity is generally uniform among reef guilds.

With confidence that these reefs naturally form balanced guilds, sensu Fagerstrom, we define four paleoecological communities (PC) that were present on the reef. Each paleoecological community is distinguished by substrate and diversity of skeletal forms within each faunal assemblage. Figure 2.9 includes an idealized sketch of each community. These communities are visually distinguishable in core and have fairly distinct arrangements of framework metazoans, reef dwelling organisms, matrix, and cement. The salient points regarding biota, sedimentology, and environment are presented for each community below.
**Figure 2.8: Reef guild identification.** A) Framework biota plotted include constructors, binders, or bafflers, plotted according to their observed skeletal growth form. Note that some biota are reported to have more than one morphology, exclusive of juvenile v. parent forms; in this case, the biota is plotted midway between guilds with arrows indicating guilds most often occupied (bold arrow) vs. lesser occupied in the Nisku reefs. Alv=Alveolites, Amp=Amphipora, Au=Auloporid, Co=Coenites, Di=Disphyllum, Ep=Epiphyton, Grv=Girvanella, Mcg=Macgeea, Pe=Peneckiella, Rn=Renalcis, Rth=Rothpletzella, Syr=Syringopora, Tha=Thamnopora, Thl=Thamnophyllum. This represents only the most common reef-building biota identified in this study. B) Each boundstone type (B1, B2, etc.) is assigned to a reef-building guild interpreted based on observed Dunham texture and paleoecology (reference Tables 2.1-2.3 for details on boundstone types).

**PC1 Coral-pelmetazoan-microbial community.**—Framework units of boundstone type 1 are thick-bedded to massive in scale. These units commonly grade into and form couplets with floatstones bearing texturally mature coral clasts of B1 boundstones, abundant pelmetazoans, and common solitary rugose corals. Framework corals in this paleoecological community have a delicate branching growth morphology. Dendroid colonies host cm-wide, sub-horizontal framework cavities that are locally lined with *in-situ* Renalcis. Rothpletzella is rare and limited *in-situ* to rugose coral encrustations. Renalcis and Rothpletzella also occur as particles in the matrix of boundstones and floatstones.
Early synsedimentary calcite cement ranges from absent to abundant and has multiple styles. Banded isopachous cement is locally abundant and fills framework cavities. Grumeleuse structure is commonly present in boundstone matrix. Grumeleuse structure is composed of cryptocrystalline calcite, has diffuse crystal boundaries, and can contain pin-point to cm-scale pores. These pores are locally rimmed with isopachous cement and later filled with equant calcite cement. In that the components are neither particle nor matrix, this texture is more properly a cementstone that develops locally.

*PC2 Coral-stromatoporoid-bivalve community.*— This community is represented by type 3 boundstones with the presence of megalodont bivalves (superfamily: *Megalodontoidea*, Morris, 1853). It is typified by a framestone composed of auloporid corals closely associated with wafer to laminar stromatoporoids, and discrete areas of coral floatstone composed of solitary rugose and *Thamnopora*. Coral skeletal morphology in PC2 is a motif of vertical and lateral growth. The calcimicrobe *Renalcis* is present but occurs only rarely as a pendant encrustation in thin cavities or as disaggregated particles in matrix. Between framestones there is a cm-scale motif of laminated, silt- to mud-sized carbonate accompanying a packstone-rudstone of gravel-sized skeletal particles and coral debris. Early marine cement is locally common in strata hosting PC2, but in general, less abundant than in units containing PC1. This reef community is distinguished by randomly oriented megalodont bivalves. Bivalves are composed of fibrous calcite with varying amounts of intramoldic, fine-grained carbonate sediment. Randomly selected bivalve molds average 2-3 cm high by 6-8 cm long in cross-sectional orientation (Kosnik et al., 2006) on the face of core slabs; systematic or oriented measurements were not possible. Their occurrence roughly coincides with the appearance of *in-situ* stromatoporoids in abundance. PC2 occurs on nearly all pinnacle reefs as a 0.5-5m unit. In stark
contrast, megalodont bivalves are rare in shelf buildups and there is no evidence that PC2
developed on the shelf.

**PC3 Coral-stromatoporoid-microbial community.**— This community is composed of
boundstones from types 2, 3, and 4 intercalated at units approximating >10 cm. Alveolitid and
auloporid corals form thin, discrete framestones among thin laminar stromatoporoids, creating
the appearance of biogenic crusts. This texture is exaggerated in the form of semi-continuous,
alternating light-dark bands of calcite cement that follow the contacts between different taxa. The
banding makes skeletal contacts diffuse in appearance. Although not definitive, this banding is
interpreted as degraded calcimicrobes, organic films, or non-calcareous sponges.

The thin boundstones in this community contain abundant *Thamnopora*, *Stachyodes*,
*Coenites*, *Cladopora*, and *Thamnophyllum*, filling inter-framework spaces. Framework
organisms have a small range of skeletal morphologies, mainly lateral to encrusting-lateral with
minute horizons of vertical growth. Calcimicrobes are common encrusters on skeletons and in
framework cavities and also occur disaggregated in matrix. The internal organization of this PC
is highly variable from the decimeter to centimeter-scale.

**PC4 stromatoporoid-microbial community.**— This PC is composed of boundstone types
5 and 6, stromatoporoid and thrombotic boundstones. Principal metazoans in this community are
*Stachyodes sp.* with lesser *Amphipora sp.* *Stachyodes* growth forms are tabular, irregular, and
encrusting lateral-to-subhorizontal. Stromatoporoids frequently exhibit low- to moderate dip,
ranging 10-50°; in some cases, higher dips can be traced to bifurcation of the stromatoporoid
with large separation between the off-shooting branches (see Fig. 2.6b) and re-orientation of
growth within these branches toward horizontal. Calcimicrobes are volumetrically minor to
stromatoporoids but are significant sediment producers and binders. *Renalcis* and lesser
Epiphyton encrust the basal and top surfaces of stromatoporoids and infill cryptic spaces that visibly result from stromatoporoid bifurcation. Inter-skeletal spaces are filled with a mudstone-thrombolite composed of light-colored Renalcis particles in a dark-brown, organic-rich, fine-grained carbonate with rare bioclasts of coral and unidentified skeletal fragments. The PC4 stromatoporoid-microbial community occurs in reef strata beginning ~10-20 m below well-laminated and fenestral (peritidal) carbonates of the Wolf Lake Member. PC4 is frequently intercalated with PC3. On the Meekwap Shelf, PC4 becomes the more dominant community moving upward.

**Interpretation of Reef Communities**

All the pinnacle reef-builders in the Nisku Formation are extinct. The philosophy herein is to use observations of the rocks in the lower and middle reef units together with inductive reasoning to interpret the conditions under which these structures—and biota—grew. Although comparison with modern coral reefs and oceanography is occasionally used, the focus is on the relationship between observed fabrics and textures.

*PC1 Interpretation.*—PC1 is interpreted as an oligophotic to aphotic, deep-water subtidal community of baffling rugose corals, principally Disphylllum sp. Solitary rugosa have been interpreted as hardground epifauna (Nelson and James, 2000) and as muddy-bottom fauna (Elias, 2010) with adaptive strategies for changes in hydrodynamic regime, thus they are not useful indicators. A volumetrically high floatstone component and a gradational nature between bafflestones and floatstones suggests regular if not frequent periods of high micrite-sedimentation that entombed individual colonies in sediment but that were not catastrophic to the community. In the absence of floatstone, syndepositional cement juxtaposed with encrusting
calcimicrobes and spongiostromate mudstone fills inter-corallite spaces. PC1 deposits are evenly distributed laterally across the reef but occur only in the lower reef interval.

PC2 Interpretation.—Elsewhere in the Alberta basin, megalodont bivalves are found on the periphery of reef slopes (Klovan, 1964; Mossop, 1971) and in fringing reefs (Hedinger and Workum, 1988), where they are interpreted as in-situ, subsidiary reef dwellers. Megalodonts are known to occur with stromatoporoids among Frasnian reefs worldwide (Tapanila, 2006; Morrow and Sandberg, 2008; Chow et al., 2013) and in commonly associated coral-stromatoporoid reefs throughout the Silurian and Devonian (de Frietes et al., 1993). In terms of ecology, well-studied megalodonts of the Silurian were commonly mud-resting, epifaunal and reclined, and hosted alga symbionts (Nevesskaja, 2006). In Miocene platform carbonates, Wiedl et al. (2012, 2013) attribute the mineralization and large size of molluscs to “favorable” climate conditions.

Megalodont bivalves present in the Nisku reefs are stratigraphically restricted to the approximate middle of the Zeta Lake Member. Their large skeleton size in reef and margin buildups that are otherwise devoid of large, robust individual carbonate skeletons warrants attention. That they are confined to a discrete unit with poorly-sorted organisms supports the interpretation of PC2 as a short-lived transition between major reef environments and stages. The range of sediments associated with PC2, from higher energy rudstones to lower energy laminated mudstone—and more specifically, the proximity of these lithologies indicates a hydrodynamically changing environment. PC2 is an oligophotic-mesophotic community transitioning from persistent low energy to a mixed, low-moderate energy environment.

PC3 Interpretation. — PC3 is a diverse association of filter feeders and autotrophs that suggests nutrients and light were not limiting factors. That none of the reef biota generated vertical relief indicates a low-relief skeletal form was advantageous for the environment, and
suggests low accommodation or exposure to continuous, high energy. PC3 is therefore interpreted as an oligophotic-mesophotic reef top community of constructors and binders.

**PC4 Interpretation.** — PC3 and PC4 communities are generally similar in their stromatoporoid and microbial components but can be distinguished based on 1) a lack of framework corals in PC4, 2) generally thicker and longer stromatoporoids in PC4, and 3) background sediments in PC3 are coarser and less sorted in contrast to thrombolitic-mudstone in PC4. These distinctions indicate that PC4 is a less-winnowed community, but re-oriented growth in stromatoporoids suggests both communities experienced disturbances. The superposition of these communities indicates repetitive environmental change where PC4 was likely more tolerant of a range in sedimentation than its coral-bearing counterpart PC3.

*Renalcis* masses and clots occurring between stromatoporoids have been interpreted elsewhere in the late Devonian record as pendant growths (Wood, 1998a, 2000). Within Nisku reefs, the apparent vertical distance between stromatoporoids can range from a few centimeters up to 0.2 m; with increasing distance between stromatoporoids, it seems improbable to qualify intervening *Renalcis* mudstone-thrombolites as “encrusting.” Where *Renalcis* is not explicitly encrusting, there remain the questions of origin and transport, underscoring that the life mode of *Renalcis* is poorly understood. This paper has described *Renalcis*-bearing mudstone-wackestone as a non-laminated microbial boundstone (B6), owing to the well-accepted sediment-binding potential of calcimicrobes (Riding and Toomey, 1972; Riding, 2002; Della Porta et al., 2004). The preponderance of *Renalcis* in shelter cavities throughout the reef indicates that they are dysphotic to aphotic biota. Renalcid thrombolite textures are also described from the late Frasnian Ancient Wall platform and are interpreted as 1) a renalcid-mudstone biofacies
(Mountjoy and Jull, 1978) and 2) a flooding-related horizon of columnar thrombolites (Whalen et al., 2002).

Figure 2.9: Paleoecology communities recognized in late Frasnian reefs.
Paleoecological communities of the Nisku pinnacle reefs are visually distinguished by diversity of skeletal morphology, and whether the community is monospecific, e.g., paleoecological communities 1
and 4, or has multiple framework taxa as in paleoecological communities 3 and 4. Preference for substrate can be exclusive, only soft-muddy bottom, or variable. The order of community as they appear vertically in core is counterclockwise from top left. PC=paleoecological community.

**Discussion**

This discussion concentrates on key features of the Nisku pinnacle reefs—those that most strongly influence either the large-scale heterogeneity or meter-scale heterogeneity—and their significance in understanding late Devonian reefs. Specific attributes considered are: 1) environmental considerations with diverse interpretations from the geologic record, including water depth as related to calcimicrobial presence, and the photic zone, 2) ecological succession, 3) space utilization and morphology, and 4) hydrodynamic regimen.

**Environmental Considerations**

*Depth and Calcimicrobial Presence.* Among calcimicrobes, the presence of cavity-dwelling organisms is evidence that some were adapted to low-light. The distribution of calcimicrobes among boundstones (see Table 2.2) indicates that *Renalcis* and *Rothpletzella* are the most abundant calcimicrobes in the pinnacle reef strata, but only *Renalcis* regularly colonized *in-situ* boundstones. The abundance of *Renalcis* and *Rothpletzella* could reflect better preservation given an encrusting, attached life mode, compared to, e.g., *Epiphyton, Wetherdella*, which are subsidiary in these pinnacle reefs. *Renalcis* was not observed in ramp members in the study area and first appears in the Zeta Lake Member in coral bafflestones in the lower reef interval. Throughout the reef interval, *Renalcis* occurs in three habits; from most to least abundant, these are: 1) pendant coelobite in crypts and shelter pores, 2) particles in the matrix of coral and stromatoporoid boundstones, and 3) pendant and crowning encrustations on stromatoporoids.
In the northeast Cynthia Basin (Meekwap), where shelf buildups are composed almost exclusively of stromatoporoids with only subordinate corals, *Renalcis* regularly colonized the ventral (bottom) and dorsal (top) positions surface, with a preference for the latter (Bingham-Koslowski, 2010). The Ancient Wall reef complex is a stratigraphic equivalent to the lower Nisku and was deposited along the western margin of the Cynthia Basin (Rocky Mountains, Alberta) (Mountjoy and Jull, 1978; Mountjoy and Riding, 1981; Whalen et al., 2002; Whalen and Day, 2010). There small bioherms composed of fenestral renalcid micrite-wackestone established on debris flows in reef foreslope strata (Mountjoy and Riding, 1981). Much emphasis is placed by the authors on the binding potential of *Renalcis*, *Izhella*, and *Epiphyton*, and the co-occurrence of suitable substrate as an ecological driver. Thus, *Renalcis*-rich deposits around the late Frasnian Cynthia Basin represent a range of depositional environments and water depth. While the presence of *Renalcis* in cavities could also reflect a preference for an existing framework or another environmental factor unique to the cavity (e.g., protection from potential grazers, low sediment flux), their preference for crypts suggests that they were dysphotic to aphotic organisms, and the presence of *Renalcis* in and of itself should not constrain the interpretation of strata containing *Renalcis* to shallow (<30 m) depositional environments.

*Metazoan Photic Considerations.* — Water depth is the primary control on light in the marine realm, determining the distribution of primary producers and of organisms with obligate or facultative photosymbionts. Use of photosymbionts, and thus mixotrophy, by highly-skeletonized Paleozoic corals and stromatoporoids remains equivocal (James and Jones, 2015): some question mixotrophy by specific groups of reef builders on the basis of functional evidence (Wood, 1993 and references therein, 1998b; Kershaw, 2012), whereas other workers interpret Paleozoic assemblages of corals and sponges as photozoan carbonate communities (Michel et al.,
in the specific absence of evidence for a heterozoan carbonate assemblage. Owing to this uncertainty, our interpretation of Nisku paleoecological communities emphasizes regional patterns in the distribution of metazoans and zone of benthic carbonate production evidenced from sedimentary indicators.

Elsewhere in the WCSB, corals typically inhabited deeper-water environments: in reefs with both corals and stromatoporoids, corals occupied deeper-water niches in the Redwater Reef Complex (Klovan, 1964) and in the extensive Fairholme Carbonate Complex (Mallamo, 1995) of western North America; stromatoporoids in Ancient Wall and Miette platforms that are age-equivalent to the Nisku Formation have been interpreted as oligotrophic and demanding fewer nutrients (Whalen et al., 2002) than downslope coral-stromatoporoid communities. Corlett and Jones (2011) reported that in Mackenzie Basin (Northwest Territories, Canada) that middle Devonian stromatoporoids reefs grew downslope to coral-dominated reefs and that the latter grew in a nutrient-enriched environment based on geochemical analyses.

Applying Pomar’s photic zone model (2001; Flügel and Munnecke, 2010) to Nisku pinnacle reefs, the PC1 reef community was most likely in the deeper oligophotic to aphotic range. Uniform progression from PCs 2 through 4 is interpreted as oligophotic-mesophotic. Evidence to support this interpretation includes:

(1) basinal shale and marl (Cynthia Member), which are temporally coeval with the reefs, are mostly devoid of reef biota except as reworked particles, but contain other light-independent biota;

(2) an assemblage of calcimicrobes in the matrix of coral and/or stromatoporoid-bearing facies have abundant, light-independent Renalcis, but laminated microbial mats that are
characteristic of the euphotic zone are conspicuously rare except below the transition from reef back to ramp;

(3) thickness and lithology, i.e., floatstones and bafflestones, of the lower reef community, along with sedimentary and diagenetic features (such as in-situ mud and silt, lack of winnowing of fine sediment, absence of flanking strata, and microbial-clotted grumeleuse structure with stromatactis) together suggest a below normal wave-base, low-energy environment across the reef trend;

(4) mound conditions originated in a depth zone with light-independent metazoans, and

(5) following deposition of PC 1, the upward change in biota from coral- to stromatoporoid-dominated is accompanied by an upward increase in calcimicrobe diversity, but not in the grain-size production that should accompany a movement into the euphotic zone.

**Ecological Succession**

Ecological succession in ancient reefs is observed through a distinct vertical zonation of fauna (Walker and Alberstadt, 1975). The ideal succession includes four stages: stabilization, colonization, diversification, and domination, although the absence of one or more stages is not uncommon. In the Nisku pinnacle reefs, stabilization was performed by an association of abundant pelmetazoans with small to medium solitary rugose, and dendroid-fasciculate corals in the transition from ramp to reef environment. Stabilization was followed by colonial rugose thickets that were predominantly dendroid-phacellloid in form with lesser fasciculate forms, interpreted as the colonization stage. The diversification stage is represented by a succession of encrusting laminar to tabular forms of both tabulate corals and stromatoporoids, accompanied by rare dendroid ceroid corals and colonial rugose, which decrease in relative abundance but do not disappear from the reef community. The colonization stage accounts for roughly half of Zeta
Lake Member thickness in most cores but is periodically interrupted and eventually damped by diversification stage strata. The same three-stage succession is observed in the southernmost Alberta Basin, where crinoidal shoals succeeded by pinnacles dominated with rugose corals developed coevally with the Pembina reef trend (Klovan, 1964; Mossop, 1971).

The diversification stage in Nisku pinnacle reefs is followed by a small, local sequence of mostly biofragmental deposits or mudstones with stromatolites, local fenestrae, and gastropods of variable thickness. These similarity of these structures and sediment to an inner ramp succession, representative of lagoonal to peritidal environments (Tucker et al., 1990; James and Jones, 2015), combined with localized distribution suggests not all reefs reached this stage at the same time, if at all. This is explained by a fall in sea level prior to Wolf Lake deposition which would impact reefs on the upper slope as well as downslope reef with high bathymetric relief, thus these shallow-water, euphotic strata were not ecologically driven.

Expectations of ecological succession are that 1) both production and growth are reduced as succession advances, and 2) changes in reef stage are not fundamentally unidirectional (Walker and Alberstadt, 1975), i.e., sudden environmental changes may result in regression of reef communities to an earlier stage. Given favorable conditions, encrusting tabulates and stromatoporoids common in Nisku reefs should progress into “massive” colonies. Interestingly, they do not. In the Nisku reefs, the preponderance of calcimicrobes, particularly *Renalcis*, early in reef growth within a lower slope setting supports the concept of expansion of calcimicrobes into deeper-water reef environments, and highlights the importance of Binder organisms during the colonization of these late Frasnian ecological reefs.

**Space Utilization and Morphology**
Moving upward through the reef succession, the utilization of reef space changes demonstrably from a low seafloor-footprint framework and free-living metazoans to high seafloor-footprint metazoans. Metazoans contributing most to reef biomass are, in decreasing abundance, colonial rugose corals, stromatoporoids, tabulate corals, pelmetazoans, solitary rugose corals, and skeletal calcimicrobes.

Low Seafloor-Footprint. — The lower reef is a bafflestone reef principally composed of fasciculate-dendroid and fasciculate-phacelloid rugose corals with subsidiary open marine fauna. Corals of both branching morphologies compose the coral-skeletal and coral-grumeleuse facies. Framework cavities here can have encrusting calcimicrobes, typically *Renalcis*, but otherwise, there are virtually no calcimicrobes on *in-situ* corals; *Rothpletzella* encrusts reworked coral clasts in floatstone, and individual “pearls” of calcimicrobe skeletons float in micrite matrix. Individual corallites are no more than a few centimeters in height. In the space of vertical decimeters, there are multiple colonies of framework coral with a vertical separation of only a few centimeters in which, importantly, no other calcitized organisms are present, however, there are abundant *Stromatactis* and grumeleuse structures that suggest activity by sponges. These facies intercalate almost exclusively with the mud-dominated, bioclastic facies and together reach aggregate thicknesses up to tens of meters. This interval represents a prolonged period without substrate competition owing to its thickness, monospecific biota, singular branching morphology among framework organisms, and lack of bioerosion in muds and of corals.

