Controls on lithofacies variability in Late Devonian, Cynthia Basin reefs, Nisku Formation, Western Canadian Sedimentary Basin

by

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ABSTRACT

The Late Devonian (Frasnian) Nisku Formation in the Western Canadian Sedimentary Basin is a homoclinal ramp composed of four stacked carbonate cycles with reefs in both shallow-ramp and downslope settings. Nisku Formation deposits in the Cynthia Basin, a westward facing sub-basin, contain two distinctly different reef types. One is composed of well-developed coral communities, stromatoporoids, synsedimentary cement and few calcimicrobes whereas the other is composed of calcimicrobes, wafer stromatoporoids and little cement. Deposits along the northeastern rim of the Cynthia Basin, the focus of this study, contain diverse calcimicrobes including Girvanella, Rothpletzella and Renalcis. Twelve lithofacies are documented and consist primarily of calcimicrobe-dominated reef-building communities which typify the first type of Cynthia Basin reefs. These deposits lack the reef-building fauna of corals and massive stromatoporoids common in southern Cynthia Basin reefs and older successions. The difference between coral-stromatoporoid and calcimicrobial communities is interpreted to be a result of increasing nutrient levels during basin restriction and shelf progradation. The nutrification can be linked to relative sea-level change as well as basin geometry and is thought to have been sourced primarily from terrestrial runoff along the northern margin of the basin. This study provides evidence that trophic resource variation could have contributed more to the development of calcimicrobe-dominated lithofacies in Devonian systems than has been previously documented.
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TABLE OF CONTENTS

Abstract .................................................................................................................................i
Acknowledgements ..............................................................................................................ii
Table of Contents ..................................................................................................................iii
List of Figures ......................................................................................................................v
List of Tables .......................................................................................................................vi

Chapter 1: Study Introduction ......................................................................................... 1
  General Introduction ...........................................................................................................1
  Scope and Objectives .........................................................................................................3
  Methods of Study ...............................................................................................................4
  Geologic Setting ................................................................................................................5
    Western Canadian Sedimentary Basin .............................................................................5
    Paleozoic Platform Phase ................................................................................................6
    Mesozoic/Cenozoic Foreland Basin Phase .......................................................................7
  Study Area Geology ..........................................................................................................8
    Devonian Successions in Western Canada .......................................................................10
    Nisku Formation and Cynthia Basin ..............................................................................10

Chapter 2: Lithofacies Analysis of the Nisku Formation, Northeastern Cynthia Basin ......................................................................................................................... 17
  Laminated Lime Mudstone ................................................................................................17
  Bioturbated Lime Mudstone .............................................................................................21
  Nodular Lime Mudstone ..................................................................................................22
  Fossiliferous Wackestone ...............................................................................................24
  Crinoid Grainstone/Rudstone .........................................................................................26
  Fossiliferous Floatstone/Rudstone ..................................................................................28
  Amphipora Floatstone/Rudstone .....................................................................................31
  Oncolitic Floatstone .........................................................................................................33
  Stromatoporoid Floatstone/Framestone ..........................................................................36
  Stromatoporoid-Spongiostromate-Renalcis Framestone ..............................................39
  Renalcis Bindstone ........................................................................................................43
  Coral Framestone/Floatstone ........................................................................................46
  Lithofacies Associations ...............................................................................................48
LIST OF FIGURES