High Seafloor-Footprint. — The principal biotic change moving upward into the middle reef section is that stromatoporoids colonize the seafloor. In contrast to colonizing corals that possess upright, vertically-dominated growth forms, the colonizing stromatoporoids are laminar-dominated. Of note is the rarity of bulbous stromatoporoids in all reef cores examined from the
southeast Cynthia basin. In other Frasnian reef strata, thick tabular and domal labachiids dominate, including in underlying Woodbend Group (Mossop and Shetsen, 1994) and the Nisku-equivalent Jean-Marie Member downslope facies in northwest Alberta basin, British Columbia, where columnar and bulbous growth are the dominant skeletal morphology (N. Bingham-Koslowski and W. Martindale, personal communication, 2017; Wierzbicki et al., 2008).

Growth morphology is inferred as causally linked to environmental conditions. Of possible stromatoporoid growth morphologies (Abbott, 1973; Stearn, 1975, 1980; Wood, 1998a; Stock, 2001), only wafer, tabular to (rare) slightly ramose, and dendroid forms occur in the pinnacle reef, with the latter present only in reworked facies.

Some tabular stromatoporoids and ramose tabulates were observed to have margins separating successive periods of lateral accretion. In other cases, tabular skeletons clearly curve and sometimes angle without disruption of the laminae and without fracturing, apparently tracking changes in the substrate. In rare (two) cases, the curving feature clearly exceeds what could be described as arcuate or wavy in growth form, with bends in skeleton reaching up to 80°. Both encrusting wafer stromatoporoids and tabulate corals demonstrate anastomosing forms (Fig. 2.9), although it is observed more frequently among stromatoporoids.

Curving may also be explained by stromatoporoid skeletons which were not rigid and thus bent as a result of slumping prior to lithification. This interpretation is not favored here, owing to an observed continuity of laminae and absence of other sedimentological indicators for slumping. In most cases of inclined growth observed in this study, shelter cavities in adjacent sediments establish depositional “up” and rule out the post-depositional torque or syn-sedimentary bending of tabular skeletons to produce higher angle geometries. Curved forms are therefore interpreted as in-situ growth.
The infrequency of inclined growth as compared to horizontal expansion suggests a temporary adjustment to the environment, similar to stromatolites that grow on sub-horizontal clasts and surfaces (Jefferson and Young, 1988). Stromatoporoids which track small or extreme topographic variations are interpreted here as a recovery adaptation to disturbance, e.g., an organism or community-specific adaptation to “maintain” population control of the substrate (see Connell, 1997 for definition of environmental disturbances affecting modern corals reefs), and might reflect an obligate encrusting life-mode in some late Frasnian stromatoporoid species.

As previously stated, it remains uncertain if stromatoporoids utilized photosymbionts (Stanley, 2001). Large colony size noted in many Silurian to Devonian stromatoporoids suggests that energy available for skeletal secretion was not a limiting factor (Nestor, 1981; Wood, 1995), whatever the source of that energy. Diminutive skeletal thickness among stromatoporoids from pinnacle reefs in this study and on the northeast (Meekwap) shelf, in combination with evidence of skeletal recovery, suggests 1) competition for resources was high during deposition of the upper Nisku Formation and 2) if seafloor space was the limiting resource, then stromatoporoids had a strategy in place to compete for it. The uncertainty around stromatoporoid trophic mode complicates the interpretation of growth morphology in terms of creating surface area in a specific direction for a symbiont’s access to light. Nonetheless, evidence of competition for substrate is observed in pinnacle reef environments where auloporid tabulates and tabular- to wafer-stromatoporoids are commonly vertically stacked (Fig. 2.10). Based on observations herein, it seems likely that because they were filter feeders, stromatoporoid growth form should be interpreted firstly as a function of providing access to water current (nutrients) in terms of water energy and rates of sedimentation, and secondly as a function of access to suitable substrate for skeletal expansion.
Hydrodynamic Regime

Depositional indicators for hydrodynamic regime in reef strata of the Nisku Formation are virtually absent: the reef transition to off-reef facies is abrupt; the scale of bedding is in almost all cases thick to massive, except for laminated sediment infilling framework and shelter cavities, and neptunian dikes which represent microenvironments atypical of current and sediment conditions at the seafloor. Bed forms resulting from current or wave processes are absent, with the exception of cavity filling sediment. In this particular case, the reefs are laterally encased in shale and overlie ramp deposits. These attributes emphasize the isolated nature of

Figure 2.10: Intra-community dynamics. A) A small boundstone composed of tabular stromatoporoids *Labechia* sp. and encrusting *Aulopora* sp. corals exemplifies the stacking behavior between low-relief organisms. This community built up over a domical stromatoporoid which are rare in Zeta Lake Member reefs but typical of many Devonian reefs. Taken together, the skeletal packstone matrix and anastomosing of stromatoporoid support a moderate to higher energy environment. B) Trace of image A, here in 6 bits
Greyscale (GRY) based on original hue emphasizes the thinness of encrusting layers, and the complicated arrangement wherein smaller encrustations were aborted. Sample location BGC-0612. DST=domical stromatoporoid, St=tabular stromatoporoid, TC=tabulate coral.

these reefs, that they are not influenced by platform sedimentation, and lay below normal wave base. Paradoxically, Nisku pinnacle reefs have ubiquitous marine cement that is typically associated with a reef crest or higher energy (above normal wave base) environment, even in mud-dominated coral communities.

A reported lifespan of modern coral colonies on the order of hundreds to thousands of years (Rosen, 1986) suggests that taxonomic groups that can adapt to variations in hydrodynamic regime should occur in multiple depositional environments and recover more efficiently from catastrophic and reef-destructive events (Connell, 1997). One observed response to hydrodynamic regime in modern coral reefs is an increase in their structural strength as wave-stress increases (Chappell, 1980). Although there are indicators for structural strength in ancient reef metazoans, these are difficult to evaluate and most models single out the following as adaptation to changing hydrodynamics: 1) morphometrics, emphasizing a reduction of height to width ratio where the total surface area of skeleton exposed to current is reduced (Kershaw, 1981), and 2) the ability to adapt an encrusting life mode, either singularly or as a community, e.g., sclerobionts.

As previously noted, at the time of reef inception, corals were solitary horn corals or fasciculate rugose corals (both dendroid and phacelloid), accounting for, on average, 40m of accumulation composing the entire “lower reef” unit. In these facies, corallites are rarely in contact with each other except at the point of bifurcation. Otherwise, they are separated by <1 cm. Moving upward through the reef succession, auloporid tabulate corals first appear as isolated or, occasionally, as thin encrustations on bioclasts in floatstone. Larger encrusting auloporids, that is, those that are centimeters thick, occur in the middle reef unit and are stacked with tabular
stromatoporoids in coral-stromatoporoid boundstones of PC3. In the reefs studied here, adoption of encrusting form by communities is empirically evidenced by the vertical succession from PC 1 to PCs 2 and 3, and suggests a change in the reef’s hydrodynamic regime, from depths essentially without large physical disturbances to a depth that experiences slight disturbance.

Timing of reef stabilization aids in understanding hydrodynamic environment. The strongest evidence for early stabilization is the prevalence of banded, isopachous calcite cement that rims framework biota from both soft-bottom and hard-bottom substrate communities. Carbon- and oxygen- stable isotope data (Anderson, 1985; Machel, 1985, 1986) establish the origin of these banded cements as “likely” marine-phreatic in origin. Additionally, Neptunian dikes filled with reworked reef sediment are occasionally lined with either *Renalcis* or cement prior to the deposition of reworked material. While these features aren’t direct evidence for an active hydrodynamic regime, they suggest that portions of the reef were exposed to open marine water for some time before burial and that both dissolution and precipitation were active at different times in that interval.

Coral bafflestones are moderately taxonomically diverse in the Nisku, with five species creating bafflestones (see Table 2.1). They represent the only muddy-bottom substrate community in the reef section, however, they are alternately entombed in mud or early marine cement. The expectation is that heavily-cemented environments have sufficient agitation to prevent the settling out of mud-sized particles (Friedman et al., 1974; Friedman, 1985), and perhaps a high water-to-rock ratio (James and Jones, 2015) in the syndepositional and early diagenetic windows. These attributes are more typical of a reef crest environment where cementation is driven by proximity to the hydrodynamic maximum, however, Nisku pinnacle reefs do not fit a hydrodynamic-maximum model: they were apparently low-relief structures,
stratigraphically organized into tabular units apparently without flank facies or intra-reef lateral facies change that would support continuous wave action.

Pertinent to the discussion of hydrodynamic energy is that, in many cases, this cementstone occurs in place of matrix (where matrix is defined as material that is mechanically deposited between particles (Bathurst, 1972)), but is: 1) in some cases intercalated with skeletal wackestone, within m-scale beds of bafflestone, and 2) in other cases, banded isopachous cement that rims fasciculate corals precedes grumeleuse structure and microbial-rich muds.

Summary

Based on the foregoing, the pinnacle reefs grew mostly in the low-light conditions and are classified as mesophotic to oligophotic based on overall benthic carbonate production and scarcity of demonstrably euphotic sediments. Calcimicrobes, particularly Renalcis and Rothpletzella are found throughout the reefs and grew in a range of environments, most of which were low light.

The reefs changed upward from a low seafloor footprint with free-living metazoans to a high seafloor-footprint of attached metazoans. Specifically, the lower reef was one of minimal substrate competition with a monospecific coral biota of branching morphologies, and no bioerosion with rare laminar stromatoporoids. The middle reef is typified by diverse subhorizontal laminar or dendroid to bulbous stromatoporoids that used underlying skeletons as a substrate. Coral diversity increases upward, in contrast to other notable late Frasnian successions.

There is clear ecological succession, sensu Walker and Alberstadt (1975). Departures from the typical succession are an expanded colonizing stage to include binding organisms, and a condensed or absent domination stage.
Awareness that members of paleoecological communities need not have identical functions, anymore than it is necessary they compete for shared resources, is demonstrated here with the inclusion of binding microbial organisms in a colonizing reef community. While relying on skeletal morphology and concepts of reef guilds (Fagerstrom, 1988, 1991) to inform relationships between an organism and the environment, using these in isolation can tightly proscribe paleoecological study. The hydrodynamic regimen overall is low energy with isolated departures from this, below normal wave base, therefore the fluctuation of carbonate mud and cement that entombs coral bafflestones is most simply explained by intermittent exposure to higher energy; this is stratigraphically coincident with basin deepening and suggests storm wave base could account for periodic energy intensity. There is a vertical succession from PC1 (solitary coral-pelmatozoan-calcimicrobe) to PC2 (coral floatstone-laminar stromatoporoid-bivalve community) to PC3 (diverse coral-thin laminar stromatoporoid-calcimicrobe community).

Conclusion

Following examination of over fifty cores penetrating pinnacle reefs and coeval shelf-buildups elsewhere in the Cynthia-Winterburn Basin, a series of four recurring paleoecological communities (PC) are recognized in these late Frasnian off-platform reefs including:

1. coral-pelmatozoan-microbial (PC1),
2. coral-stromatoporoid-bivalve (PC2),
3. coral-stromatoporoid-microbial (PC3), and
4. stromatoporoid-microbial (PC4).

Utilization of reef space by metazoans as evidenced by substrate drove community development and upward ecological change, consistent with ecological succession, prior to reef
demise by shallowing sea level. Euphotic sediments occur locally in the transition from Zeta Lake Member to Wolf Lake Member, but are absent from the lower ~70-80 m of most reefs.

Nisku Formation reefs had a distinct and likely prolonged colonization stage, typified by baffling coral-microbial strata hosting varying amounts of internal cavities with pendant and massive *Renalcis*, synsedimentary cement, and internal sediment, many resembling stromatactis. A paradox of mud-rich and early marine cement-rich areas within (typically low-energy) coral bafflestones suggests that reefs grew in proximity to a fluctuating hydrodynamic boundary in a deeper-water setting, however the nature of that boundary needs further investigation.

Thus, off-platform reef strata of the Nisku Formation are an interesting footnote in Devonian reef evolution in that i) the nature of Nisku Formation pinnacle reefs is demonstrably metazoan-microbial from the point of origin—with diverse coral and microbial assemblages, with true framestones and bindstones—and ii) the reefs accrued predominantly in deeper water environs. Further, the ubiquity of calcimicrobes, particularly *Renalcis*, in crypts and in matrix lithologies throughout the Zeta Lake Member indicate that calcimicrobes played a significant role in binding and stabilizing the reef throughout its formation, and that these calcimicrobes were not constrained to shallow-water environments during the late Frasnian reef twilight.

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Chapter 3

Late Devonian pinnacle reefs: twilight of framework reefs, rebirth of mud-mounds

Abstract

Late Frasnian reefs of Laurentia’s western platform (Nisku Formation, western Canada subsurface) have attributes of framework reefs and mud-mounds. They represent the last pulse of reef carbonate deposition in the central Western Canada Sedimentary Basin prior to the Frasnian-Famennian extinction and are economically developed as reef reservoirs. Tens of pinnacles average 80-100 m in thickness and range in width from 1-3 km. Buildup growth is contained within a single, third-order transgressive-regressive cycle in an equatorial greenhouse setting. A detailed facies study is made of seven pinnacle reefs representing the proximal, middle, and distal portions of the carbonate slope. Stromatactis-rich bafflestones in the lower reef have a rugose coral framework and synsedimentary cements typically associated with shallow and perhaps warm-water masses. Microfacies of lower reef boundstones, however, indicate a deeper water and microbially-influenced matrix. These microfacies are: (1) microbial-peloid calcilutite to calcarenite; (2) siliceous, microbial bioclastic calcarenite to calcilutite; (3) spiculitic, microbial micritic mudstone-wackestone; and (4) microbial-micritic mudstone-floatstone. *Rothpletzella* is the predominant calcimicrobe in microfacies 1 through 3 with subsidiary *Renalcis*, whereas microfacies 4 consists of *Renalcis*. The paradox in sediment—metazoan framework with microbial mud-mound matrix—defies the concept of a shallow subtidal environment commonly invoked for light-dependent corals and cyanobacteria. Microfacies 1 through 3 are exclusive to the lower Zeta Lake Member, whereas Microfacies 4 also occurs in the coral-stromatoporoid
facies of the upper Zeta Lake Member. The paradox suggested by sediments in the reef core can be attributed to periodically increased turbidity and delivery of nutrients and siliceous material, most likely by currents or storms. All buildups show a two-part facies succession indicating shallowing upward from a Phase I mud-mound core with metazoans deposited under rising sea level to more conventional Phase II reef top and eventual resection of the reef with a prograding ramp under falling relative sea level. An upward shift in benthic carbonate factory from mud-dominated to skeletal dominated reflects diminishing of the mud-mound environment with falling sea level, a termination event recognized elsewhere in the basin.

Introduction

In western Laurentia during the late Frasnian, a series of carbonate buildups developed on the slope bordering the Nisku platform in the Western Canada Sedimentary Basin (WCSB). Now in the subsurface of central Alberta, the buildups are known as the Pembina Pinnacle Reef Trend (abbreviated herein as PPRT) and are assigned their own reef member (Zeta Lake Member) within the Nisku Formation, Winterburn Group. The Zeta Lake Member is the subject of numerous diagenetic studies (Machel, 1985, 1986; Machel and Anderson, 1989; Machel et al., 2009) and resource “pool” studies (see, e.g., Chevron Standard Exploration Staff, 1979; Watts, 1987; Anderson and Machel, 1988; Bachu et al., 2008) focused on hydrocarbon production. These studies document attributes of framework reefs but have also introduced language associated with mud-mounds and lithoherms without exploring the comparison.

Pinnacle reef nomenclature advanced by early work on the Nisku buildups (Chevron Standard Exploration Staff, 1979) seems to have emerged from a combination of stratigraphic and paleoecological evidence, including (i) slope setting, (ii) that the structures are laterally encased with shale but overlain by ramp carbonates, i.e., avoided termination caused by flooding,
and (iii) these carbonates have a highly skeletonized, benthic marine (coral, stromatoporoid) and microbial biotic association traditionally interpreted as a shallow reef-building assemblage.

However, several features of the PPRT and of their (age-)stratigraphic equivalents around the Alberta basin hint at a diminished reef factory, particularly in the lower half of the Zeta Lake Member, and call into question the role of framework biota in buildup origin and aggradation. Anderson (1985) and Machel (1985) have examined diagenesis of the Nisku Formation in detail and documented several phases of early marine cementation that indicate a local similarity of the PPRT to mound-like structures (see also Machel, 1986). Krause (1984) noted the resemblance of early lithification of late Devonian carbonate mounds exposed in the Canadian Rocky Mountain Front Range to the lithification of Holocene deep-water lithoherms of the Little Bahama Bank (Neumann et al., 1977) and to mud-mounds documented by Wilson (1975). In that same paper, Krause extended the analogue concept to the PPRT and proposed that, “the Nisku reefs are lithoherms,” on the basis of several features observed in drill cores. Exact dimensions of individual reefs are difficult to resolve because of their subsurface location, but published estimates range between 80-100m thick, whereas width varies more substantially from several hundreds of meters to a few kilometers (Watts, 1987, and pers. comm., 2016). Consequently, PPRT buildups are dwarfed in size compared to those of the underlying lower Frasnian Leduc reef trend (Mossop and Shetsen, 1994) and in comparison to late Frasnian pinnacle reefs of the Devonian Canning Basin (Chevron Standard Exploration Staff, 1979; Watts, 1987; Playford et al, 2009). Core studies indicate that reef-building fauna present were mainly small, baffling corals and encrusting stromatoporoids that did not generate significant vertical synoptic relief (this thesis, Chapter 2), and therefore likely contributed little to overall rigidity and aggradation.
potential. These observations seem to indicate the PPRT is not a complex of pinnacle reefs *sensu stricto*.

The main aim of this paper is to re-examine and re-interpret the origin of the Zeta Lake Member buildups known as the Pembina Pinnacle Reef Trend. The PPRT is described using an approach that incorporates depositional carbonate (specific biota and coated grains) and carbonate resulting from syndepositional processes (stromatactis, spongiosalnikate structure) as defining facies criteria. The source of carbonate is compared from individual buildups across the proximal and distal portions of the slope. Specific attention is then given to the nature and relative importance of fine-grained microfacies, i.e., mud, in consolidation of the buildups and to an overall interpretation. Finally, aspects of paleogeography and the nature and origin of calcimicrobes are brought to bear on resolving the origin of the Zeta Lake Member buildups.

**Regional geology**

The prominent geological features concerning the Nisku Formation in this study are (i) the Cynthia-Winterburn intrashelf basin and its parent basin, the Devonian Alberta Basin extending south of the Peace River Arch (presently the central portion of the Western Canadian Sedimentary Basin as recognized now), (ii) a ~25 km long slope margin separating the Cynthia-Winterburn basin from the shallow marine Nisku platform, and (iii) the southwest-northeast oriented PPRT which extended from the proximal- to outer-slope, subparallel to the platform margin (Fig. 3.1).

The Winterburn Group (Fig. 3.2A) was deposited in the central Alberta Basin during the late Devonian, on the western margin of paleoequatorial Laurentia (Carmichael et al., 2019, and references therein). The Alberta Basin formed as a result of tectonic activity along the continental margin, characterized by numerous smaller basins, including the Cynthia-Winterburn
(a.k.a. Winterburn Basin, West Shale Basin). Miall (2008) has indicated that the Alberta Basin was intermittently separated from the (ancestral Pacific) ocean by the West Alberta Ridge to the west and by the Peace River Arch to the north for parts of the middle to late Devonian. The Alberta Basin hosted alternating organic-rich shale and shallow marine carbonates beginning in the middle Givetian and continuing through the end of the Frasnian (Pana et al., 2018). The late

Figure 3.1. Location maps. The Cynthia-Winterburn Basin is part of of the (A) Western Canadian Sedimentary Basin, Canada. B) Late Frasnian paleogeography (compiled from Switzer et al., 1994; Wendte et al., 1995; Potma et al., 2001; McLean, 2005; Bachu et al., 2008) is well-mapped largely owing
to well-control in the subsurface, except where constrained by deformation and uplift of the westernmost portion. Also shown are the location of the Pembina Pinnacle Reef Trend (PPRT), and the location of an isolated Nisku reef named Scion (SC) at the eastern margin of the Cynthia-Winterburn Basin. C) Carbonate buildups of the Zeta Lake Member, Nisku Formation strike in a southwest-northeast direction averaging 3-10 km distance from the platform margin. Margin location illustrated represents maximum shoreward deposition of the basinal Cynthia Member, Nisku Formation (Watts, 1987). Transect line A—A’ is detailed in Figure 3.15.
Frasnian Alberta Basin had three elements where sedimentation was in transition around the region of this study: (i) a siliciclastic shelf developed on the northeast carbonate platform, (ii) carbonate platforms along the western and east to southeast margins of the basin (Whalen et al., 2002), and (iii) an eastern shallow marine platform developed dolomitic and potentially evaporitic paleoenvironments (Mossop and Shetsen, 1994).

Maximum flooding in the Alberta basin occurred at the top of the Woodbend Group with deposition of ~100m of Ireton shale (Mossop and Shetsen, 1994) (Fig. 3.2A). Regressive deposits of the Nisku Formation floor the Winterburn Group. Paleogeographic reconstructions indicate this stratigraphic boundary resulted from the progradation of carbonate deposits over basinal sediments and initial siliciclastic influx in the northeast shelf margin (Potma et al., 2001). Johnson et al (1985) established the base of the Nisku Formation is correlative to the base of Devonian transgressive-regressive (T-R) cycle IIId.

**Nisku Formation Stratigraphy**

Stratigraphy of the Nisku Formation is complex and consists of several members that comprise a series of barrier and pinnacle reefs, platform interior carbonates, slope carbonates, fine-grained siliciclastic sediments, and basinal shales (Chevron Standard Exploration Staff, 1979). The Chevron Standard model documents two areas of reef deposition including i) a series of platform margin structures generally referred to as the Nisku Reefs and ii) a series of discrete downslope “pinnacle reefs” which they designate the Zeta Lake Member (Fig. 3.2B) and are the focus of this paper.

Carbonate facies in the lee of the shallow water Nisku Reefs are unnamed and consist of shallow subtidal to peritidal carbonates, and east-to-west prograding evaporites farther landward. Slope or ramp facies comprise three lithostratigraphic units, the basal Lobstick Member, the
middle Bigoray Member, and the upper Cynthia Member. These three members are largely composed of argillaceous and nodular mudstones to packstones with increasing upward siliceous siliciclastic background sedimentation and normal marine fauna. The whole package is overlain by the peritidal Wolf Lake Member.

**Terminology and depositional environments:**

1. Published interpretations invoke terminology of a ramp for the Lobstick Member and Bigoray Member, a basin for the Cynthia Member, and a reef for the Zeta Lake Member (Chevron Standard Exploration Staff, 1979; Anderson, 1985; Machel, 1985; Watts, 1987; Anderson and Machel, 1988; Mossop and Shetsen, 1994).

2. There are several carbonate depositional environments addressed throughout this paper. A schematic of these environments (Fig. 3.2C) clarifies their position and relationship to each other.

3. The principal aim of this investigation is to resolve the nature of the Zeta Lake Member, which has been historically characterized as a reef member, so to avoid carrying dual-labels or cumbersome language throughout the text, the buildups are referred to as “reef,” with immediately adjacent environment referred to as “inter-reef.” “Off-reef” should convey no proximity to the buildup.
Figure 3.2: Local Map with Wells, Stratigraphy. A) Subsurface stratigraphy of the West Central Plains, Alberta, modified from Hannah et al., 2018. B) Schematic of depositional environments applied to the Zeta Lake Member, composed from data from Chevron Standard Exploration Staff, 1979 and Watts, 1987. C) Reference diagram for terms and depositional environments relevant to the Winterburn Group.
Facies

This section presents facies established for the Nisku Formation carbonate buildups. Across the PPRT, buildups are internally composed of four lithologic associations: (i) tabulate and rugose coral bafflesstones and crinoid-pelmatozoan floatstones, (ii) calcimicrobial-coral floatstones and couplets of microbial-rich stromatoporoid and spongiostromate boundstones, (iii) coral and stromatoporoid floatstone with (iv) local reworked biofragmental packstones and rudstones and muddy carbonate. Data comes from core logs drafted for seven PPRT cores, totaling 546 meters from six reef wells and one off-reef well (Appendix B). This is complemented by observations made from an additional eleven PPRT cores and from location SC-1402 in the eastern Cynthia-Winterburn Basin (Fig. 3.1, Appendix A, B). Sedimentology was investigated using core observations, over 900 high-resolution core photographs, and petrographic examination and digital scans of 115 thin sections (Appendix C). Parameters for digital scans are indicated using bit depth (#) followed by red-green-blue (RGB) or greyscale (GRY). Eight samples representative of fine-grained material in the PPRT were selected for X-ray diffraction (XRD) analysis via micro-drilling (Appendix D). Twenty-one thin sections from SC-1402 were stained with alizarin red-S (ARS) for carbonate mineralogy. Detailed well locations and measured depths of each core are documented in Appendix A.

Facies were defined while logging using a combination of relative abundance of biota and the organization of matrix sediment using the following categories (Fig. 3.3A):

1. framework biota, includes metazoans (corals, stromatoporoids, bryozoans) and microbial carbonate (presence of calcified microbes)
2. non-framework biota
3. matrix organization, whether it appears normal (bedded, massive) or syndepositionally altered, e.g., grumeleuse, spongiostromate, stromatactis.
Figure 3.3 Facies components and environment. Facies in the Zeta Lake are expressed by two matrices. A) Individual components are organized left to right into associations of primary skeletal reef fauna (coral, stromatoporoid, bivalve), bioclastic and oncoidal material, and structured (bedded or disturbed bed) non-reef lithology. The latter group is typically fine-grained. These same groups almost uniformly host varying amounts of microbial and cemented carbonate, organized vertically here. $\text{CS}=$coral skeletal, $\text{CM}=$coral microbial, $\text{CSp}=$coral spongiostromate, $\text{StC}=$stromatoporoid coral, $\text{StCM}=$stromatoporoid coral-microbial, $\text{StM}=$stromatoporoid microbial, $\text{StMdCt}=$stromatoporoid, mud-rich and cemented, $\text{BclGd}=$bioclastic grain-dominated, $\text{OnGd}=$oncoidal grain-dominated, $\text{OnMd}=$oncoidal mud-dominated, $\text{BclMd}=$bioclastic mud-dominated, $\text{Silt}=$quartzose silt, $\text{LMa}=$laminated marl, $\text{FgLith}=$fine-grained lithoclastic, $\text{ClMd}=$clotted mud-dominated, $\text{ScCm}=$stromatactis pervasive coral mud-dominated, $\text{ScCSt}=$stromatactis pervasive coral-stromatoporoid. B) Facies are organized by process within the bounds of an environmental matrix. Depth of process relative to the seafloor (vertical axis) both impacts and controls seafloor topography, while degree of reorganization (texturally or compositionally) of sediment particles (on the horizontal axis) affects composition.

In most cases, the facies name reflects the primary biotic components, decreasing from left to right. When the matrix style is consistently altered, e.g., stromatactis is pervasive, or when biota are rare then the matrix style will appear in the facies name. While this method generated a considerable number of facies, twenty-one in total including off-reef facies, it allowed us to easily visualize in log form the change in relative abundance of framework and non-framework biota, and the distribution of extensive syndepositional diagenesis. Two factors that exert the most control over texture and composition of the Zeta Lake Member are environment of carbonate-forming processes with respect to the seafloor, and the degree to which skeletal material and other sediments become re-organized as they become rock particles (Fig. 3.3B).

A graphic summary of facies thickness and their Dunham (1962) composition (Fig. 3.4) accompanies a detailed description of the most distinctive reef facies as follows:

**Coral-skeletal and bioclastic mud-dominated facies (CS-BclMd)**

Facies CS-BclMd dominates the lower reef interval and generally decreases upward with proximity to the Cynthia Margin. This facies is mostly composed of fasciculate phacelloid and fasciculate dendroid rugose coral bafflestone with mudstone-wackestone matrix and bioclast floatstone (Fig. 3.5A) alternating at ~0.2-0.5 m intervals. A crinoidal-coral mudstone-wackestone matrix hosts large, scattered stromatactis as well as irregular-shaped pores
throughout. For the most part, matrix sediments lack bedding structures; rare horizons in
mudstone-wackestone are mm-scale deposits of planar to subtly cross-laminated carbonate that
indicate episodic deposition of fine material. Wackestones can grade into a mottled texture with
irregular layering interpreted here as biomicrite crusts *sensu* Pratt (1995) and hosts smaller
stromatactis and horizontal cavities filled with banded, isopachous calcite cement. Secondary
fauna include, in increasing abundance, nautiloids, homectenids (*Tentaculitid*), brachiopods, and
calcispheres.
Figure 3.4: Facies Characterization. Based on 546 m of measured section, including 470 m of reef section and 76 m off-reef, A) coral-skeletal and bioclastic mud-dominated are the most abundant and evenly distributed of 21 facies. B) Dunham texture among PPRT reef cores is mud-dominated, composed primarily of boundstone and floatstone with rare rudstone and other grain-dominated lithologies. Different colours apply to different reef and off-reef cores, at right.

Coral-spongiostromate facies (CSp)

This facies occurs in the lower and middle reef interval. The macro-texture of CSp is similar to CS facies however the matrix is compositionally distinct. In the CSp facies, skeletal particulates are present but not abundant and the matrix is spongiostromate, strongly resembling “structure grumeleuse” (Folk, 1962) sensu lato. Patches of clotted micrite and calcite spar form interwoven fabric more organic than geometric in appearance (Fig. 3.5B-C). Grumeleuse sensu Cayeux (1935) necessitates that micrite must be enveloped in calcite spar, whereas in Nisku reefs the proportion of micrite and cement often appear equal. Additionally, the boundary between micrite and cement is typically diffuse or indistinct (discussed in the Diagenesis section of this paper).

Coral-microbial facies (CM)

This facies occurs in the stratigraphic middle of the reef interval. It is composed of Renalcis-coral floatstone with local, small rugose and tabulate framestones rarely exceeding 1-3cm thick. Renalcis is patchy throughout the mud component of floatstone with rare Epiphyton. In the reef front position, open cavities throughout are rimmed with isopachous cement. Thamnopora boundstone with primary cavities occluded by isopachous cement are interbedded with Thamnopora-Disphyllum rugose-Renalcis rudstone-boundstone. Thamnopora are denser in rudstone than in the floatstone.
Figure 3.5: Framework facies representation. These facies vary in abundance of coral boundstone to floatstone and stromatoporoid boundstone. A) Fasciculate rugose coral with between particle (BP) porosity in a mud-matrix (M) with rare laminated sediment (LS) (BGB-1209, 2368.15 m). B) Isopachous cement (IC) in dendroid rugose boundstones with a spongiostromate mud (M) matrix and stromatactis (Stc) (SC-1402, 1474.7 m). C) Spongiostromate matrix in auloporid coral bafflestone displays episodic sedimentation between (a) graded biomicrite and (b) automicrite with “cauliflower structure” (Pratt, 1995) (BGB-1209, 2333.5 m). D) Laminar Stachyodes sp. stromatoporoid (St) boundstone with a spiculitic ghost (Sg) matrix (BGC-0612, 2393.72 m). All images are digital scans of covered thin sections, 16#RGB.

Stromatoporoid-calcimicrobial (StM)

This facies occurs in the Zeta Lake strata of the PPRT and is also reported from Meekwap Shelf (Bingham-Koslowski, 2010). In the PPRT, the first occurrence of StM facies is in the middle of the Zeta Lake Member. StM facies has several lithologies. One is a laminar stromatoporoid mud-dominated bindstone and packstone, macroporous with sparse cement. Corals are present but volumetrically insignificant. The second lithology is a Renalcis-
stromatoporoid bindstone with laminar or dendroid stromatoporoids, *Amphipora sp.* and *Idiostromid sp.*, interbedded with *Renalcis*-coral floatstone. In this variant, there are two occurrences of *Renalcis*: 1) stromatoporoids form wavy laminar boundaries with *Renalcis* as pendant undergrowth, or 2) *Renalcis* occurs in significant volumes as a matrix component, forming massive boundstone. The matrix is reworked, fine-grained skeletal hash and coral fragments, with between particle cement. Locally, small boundstones of rugose as well as tabulate coral occur. Open cavities throughout are rimmed with isopachous cement.

The third lithology of this facies has domal-digitate stromatolite and digitate stromatoporoids at its base with thin, crinkly laminated microbial beds at top. Rare molluscs are intact and very small, filled with cement; rare coral fragments are present. Abundant vugs and some small stromatactis can be open or cemented. *Renalcis* is noticeably rare in this variant, relative to underlying units but microbial growth is apparent in stromatolites with micrite and *Girvanella* or *Rothpletzella*.

**Bivalve-coral-stromatoporoid facies (BiCSt)**

BiCSt facies is an intercalation of coral-stromatoporoid boundstone-floatstone, stromatoporoid-microbial boundstone, or bioclastic rudstone—with the addition of megalodont bivalve molds (Fig. 3.6A). Molds are cemented with calcite. When calcimicrobes are present they may have encrusted the bivalve shell top, intraparticle pore space, or shelter cavities created by the shell. More properly a bed or event, BiCSt was only ever observed once in each section of the Zeta Lake Member. BiCSt increases in thickness downdip, from ~1.3 m to ~9.8 m. Comparing proximal slope and distal slope buildups, this unit steps slightly upward stratigraphically, from 55 meters when measured from the top of the Nisku Formation at location BR-0327 to 33 meters at location BGC-0612. At the most downdip core that was logged, BGI-
both the bivalve unit and stromatoporoid-facies are absent. No bivalve unit was observed in inter-reef cores.

**Bioclastic grain-dominated facies (BclGd)**

Bioclastic grain-dominated facies are composed of a variety of carbonate wackestone-floatstones or carbonate sands and gravels (Fig. 3.6). One variation of BclGD is a skeletal grainstone-rudstone interbedded with oncolite rudstone with interparticle fill that alternates on the cm-scale between predominantly calcite cement and predominantly micrite. Smaller grains are reworked, well-rounded rugose and tabulate coral clasts; skeletal particulates of (in decreasing abundance) brachiopods, bryozoans; and small (mm-scale) molluscs or mollusc molds. Brachiopod shells locally have geopetal sediment and isopachous (calcite) cement. Intraclasts of skeletal grains form oncolite nuclei. Beds are high angle with faint, contorted lamination apparent. Discrete thin beds of carbonate mud occur but are stylolitic and brecciated, as are the contacts between the rudstone and mud.

The second variation of BclGd facies is an intraclast-skeletal rudstone to grain-dominated packstone. The matrix is commonly green-coloured carbonate with a clay-like appearance. Semi-vertical dikes of massive clay are also present. Grains are all well-rounded.

A third and less common variant is a rudstone composed of massive tabulate corals (mainly *Thamnopora*), molluscs, stromatoporoids, and lithoclasts. This high-diversity skeletal rudstone has ubiquitous isopachous pore-filling cement. Clasts are poorly sorted with respect to fauna, and are angular to sub-angular. This lithology is occasionally interbedded with coral-skeletal facies near the top of the lower reef unit, or, more frequently, as thin beds associated with stromatoporoid-calcimicrobial facies.
Figure 3.6: Bioclastic facies. True grainstones are rare in Zeta Lake strata. Most bioclastic, i.e., non-framework facies are composed of mud-dominated packstone. A) Rare cemented rudstone with pore-filling cement such as in a bivalve (Bi)-skeletal rudstone with inverted grains (In) (BGB-1209, 2322.1 m).
B) Early marine isopachous calcite cement (IC) separates stages of oncolite growth between the (a) microbially coated coral-nuclei and (b) encrustation by metazoans in a bioclastic floatstone (BGD-1404, 2487 m). C) Typical mud-dominated packstones of the upper Zeta Lake Member have an normal marine biota with brachiopods (B), ostracods (Os), with both rugose and tabulate corals (C), *Thamnopora* (Tha), *Thamnophyllum* (Thl) (SC-1402, 1445.2 m, stained with ARS). D) Inset from C, *In-situ*, small encrustations of metazoans suggest intermittent sedimentation and displays close relationship between encrusting stromatoporoids (St) *Stachyodes* ?*Verticillata*? and encrusting auloporid (Au) corals with only mm-scale relief. Affinity in D uncertain, due to similarity between some stromatoporoids, inozoan sponges and chaetetids, but low diversity of the latter two pre-Carboniferous (Senowbari-Daryan and Rigby, 2011) suggests this a most likely a rare section of stromatoporoid. All images are digital scans of covered thin sections, 16#RGB.

Among all cores in PPRT, beds of the grain-dominated facies are thin. We do not have data on lateral distribution but in general BclGd appears to fill between carbonate crusts or small framestones. Noticeably absent from grain-dominated facies are internal lamination and ooids.

**Internal Deposition and Diagenesis**

**Laminated pore fill**

Laminated, fine-grained carbonate (<60 μm) is an overall rare but locally abundant source of pore fill in the reefs (Fig. 3.7). Planar- to subtly cross-laminated sediment composed of carbonate, clay, and silica occurs in shelter porosity created by fasciculate corals. In shelter cavities, laminated sediments often have a curved, concave-up basal surface. Mud-supported pores containing laminated sediment are common in coral-skeletal facies and coral-spongistromate facies; these pores are thinly lined (>1 mm) with opaque calcite cement that pre-dates laminated fill.

**Internal sediment**

Newell (1955) referred to pore-filling sediment as a secondary deposit. Ginsburg and Schroeder (1973) used the term “internal sediment” to name the intergrading textural types of sediment found in the pores of algal cup reefs. Nisku buildups have pore-fills that are uniform.
and very well-sorted, such as laminated pore fill, and those which are less sorted but still have multiple layers of fine fractions—each of a different composition that grades vertically into the next. Therefore, although lamination can and does occur within internal sediment, we consider intergrading as a defining feature of internal sediment and separate it from “laminated pore fill” previously described.

Mud- to fine-sand-sized carbonate composed of micrite, peloids, or spar are ubiquitous in shelter cavities, secondary pores, and open cavities. Occasionally microfossils or microbioclasts are present. Intergrading is characterized by diffuse boundaries in textural maturity and in composition. These sediments form units that are mm-scale to sub-mm in scale. Units often lack a recognizable, overall coarsening or overall fining direction. The cement-to-grain ratio is locally high at the mm-scale, creating the appearance of cement layers with occasional skeletal fragments in float.

**Spongiostromate Texture**

“Spongiostromate” is used here as a textural description for densely organized micrite bearing a spongy texture and usually hosting loosely organized sub-cm pores. The organization of pores and micrite is very rarely laminated, and when present the laminations are poorly developed, therefore spongiostromate used herein does not imply a genetic similarity to spongiostromate oncoids (Flügel and Munnecke, 2010) in which the pores are organized into lamination-like structure (see Fig. 3.5).

In the Zeta Lake buildups, spongiostromate texture occurs almost exclusively in the matrix of coral boundstones-floatstones. Similar to grumeleuse structure, spongiostromate are characterized by clots of micrite surrounded in whole or in part by cement. Boundaries between micrite clots and cement are diffuse. Spongiostromate texture is frequently intergradational with
structureless micritic mudstone. Cement-filled pores arranged in the pattern of sponge are rare. It is more common that mudstone hosts mm-scale, cement-filled pores with irregular geometry. Where skeletal particles are present, these pores do not cross mud-allochem boundaries and so cannot be considered vugs in origin. At hand-scale, spongiostromate texture is most easily recognized by the presence of mud-supported cavities. Petrographic work revealed that a clotted texture is more prevalent than recorded at the core scale. Spongiostromate texture is noticeably absent from mud-dominated textures that have lamination, including cavity fills with laminated internal micrite. Taken together, the distribution of pores, clot-to-cement diffuse boundaries and the absence of spongiostromate texture in laminated carbonate suggest that spongiostromate texture results from internal re-organization of organic framework micrite, most likely during early- to syn-depositional diagenesis.

**Banded and isopachous calcite cement**

Banded calcite cement is prevalent in pinnacle reef cores in a variety of facies. Banding is composed of alternating opaque-creamy and medium-brown layers of radiaxial fibrous calcite (RFC) to clear, bladed calcite. Individual cement layers average 0.1-0.4 cm thick. Most notably, isopachous, banded calcite occludes framework porosity in bafflestone with branching rugose and tabulate corals (see Fig. 3.5, 3.7). The contact between fibrous calcite cement and matrix mud is typically characterized by a transitional zone composed of micrite cement and spheroids of unknown origin. Outside of the bafflestone lithology, banded calcite tends to only partly occlude framework or shelter pores in stromatoporoid and coral-stromatoporoid rock types having dominantly horizontal skeletal growth forms. Isopachous calcite without colour-banding occurs in stromatactis voids (discussed below). The relative abundance of massive isopachous calcite was logged at the core scale. Based on that data, banded calcite generally decreases
upward, moving from the lower reef interval to the upper-reef but abundance does not appear systematic or facies selective. Paragenesis and geochemistry of calcite cements from the PPRT indicate a submarine isotopic composition for radial-fibrous cements with strontium levels comparable to Devonian seawater (Anderson, 1985; Anderson and Machel, 1988). Recent analyses of banded calcite cement from SC-1402 (pers. comm., Weldeghebriel, M.F., 2019) yielded elevated salinity values consistent with re-equilibration of primary fluid inclusions in the burial realm.

**Stromatactis**

Stromatactis cavities occur throughout the reef. These are sub-cm scale, with a planar-horizontal or planar-curved base. The roof geometry is varied. The roof is typically a combination of irregular and locally digitate; some cavity roofs are fully diffuse into overlying sediment. There are isolated and anastomosing cavities. Vertically anastomosing cavities are connected by sub-horizontal, spar-filled veins that usually originate from diffuse roofs; in many cases, anastomosing cavities have a shingled arrangement. Anastomosing is most common in coral-bafflestone facies having a green-grey mud matrix, and in coral-skeletal facies.

Sheet stromatactis is rare in Nisku buildups, but appears to occur in two populations: 1) macroscale sheets (cm-scale) were observed only in the upper (proximal) slope (location BR, Fig. 3.7), while 2) microscale (mm-scale) sheets are more prevalent in downdip.
Figure 3.7 Characteristic diagenetic features. In the Zeta Lake Member, A) isopachous calcite, typically RFC, entombs corals in a framestone-bafflestone with spongiostromate mud matrix. B) Sheet stromatactis in an inner-reef setting on the proximal slope. C) A colonial rugose coral and Renalcis-thrombolite boundstone community host ramose stromatoporoid. The large framework cavity created by the sponge is partly filled with laminated internal sediment. It was likely completely filled before burial dissolution. D) Coral bafflestones commonly host laminated sediment in shelter cavities and cream- to brown isopachous calcite cement which predates burial fracture cemented with coarse calcite. E) A typical megalodont bivalve and reworked skeletal facies is heavily cemented and lacks the fine-grained sediment fill that accompanies isopachous calcite in other (framestone) facies. All images are of core slabs. White scale bar is equal to 1 cm in each image.