FIGURE 1.1: Locations of known Frasnian carbonate platforms worldwide. ..............................................2
FIGURE 1.2: Late Devonian (360 Ma) North American paleogeographic map of the WCSB......................3
FIGURE 1.3: Location map of the study area..................................................................................................5
FIGURE 1.4: Detailed location map of the study area with Google Earth underlay.................................9
FIGURE 1.5: Relative Devonian sea-level curve of the WCSB.....................................................................11
FIGURE 1.6: Stratigraphic column (Mid Devonian to Mississippian) of the WCSB.................................12
FIGURE 1.7: Frasnian stratigraphy in the Cynthia Basin area........................................................................12
FIGURE 1.8: Generalized lithofacies and isopach map of the Nisku Formation.....................................15
FIGURE 1.9: Location map of oil and gas production from Nisku pinnacle reefs....................................16
FIGURE 2.1: Core photographs of the Laminated Lime Mudstone and Bioturbated Lime Mudstone Lithofacies. ..........................................................................................................................18
FIGURE 2.2: Core photographs of the Nodular Lime Mudstone Lithofacies..........................................23
FIGURE 2.3: Core photographs of the Fossiliferous Wackestone Lithofacies..........................................25
FIGURE 2.4: Core photographs of the Crinoid Grainstone/Rudstone Lithofacies.................................27
FIGURE 2.5: Core photographs of the Fossiliferous Floatstone Lithofacies............................................30
FIGURE 2.6: Core photographs of the Amphipora Floatstone Lithofacies.............................................32
FIGURE 2.7: Core photographs of the Oncolitic Floatstone Lithofacies.................................................35
FIGURE 2.8: Core photographs of the Stromatoporoid Floatstone/Framestone Lithofacies..................38
FIGURE 2.9: Core photographs of the Stromatoporoid-Spongiostromate-Renalcis Framestone Lithofacies........................................................................................................................................42
FIGURE 2.10: Core photographs of the Renalcis Bindstone Lithofacies.................................................45
FIGURE 2.11: Core photographs of the Coral Framestone/Floatstone Lithofacies...............................47
FIGURE 3.1: Comparison of reef styles within Cynthia Basin pinnacle reefs.........................................51
FIGURE 3.2: North-south cross section of the Cynthia Basin.................................................................53
FIGURE 3.3: Lithological summary of Zeta Lake member type section..................................................54
FIGURE 3.4: Depositional elements and reef lithofacies map of the Cynthia Basin.............................56
FIGURE 3.5: Stratigraphic relationships of the Winterburn strata in the Cynthia Basin.........................56
FIGURE 3.6: Nutrient-gradients for modern carbonate sedimentation....................................................62
FIGURE 3.7: Nutrient-gradient model for Devonian reef systems..........................................................62
FIGURE 3.8: Schematic illustration of Cynthia Basin evolution..............................................................72
LIST OF TABLES

**TABLE 2.1:** Summary of lithofacies documented along the northeastern rim of Cynthia Basin and their variation from lithofacies at the Meekwap field..........................................................19

**TABLE 3.1:** Reef lithofacies by well location ..................................................................................50
CHAPTER 1: STUDY INTRODUCTION

GENERAL INTRODUCTION

The Devonian period is regarded as one of the most remarkable times of reef-building in the Phanerozoic. During the 80 Ma of carbonate productivity in the Silurian and Devonian, reefs reached their maximum known geographic extent (Copper, 2002a). High average earth temperatures, paired with large amounts of atmospheric CO$_2$, allowed reefs to flourish in latitudes greater than 45°S and possibly greater than 60°N (Figure 1.1) (Copper, 2002b). The biotic diversity of shallow-water carbonate systems was immense with reef-builders showing a variety of complex morphologies (Wood, 1999). The extensive documentation of Devonian reef systems is partly due to the economic interest in Devonian carbonates of the Western Canadian Sedimentary Basin (WCSB) and the occurrence of superb outcrops in the Canning Basin, Australia (Playford et al., 1976; Playford, 1980; Wood, 1998; Wood, 1999).