Cavities

Framework cavities other than stromatactis that are indicative of syndepositional relief are common in the Zeta Lake Member. Cavities are filled with any combination of the following four components: i) banded, isopachous calcite cement, ii) equant calcite cement, iii) internal sediment (automicrite), iv) skeletal calcimicrobes. These fill-components frequently occur together within cavities, e.g., pendant Renalcis is followed by banded, isopachous cement, followed by internal sediment. Additionally, the order (timing) of various fill components can vary within single facies in a reef section in the space of a few centimeters. In particular, the order of internal sediment and creamy calcite cement is commonly transposed, and, while rare, there are instances of multiple generations of cement and internal sediment in larger framework cavities. Exceptions to multi-component cavity fills occur in the most heavily cemented portions of the reef where banded isopachous cement occludes all primary pore space.

Carbonate crusts

Carbonate crusts are typified by a vertical succession of skeletal carbonate, biomicrite, and calcite cement. This feature is interpreted as a crust because it is composed of biotic and abiotic calcite organized in laminar form. Thickness of the crust ranges from 3 mm up to 3-5 cm. Carbonate crusts are distinguished into two types here based on thickness for purposes of description:
1. Type A: Crusts ~1-5 cm thick are rare and localized. Individual components are laterally discontinuous, yielding a sutured appearance. *In-situ* crusts of this size are also boundstones *sensu stricto*.

2. Type B: Crusts <1 cm thick are abundant. In the lower reef these develop at the top of graded biomicrite. In the upper Zeta Lake Member, a biotic “crust” often develops from a vertical succession of encrusting organisms with intervening cement (see Fig3.7C). Well-developed carbonate crusts form when biomicrites are superceded by an interval of pervasive calcite cement and new framework biota. Less developed crusts arise from the superposition of biomicrite and micrite cement or from emerging cavity cements such as stromatactis (see Fig. 3.5C). Petrographic examination reveals that extremely thin crusts, in the <2-5 mm thick range are polytaxic, having multiple generations or “laminae” of encrusting stromatoporoid, coral, micrite, and calcite cement. This type of crust occurs in two host lithologies: 1) poorly-sorted wackestone-floatstone, medium to dark brown, with gravel-sized coral clasts, typically *Thamnopora*, and molluscs with subsidiary fossil fragments, and 2) well-sorted floatstone, typically light brown, with gravel-sized clasts of crust in a *Renalcis*-micrite-cement matrix.

Crusts can appear horizontal to bedding or noticeably at high angles. Type A and B crusts exhibit rare rip-up corners. Local concentrations of Type B crusts at high angles indicates these biotic features were indurated early enough to respond as clasts under erosion.

**Dolomitization**

Much of the Pembina reef trend in the southwest of the study area is extensively dolomitized, while in the northeast dolomitization is local and tends to be fabric retentive. The origin of dolomitization in the Nisku Formation has been investigated in numerous studies.
(Machel, 1985; Machel and Anderson, 1989; Potma et al., 2001; Machel et al., 2009). Current understanding from these studies is that there were as many as three dolomitizing events that impacted pinnacle reefs in this region although the nature of dolomitizing process in the Nisku Formation are debated. The reader is referred to the works above for additional information on dolomitization events.

Reef Evolution

Ramp-to-reef transition

Immediately above the organic- and marl-rich bioclastic-nodular wackestones of the ramp environment is a coral-pelmetazoan wackestone-floatstone of the CS facies. Core coverage is particularly limited at this depth in the limestone area of the PPRT so the thickness of this coral-pelmetazoan unit is unknown. The unit has indications of minimal reworking and of lags in sedimentation: many of the crinoid particles are plates with minor alteration, some possess micritized rims, and biogenic boreholes are sometimes present. Boreholes are typically filled with coarse, equant calcite spar. Coral bioclasts are larger than most of the crinoid plates. Coarse silt-sized peloids accumulated in coral zooecia and these are almost without exception geopetal in nature and filled no more than half of the available vertical space.

This unit is indicative of reef initiation as a crinoidal-rugose coral bioherm environment. Watts (1987) interpreted this unit as an “incipient reef,” and distinguishes it from the overlying “deep reef,” including both units in the Lower Zeta Lake Member. Most simply, the organic-rich marl and wackestones of the lower Nisku ramp members indicate a period of eutrophy and limited carbonate production by heavily calcified organisms. The depositional environment for the initial biosparite units was likely a broad, low-relief bioherm with intermittently moderate energy, consistent with a mid- to outer-ramp.
Slope Geometry During Reef Aggradation

Interpreting the Nisku reef environment in terms of water depth is complicated for two reasons. First, the reefs are laterally encased in basinal sediments but were never covered by them, i.e., it appears that reefs kept up with relative sea level increase throughout deposition of the Cynthia Member. Second, depending on one’s interpretation of the trophic requirements of Paleozoic corals and stromatoporoids and whether they were strongly dependent on light, the Zeta Lake Member has both deep-water and seemingly shallow-water aspects. The implication is that the Zeta Lake Member could be a record of either a shallow-marine reef which achieved high synoptic relief and kept up with rising sea level, or the opposite, a deeper-water reef which only needed to keep pace with relative sea level rise.

In this case, more regional information about basin geometry might improve understanding of the conditions which the Zeta Lake Member reefs grew.

Regional seismic interpretation indicates a low-relief, accretionary margin (Watts, personal communication 2017); this is supported by an absence of bypass sedimentation and absence of other features indicative of a steeper, escarpment-type margin at the seismic scale. Anderson (1985) attempted to reconstruct the dip of the slope underlying the Pembina reef trend using regionally well-defined stratigraphic markers. He calculated an initial dip of 0.1 degrees, but he and other workers (Watts, 1987; Stoakes, 1992) have suggested that the Nisku ramp became distally steepened sometime during the deposition of the Cynthia Shale Member, increasing in dip up to 2 degrees. It seems unlikely that the ramp dipped <1 degree, even initially, since it is downdip of the platform margin. A survey of ramp and slope models with similarities to the Nisku Formation includes the following: 1) the shallowest, accretionary-type margins dip at 1-2 degrees; carbonates with lower slope bioherms average 5-10 degree dip; mud
and mud-supported depositional fabrics support slopes between ~3-12 degrees (Tucker et al., 1990; Kenter et al., 2004; Flügel and Munnecke, 2010; Schlager and Purkis, 2015).

To reconstruct water depth at the time of maximum deepening, we 1) assume uniform dip across the slope and 2) retain mapped rugosity in the Cynthia Member margin location, but use the shortest distance measured between buildup locations and the margin. Wells in this study penetrate pinnacle reefs that were grouped in distance from the Cynthia basin margin as follows (see Fig 3.1 for location map): BR at 3 km, PM at 7 km, PBT at 10 km, BGD and BGB at 16 km, and BGC and BGI at 20 km. Water depth (A) is calculated using the tangent of the angle of slope (Θ), and the distance from margin to reef (B), as follows:

\[ \tan(\Theta) = \frac{A}{B} \]

Some remarks must be made here as to the utility of a trigonometric model in the investigation of ancient water depth, which might appear crude or inelegant. This approach is chosen because it is the simplest mathematical model with the least geologic uncertainty. Other approaches back strip sedimentation, rely on rates of sea-level rise, rate of carbonate production, or amount of compaction during burial: these are assumptions. The assumptions in this trigonometric approach are that reefs grew normal to the seafloor (straight up) and that the dip was uniform across the ramp. If the slope is distally steepened, the depth difference across the slope would only increase as the basin filled. Lastly, we could assume a platform water depth of 3-5 meters given the shallow-subtidal nature of the lower Nisku platform sediments; this amount seems reasonable, since it does not exceed the typical reach of fair-weather wave base, however the platform depth becomes increasingly negligible as dip of the carbonate slope increases.
Figure 3.8: *Dip model for PPRT buildups across the slope.* For buildups located 3-20 km from the Nisku platform margin during deposition of the basinal Cynthia Member, concurrent with the Zeta Lake Member, a modeled dip is plotted A) linearly and B) in a log form. Water depth (km) is calculated for slope dips ranging from 0.1° to 10°.

**Model Results**

There is a calculated difference of approximately 7X between the pinnacles at 3 km from the margin and those at 20 km from the margin. Because the margin-to-reef distance is fixed, the depth difference of 7X between inner- and outer-slope would not change when the angle of the slope is adjusted under a uniform dip model. Thus, even at absurdly low slope angles <0.2 degrees, and if the Nisku platform were a peritidal environment behind the margin (at 0 m relative sea level (RSL)), water depth would range from ~10 m on the upper (proximal) slope to ~70 m at the outer (distal) slope (Fig. 3.8). Assuming a modest slope dip of 2 degrees, water depth during deposition of the Cynthia Member would have increased dramatically to ~105 m on
the inner (proximal) slope and ~698 m on the outer (distal) slope. In either case, the distal slope was between seventy to a few hundred meters at its deepest.

**Fines**

Among six nearly continuous reef cores in PPRT, the texture is 7% grain-dominated, 59% mud-dominated, and 34% boundstone lithologies¹ based on measured thickness (see Fig. 3.3B, Appendix E). Typically, boundstones in the Zeta Lake Member possess a low skeletal framework to matrix ratio and are predominantly micrite or other fine-grained carbonate by volume (Stagner et al., 2018, and Chapter 2, this volume), therefore the characterization of sediment using Dunham texture alone likely underrepresents the significance of mud in this system. For these reasons, an evaluation of fine-grained carbonate in the Zeta Lake Member should be key to any interpretation of buildup origin. This section establishes microfacies for fine-grained carbonate that composes mud-dominated lithologies and matrix in framework lithologies.

Petrographic samples for microfacies were selected with the following criteria: 1) matrix has carbonate particles of mud or silt size, with no restriction on allochem size, and 2) sediment forms the matrix of metazoan-boundstone or a mudstone-floatstone that bears reworked framework metazoans. Criteria used to distinguish microfacies are texture, indication of biogenic silica (ghosts of siliceous spicules), terrigenous silica (angular, typically silt-sized quartz), microbial presence (calcimicrobial clots, coatings, or particles or filaments of calcimicrobes), (auto)micrite, and (micro)spar. Components were evaluated semi-quantitatively in thin section using Baccelle and Bosellini comparison charts (in Flügel and Munnecke, 2010) with their

¹ Percentages based on a total 470 m measured section, exclusive of 4 m missing core at location BR-0327 and 1.2 m missing core at location BGI-1320.
presence ranked as rare (estimated <5%), moderate (estimated 5-20%), or abundant (estimate >20%). All grains and skeletal clasts are described using the Wentworth classification. Where appropriate, the terms calcilutite, calcarenite, and calcirudite are used to indicate lithologies composed of transported or reworked grains, although this should not be construed as substantial transport, e.g., transport from off-reef. Using these criteria, four microfacies of fine-grained carbonate (Fig. 3.9) are identified as primary components in the buildup. These microfacies are described below as Mud 1 (M1) through Mud 4 (M4), and an interpretation follows.

**Microfacies**

M1 is a microbial-peloid calcilutite to calcarenite (Fig. 3.10). This lithology is characterized by a matrix of intergrading microbial-peloids and sand-sized masses of *Renalcis* and lesser *Rothpletzella* and *Epiphyton* enclosed in a spar matrix. Rare faunas are predominantly medium to coarse sand-sized ostracods and coarse sand-sized coral fragments. Additional unidentified skeletal grains appear to have undergone textural inversion. Peloids are poorly sorted ranging from medium silt- to very fine sand-sized, sub-rounded to well-rounded; these are composed of mud or microbes. Additional silt-sized particles of microbes are disseminated throughout. Interparticle calcite cement locally accounts for >50% of rock volume but averages ~20-25%. This grades from inclusion-free mosaic spar to dark, cryptocrystalline calcite. Cement surrounding microbial masses varies in thickness but is demonstrably thicker than cement domains enclosing peloids and skeletal fragments. Crude lamination is apparent in hand sample, but in thin section this appears to result from the local concentration of cement vs. allochems, rather than systematic variation in grain size.
Figure 3.9: Characterization of fine-grained carbonate microfacies in PPRT buildups. Microfacies were defined by the presence of ten components which aim to determine the importance of *in-situ* carbonate production. The relative abundance (abundant, common, rare) of compositional and textural components are illustrated for each microfacies, Mud 1 (M1) through Mud 4 (M4).
M2 is a siliceous (quartzose) microbial bioclastic calcarenite to calcilutite. *Rothpletzella*-coated coral clasts are the largest and most abundant skeletal carbonates (Fig. 3.11). Invertebrate fossils vary in abundance and size and include *Thamnopora*, syringoporids, solitary rugose corals, crinoids, stromatoporoids, tentaculitids, and other unidentified microfossils; fossils are only occasionally fragmented and are texturally immature. There is no indication of micritization or microbial coating on non-coral fossil components, however there are partially developed, asymmetric oncolites. The matrix is composed of randomly oriented, sub-angular quartz silt, clotted peloidal micrite, and *Rothpletzella* particles. Occasional hemispherical features resembling round borings or dissolved thin shells have geopetal fill that grades upward from dense micrite into matrix sediment. Intraparticle pores of corals are fully occluded with 1) matrix material or 2) finely crystalline druse lining the pore and later equant calcite. Micrite matrix locally intergrades with interparticle cement, either forming or following subtle lamination. Except for corals, all fossil fragments and matrix micrite have evidence of chemical alteration, including etched skeletons, indistinct grain boundaries, and relic structures. Internal sediment is rare.

M3 is a spiculitic microbial micritic mudstone-wackestone (Fig. 3.12). In hand sample, this lithology is a green-grey, stromatactoid-rich, dense micrite that is locally fossiliferous. *Rothpletzella* is the main source of microbial sediment. Strands of the microbe are easily detected in thin section and are disseminated throughout a dull, slightly ferruginous matrix. More
numerous than strands are the individual “pearls” of *Rothpletzella*, which may be disarticulated strands or strands in tangential section. These pearls can locally compose up to 35-40% of the sediment volume. Skeletal carbonates that make up less than 10% of the rock volume are mostly tentaculitids with subordinate radiolarians and unidentified molluscs. Calcite-cemented ghosts of mono-axial and tri-axial sponge spicules are common and also disseminated; there is no evidence that spicules were localized around pores or other fossils.

Figure 3.11: PPRT mud Microfacies 2 (M2). M2 is a siliceous microbial bioclastic calcarenite to calcilutite. A) Smaller reworked corals (c) form the matrix; microbially (M) coated corals (C), bioclasts (BC), and oncolites (O) are typically coarser-grained (SC-1402, 1458.25 m). B) Is an inset of A, displaying a range in distribution of fine-grained quartz, interpreted as terrigenous silica (TS) in intraparticle pores of a Rothpletzella (Rth) coated rugose coral, and matrix with peloidal micrite (MP). Image A is a digital scan of thin section, 16#RGB; image B is photomicrograph, PPL.
Figure 3.12: PPRT mud Microfacies 3 (M3). M3 is a spiculitic microbial micritic mudstone-wackestone. M3 has an organic appearance with a A) dull, dark automicrite, Rothpletzella (Rth) and
Wetherdella (W) particles, photomicrograph, PPL. B) locally abundant vugs and spicule ghosts with Wetherdella, photomicrograph, PPL, stained with ARS. C) Host rock of image A is dense micritic mudstone with stromatactis and a spongiostromate texture, digital scan of thin section 16#GRY. D and E) Coral-microbial boundstone is composed of M3 with spongiostromate texture that grades into stromatactis and micrite cement (MC), and rare in-situ corals coated with Rothpletzella and Wetherdella. This consortium demonstrates the direct relationship and timing between biotic and abiotic carbonate. Image D is photomicrograph, PPL, stained with ARS; image E a digital scan of thin section stained with ARS, 24#RGB. Location BGB-1209.

M4 is a microbial-micritic mudstone-floatstone (Fig. 3.13). This is the most compositionally mature of the mud-types. Renalcis clusters float in a structureless, automicrite matrix. The matrix is medium- to dark-brown with subtle colour contrasts reflecting crystal size. If Renalcis clusters are large enough, generally >0.3-0.5 cm, they stand out to the naked eye in core as cream-coloured clasts. Stromatactis and vugs are present in M4 but not as common as in M3. Invertebrate fossils are rare to absent; if present, they are typically crinoid plates or rugose coral fragments with local encrustations of Rothpletzella. M4 sediments have a unique affinity relative to other microfacies: this mud type appears to adhere to under-surfaces of certain skeletons and the edges of other lithologies in a manner similar to micritic cement or microbial coatings on reef knobs; it can form thin, structureless beds. Finally, M4 also locally fills syndepositional slumps and dikes, but is never observed as intraparticle fill within in-situ or reworked skeletal components.
Figure 3.13: PPRT mud Microfacies 4 (M4). M4 is a microbial micritic mudstone-floatstone. **A** In a stromatoporoid-coral boundstone, M4 is only mud matrix and hosts primary voids (V). In this case the void fill, both internal sediment (IS) and overlying cement, are diagenetically altered but the microbial mudstone matrix is not. Digital scan of thin section 24#RGB, location PBT-1112. **B** Taken from a serial thin section in coral floatstone, there are two generations of M4: on the left, lining a dissolution feature and showing clotting at the boundary, and on the right, a primary mud hosting shingled stromatactis (Stc) that are contemporaneous with mud, and other, later dissolution voids (V). Digital scan of thin section stained with ARS, 24#RGB. Location SC-1402.

**Interpretation of Mud Microfacies**

A major challenge in the interpretation of reef microfacies is the question of how to treat microbial components: are they *in-situ* or not, and did their presence affect the formation of rock? We take the majority view that the processes of binding and facilitating cementation that are routinely attributed to cyanobacteria broadly and to skeletonized microbes are applicable to the ancient record, and address the implication of this decision in the discussion section of this paper.
M1 and M2 are interpreted as reworked biogenic sediments. Grain inversion, partial micritization of skeletal clasts, abundant interparticle cement, and geopetal fill grading to matrix are all indicative of syndepositional diagenesis consistent with time spent on the seafloor. These aspects of M1 and M2 resemble hardgrounds (Wilson and Palmer, 1992). The significant difference between these reworked microfacies is grain assemblage: M1 is microbial-enriched and low skeletal diversity, while M2 has the highest skeletal diversity of all the mud-fabrics and has terrigenous siliciclastics. Poor sorting, peloidal abundance, and paucity of open-marine fauna in M1 suggest a lower energy, restricted or basinal origin, with deposition likely from suspension (Pratt, 1995), while the skeletal diversity, microbial-coated grains, pseudo-oncolites, and quartz in M2 suggest dynamic—and likely higher—energy and a more robust carbonate environment on the seafloor, with deposition controlled more by hydrodynamic forces on the seafloor.

M3 and M4 are interpreted as organic framework in origin. They differ in microbial-population: M3 is Rothpletzella-dominant whereas M4 is Renalcis-dominant. The distribution of calcimicrobes throughout M3 and M4 is randomly dispersed, unlike when they encrust specific organisms, and is likely unrelated to hydrodynamic activity or settling, consistent with in-situ colonization of the sediment. M3 and M4, respectively, are analogous to Pratt’s (1995) i) biomicrite with stromatactis and ii) sessile metazoan-associated thromboids, which he describes as microbial fabrics that construct organic framework in lower-energy, deep-water reefs or deep shelves. Together M3 and M4 represent nearly all matrix sediment within in-situ coral lithologies of the Zeta Lake Member, while only M4 is prevalent in stromatoporoid-microbial facies here and in bioherms from the Meekwap Shelf (Bingham-Koslowski, 2010). Mountjoy and Riding (1981) describe a fenestral-renalcid micrite-wackestone from foreslope bioherms that also occurs
with stromatoporoids (Southesk Formation, surface-exposed equivalent to west Cynthia-Winterburn Basin), which we suggest corresponds to our microfacies M4.

**Interpretation of Zeta Lake Member buildups**

Considering facies composition and syndepositional alteration (summarized in Fig. 3.14) with distribution of facies across the PPRT (Fig. 3.15), growth of Zeta Lake Member buildups is divided into two phases, represented lithologically by a (Phase I) mud-mound core and (Phase II) reef top.

*Figure 3.14 Relative abundance of the skeletal, microbial, mud, and cement components in Zeta Lake Member pinnacles.* The relative abundance of primary building components are summarized in line-graph form based on the general distribution of facies observed in drill core and detailed petrographic examination. Fine-grained microfacies are indicated by M1-M4.
Figure 3.15: Zeta Lake Member internal stratigraphy. Facies (left track) and relative abundance of isopachous cement (right track) are plotted for BGD-1404 and BGC-0612, representing buildups from the middle slope and distal slope. Isopachous cement increases in relative abundance from 1 to 3. Phase I and Phase II of the Zeta Lake Member are separated by a bivalve-metazoan bed that is present in all reef cores studied except BGI-1320, highlighted here (grey). Note that Phase I and Phase II do not have exclusive facies but are defined by a general shift in facies away from baffling communities toward constructor-binder communities (see Chapter 2, this thesis) and a variety of syndepositional and diagenetic features, listed. (Facies colors same as Fig. 3.3)

Growth Phase I—Mud-mound Core

The mound-core interval deepens upward from ramp to a mud-mound environment.