Devonian reefs were predominantly constructed by stromatoporoids, corals, and calcimicrobes (calcified microbial microfossils). It is thought that calcimicrobes became more prevalent in reefs towards the end of the Devonian through a shift in reef composition (Wood, 1999; Shen et al., 2010). The Frasnian-Famennian boundary is marked by the Kellwasser extinction event that eliminated many reef-building skeletal biota on carbonate platforms worldwide, including many stromatoporoids and tabulate corals (Copper, 2002a; Stephens and Sumner, 2002; Whalen et al., 2002; Morrow et al., 2011). However, despite the loss of many principle reef-building fauna, reefs in the Famennian thrived and even prograded (Playford, 1980; Stephens and Sumner, 2002). Microbial abundance in shallow-water carbonate environments was particularly common in the Famennian, yet there is debate as to whether calcimicrobes rose to dominate Famennian reefs post-extinction event only as a “disaster taxa” (Whalen et al., 2002; Shen et al., 2010). There is some discussion that calcimicrobes came to dominate shallow-reef environments well before the end of the Frasnian and their occurrence was dependent on local and basinal factors (Whalen et al., 2002; MacNeil and Jones, 2008; MacNeil, 2011).
Widespread carbonate systems with giant reef complexes covered the North American craton during the Devonian but decreased during the Frasnian and Famennian (Figure 1.2) (Copper, 2002a). Although there has been extensive data gathered on Devonian reef systems, with emphasis on studies in the WCSB, the exact geometry and ecology of these tracts are poorly understood because they are subsurface and often dolomitized (Wood, 1999). Devonian aged reef deposits within Canada are predominantly located in the subsurface of the Western Canadian Sedimentary Basin with local exposure in the Rocky Mountains (Watts, 1987; Copper, 2002a; Whalen et al., 2002). This study focuses on WCSB Nisku Formation deposits of Frasnian age within the Cynthia Basin.

The paleogeography, stratigraphy, and evolution of Nisku Formation buildups and reefs along the southern rim of the Cynthia Basin have been previously documented by Chevron Exploration Staff (1979) and Watts (1987). The producing oil field at Meekwap within the Cynthia Basin warranted scientific study of the northwestern rim of the basin due it economic interest (Chesire and Keith, 1977; Bingham-Koslowski, 2010). Nisku deposits along the northeastern rim of the Cynthia Basin are relatively undocumented with the exception of overview studies (e.g., Watts, 1987; Rennie et al., 1989; Switzer et al., 1994).
Nisku deposits on the northeastern rim of the Cynthia Basin contain a volumetrically significant amount of calcimicrobes along with stromatoporoids and few corals. This is contrary to some previously described Nisku reef lithofacies that were dominated by corals and stromatoporoids (Chevron Exploration Staff, 1979; Watts, 1987).

Drill cores intersecting a number of pinnacle reefs on the northeastern rim of the Cynthia Basin provided an opportunity to examine the shelf and reef lithofacies. Lithofacies interpretations provided insights into the nature of the carbonate system along the northeastern rim of the basin and paleoceanographic conditions at the time of deposition.

**SCOPE AND OBJECTIVES**

Calcimicrobes are principle components in many Devonian reef systems (e.g. Wood, 1998; MacNeil and Jones, 2008; Shen et al., 2008; Wendte et al., 2009) with stromatoporoid-microbe dominated reef lithofacies being the standard for pre-Famennian reef systems (cf.
MacNeil and Jones, 2008). While this may be true for certain large, well-documented reef systems such as the Canning Basin in Australia (Playford, 1980; Wood, 1993, 1998, 2000) and those within the Frasnes Group of Belgium (da Silva and Bouv lain, 2004; Bouv lain et al., 2005), the presence of calcimicrobes seems to be an indicator of paleoceanographic conditions and not a lithofacies model for pre-Famennian reefs (e.g. MacNeil and Jones, 2008; MacNeil, 2011; Shen et al., 2011). Calcimicrobes seem to be prevalent in many lithofacies at Meekwap (Bingham-Koslowski, 2010) whereas they have been documented as being less significant in lithofacies described in the southern part of the basin (Chevron Exploration Staff, 1979; Watts, 1987).

The purpose of the study is to: 1) document the reef and shelf lithofacies in cores from along the northeastern margin of the Cynthia Basin; 2) compare lithofacies to previously documented Nisku lithofacies at Meekwap and along the southern margin of the basin; 3) relate the findings of the study to the paleoceanography of the basin; and 4) determine the controls on reef-building in the Cynthia Basin.