There are multiple lines of sedimentological evidence that guide interpretation of a mud-mound core: 1) baffling corals are mainly in-situ but typically <1-2 cm high, and primarily <1 cm high; 2) when reworked, corals are frequently encased by a <1 mm thin coating of Rothpletzella only, and only rarely develop into oncoids typical of ramp strata in the lower Nisku Formation; 3) other skeletal organisms larger than microfossils are an open-marine fauna that—with the exception of those in microfacies M2—conspicuously lack micritization or obviously microbial-coatings; 4) an association of grumeleuse and spongiostromate texture, stromatactis and calcimicrobes in in-situ boundstone is analogous to polymuds; and 5) microclastic micrite, calcimicrobes, and microspar are the main source of matrix carbonate.

This deep-water microfacies in the mud-mound core and reconstruction of minimum water depths associated with maximum transgression support an interpretation of below fair-weather wave-base during Phase 1. The evidence suggests that both skeletal and microbial activities contributed to local production and accumulation of sediment but that the benthic carbonate factory is mostly driven by the production and distribution of non-skeletal, mud-sized carbonate rather than the production of skeletal calcite. Organic framework in the core is envisaged as a multi-step process where 1) initially superstratal relief on the order of centimeters or tens of centimeters was created by colonial corals in a meadow-style, after which 2) relief was
filled and additional constratal relief created through microbial carbonate production, and trapping and binding of micrite by the same community. We envision the mound-cores as a series of smaller, stacked bioherms with mud-mound features that expanded laterally while coalescing upward. Two age-equivalent mud-mounds from the nearby Mount Hawk Formation (MHF) (Rocky Mountains, AB) are 46-53 m thick and 38-72 m wide (Zhou and Pratt, 2019). Thus, bioherms of the lower Zeta Lake Member are within the range of the MHF mud-mounds but the width of Zeta Lake buildups is an order of magnitude greater. This can be explained by expansion of lower Zeta Lake mounds across the toe of slope into an oceanographic feature that was tens of kilometers long.

During Phase I, the relationship between corals and microbes during was implicit. In each drill-core studied here are 10s of meters of in-situ coral that, with few exceptions, notably lack microbial encrustations yet the majority of reworked corals of the same taxonomy bear Rothpletzella coatings. The preponderance of organic framework microfacies M3 and M4 indicate that Renalcis and Rothpletzella were major sources of carbonate sediment throughout the mound core. Microfacies 1 and 2 are reworked facies representing episodic erosion and subsequent periods of non-deposition. Together, these observations are interpreted as evidence of microenvironments. where framework metazoans, automicrite, and redeposited sediment accumulates under locally different physiochemical conditions. Vertical sections indicate that this coral-microbial cycle was ongoing unless interrupted locally.

The upward transition between the Phase I and Phase II is expressed by a gradual disappearance of coral-dominated facies and an increase in stromatoporoid-dominated facies. This trend is associated with a discrete occurrence of megalodont bivalves present in all but two of the drill cores evaluated from buildup locations, PBT-1112 and BGI-1320. The absence at
PBT-1112 is attributed to an incomplete Zeta Lake Member drill core, and at BGI-1320 as a true absence at this, and likely other, distal buildups. The introduction of large bivalves into the buildup does not track directly with the introduction of stromatoporoids since the latter appear locally lower in the mound-core, but the absence of both the bivalve facies and stromatoporoid facies from the most downdip core BGI-1320 is most simply explained by increased relative sea level at this location. It also indicates that BGI-1320 remained in Phase I while updip locations moved into Phase II, and is the strong evidence for a shift in the direction of sea level change between Phase I and Phase II. The other salient points of the transition between buildup phases are that i) the bivalve unit is most noticeable because it appears only once in each buildup succession, ii) a tenuous connection could be made between the bivalve unit and underlying stromatactis-facies in several cores, and iii) where the bivalve unit is present, there is always an upward change in metazoan population.

**Growth Phase II—Reef Top**

Phase II is characterized by a skeletal benthic carbonate factory, beginning where the coral population changes from baffling rugose coral-dominated to an auloporid- and *Thamnopora*-dominated tabulate coral assemblage. Stromatoporoids increase in abundance and are mostly laminar to tabular in form. Higher energy is indicated by high-angled stromatoporoid-coral crusts and bifurcation of stromatoporoid skeletons, with the intervening space filled by fossil detritus, internal sediment, and cement infill. Larger shelter cavities are common. A change in the diversity of calcimicrobes is evident: the *Renalcis*-micrite M4 microfacies from the lower buildup is present but is subordinate to demonstrably in-situ encrustations of *Renalcis* on stromatoporoids. Skeletal morphology and a decrease in the thickness of mud-dominated beds relative to the underlying bafflestones interval could indicate a higher energy environment than
the mud-mound core, however these characteristics could also result from a decrease in the production or deposition of carbonate mud. The reef is still interpreted as a deep subtidal marine environment shallowing to subtidal on the basis of biotic composition, poorly sorted wackestone, and a persistent lack of tidal indicators below the Wolf Lake Member.

**Continuity**

The Zeta Lake buildups display ecological succession (Chapter 2, this thesis) *sensu* Walker and Alberstadt (1975). Facies variation among buildups across the limestone-dominated buildups arises from thickness and stacking pattern. A recurring lithologic pattern in Phase I and Phase II growth is that of an *in-situ* reworked cycle. This cycle is evidenced by sub-meter to meter-scale couplets of boundstone-floatstone or boundstone-wackestone-mud-dominated packstone. In Phase I and Phase II a similar pattern is observed wherein (i) framework biota establish a local community, (ii) framework biota are disturbed, fragmented, and redeposited as thinly-bedded biomicrite or floatstone, and (iii) following redeposition, hard-bottom areas develop and expand as a result of early marine cementation which produces carbonate crusts, cement-rich mud facies such as M1 and spongiostromate bafflestone, and locally pervasive pore-occluding calcite cement. This cycle produces a macrotexture that can vary in scale from a few centimeters (Fig. 3.16) up to full meters. Periodic destabilization of the seafloor is followed by recolonization by organisms that are distributed according to relative sea level, thus the driving processes for this pattern are both depositional and diagenetic.
Figure 3.16 Cyclic macrotexture. This ~17 cm vertical succession is floored by an intergrowth of stromatoporoid (St) and thamnoporid tabulate corals (TC), and thin zones of dendroid rugose corals, *Smithphylum?* with sub-cm corallite width. Non-framework material makes up a majority of the carbonate in this succession and includes laminated pore fill (dark brown), banded and cream-colored isopachous calcite cement (nested triangle), and biomicrite (triangle). A well-developed carbonate crust is composed of ~1.2 cm biomicrite overlain by a new growth of dendroid coral and isopachous calcite cement.
**Paleogeography**

This section addresses the paleogeography of the region and continental seaway, the location of the basin with respect to the equator, and how its orientation and site in regional context impact sedimentation.

Paleogeographic reconstructions vary in their placement of the Western Canadian Sedimentary Basin with respect to the palaeoequator, and orientation of the basin. More recent paleomagnetic reconstructions (Scotese, 2013) place the basin within ~5-10 degrees south of the equator, having a northeast-southwest trending pericontinental seaway. The model favoured here is an earlier, less cited alternative that is based on principles of modern carbonate sedimentation and the distribution of climatic-sensitive strata such as evaporites, coal, and thick clastic sequences (Heckel and Witzke, 1979) (Fig. 3.17). Using physiochemical lithic patterns, the occurrence of evaporites in (modern) southeast Alberta and western Saskatchewan supports a 5-10 degree south-equatorial placement in the late Devonian, but requires rotation of the intercontinental seaway to a slightly more east-west direction. In the Heckel and Witzke model, rotation is necessary because: 1) evaporites do not form in the equatorial doldrums (thus the Alberta-Saskatchewan evaporites must have originated in either the north or south dry westerly belt during the late Devonian), and 2) the deposition of a halite-sulphate-terrigenous-shale sequence in the late Devonian (trending from the modern Pacific Coast to the Appalachian Mountains) must reflect a paleo south-north progression of Laurentia across climate zones where specific rock types are more likely to occur.
Figure 3.17: Upper Devonian Lithofacies of North America. Lithic and paleoclimate indicators inform the Devonian paleogeography proposed by Heckel and Witzke (1979). Their paleogeographic model for the Frasnian-Famennian has a northeast-southwest trending seaway in over Alberta. Southeast migration of the western Canadian evaporite province among lower to upper Devonian strata is believed to reflect encroachment of the doldrum climate belt as the paleocontinent moved toward the equator. (Map modified from Heckel and Witzke, 1979).

Orientation of the ancient seaway is significant when considering oceanographic principles that strongly impact carbonate sedimentation and whether, in this study, the predicted depositional environment is a deep-water mud-mound or a shallow, tropical reef. Paradoxically, Zeta Lake buildups possess boundstones composed of both oligotrophic, warm-water fauna and typically nutrient-indicative siliceous sponge components, in superposition with radiolarian-bearing floatstones. Radiolarians, siliceous sponges, and diatoms are signs of high productivity,
frequently explained in carbonate strata as a product of nutrient-rich water from upwelling, occurring at western continental boundaries or monsoon-driven, (see e.g., Hallock, 1987, 2001; Stanton Jr., 2006 and references therein; De Wever et al., 2014; Budai et al., 2017). A north-south trending (Alberta Basin) ancient seaway would experience western-continental margin upwelling, explaining siliceous fauna and other deep-water nutrification aspects of the Zeta Lake mound-core. However, the carbonate platform upon which the Frasnian, upper Fairholme Group (Rocky Mountains, Canada) was deposited sat between the intrashelf Cynthia Basin (see Fig. 3.1) and the open-ocean (Morrow and Geldsetzer, 1988; McLean and Mountjoy, 1994), thus the Fairholme Group platform would have diminished if not prevented upwelling into the Cynthia-Winterburn Basin. Western-margin upwelling also fails to explain the source of terrigenous quartz in muds of the Zeta Lake Member.

Slight rotation of the intracratonic seaway to a more east-west orientation in a south-equatorial latitude, as suggested by Heckel and Witzke (1979), solves two problems in our reef study. In this scenario, equatorial easterlies become the prevailing current, and water still generally moves from (modern) NWT and NE British Columbia toward central Alberta and Saskatchewan. The palaeoceanographic implication of this model is to eliminate direct western-margin upwelling as a source of cold, nutrient-rich water for the Cynthia-Winterburn Basin, but to enable clockwise current-delivery in the Cynthia-Winterburn basin. In the final outcome, this facilitates redistribution of siliciclastic sediment and terrigenous runoff from the northeast Meekwap Shelf, from the shallow promontory between the Peace River Arch and the continent, and potentially from the eastern platform.
Discussion

Carbonate buildups along the slope of the southeast Cynthia-Winterburn Basin are characterized by overall texturally similar facies in terms of high mud-to-grain ratio. Lower portions of the buildups display a range of clotted and cemented textures that are mediated by the presence of microbial organisms, with at least periodic influence by sponges and other deeper water fauna. These faunal components are typically associated with nutrient enrichment and speculative hypoxic conditions in late Frasnian (Buggisch, 2001 in Bridges et al., 1995; Boulvain, 2001; Buggisch and Joachimski, 2006) and are comparable to faunal motif found in numerous middle and late Paleozoic mud-mounds from carbonate slope environments. On the other hand, PPRT buildups host recurrent colonies of frame building rugose corals, and later stromatoporoids, which conventionally indicates clear, oligotrophic, and warm water masses. The question is then, is this a real or imagined paradox of depositional environments? That the full range of these components combine at the cm- to dm-scale warrants awareness, but interpretation is significantly challenged by a maximum 7 cm lateral scale of investigation in dealing with subsurface core. Wood (2001) has previously summarized the predicament in differentiating reefs and mud-mounds, pointing out (i) the substantive differences between reefs and mud-mounds are the significance of wave-resistant metazoan carbonate in the former and the abundance of micrite-supported cavities in the latter and (ii) the recognition of autochthonous carbonate factories in mud-mounds but also perhaps also in “ecologic reefs.” Indeed, that is the textural distinction which we have used herein to distinguish between Phase I deposits and Phase II deposits in PPRT buildups, building on paleoecological findings (this thesis, Chapter 2).

Wilson (1975) argued that deep-water mud-mounds originated from the baffling of allochthonous lime mud and bioclasts. Several others (Pratt, in Monty et al., 1995; Bourque and Gignac, 1983) have argued against an allochthonous origin for lime mud. The PPRT buildups
corroborate an autochthonous origin for lime mud. They are uniquely situated as an example of a single transgressive-regressive cycle, and we can conceptually evaluate the accompanying scenario if mud were sourced from the platform during either ramp or basinal deposition. First, it is feasible that the lowermost reef section was deposited contemporaneous with ramp deposits of the lower Nisku Formation, however the Lobstick Member and Bigoray Member ramp strata are lithologically distinct from all cores that penetrate the mud-mound core. Geometry of the Nisku ramp suggests line-driven sedimentation from the platform, which is key to interpreting downslope sediment as autochthonous or allochthonous: if sourced from the platform, then deposits of lime mud should occur in similar thickness off-reef as well as on-reef.

Microbial boundstone and microbial-rich microfacies within coral facies in the buildup core are variably clotted and lack lamination except for redeposited grains: they are interpreted as thrombolites that developed in the interskeletal space of coral boundstones and larger primary cavities. This lithologic conclusion is obvious but raises a fair question as to why microbes are there. The life-mode of Paleozoic calcimicrobes is poorly understood (Wood, 1948; Riding, 1975, 2002). That an environmental distinction should exist between Rothpletzella and Renalcis becomes evident when considering their taphonomy and sediment-potential: 1) both occur as sand- to silt-sized clots and masses, but only Rothpletzella and Wetherdella are preserved as mud-sized disaggregated skeleton particles; 2) Rothpletzella and Renalcis form mm-thick encrustations or coatings but exhibit different affinity: Rothpletzella forms grain coatings ~2-3X the width of its skeleton, particularly on solitary rugose corals but also on reworked fragments of colonial rugose and tabulate corals; Renalcis is the only microbe in this system preserved in crypts and shelter cavities, where it forms a thrombolite with micrite or automicrite; and 3) the co-occurrence of Renalcis and Rothpletzella is limited to reworked peloidal mudstone in the
mound core, and to stromatolites and large oncolites that—while a common feature in the transition from Zeta Lake Member buildups to the overlying Wolf Lake ramp carbonate—are rare to absent in the mound core.

*Renalcis* forms an interconnected biogenic framework and is a major component of lime mud with or without bioclasts. In contrast, *Rothpletzella* and *Wetherdella* are disconnected fragments in lime mud; these form frameworks in oncocids, as grain-coats (typically of solitary rugose corals), and in rare stromatolites. The largest and best developed microbial oncocids observed in this study occur in ramp deposits and in small pinnacles of the middle-slope belt. They have polytaxic nuclei. Matted *Rothpletzella* and skeletal metazoans form an intergraded coating. Interestingly, the coating of numerous large oncocids includes *in-situ* encrusting corals and thin stromatoporoids, which are also abundant in the reef top. These metazoans are also documented as occasional ramp sediments. It is apparent that upper Zeta Lake Member microbial activity is dominated by *Renalcis* in terms of sediment production and sediment binding, and that *Rothpletzella* are more prevalent in the reef core and off-reef with subsidiary *Renalcis*. It is possible that *Rothpletzella* was favoured in the relatively deeper water where the mound-core accreted.

Phase II coral-stromatoporoid reef top does not show the magnitude of change among rock fabrics that the Phase I mound core does. From this, we can offer a couple of hypotheses: 1) the reef top was deposited under less dynamic conditions than the mound core, i.e., fewer storms and related meteorologic phenomena, or 2) the reef top inclusive of organisms, non-skeletal sediments, and cement was more resilient to modification (by certain forces) than the core. It is important to note that hydrodynamic refers here to the amount or frequency of change in energy and physical properties of water, not being simply more energetic or less energetic.
Hydrodynamic states are driven by currents, weather phenomena, and normal wave activity. Rock fabric changes across the PPRT arise from the variety of syndepositional and early diagenetic processes at work. These features, although diagenetic *sensu stricto*, are also often impacted by hydrodynamic forces, since hydrodynamic forces in and around the living reef control the recharge of pore waters. Since the reef top is composed of shallower-water facies than the core and grades into shallow subtidal ramp facies, it seems probable that the reef top would be equally if not more frequently impacted by climate and weather phenomena, which weakens the first hypothesis, but lends support to the presence of a deeper-water hydrodynamic boundary such as storm wave base or a migrating oxygen minimum zone in the lower Zeta Lake which periodically but significantly altered rock formation.

Hydraulic conductivity (permeability) immediately below the sediment-water interface is typically higher in mud-poor, vuggy reef zones, allowing for the flux of water required to precipitate cement and occlude pore space. This is observed within ~1 m below the reef-water interface in more modern settings, e.g., algal cup reefs in Bermuda (Ginsburg and Schroeder, 1973), and in seaward margin of Belize (James & Ginsburg, 1979). The convention is to think of mud-rich systems as impermeable, but the presence of stromatactis, other mud-hosted pores and molds of siliceous and aragonitic fossil components indicates an active fluid system in mud-dominated facies in the syndepositional and very early diagenetic window. It is apparent from Neumman’s (1977) exploration of the deep-water Florida Straits that submarine lithification, bioerosion, and coral colonization are features one can expect to see in deep-water carbonate environments.

In summary, boundstone matrices of the Zeta Lake Member range from mudstone to floatstone with rare rudstones, but by virtue of microbial presence and inferred microbially-
induced precipitation their true nature is boundstone, or what some workers more conservatively
term, microbialite. The visual that emerges is of boundstone nested in a boundstone. A similarity
of mud-mounds and reefs is that microbial and skeletal factories operate synchronously. Nisku
slope buildups are predominantly mud-dominated and while their accumulation in subtidal
depths well below fair-weather wave base is not evidence enough, together with the
demonstrated importance of syndepositional carbonate and mud towards accretion of these
features, this study lends strong support to the interpretation that these late Frasnian buildups
originated as mud-mounds and not as shallow water reefs. This (Phase I) mud-mound
environment persisted through transgression and deposition of the off-reef lower Cynthia
Member and was terminated by falling sea level after highstan. Thus Phase II represents the
regressive phase of the Nisku Formation, where bathymetric relief and ecology of the existing
buildups permitted continued reef accretion.

**Importance in the late Devonian**

Visual inspection of the late Frasnian buildups of the Nisku Formation gives two
immediate and clear impressions: first, the structures are a hybrid of two Paleozoic carbonate
buildup styles—reefs and mud-mounds—and second, they have little similarity to mega-reefs
deposited earlier in the Devonian within the Alberta Basin. In select areas, the core of the reef is
strikingly similar to Permian and Triassic reefs that bear cavernous framework porosity and
significant volumes of marine cement, with monospecific taxa filling the constructor and binder
reef guild roles. In the Zeta Lake buildup environment, these roles are filled by corals with
subordinate stromatoporoids and *Renalcis*, and in the Permian, by sponges with subordinate
bryozoans, fusulinids, and phylloid algae. In contrast, many aspects of the PPRT resemble
Paleozoic mud-mounds, most notable in the Carboniferous (Lees et al., 1985; Pratt, 1995), but by
virtue of age cannot be interpreted as Waulsortian (Lees and Miller, 1995). An ecological argument can be made that the Waulsortian Phases A-D which are (i) guided by fenestrate byrozoans, hyalosteliids sponges, and plurilocular forams, and (ii) used with polymuds to define Waulsortian banks could, and likely do, have analogues in other geologic time periods. Given that the PPRT developed in a geologic window of global reef contraction (Copper, 1994, 2002) but prior to the end Frasnian-Famennian extinction which resulted in the displacement of stromatoporoids and non-scleractinian corals in reef-building, this dichotomy should be unsurprising and has value in and of itself.