**METHODS OF STUDY**

The study consisted of detailed logging of eleven drill cores through the Nisku Formation in the Cynthia Basin. Two supplemental cores, previously logged by Dr. William Martindale, were examined by the author and are included in the study as well. Drill cores were from wells ranging from Township 56, Range 1W5 to Township 65, Range 8W5 (Figure 1.3). Cores were examined at the ERCB Core Research Centre in Calgary, Alberta during the month of May, 2011. Cores penetrating Nisku pinnacle reefs were chosen to document the nature of reef lithofacies around the eastern rim of the basin and were predominantly limestone with limited dolomite to maximize fabric preservation. Depositional fabrics, biologic components, sedimentary structures, and lithologies were recorded based on a template originally created by Dr. William Martindale. Digital logs were created afterwards using Adobe Photoshop CS2 and are found in Appendix A. Samples were taken for thin section analysis based on anomalous microbial features in reef lithofacies. Core photography was performed with a Nikon D3100 D-SLR camera and the majority of core photographs have not been digitally altered.
FIGURE 1.3: Location map of the study area. Dominion Land Surveyors System location: Township 55, R1W5 (southeast) to Township 66 R9W5 (northwest). All wells with core intervals through the Nisku Formation shown. Cores from wells logged by author shown in blue while those only reviewed by author shown in green.

Core descriptions and photographs were utilized to determine common lithofacies in the deposits which were then used to determine the environments of deposition. The depositional environments, along with the nature of the lithofacies were used to determine the paleoceanography and evolution of the basin at the time of deposition.

GEOLOGIC SETTING

WESTERN CANADIAN SEDIMENTARY BASIN

The WCSB can be divided into two fundamentally distinct depositional phases: a succession of predominantly carbonate rocks of Paleozoic age, and a younger succession of Mesozoic/Cenozoic, principally siliciclastic rocks. The initial depositional phase resulted from the transgression of a platform and onlap of carbonate sediments onto the craton. A
regionally extensive carbonate ramp was established during the Givetian and deposition continued during the Late Devonian as strata transgressed across a widespread subaerial unconformity (Whalen et al., 2002). Carbonate deposition in the WCSB continued through the Permian. Siliciclastic sedimentation followed during a subsequent foreland basin phase related to collisional orogenic events and synorogenic shedding of clastic detritus (Porter et al., 1982). This deposition created a northeastward tapering wedge and a succession greater than 6 km in thickness in the Cordilleran foreland thrust belt that is strongly linked to the evolution of the Canadian Cordillera and the superposition of foreland basin deposits overlying passive continental margin deposits (Porter et al., 1982).

**Paleozoic Platform Phase**

The North American proto-continent was the result of multi-phase rifting from a Late Proterozoic supercontinent (Kent, 1994). This process resulted in the formation of eastern and western continental margins from 730 to 555 Ma (Kent, 1994). A regionally extensive unconformity within the Sauk Sequence separates Cambrian rocks from Precambrian cratonic and sedimentary rocks (Kent, 1994). In early phases of passive continental margin deposition (Cambrian to lower Ordovician), shallow shelf siliciclastics dominated deposition in close proximity to the western continental margin with shallow shelf carbonate deposition occurring further offshore (Kent, 1994). Deposition throughout the remainder of the Paleozoic was punctuated by a series of eustatic sea-level falls, creating unconformities and sequence boundaries (*sensu* Catuneanu, 2006) in a series of second-order sequences (Ziegler, 1988).