Microbial mud-mounds of the early- and mid-Frasnian from Belgium may be the root of a pre-Carboniferous expansion of the muddy carbonate factory and provide a analogue for our deeper-water interpretation of the Zeta Lake Member. The Petit-Mont Member mud-mounds (Belgium) share an overwhelming majority of fauna with the Nisku reefs and are regarded as initiating at a water depth of 100-150 m. Hladil (1986) made an exhaustive, albeit early, comprehensive study of the trends and cyclicity in Paleozoic reefs using microfacies associations. His conclusions provide two additional guardrails for this study: 1) close to 80% of Devonian reefs arose during periods of rapid deepening which suggests, if nothing else that in the Cynthia-Basin, accretion of the Zeta Lake Member through transgression and distal steepening was not only possible but likely probable, and 2) ancient platform slopes were angled lower than recent ones. Earlier we estimated that slopes of 3-13 degrees were comparable to modern carbonates slopes with similar components, but under that scenario relative sea level at some distal locations in the Nisku reef environment would have exceeded 1500 m. If lower slope angles could indeed yield similar carbonate texture and stability as steeper modern slopes, this gives some justification as to how the Nisku reefs could grow so far outboard of the margin.
We have demonstrated that early cementation and inferred lithification is common regardless of depth of the slope or stratigraphic position, i.e., mound core or later reef top, thus the presence of voluminous marine calcite is not necessarily helpful in understanding importance. From buildup nucleation throughout aggradation, the origin of cement—whether driven by extensive cavity fill or stabilization by automicrite and micrite cementation—changes spatially within centimeters or decimeters at most. By the criteria of Bosense and Bridges (1995), the i) microbial and biodetrital character of muds M1-M4, ii) thrombolitic fabric and fibrous cements, and iii) arrangement of stromatactis cement, grumeleuse structure and polymuds that is so typical of lower buildup facies are all characteristics of Paleozoic mud-mounds, and the PPRT biota are characteristic of late Devonian mud-mounds specifically (Boulvain, 2001). One might observe that these features can also be explained by a transgression and sea-level highstand during a period of calcite saturation without biotic competition from, e.g., benthic forams or more coralline algae. In the western Alberta Basin, a small number of mud-mounds in the Mount Hawk Formation are age-equivalent to the Nisku Formation and also originated on a ramp setting (Zhou and Pratt, 2019). The Mount Hawk mounds are more straightforward mud-mounds with only a sparse metazoan population and, in addition to calcimicrobes, various algal components. They are believed to initiate during transgression and terminate by a detrimental influx of silt, clay and terrigenous sediment coincident with a relative sea level fall. In both Nisku Formation and Mount Hawk Formation, mounds have similar lifespans and the key difference is that rather than shut down the carbonate factory as in Mount Hawk Formation, upon relative sea-level fall the carbonate factory in the southern margin continued as a simple ecological reef.

Thus, the importance of these specific deeper-water, coral-microbial buildups in the late Frasnian Nisku Formation could be that they—along with other Frasnian buildups—foreshadow
the Carboniferous increase in mud-mounds carbonate factory, or more simply that they model a combination of factors favoring the formation of mud-mound sedimentation in a distally steepened ramp setting.

**Conclusion**

The structures known as the west Pembina Pinnacle Reef Trend within the Nisku Formation are re-interpreted to have two different carbonate growth phases: 1) Phase I is a mud-mound core with corals deposited in a muddy benthic carbonate factory during transgression and highstand, and 2) Phase II is a more-typical Devonian reef top with a skeletal benthic carbonate factory deposited under falling sea level. These phases are distinguished not as much by faunal motif—corals and calcimicrobes are present throughout—as they are by the proportion of mud-dominated facies, composition and arrangement of fine-grained material, and syndepositional features typical of Paleozoic mud-mounds.

Four fine-grained microfacies, M1 to M4, are established for the Zeta Lake Member boundstones. Spiculitic, microbial-micritic mudstone and microbial-micritic mudstone-wackestone microfacies in Phase I growth of the PPRT also bear open-marine and basinal microfossils. These microfacies are interpreted as organic framework. The presence of organic framework and autochthonous fine-grained carbonate created conditions favourable to the formation of structures associated with mud-mound environments, including spongiostromate and grumeleuse textures, biomicrites, stromatactis. These features enhanced seafloor cementation and stabilization of the coral-meadow depositional environment, likely enabling its keep up with sea-level rise and explaining the relative thickness of bafflestone facies compared to other ancient pinnacle reefs.
Rothpletzella and Renalcis were a major source of biogenic carbonate at water depths approximating the 70-100s meters range. Skeletal calcimicrobes are exceptionally well-preserved in this system. This should reduce some ambiguity around the life-mode. The co-occurrence of Rothpletzella, specifically with solitary rugose and open-marine fauna, suggests that their environmental range should be extended to include mesophotic in areas of high-productivity.

Within ancient buildups, pinnacle reefs remain one of the least documented and least understood carbonate environments, perhaps unsurprisingly, owing to the inherent isolation from platform stratigraphy and lack of control points for relative sea-level change. For this reason, they can be mischaracterized and ambiguity about trophism of Paleozoic biota remains a significant handicap in geologic interpretation. Where trophism is uncertain, we need to expand the field of view to bring in truisms from regional paleogeography and paleoceanography.

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Chapter 4

Detection of carbonate reef phases using short-wave infrared light

Abstract
Supervised classification of late Devonian reef carbonate in core is conducted on spectra collected from thin-section slabs. Hyperspectral images acquired in the short-wave infrared (SWIR) range of the electromagnetic spectrum are used to produce reflectance intensity-based, spectral signatures and yield feature strength 2D maps for four different carbonate phases. Supervised classification of spectral bands resulted in successful isolation of micrite, calcimicrobial carbonate *Renalcis*, skeletal carbonate, and pore-filling calcite cement phases that comprise four principal components of late Devonian reefs. Bands for calcite and water absorption, based on wavelength response in the 2175-2375 nm and 1850-2100 nm wavelength ranges respectively, have the most significant impact on segmentation, highlighting cement and of skeletal carbonate, while masking microbial carbonate. 2D maps of each carbonate phase allow validation of the volumes of each carbonate phase relative to petrographic thin sections.

Introduction
Theorized gaps in our understanding of Phanerozoic reef evolution (Webb, 1996) have been attributed to our tendency to focus on the metazoan components in classifying reefs and it is suggested that the role of microbial carbonate and biologically-induced cement are underrepresented in findings from ancient reef studies. Calcimicrobes are an intricate component of the Paleozoic reef record but, absent exhaustive and cost-prohibitive petrographic analysis, there is no mechanism to properly characterize the distribution of microscopic organisms when working at the core scale. Point-counting is commonly used at the petrographic scale to evaluate
grain types and abundance but there are substantial hurdles in relying solely on petrographic analysis to characterize calcimicrobes, e.g., the need for increasing density of point per sample when the object of interest is mud-sized particles, and the number of contacts, shapes, and edges used to describe distribution that also must be counted. To overcome the challenges of time and upscaling associated with standard petrographic analysis, we need to explore and evaluate new techniques for bridging microscale and macroscale investigations.

Hyperspectral imaging is a technique that integrates reflectance spectroscopy and dimensional properties, typically in 2D, yielding a visualization combined of i) a spatial reference information in the form of x,y coordinates and ii) spectral information represented as l, where l is the response of matter at x,y in an em wavelength range. Hyperspectral imaging in the near-infrared (NR), short-wave infrared (SWIR) and thermal infrared (TIR) ranges is applied in geological science activities, e.g., mapping surface components in terrestrial and oceanographic environments (Hochberg et al., 2003; Stephens et al., 2003; Feng et al., 2018), resource exploration and production, the identification and characterization of minerals and objects in planetary geology (Kaplan et al., 2020) and related analogues (Bishop et al., 2008; Cloutis et al., 2010; Harner and Gilmore, 2015). Notable uses of hyperspectral imaging toward carbonate geology have typically focused on hyperspectral signatures resulting from mineralogical difference or specific impurities that reflect carbonate diagenetic processes, such as the characterization of diagenetic dolomite in the High Atlas mountains (Moroccan Atlantic; Baissa et al., 2010), differentiation of paleokarsts and hydrothermal dolomite facies in Albian limestone (Spain; Kurz et al., 2012), and borehole identification of carbonate mineral species in volcanic hosted massive sulfide deposits (Tasmania; Green and Schodlok, 2016). These studies have established confidence in field applications of spectral attributes that are well-established from
laboratory studies using pure mineral powders (Chester and Elderfield, 1967; Gaffey, 1985, 1986) or whole rock samples ground into powders (Hunt and Ashley, 1979).

One area largely unexplored is the potential of hyperspectral imagery in identification of carbonate grain types, e.g., skeletal grains vs. non-skeletal carbonate grains, matrix, and other components common in lithified carbonates which will, by necessity, require analysis of intact, whole rock samples. This study aims to step into that gap and increase remote-sensing of microbial carbonate. Here we test the use of short-wave infrared (SWIR) hyperspectral imaging to identify carbonate grain types and components in a small suite of limestone samples from the Western Canada Sedimentary Basin, Canada. Hyperspectral imaging is used to discriminate skeletal, non-skeletal, and microbial carbonate phases in polished slabs of Devonian reef rock.

The Problem

Carbonate grains and cements have significant depositional and diagenetic information retained in individual crystals and groups of crystals. Carbonate crystal assemblages on the order of $10^3$-$10^6$ have shared optical reflectance properties that can be mapped in 2D but the spatial distribution of like crystals are often masked by the high degree of magnification applied in petrographic studies which is one of, if not the primary investigative tool for a carbonate geologist. Conventional image segmentation using a photograph or photomicrograph, etc. is arduous and typically lacks repeatability owing to high textural heterogeneity and biotic diversity in carbonate strata and in ancient reefs particularly. Thus, the identification of carbonate phases in image analysis must overcome the complex situation of components which have relatively similar composition, even if only having one or two mineral species, but are composed of potentially hundreds to thousands of crystals of different sizes which are not uniformly oriented.
and frequently overlapping. Two concepts illustrate why this complexity is an issue: the mechanics of image analysis and the mechanics of carbonate sedimentology.

**The Mechanics of Image Analysis**

An image is simply an outputted array of pixels, each with an assigned numerical value, that together record variation in the object of interest. In the digital age, input data is a function of energy source used for acquisition and is measured in terms of the electromagnetic spectrum, either in spectra or processed wavelengths. While the human eye might detect less variation in black and white relative to color or a multi-channel image such as fluorescence, each of these image types can mathematically retain a similar amount of information without altering the object’s natural properties. Image analysis is used to investigate and describe natural properties and relationship between properties. A good description of the fidelity of image analysis to the natural world is to consider that an elephant does not change its color whether it is photographed by day in black and white or color film, or by night or day in infrared, although these images will appear drastically different to the human eye. Similarly, the true relationship between the animal’s tibia and tarsals does not change whether measured from image in inches and degrees or in meters and radians, or pixels and intensity.

Image analysis applies a variety of manually-selected thresholds or algorithms (commonly called filters) to select pixels in an image in order to detect, mask, or enhance natural, measurable features—say, the geometry of a joint on a quarry surface or the opacity of cells in a blood sample. Then, each feature is described numerically allowing the investigator to do such things as determine abundance, identify similar features, interpret relationships between features, and to construct a model, heat map, or another such plot to convey the findings.

Image analysis can be summarized as a process of:
1. Pre-processing: evaluate signal to noise (S/N), reduce noise, smoothing, sharpening, histogram stretching; this will alter the raw data and must be done on the whole image;

2. Segmentation: survey the properties of area, position, and intensity of pixels; identify random groups of pixels that share properties (called unsupervised classification), or identify specific groups that share properties, usually composing a desired feature (called supervised classification); and,

3. Feature Detection: establish the relationship and strength of the relationship between the initial group and neighboring groups, if indeed a relationship exists. Those relationships might involve edges, the sharpness of an edge, intersections, adjacency, or simply a correlation between volume.

The Mechanics of Carbonate Sedimentology

In all cases, textural diversity in a carbonate rock (a feature that is readily observable to the naked human eye) stems from a variety of shapes, fabrics, the position of skeletal and non-skeletal rock components, and the position of differently sized particles with respect to each other. These mechanics were used by Dunham (1962) to generate carbonate rock types on the basis of three carbonate grain sizes, those less than 4 um, those between 4 and 2000 um, and those greater than 2000 um. Carbonate is a sedimentary rock type typically produced by the accumulation of skeletons and waste of living organisms. The texture and subsequent spatial properties of carbonate grains can be affected by some of the mortem and post-mortem encounters between organisms and their environment, e.g., scavenging and boring, in addition to reworking, transport, and burial. At other times, carbonate results from the precipitation of anhydrous and hydrous carbonate minerals in cement form which can be arranged in laminar,
ovoid, or chaotic shapes. Other constituents might contribute to the total rock volume as well, such as lithoclasts, non-carbonate grains, and pore-space. For the purposes of image segmentation, which is defining features in an image and constructing classes, each carbonate constituent can form a unique class, depending on the medium analyzed and the scale of investigation.

It is evident that the principles of area and position embedded in image analysis are equally important in the characterization of carbonate sediments. In theory, the two disciplines should be compatible. The drawback is that traditional (optical) image segmentation is computationally demanding, operating most effectively with only one or a few feature classes that must be separated from the background, and where features can be characterized with a minimal number of parameters.

The Study Approach

Image analysis of petrographic samples and polished slabs for the purpose of phase volumetrics is a technique with the opportunity to provide fully quantitative assessment that can be used to complement field and regional studies in sedimentology. Hyperspectral imaging provides spatial and compositional information in one data set which can be re-used and re-examined, and its application for carbonate sedimentology using petrographic samples is tested here. A typical image analysis workflow is illustrated in Figure 4.1. Note that the same workflow would be followed for images acquired in the visual- and SWIR-ranges since both data types result in single-channel, pixel-based images where each pixel will have a histogram for red, green, and blue.

Image segmentation is the most challenging and input-dependent task in the workflow and is the area where the bulk of decision-making is made. In simple grain investigations where
one property is investigated, and that property is independent of other geologic properties which can be measured, e.g., sorting, organization of grains, or the geometry of grain contacts, then the operator might experiment using a number of image-processing algorithms which technique faithfully documents variation in grain size. Investigations as simple as that are rare.

Segmentation by manual thresholding, which is applied here, is more typical and requires fundamental knowledge of image properties, and how each property might be influenced by geological attributes. Reproducibility will be high on a single sample, and between User A and User B, but reproducibility across samples has not been demonstrated except for laboratory-prepared sediment samples. The lack of reproducibility exists today as a function of 1) the small number of imaging investigations conducted on natural geologic samples that are complicated by diagenetic alteration versus laboratory-prepared geologic materials that are extensively documented, and 2) the sheer number of objects—and the literal overlap of objects within samples—that one might need to spatially characterize, which remains computationally significant perhaps even with the recent availability of deep-learning machine tools to petrographic and other imaging disciplines.

This study is an investigation of image analysis to progress the study of carbonate sedimentology in the digital realm. The main goal is feature isolation of microbial carbonate. This is accompanied by feature isolation of calcareous allochems, e.g., skeletal calcite, micrite, and pore-filling calcite cement using single-channel, multi-band reflectance in the short-wave infrared range (0.90-2.50 μm). Isolation of these carbonate rock constituents using hyperspectral imaging is tested using supervised image segmentation of absorption data in the short-wave infrared range (SWIR) of electromagnetic energy, acquired by hyperspectral scanning of polished thin section blocks. Supervised classification was conducted on spectra by thresholding

Methods

The study aims to identify unique spectral properties of four compositionally-similar constituents of ancient reefs: 1) micrite (M), 2) pore-filling calcite (PFC), 3) microbial calcite, *Renalcis* (R), and 4) skeletal calcite (S). Four samples were selected for study based on petrographic screening for dominantly limestone mineralogy, fabric preservation, and the presence of two or more of the desired constituents. All samples were collected from a single
drill core of reef material from the Penn West Pembina 11-12-50-10W5 (sample code PBT-1112
this dissertation), Frasnian Nisku Formation, subsurface Alberta.

Carbonate phases were identified using standard petrography on unstained thin sections. High-resolution scans of the thin sections were created using an Epson V600 flatbed scanner, in 16-bit (#) red-green-blue (RGB) at 4800 dpi resolution (transmitted light mode). The cut-face of the thin-section bricks, a.k.a. slabs, were used in hyperspectral analysis. Slight offset of some features between thin sections and slabs result from the ~2 mm difference in sampling location, covering the width of a saw blade. This offset is considered very manageable because the carbonate phases are easily correlated with visual examination. Each sample is described following the carbonate rock classification established by Dunham (1962) (Table 4.1).

Note on terminology
- “Pore-filling calcite” includes cement appearing in stromatactis, fractures, cavities, or mud-hosted pores.
- “Skeletal calcite” includes different skeletal grain types, e.g., coral, stromatoporoids with low-magnesium calcite (LMC) mineralogy.
- In this paper, the word texture appears numerous times. Texture has meaning in the study of sedimentology as a modifier in lithological definitions and in grain size analysis. In the discipline of image analysis, “texture” refers to the spatial description of features, importantly, as the parent feature of a group of algorithms that detect morphological features, e.g., edges, intersections. To avoid the reader’s confusion, the term texture will henceforth refer to its use in image analysis, unless preceded by the word carbonate.
- The phrase “geologic feature” is used herein to mean a spatially-constrained attribute that is native to the rock and therefore unlikely to occur in other, non-geologic images, and
unlikely to exist as an artifact of image processing. This is different from the use in image analysis where feature refers to the measurement of an attribute unique to spatial description, e.g., wavelength(s), reflectance, absorption, symmetry, and position.

Table 4.1: Description of samples selected for hyperspectral analysis. Petrographic slabs containing four of the main carbonate components typical in Devonian reefs. Components were identified in standard petrographic analysis of the mirrored thin section for each slab.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample Location (UWI and depth (m))</th>
<th>Rock Type</th>
<th>Includes the constituents:</th>
<th>Diagenetic feature(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>11-12-50-10W5, 2635.0m</td>
<td>Mudstone</td>
<td>M, PFC, S</td>
<td>Fracture</td>
</tr>
<tr>
<td>B.</td>
<td>11-12-50-10W5, 2643.1m</td>
<td>Microbial boundstone</td>
<td>M, R, PFC</td>
<td>Cement-lined cavity</td>
</tr>
<tr>
<td>C.</td>
<td>11-12-50-10W5, 2643.8m</td>
<td>Stromatoporoid-coral-microbial boundstone</td>
<td>M, R, PFC, S</td>
<td>Open pores, cement-filled cavity</td>
</tr>
<tr>
<td>D.</td>
<td>11-12-50-10W5, 2644.41m (Vertical)</td>
<td>Stromatoporoid-coral-microbial boundstone</td>
<td>M, R, PFC, S</td>
<td>Open pores, incipient stylolites, blocky calcite</td>
</tr>
</tbody>
</table>

Hyperspectral data was collected using a SisuRock® hyperspectral scanner in the short-wave infrared range of 1000-2500 nm with an 8 nm bandwidth. The remote-sensing software ENVI was used to process and analyze hyperspectral data. Scanning and analytical work was conducted at the University of Alberta’s core-sensing facility.
Analytical Workflow and Results

This section follows the general workflow outlined in Fig. 4.1.

Segmentation

Segmentation was conducted using the threshold method. Initially, processed images composition were prepared and examined next to annotated scans of thin sections. The images were created by thresholding based on absorption strengths at 2320 nm (dolomite), 2335 nm (calcite), and 2200 nm (clay). A comparison of the optical scans and carbonate mineralogy is shown in Figure 4.2. An additional false color RGB image was prepared with at R=1940 nm (water), G=2200 nm, B=2335 nm. From these images which indicate mineral abundance, it was apparent that all four carbonate phases under investigation exhibit slightly different reflectance in the calcite wavelength. False colour imagery suggested a potential grain-size or water response. Together, these images validated continued analysis to constrain reflectance properties.

Segmentation was completed by analyzing transects of each sample in well-defined areas of interest (AOI), and averaging the wavelength using a 5x5 pixel kernel along the transect. Segmentation was conducted for each phase using all samples in the set and resulted in a supervised class, i.e., spectral end-member, for micrite, Renalcis, and pore-filling calcite. Spectral response varied enough across samples of skeletal calcite such that it was not possible to create a single class; three sub-classes were erected bringing the total class count from four to six.

Raw reflectance data and continuum-removed spectra (Fig. 4.3) were charted to illustrate absorption depth of each class. From these we observed that all six classes have an absorption feature in the 1850-2100 nm range that is broadly parabolic, and a second absorption feature in
the 2175-2375 nm range that is more steeply parabolic. A composite image was subsequently made to demonstrate water feature strength in each sample.

Figure 4.2: Composition of Devonian reef samples shown using (L-R) total carbonate, dolomite, and calcite mineral SWIR wavelengths. Total carbonate (representing dolomite and calcite) is shown in false color; individual calcite and dolomite are shown in greyscale. Mirrored thin sections of each sample slab A-D (left column) are used to validate and train segmentation by threshold analysis. Nearly all petrographic features are visible in the carbonate and calcite abundance images.
Figure 4.3: Spectra for supervised classes of micrite (M), pore-filling calcite (PFC), *Renalcis* (R), and subclasses of skeletal-calcite (S(n)). *Renalcis* is highly reflective overall.
based on A) spectral amplitudes. The continuum-removed reflectance B) illustrates absorption depth features for all classes in the water and calcite wavelength ranges.

**Feature Detection**

Spectral angle mapping (SAM) was conducted for each of the six classes across the data set using two band spectra. These bands were selected for water and calcite, based on analysis of the continuum-removed reflectance. Figure 4.4 demonstrates SAM results for the micrite, *Renalcis*, and pore-filling calcite (maps for skeletal calcite sub-classes appear in Appendix F). Grey-tone images outputted from SAM are used to illustrate the probability of each pixel classifying as a defined end-member. Although spectral angle maps are models, they can be empirically validated in terms of fitness by their relative comparison with a training set. In this case, spectral angle maps were visually assessed for comparison with the distribution of carbonate phases in petrographic thin section.

Finally, a supervised classification was run on all raw spectral data in the sample set, using all six defined endmembers. The classification maps presented here (Fig. 4.5) use a forced classification, meaning that every pixel must be assigned a class, and no pixels can belong to an “unknown” class.

**Results**

From initial mineral abundance maps it is apparent that the samples are composed of calcite in various stages, i.e., the four targeted phases are compositionally similar. Dolomite and clay were detected only in trace amounts and when present these were frequently located at the edge of the samples, indicating they were most likely dust from the scanning environment. Furthermore, even when occurring within the sample these spectra were not spatially abundant enough such that they would steer segmentation. These compositional results were expected based on sedimentology determined by petrographic work.
Continuum reflectance spectra, i.e., raw spectra (Fig. 4.3a) of each segmented feature indicate the *Renalcis* class is the most strongly reflective in the SWIR wavelength range, and *Renalcis* is clearly separated from all other classes using only this property. Additionally, the overall slope and shape of raw spectra are similar among all six classes with one exception: lower reflectance in the ~1440-1460 nm range occurs in all classes but is slightly more pronounced in pore-filling calcite and in all three skeletal carbonate classes.

### Table 4.2: Continuum-removed spectra for supervised carbonate classes

<table>
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<tr>
<th>Carbonate Class</th>
<th>Peak 1 nm</th>
<th>Peak 1 R</th>
<th>Peak 2 nm</th>
<th>Peak 2 R</th>
<th>Peak 3 nm</th>
<th>Peak 3 R</th>
<th>Peak 4 nm</th>
<th>Peak 4 R</th>
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<th>Peak 5 R</th>
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<tr>
<td>Micrite</td>
<td>1275.76</td>
<td>0.999267</td>
<td>1452.31</td>
<td>0.988132</td>
<td>1942.52</td>
<td>0.880594</td>
<td>2155.46</td>
<td>0.97274</td>
<td>2336.74</td>
<td>0.59392</td>
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<tr>
<td>Pore-filling Calcite</td>
<td>1263.14</td>
<td>0.999467</td>
<td>1452.31</td>
<td>0.934759</td>
<td>1929.98</td>
<td>0.733956</td>
<td>2155.46</td>
<td>0.96737</td>
<td>2336.74</td>
<td>0.59065</td>
</tr>
<tr>
<td><em>Renalcis</em></td>
<td>1263.14</td>
<td>0.997915</td>
<td>1452.31</td>
<td>0.987055</td>
<td>1942.52</td>
<td>0.896876</td>
<td>2155.46</td>
<td>0.97921</td>
<td>2336.74</td>
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<td>Skeletal calcite-1</td>
<td>1275.76</td>
<td>0.999416</td>
<td>1452.31</td>
<td>0.951185</td>
<td>1936.25</td>
<td>0.752791</td>
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<td>Skeletal calcite-2</td>
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<td>0.999179</td>
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<td>0.951175</td>
<td>1929.98</td>
<td>0.781636</td>
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<td>Skeletal calcite-3</td>
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<td>0.96797</td>
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<td>0.55824</td>
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Continuum-removed spectra demonstrate absorption feature depths (Table 4.2) and yield more comparative information. Of five absorption peaks in the short-wave infrared wavelength, here are two very strong absorption features recorded in the 1850-2100 nm and 2175-2375 nm ranges that appear in every supervised class; these are interpreted as water and calcite features, owing to peak absorption ~1936 nm and ~2336 nm, respectively (Gaffey, 1985, 1986). A weaker absorption feature peaking at 1456 nm and is also interpreted as water. Using continuum-removed spectra, three interpretations can be made based on relative absorption feature strength:

1. a weak-water/weak-calcite absorption feature characterizes the *Renalcis* (R) class,
2. a weak-water/strong-calcite absorption feature characterizes the micrite (M) class,
3. a strong-water/strong-calcite absorption feature characterizes all skeletal carbonate classes (S1, S2, and S3) and the pore-filling calcite (PFC) class.
Pore-filling calcite has the strongest liquid water features, followed by skeletal carbonates. Skeletal carbonate classes (S2, S1, and S3 respectively) have the strongest calcite absorption features. Pore-filling calcite and micrite classes have very similar peak calcite absorption. The *Renalcis* class is readily distinguished by having the weakest water and carbonate absorption features.
Figure 4.4: Spectral angle maps for micrite, pore-filling calcite and microbial carbonate, *Renalcis*. Light tones on the spectral angle map (SAM) indicate a high probability that a pixel will match a class, based on the difference in spectral angle being closer to 0 radians. Scale bar is in radians. Mapping and scales are in grey tone. The lack of neutral (grey) values suggests each class is well-segmented. The boundaries of physical samples within each map are outlined with a dashed red line to aid the viewer. Additional SAMs showing skeletal calcite sub-classes are in Appendix F.
Figure 4.5: Supervised classification maps of late Devonian reef samples. Of note is the agreement between expected constituents from Table 4.1 and the modeled constituents. The modeled presence/absence of each constituent tracks with the predicted presence in Table 4.1, indicating successful segmentation.

Discussion

This hyperspectral imaging study was designed around a small sample set with relatively few features of interest, for the purpose of determining if certain microbial carbonates are
spectrally discernable in the SWIR wavelength range from other carbonate constituents typical in Devonian reef strata. The sedimentology of all samples was previously determined from petrographic analysis and was critical to supervised classification. Using only raw reflectance spectra and continuum-removed spectra, it is apparent that microbial carbonate can be readily distinguished from other carbonate phases with similar mineralogical composition using threshold segmentation.

All four carbonate phases of interest in this study (micrite, pore-filling calcite, microbial calcite, and skeletal calcite) are distinguished by combined absorption features in the calcite and water bands and only *Renalcis* could realistically be distinguished using isolated bands. There are remarkable similarities in the shape and position of these absorption features, but sufficient differences in amplitude of absorption to distinguish each class when using more than one band for segmentation. This suggests that multi-band image analysis with even just two or three bands will be adequate for future image analysis of carbonate sediments, provided there is sufficient textural difference. The bright reflectance evidenced by the calcimicrobe *Renalcis* class relative to all other classes, but especially in comparison to micrite, suggests that the calcified cyanobacteria are highly reflective as a result crystal size since a *Renalcis* skeletal sheath is composed of minimicrite. Looking at just the continuum-removed spectra *Renalcis* displays weaker absorption features than all other classes, but if another class of carbonate with similarly small crystal size were introduced, e.g., another species of calcimicrobe, the expectation should be that the new class would mimic *Renalcis*.

An observed progression in the absorption feature strength of water as moving from muddy carbonate to coarse, crystalline carbonate suggests that water trapped within the carbonate drive the spectral response. The dual presence of water features at 1450 nm and 1940
nm is indicative of the presence of fluid water as opposed to, e.g., bound water (Gaffey, 1985, 1986). Since there is no indication of clay, these features in our carbonate reef samples are interpreted as fluid inclusions in calcite. Therefore, the progression of water feature strength from its highest in pore-filling calcite class to a minimum in the microbial *Renalcis* class, is justified by calcite cement hosting abundant and potentially larger aqueous fluid inclusions than either skeletal carbonate or mud-sized carbonate would.

Skeletal calcite in these samples has various spectra responses. During manual sampling of spectra to establish endmembers, it was necessary to create three subclasses of skeletal calcite in order to train all pixels to the phase evident on the face of the sample and in thin section. Comparison of thin section to spectral maps indicates that variations across skeletal calcite classes do not track broad taxonomic distinction, e.g., corals vs. stromatoporoids. This suggests spectral response could be accounted for by slight variation in magnesium content across an individual skeleton or the amount of water trapped within the skeleton, e.g., inclusions within the skeleton itself or within intraskeletal pores. These classes likely reflect a combination of original mineralogy and diagenetic overprinting, with the anticipated loss of magnesium during early diagenesis. There is no shift in the position of water or calcite bands among the three sub-classes of skeletal carbonate, which complicates interpretation. Additional work of a geochemical nature would be necessary to investigate the impact of trace elements that might impact absorption features for the purpose of image segmentation.

Some of the data shown here is ancillary to the defined problem, specifically the production of supervised classification maps on a data set this size. This is because our tool set for validating spectral mapping is, at this point, limited to point-counting or other statistical analysis based on composition that can sample a high volume of points and has superb
resolution, e.g., x-ray diffraction. Even traditional image analysis based on object identification, e.g., grain shapes, does not yield compositional information. In this case, the use of spectral angle mapping was sufficient enough to visualize how each class would likely expand or shrink with additional modeling, in relation to the distribution observed via thin section. With spectral angle mapping, again, each class seemed well-constrained and the range of probability of mismatching to another class was rare.

The use of reflectance spectroscopy in the medium of drill-core medium is not a novel technique (Feng et al., 2011; Speta et al., 2015), however its application to carbonate sedimentology in the study of limestone reef strata is a novel application. This paper documents the first known use of short-wave infrared hyperspectral analysis in order to segregate compositionally similar carbonate grain-types. Its strength and limitation both stem from the relatively narrow scope of investigation. While it is apparent that *Renalcis* is readily distinguishable from the other main carbonate phases in these Devonian reef strata, there are numerous other calcified cyanobacteria that have yet to be profiled and do require investigation if we are to get at recording the full diversity of microbial carbonate in ancient reefs.

Additionally, these results indicate that grain size is the principal attribute that accounts for the unique spectral signature of *Renalcis*, relative to the other carbonate phases investigated here. There is the possibility that were the samples more texturally homogeneous, *Renalcis* would not be so distinct. The implication is that in this case, reflectance spectroscopy is a useful tool because the general sedimentology is already known.

**Conclusion**

Hyperspectral analysis in the short-wave infrared range is applied here for the first time in mineralogically uniform (limestone) samples to conduct image analysis in ancient reef strata.
using polished core samples. Segmentation based on threshold method resulted in successful
discrimination of micrite, microbial calcite composed of Renalcis particles, pore-filling calcite,
and skeletal calcite.

The targeted carbonate phases all have primary absorption depth features in the water and
calcite bands. These multi-band pattern is a feature depth progression going from muddy
carbonate to coarser, more crystalline carbonate. This progression is explained by an increase in
relative abundance and size of fluid inclusions among each supervised class, maximized in
skeletal carbonate and calcite cement.

The calcimicrobe Renalcis exhibits high raw reflectance (up to 70%) resulting from very-
fine grain-size. In continuum-removed spectral analysis, Renalcis can be further distinguished
from other mud-sized carbonate when using absorption depths in the water and calcite bands,
approximately 1935nm and 2336nm.

As a result of internal variation among reflectance intensity, skeletal calcite in these
samples required additional classification into three sub-classes in order to avoid false-
classification as pore-filling cement. Skeletal calcite sub-classes are not taxonomically controlled
based on comparison with mirrored thin sections. Variation most likely reflects a combination of
depositional and diagenetic features but will require additional data and larger sample set to
resolve.

Acknowledgments

Benoit Rivard and Juli Feng (University of Alberta) shared their expertise in
hyperspectral imaging acquisition and theory. The author thanks Hilary Corlett (MacEwan
University) for a thoughtful review of this manuscript. An effort was made early on in this study
to image carbonate phases using excitation spectroscopy, as opposed to hyperspectral imaging. Although excitation spectroscopy was ultimately unsuccessful toward this application, the author wishes to thank Michael Robertson (Acadia University) for his time, laboratory resources, and expertise in materials physics. Successful failures are necessary steps of discovery! This work was supported by University of Alberta’s Core Sensing Facility and a grant from the Natural Sciences and Engineering Research Council of Canada to principal investigator N.P. James.

References


Gaffey, S.J., 1985, Reflectance spectroscopy in the visible and near-infrared (0.35-2.55 um): Applications in carbonate petrology: Geology, v. 13, p. 270–273.

Gaffey, S.J., 1986, Spectral reflectance of carbonate minerals in the visible and near infrared (0.35-2.55 microns); calcite, aragonite, and dolomite: American Mineralogist, v. 71, p. 151–162.


Chapter 5

Conclusion

The move from obligate to non-obligate carbonate components in the global reef system during the end-Devonian is already established in the fossil record. Factors which we recognize in the modern to promote restriction of skeletal fauna such as nutrification from increased runoff, increased primary productivity, and discrete fluctuations in basin temperature and currents are difficult if not impossible to establish for the mid-Paleozoic skeletal reef to the degree of accuracy required. Existing research has focused heavily on trying to tackle this using an ecology strategy of, “What do relationships in the reef community indicate is going on in the seawater column of this or the neighboring reef,” almost exclusively on large barrier or fringing reef systems. Limestone and partially dolomitized cores from the WCSB Nisku Formation provided an opportunity to characterize the postulated decline in metazoan and emergence of microbial influence among multiple, isolated buildups. This was completed through paleoecological interpretation of drill core from the Pembina Pinnacle Reef Trend (PPRT) in subsurface Alberta, Canada, which records the last episode of Late Frasnian off-platform buildup in the Cynthia-Winterburn Basin (Zeta Lake Member, Nisku Formation, Winterburn Group). Over 50 cores penetrating buildups or inter-reef strata were examined to varying degree. Detailed stratigraphic logs, facies interpretations, and petrographic work was completed for seven of these cores, totaling 546 meters of stratigraphic section and one core from the eastern margin of the Cynthia-Winterburn Basin. Comparison of Dunham texture among logged PPRT buildups is 7% grain-dominated, 59% mud-dominated, and 34% boundstone. The origin and paleoecology of the Zeta Lake Member, which Machel (1983) characterized as "coral-bearing mud-mounds," are
emblematic of a robust carbonate factory that is both microbial and metazoan-rich that grew in deeper water.

In work presented in Chapter 2, seven types of boundstones were identified based on relative abundance of skeletal metazoans and calcimicrobes. Distribution of these boundstones and the paleoecological indicators associated with each support as many as four different paleoecological communities (PC) in the buildup environment, including: i) coral-pelmetazoan-microbial, ii) coral-stromatoporoid-bivalve, iii) coral-stromatoporoid-microbial, and iv) stromatoporoid-microbial communities. PCs 1 and 2 are characteristic of the majority of lower buildup strata. PC2, the coral-stromatoporoid-bivalve community is interpreted as a transitional community because it occurs only once in each reef succession. The variety of PPRT biota filling the baffling, constructor, and binder-roles (defined as reef guilds throughout the geologic record) indicate balanced reef communities and their overall vertical progression is interpreted as incipient ecological succession within the Zeta Lake Member.

Previous Nisku research in the Nisku Formation has ignored entirely the hypothesis that mud-rich mounds are in fact microbial in origin and have not addressed the impact of synsedimentary and early diagenesis on reef evolution, even though the reefs are pervasively cemented. This dissertation tests that hypothesis, largely through work presented in Chapter 3, but which findings are reenforced by the paleoecological evidence presented in Chapter 2.

The source of carbonate mud in the PPRT buildups is reworked biogenic and microbial particles, with ancillary peloids and nontrivial molds of siliceous spicules. This is demonstrated through microfacies analysis of fine-grained sediment infilling boundstones in the lower buildup. An empirical relationship derived from the co-presence of microbial skeletons and siliceous spicules, tentaculitids, radiolarians is that these sediments originated in deep water. It is
impossible to say how deep, particularly given the ambiguity around the affinity of Paleozoic corals, stromatoporoids and calcimicrobes, however reconstruction of the paleo-dip suggests that the distal slope was in 70 m or more at maximum transgression of the Cynthia Member shale.

The nature of cementation in the pinnacle reef environment is two-fold: that arising from mud-supported voids in microbial-dominated mud throughout the buildup, and an exceptional amount of early marine calcite cement infilling shelter and framework porosity in low-relief boundstones. Calcimicrobes are non-obligate calcifiers but have CaCO₃ supersaturation constraints that also favour early cementation, a relationship empirically supported by the co-occurrence of calcite cement in microbial-mudstone and metazoan-supported porosity in these late Frasnian buildups. Through facies analysis and applying modern (present) oceanographic principles, the Zeta Lake Member is re-interpreted as a hybrid mud-mound to reef system with the implication that framework metazoans occupied a subsidiary role in buildup origin.

The significance of calcimicrobes, aka, non-obligate calcifiers, in the Paleozoic reef record is, I believe, still poorly constrained. While numerous factors likely contribute to under-recognition, one that stands out clearly is perhaps one of the simplest—in short, the size of calcimicrobes vs. the size of an outcrop or a drill core means that we do not see them in these surface studies, and they are under-recognized in field studies. This could be remedied by re-sampling systematically within the known record of fossilized microbes, and by developing a technique to detect the presence of calcimicrobes at the core or outcrop scale. Chapter 4 addresses such a technique.

During work conducted for chapters 2 and 3 of this dissertation the primary carbonate phases of the Zeta Lake Member were identified. These are pore-filling calcite cement, skeletal calcite, micrite, and calcimicrobial calcite. The spectral signature of these four carbonate phases
were explored by single-channel, multi-band, intensity-based image analysis using spectral response in the short-wave infrared (SWIR) range of the electromagnetic spectrum. Under supervised classification based on the threshold method, three combinations of spectral behavior are noted: 1) pore-filling calcite cement and skeletal calcite are identified as having strong water/strong calcite absorption depth features, 2) micrite is identified as having weak water/strong calcite absorption depth features, and 3) *Renalcis* is characterized by high raw reflectance and weak-water/weak calcite absorption depth features. This study proposed and validated an objective, and repeatable technique for the discernment of carbonate phases in core samples using hyperspectral analysis. This technique can be immediately applied to larger-scale core studies.
Appendix A

Location Descriptions & Depth
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<th>Well/ Sample Code for Study</th>
<th>Subsurface Well Name</th>
<th>Legal Survey Location of Well (Alberta, Canada, W5)</th>
<th>Lateral Position on Reef/ Mudmound</th>
<th>Measured Depth at Top of Core (m)</th>
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<td>2663.6</td>
</tr>
<tr>
<td>BR-0327</td>
<td>Chevron Brazeau 3-27-48-12</td>
<td>T048/R12/SEC27/LSD03</td>
<td>Reef Interior</td>
<td>3003.0</td>
<td>3098.0</td>
</tr>
</tbody>
</table>

1. All locations listed using the Dominion Land Survey System, west of the fifth meridian, T=township, R=range, SEC=section, LSD=legal subdivision

2. Lateral position interpreted by author using map view of reef boundaries provided by geologist Watts (N. Watts, personal communication 2016) based on lithology interpreted from wireline logs.
Appendix B

Core Logs
Notes on core logs

1. Core logs appear in alphabetical order by sample location name and then by number, as follows:
   a. BGB-1209
   b. BGC-0612
   c. BGD-1209
   d. BGD-1404
   e. BGI-1320
   f. BR-0327
   g. PBT-1112
   h. SC-1402

2. All logs generated at a 1:60 depth scale in drafting program. Actual scale on printed page might vary.

3. Core depth is measured in subsurface meters, inclusive of Kelly bushing or drill floor height.

4. Cores were logged by A.F. Stagner during 2016-2017 at the Core Research Facility, Alberta Energy Regulator, Calgary, AB.

5. A track for “depositional environment” on reefs was logged based on a hypothesized shallow water depositional environment, and the assumption that highest energy indicators equate to a reef crest within that depositional environment. Subsequent petrographic and microfacies work did not support a shallow water reef interpretation. The track is shown here as part of the scientific process although the data does not appear elsewhere in this thesis.
Core Name: BGB-1209, pg. 1 of 7

<table>
<thead>
<tr>
<th>Lithologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomitic Limestone</td>
</tr>
<tr>
<td>Limestone</td>
</tr>
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<table>
<thead>
<tr>
<th>Admixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhydritic</td>
</tr>
<tr>
<td>Sandy</td>
</tr>
<tr>
<td>Silty</td>
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</table>

<table>
<thead>
<tr>
<th>Grain Type</th>
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</thead>
<tbody>
<tr>
<td>Skeletal</td>
</tr>
<tr>
<td>Skeletal - Coral</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Structure</th>
</tr>
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<tbody>
<tr>
<td>Brecciated</td>
</tr>
<tr>
<td>Faintly Laminated</td>
</tr>
<tr>
<td>Grumeleuse</td>
</tr>
<tr>
<td>Planar Laminated</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight</td>
</tr>
<tr>
<td>Undulating</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Accessories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coated grains</td>
</tr>
<tr>
<td>Collapse</td>
</tr>
<tr>
<td>Fenestral Structure</td>
</tr>
<tr>
<td>Horse-tailing</td>
</tr>
<tr>
<td>Pull-apart Structure</td>
</tr>
<tr>
<td>Stromatactis</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Fossils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae</td>
</tr>
<tr>
<td>Amphipora</td>
</tr>
<tr>
<td>Bivalves</td>
</tr>
<tr>
<td>Brachiopods</td>
</tr>
<tr>
<td>Branching coral</td>
</tr>
<tr>
<td>Calcimicrobe Rhenicis</td>
</tr>
</tbody>
</table>
Core Name: BGB-1209, pg. 2 of 7

**Pore Types**
- Fenestral Porosity

**Sedimentary Structures**
- Convolute Lamination
- Fining Upward
- Geopetal
- Horizontal cavity - sediment filled
- Inclined cavity - banded fill
- Sediment cavity - mixed fill
- Slumped Bedding

**Lithofacies/Components**
- **Bioclastic Grain-dominated (BcGD)**
- **Bioclastic Mud-dominated (BcMd)**
- **Coral-Skeletal (CS)**
- **Coral-Spongiosstromate (CSp)**
- **Stromatoids-Coral Mud-dominated (SoCMd)**
- **Stromatopoid-Lamellar (StSea)**
- **Stromatopoid-Lamellar-Coral (StCS)**
- **Stromatopoid-Lamellar-Coral-Algal (StCAl)**
- **Bivalve-Coral-Stromatopoid (BCSI)**
- **Laminated Marl (Lm)**

**Depositional Environment**
- **Backreef (RB)**
- **Reef crest 1 (RC1)**
- **Reef crest 2 (RC2)**
- **Reef front (RF)**
- **Reef slope (RS)**

**Petrographic Samples**

<table>
<thead>
<tr>
<th>Core Depth (Meters)</th>
<th>Core Description Profile</th>
<th>Rock Color</th>
<th>Grain Components</th>
<th>Sedimentary Structures</th>
<th>Notes</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>B R G P F M W M S C</td>
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<td>-----------------</td>
<td></td>
<td></td>
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<tr>
<td>2351.5 m</td>
<td>2462.5 m</td>
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**Depth Scale**
1 : 60

**Well Name & No.**
Texaco Bigoray 6-12-52-9W5

**Location**
T052/R9/SXN12/LSD6

**Geologic Location**
100/06-12-052-09W5/00

**Field**
Bigoray Nisku 'C'

### Lithologies

- Clast supported
- Dolomitic Limestone
- Dolostone
- Limestone

### Admixture

- Anhydritic
- Sandy
- Silty

### Grain Type

- Oncolid
- Peloid
- Skeletal
- Skeletal - Coral

### Structure

- Faintly Laminated
- Grumelose

### Contacts

- Gradational
- Straight

### Accessories

- Anhydrite Nodules
- Birdseye Structure
- Fossil Ghosts
- Pyrite
- Stromatolite
- Synsedimentary Microfaults

### Fossils

- Bivalves
- Brachiopods
- Branching coral
### Core Name: BGC-0612, p. 2 of 9

**Sedimentary Structures**
- Convolute Lamination
- Faint Lamination
- Inclined cavity - banded fill
- Inclined cavity - mixed fill
- Horizontally cavity - sediment filled

**Lithofacies/Components**
- **BiOd** Bioclastic Grain-dominated
- **BiMo** Bioclastic Mud-dominated
- **BiCS** Bivalve-Coral-Stromatoporoid
- **CMDo** Clotted Mud-dominated
- **CM** Coral-Microbial
- **CS** Coral-Skeletal
- **CSp** Coral-Spongiostromate
- **OPMD** Oncoideal-Particulate Mud-dominated
- **Sto** Stromatoporoid or Siliceous Mudstone
- **SICM** Stromatoporoids-Coral Mud-dominated
- **SIC** Stromatoporoid with Alt. Mud-Cement
- **SICA** Stromatoporoid-Coral-Algal

**Depositional Environment**
- **RB** Backreef
- **RF** Reef front
- **RC1** Reef crest 1
- **RC2** Reef crest 2
- **Sh** Shelf
- **TP** Tidal-Peritidal

<table>
<thead>
<tr>
<th>Core Depth (Meter)</th>
<th>Core Description Profile</th>
<th>Rock Color</th>
<th>Lithofacies/Components</th>
<th>Sedimentary Structures</th>
<th>Notes</th>
<th>Petrographic Samples</th>
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<tbody>
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</table>

- Petrographic Samples (Note: Sample 1 is brown, Sample 2 is blue, Sample 3 is red.)

- Core Description Profile (Note: Sample 1 is green, Sample 2 is blue, Sample 3 is red.)
End of core log
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<td>Dolomitic Limestone</td>
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<td>Coated</td>
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<table>
<thead>
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<table>
<thead>
<tr>
<th>fossils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brachiopods</td>
</tr>
<tr>
<td>Crinoids</td>
</tr>
<tr>
<td>Solitary Corals</td>
</tr>
</tbody>
</table>
### Sedimentary Structures

- Oncoid
- Planar Lamination
- Wispy Lamination

### Lithofacies/Components

- BdMd: Bioclastic Mud-dominated
- OPGD: Oncolitic-Particulate Grain-dominated
- CS: Coral-Skeletal
- STN: Stromatoporoid w/ Alk. Mud-Cement
- LM: Laminated Marl
- SIC: Stromatoporoid-Coral

### Depositional Environment

- Ba: Basinal
- RF: Reef front

### Core Description Profile

<table>
<thead>
<tr>
<th>Core Depth (meters)</th>
<th>Core Description Profile</th>
<th>Rock Color</th>
<th>Grain Components</th>
<th>Sedimentary Structures</th>
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</tr>
<tr>
<td>SY 2/1</td>
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</tbody>
</table>

- Rugose coral-skeletal fitstn, skeletal fitstn/mud-dominated PSTN with large Sample #2 at 2488.76 - coral or rugosina. Well laminated, wavy to undulating, abundant horsetails, dk GRY dolom crinoidal wackstone 1.7 m Coral floatstone interbeded @ 3-5 cm scale with bioclastic

<table>
<thead>
<tr>
<th>Petrographic Samples</th>
</tr>
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<tbody>
<tr>
<td>BdMd</td>
</tr>
<tr>
<td>RF</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Lithofacies/Components</th>
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<tbody>
<tr>
<td>BdMd</td>
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<td>RF</td>
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<th>Major Interval</th>
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<tr>
<td>RF</td>
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<table>
<thead>
<tr>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
</tr>
</tbody>
</table>

196
DG GRY mostly barren
laminated
dolomdsin/shale
- NOT LOGGED
IN DETAIL
FROM HERE
DOWNTWARD
ispacious
cement

LMa  3  Ba
Sample #5 @ 2517.5 - faintly laminated bioclastic hash
WKSTN/PKSTN, near the top of Tongue #2

Sample #6 @ 2522.32 - coral floatstone - corals are sparse but intact, in dark grey mud matrix
Sample #7 @ 2532.75 - pebble sz coated grain-bioclastic Rdtn to GD PKSTN

Sample #8 @ 2534.4 - 2-cm thick tabular stromatoporoid and wafer strtnp
DK GRY well, planar laminated shale/ nodule marble - interpreted basinl - NOT LOGGED and intracst brecation
End of core log
<table>
<thead>
<tr>
<th>Core Name: BGD-1404, pg. 1 of 7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lithologies</strong></td>
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<tr>
<td><img src="https://via.placeholder.com/15" alt="Limestone" /></td>
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<tr>
<td><strong>Admixture</strong></td>
</tr>
<tr>
<td><img src="https://via.placeholder.com/15" alt="Argillaceous" /></td>
</tr>
<tr>
<td><strong>Grain Type</strong></td>
</tr>
<tr>
<td><img src="https://via.placeholder.com/15" alt="Coated" /></td>
</tr>
<tr>
<td><img src="https://via.placeholder.com/15" alt="Peloid" /></td>
</tr>
<tr>
<td><img src="https://via.placeholder.com/15" alt="Skeletal - Stromatoporoid" /></td>
</tr>
<tr>
<td><strong>Structure</strong></td>
</tr>
<tr>
<td><img src="https://via.placeholder.com/15" alt="Brecciated" /></td>
</tr>
<tr>
<td><strong>Contacts</strong></td>
</tr>
<tr>
<td><img src="https://via.placeholder.com/15" alt="Gradational" /></td>
</tr>
<tr>
<td><strong>Accessories</strong></td>
</tr>
<tr>
<td><img src="https://via.placeholder.com/15" alt="Cemented Fractures" /></td>
</tr>
<tr>
<td><img src="https://via.placeholder.com/15" alt="Stromatolite" /></td>
</tr>
<tr>
<td><strong>Fossils</strong></td>
</tr>
<tr>
<td><img src="https://via.placeholder.com/15" alt="Amphipora" /></td>
</tr>
</tbody>
</table>
**Sedimentary Structures**
- Faint Lamination
- Inclined cavity - banded fill
- Sediment cavity - mixed fill

**Lithofacies/Components**
- Bioclastic Grain-dominated
- Bioclastic Mud-dominated
- Bivalve-Coral-Stromatoporoid
- Clastic Mud-dominated
- Coral-Skeletal
- Fine-grained carbonate-marl w/ Lithoclasts
- Laminated Marl
- Oncoidal-Particulate Mud-dominated
- Stromatocyst-Coral Mud-dominated
- Stromatocyst-Stromatoporoid
- Stromatopora-Coral-Red algae
- Stromatopora-Coral-Algal

**Depositional Environment**
- RC1: Reef crest 1
- RC2: Reef crest 2
- RF: Reef front
- RS: Reef slope
- Sch: Submarine channel

---

**Core Name: BGD-1404, pg. 2 of 7**

<table>
<thead>
<tr>
<th>Core Depth (Meters)</th>
<th>Core Description Profile</th>
<th>Rock Color</th>
<th>Grain Components</th>
<th>Sedimentary Structures</th>
<th>Notes</th>
<th>Petrographic Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>B R G R h F W M s C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Top of Nisku above cored interval, @ 2454 m</td>
</tr>
</tbody>
</table>

---

203
Encrusting dendroid-colonial coral (Sample #2)

Tabulate-bivalve-brae flint in GRN matrix, with cm Sample 3.7mm of - shellite flint, cemented pore-filling, microcrystalline cement (creamy); shells are not fragmented, sub-cm scale, very thin walled, moldic & gyspsitic fills of grn carb mud are moderately abundant

Bivalve-coral-helically mud-dominated packstone to Pelmophyllum Interbedded skeletal (brachiopod-shelly), isopachous cement rich floatstones with solitary coral wackestones. Gypsum structures have mud fill
unconsolidating cement.

Interbedded coral floatstone (Type 3)
Interbedded coral framestone, coral floatstone (coral 1), and skeletal cement wackestone-floatstone. Cement is moderate to abundant as Sample 5.

Branching coral framestone (as below), with 5-6 cm intervals of GRY/GRN floatstone. Floatstone has smaller intervals of coral-cement.

Thick and massive GRY-GRN branching coral framestone, finger corals, small patches of BRN fill have Sample 7. Coral Type 1: dendroid/ finger tabulate coral, framestone/ battlementstone with microspar-

cementstone

MED BRN grainy carbonate (~3-5 cm) withstromatolite

MED BRN skeletal PKSTN-FLSTN with discrete horizons (cm's thick) of branching coral. Stromatoporoids are laminar and small, rare.

Infraclass-skeletal RDSTN to GD PKSTN. Matrix is green clay (replacement). Semi-vertical dikes of massive clay also present. Grains are all well-rounded.

Gravel and coarse sand size lithoclasts of fine-grained LT BRN-GRN
dotted WK-MDSTN grades upward into grain-dominated skeletal-coral packstone. The WKSTN-MDSTN is modified and granulelose but also shows incipient stylolites and texture is Massive GRN GRN coral floatstone with discrete intervals of GD packstone in occurrence with laminar stromatoporeids. Volcanicite and isoepithelial cement around grains and also cement between grains (can't tell if originally a grainstone or packstone).

Intricate skeletal GRN coral skeletal FLSTN, THick laminar STROM in middle of unit, inclined GRN coral-cement floatstone: ISO Coral floatstone in red GRN mud matrix alternates with buff colored v/gy grainstone (there is no mud, the organisms are translucent like cement, but have distinct geometry -- looks mix of tubiform Grevnestels OR an Intricate floatstone in very Skeletal GSTN-RDSTN interbedded with coquina RDSTN. Matrix alternates Coral FLSTN -- lower 60 cm has larger rugose corals at the base.
and then decreases to sub-cm diameter for the remainder of the unit; also is ferruginous in lower 60 cm within the green mud and surrounding corals, single occurrence of slumped and laminated carbonate mud in dikes.

- Coarse-grained, shelly floatstone.

- Significant increase in L1 GRY to BFF mottled mudstone—possible boundstone.

- Internal structure at core scale

- DK GRN/GRY polymicro breccia: DK GRN coral floatstone hosts sediment filled, high angle fractures (>2 up to 10 cm length can be traced vertically; half-cm to cm’s wide). Fill is 1) graded massive to well sorted Nisku Fm continues downward to 2571 m (Top of Ireton) in BRN mud matrix. 2) DK GRN mud has a sub-mm feature, spherical and rounded, occurs in clumps, that I can’t recognize. Calcite filled fractures are truncated by sediment filled cavities.

End of core log
<table>
<thead>
<tr>
<th>Depth Scale</th>
<th>1 : 60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Name &amp; No.</td>
<td>AMOCO ET AL BIGORAY 13-20-52-8</td>
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<tr>
<td>Location</td>
<td>T052/R08/SXN20/LSD13</td>
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<tr>
<td>Source</td>
<td>Western Canadian Sedimentary</td>
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<td>UW No.</td>
<td>100/13-20-052-08W5/02</td>
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</tbody>
</table>

**Lithologies**
- Dolomitic Limestone
- Limestone
- Marl

**Admixture**
- Argillaceous

**Grain Type**
- Coated
- Intraclast
- Peloid
- Skeletal
- Skeletal - Coral

**Structure**
- Brecciated
- Faintly Laminated
- Grumuleuse

**Contacts**
- Gradational
- Straight

**Accessories**
- Cemented Fractures
- Coated grains
- Intraclast
- Lithoclast
- Stromatolids

**Fossils**
- Brachiopods
- Branching coral
- Calcareaous Algae
- Coral Compound
- Gastropods
- Solitary Corals
- Stromatoporoid Laminar
- Stromatoporoids
- Thamnopora
## Pore Types
- Fine Interparticle Porosity
- Intraskeletal Porosity
- Mouldic Porosity
- Shelter Porosity

## Sedimentary Structures
- Geopetal
- Inclined cavity - banded fill
- Oncolith

## Lithofacies/Components
- **BoiGD**: Biodiastic Grain-dominated
- **BoiMd**: Biodiastic Mud-dominated
- **ClMd**: Clotted Mud-dominated
- **CM**: Coral-Microbial
- **CS**: Coral-Skeletal
- **CSp**: Coral-Spongiosormate
- **FG:tch**: Fine-grained carbonate-marl w/ Lithoclasts
- **LMa**: Laminated Marl
- **OPM**: Oncoloidal-Particulate Mud-dominated
- **StCM**: Stromatolitic-Coral Mud-dominated
- **SIC**: Stromatoporoid-Coral
- **StSM**: Stromatoporoid-Skeletal Mud-matrix

## Depositional Environment
- **Ba**: Basinal
- **RC1**: Reef crest 1
- **RI**: Reef interior/flat
- **TPe**: Tidal-Peritidal

## Core Depth (Meters)

<table>
<thead>
<tr>
<th>Core Description Profile</th>
<th>Rock Color</th>
<th>Grain Components</th>
<th>Sedimentary Structures</th>
<th>Notes</th>
<th>Petrographic Samples</th>
<th>Lithofacies/Components</th>
<th>ISL Cement</th>
<th>Major Interval</th>
<th>Depositional Environment</th>
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</tr>
</tbody>
</table>

Top of NSKU Fm @ 2277m

CIMdD
Thick section of interbedded robust coral and Thermoporoza
FLITON and PKSTON.
Beds average 10-12
cm thick, contacts are
distinct except at base of rare batheorene-
type beds (where
corals appear upright
and in-situ); the
density of corals is not
thick enough to create
a true batheorene.
Cobblestone fill and
shallow cavities filled
with sediment
common throughout.
This FLSTN has a lower dolomitic mud ratio than the fossils that occur in the same section and it is a brachiopod. The matrix seems to be mudrock with minor bafflestones.

- LG: (cm high) donut stromatoporoid caps a unit of coral FLSTN.
- FLSTN has a bi-modal matrix with Type A matrix is a drier GRY-GRN matrix. Type B is a silt GRN that looks lepaceous in some places as if filling interior veins. The boundary between the two matrix types is diffuse.

- LGRN (tabulate coral FLSTN) which is a unit of isopachous cement, mud (cracks?) with lac cement on all sides (example 1/3): matrix is a bi-modal (a) dense marine surrounding most cortals and postdolites isopachous cement, and (b) lighter, structureless mudrock (matrix appears barren).
- Matrix type B appears to predominate Type A.
End of core log
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**Lithologies**
- Dolomitic Limestone
- Dolostone
- Limestone

**Admixture**
- Anhydritic
- Argillaceous
- Silty

**Grain Type**
- Coated
- Oncoid
- Peloid
- Skeletal
- Skeletal - Coral

**Structure**
- Brecciated
- Faintly Laminated
- Grumleuse

**Contacts**
- Gradational
- Straight

**Accessories**
- Anhydrite Nodules
- Birdseye Structure
- Fossil Ghosts
- Stromatactis
- Stylolites

**Fossils**
- Amphipora
- Bivalves
- Brachiopods
| Core Name: BR-0327, pg. 2 of 8 |

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**Pore Types**
- Fenestral Porosity
- Mouldic Porosity
- Vuggy Porosity

**Sedimentary Structures**
- Domal Stromatolite
- Geopetal
- Inclined cavity - banded fill
- Lenticular Bedding
- Mottled Bedding
- Oncoid
- Thrombolite
- Wispy Lamination

**Lithofacies/Components**
- BAMd: Barren Cretaceous Mud-dominated
- BdGD: Bioclastic Grain-dominated
- BdMd: Bioclastic Mud-dominated
- BICs: Bivalve-Coral-Stromatoporoid
- BrSp: Bryozoan-Sponge
- CM: Coral-Microbial
- CS: Coral-Skeletal
- CMs: Coral-Spongiosostome
- MG: Mottled-Grunulesse
- OPMd: Oncoidal-Particulate Mud-dominated
- Sh: Sh/Silts/Dolostone or Silicious Mudstone
- SCM: Stromatoporoid-Coral Mud-dominated
- SIM: Stromatoporoid-Calcimicrobial
- StC: Stromatoporoid-Coral
- StICA: Stromatoporoid-Coral-Algal

**Depositional Environment**
- RB: Backreef
- RC1: Reef crest 1
- RI: Reef Interior/flat
- RS: Reef slope
- Sh: Shelf
- MS: Shelf margin/slope
- TIm: Tidal-Intertidal
- 1Pe: Tidal-Peritidal

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<th>Grain Components</th>
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218
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Buffer: 2664 m
Depth Scale: 1:60
Country: Canada
Well Name & No.: PENN WEST PEMBINA 11-12-50-10
Location: T050/R10/SXN12/LSD11
Area: Western Canadian Sedimentary
UW No.: 100/11-12-050-10W5/00
Field: Nisku 'T'
Geologic Location: Reef front
### Pore Types

- Vuggy Porosity

### Sedimentary Structures

- Domal Stromatolite
- Inclined cavity
- Parallel Wavy Bedding

### Lithofacies/Components

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### Depositional Environment

- RB: Backreef
- RC1: Reef crest 1
- RF: Reef front
- Sh: Shelf

### Petrographic Samples

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### Core Data

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### Lithologies
- Limestone

### Admixture
- Argillaceous
- Pyritic
- Silty

### Grain Type
- Skeletal
- Skeletal - Coral

### Structure
- Faintly Laminated
- Grumelose

### Contacts
- Scoured
- Straight

### Accessories
- Cemented Fractures
- Stromatolite
- Synsedimentary Microfaults

### Fossils
- Brachiopods
- Branching coral
- Calcimicrobe Renalcis
- Calcimicrobe
- Coral Compound
- Corals
- Crinoids
- Fossils Broken
- Molluscs
- Radiolarians
- Solitary Corals
- Spicules
This (1-2 cm scale) crust is composed of alternating subporoid coral and fenestrate fenestraoporoid encrusting one another. High microboreal content (sporophyto species replaced w caliche), radiolarians. Crusts are separated by intervals of grain-dominated pelagic foraminifera.

Thoremaparaphyllia and calcareous algae
Crust BOSTN - borings in coral and fenestrate common in matrix, sponge spicules present.

Eg. softly rugose, Thoremaporia, and Corallites corallid spicules, silty, corals are coated on some sides (90° uniform side) with Rutepithecus; rare encrusting is symmetric, widening up.
End of core log
Appendix C

Petrographic Index
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Appendix D

XRD Data Table
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<td>2524.15</td>
<td>fine-grained, green dike in grainstone matrix</td>
<td>inclined, faintly bedded bioclastic wackestone, locally euhedral dolomudstone</td>
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<td>grey-green mud hosting coral and wafer stromatoporoids</td>
<td>dolomudstone</td>
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<td>fasciculate rugose bafflestone w/ medium-grained dolomudstone matrix</td>
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<td>auloporid-microbial boundstone matrix</td>
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<td>matrix in coral bafflestone</td>
<td>rugose bafflestone w/ polymud and microbioclastic matrix, shelter pores at lower base are well-defined and Ca-cement filled</td>
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<td>matrix in coral bafflestone</td>
<td>rugose bafflestone with microbioclastic-spiculitic mudstone matrix; mud is locally dolomitized</td>
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**Mineralogy key**: Ankerite (A), Calcite (C), Dolomite (D), Ferroan dolomite (FD), Illite (I), Illite 2M1-NR (I2), Kaolinite (K), Magnesian calcite (MgC), Magnesian siderite (MgS), Montmorillonite (MMT), Quartz (Q), Siderite (S)
Appendix E

Facies Analysis
Appendix F

Hyperspectral Data
Distribution of Spectral Classes by Sample

A

B

C

D

Skeletal calcite 1 (S1)

Skeletal calcite 2 (S2)

Skeletal calcite 3 (S3)
Distribution of Spectral Classes by Sample

A

B

C

D

Micrite (M)  Pore-filling calcite (PFC)  Renalcis (R)

1.57  0.00  1.57  0.00  1.57  0.00