The clastic transgressive phase of the Cambrian and lower Ordovician was followed by a long period of predominately carbonate deposition over much of proto-North America (Kent, 1994). As was the case in the Cambrian, seas of the Ordovician and Silurian flooded the western margin of the proto-continent (Porter et al., 1982). Following the conclusion of the Sauk Sequence, marked by a eustatic sea-level fall, basal transgressive sandstones of the Tippecanoe Sequence onlapped the eastward upper surface of the Sauk Sequence (Porter et al., 1982). Initial transgressive sandstone units of the Tippecanoe Sequence are overlain by shallow-water carbonates with local reefs and minor amounts of clastics, evaporites, and
shales (Norford et al., 1994). The Tippecanoe Sequence was followed by 36 Ma of exposure leading into the deposition of the Kaskaskia Sequence (Kent, 1994). A series of intracratic arches, with limited to no carbonate sedimentation, interrupted the linear depositional pattern of carbonates creating numerous ‘sub-basins’ through the Tippecanoe and Kaskaskia sequences (Porter et al., 1982). These arches also supplied clastic sediment that resulted in basal transgressive deposits (Porter et al., 1982). The complexity of epeirogenic uplift of cratonic arches during the Kaskaskia Sequence controlled the distribution, thickness, and character of Kaskaskia Sequence deposits (Porter et al., 1982). Initial deposits of the Kaskaskia were a mix of siliciclastics, shallow-water carbonates, and evaporites (Porter et al., 1982). Reefs extensively developed throughout the Devonian from the middle Eifelian through the middle Givetian, ranging from pinnacle to barrier types and stretched from south of the Canadian border to the Mackenzie Delta (Copper and Scotese, 2003). Reef size had diminished by the Frasnian and retreated largely to central and southern Alberta possibly related to a series of regressive cycles (Moore, 1989). Carbonate platform growth was able to keep-up with a 2nd order sea-level rise and outpaced basinal sedimentation for much of the Frasnian (Whalen et al., 2002). The depositional style of the following Absaroka Sequence is characterized by a westward tilt of the craton, the emergence of the Sweetgrass Arch, and an upward increase in terrigenous clastic detritus (Porter et al., 1982). Sedimentation in the Mississippian began with an abrupt transgression marked by a thin, widespread, organic-rich shale, followed by a depositional stage of open marine calcareous shales and limestones that was ultimately capped by silts and sands recording a reactivation of cratonic arches. This marks the end of the passive continental margin phase of deposition (Porter et al., 1982).

**Mesozoic/Cenozoic Foreland Basin Phase**

The Zuni Sequence records the evolution of the WCSB from a passivecontinental margin with numerous arches and sub-basins into a foreland basin with northeastward thinning wedges of siliciclastics that, for the most part, prograded toward the middle of the craton (Porter et al., 1982). The foreland basin formed a craton-ward migrating moat due to isostatic flexure of the lithosphere and subsidence in response to the increased tectonic
loads of terrain accretion (Porter et al., 1982). During the late Jurassic there was a reversal (from westward to eastward) in the direction of net sediment transport and a sudden increase in the volume of clastic sediment being shed from the emerging Cordilleran fold and thrust belt. An extensive marine transgression occurred throughout the Jurassic and Cretaceous, flooding the craton and creating the Western Interior Seaway (Nicholls and Russell, 1990). A series of sea-level fluctuations, both varying in temporality and magnitude, resulted in the formation of alternating sandstone and shale layers with sediment derived (mostly) from the Cordillera (Smith, 1994). The deposits formed during the foreland basin phase include the Zuni and subsequent Tejas Sequence (Porter et al., 1982). Marine deposition ended in the WCSB following the sea-level fall at the end of the Cretaceous. Deposits of glacial, fluvial, lacustrine, aeolian, and organic origin comprise sedimentation from the end of the Cretaceous Western Interior Seaway to present day on the Interior Platform (Fenton et al., 2008).

**STUDY AREA GEOLOGY**

The study area is centered approximately 150km northwest of Edmonton, Alberta (Figures 1.3 & 1.4). Core intervals were studied from wells that targeted pinnacle reefs to determine lithofacies variability along the Meekwap Shelf. Well locations of cores studied are shown in Figure 1.4. Numerous pinnacle reefs on the southern flank of the basin (in the West Pembina area) along with pinnacles in the Meekwap field (Township 66, Range16W5) are prolific hydrocarbon producers (Burrowes and Krause, 1987). Figure 1.4 shows the study area along with the Dominion Land Surveyors System location of wells with core intervals studied. The deposits of interest are part of the (Frasnian) Nisku Formation and are found at measured subsurface depths between 1300m and 1800m. The studied deposits belong to a sub-basin, the Cynthia Basin, representing a small portion of unfilled accommodation during the Mid to End Frasnian (Burrowes and Krause, 1987).
FIGURE 1.4: Detailed location map of the study area with Google Earth underlay. All wells with core intervals through the Nisku formation shown. Cores from wells logged by author shown in blue while those only reviewed by author shown in green. Core intervals included in this study (blue and green) have well locations adjacent.
Devonian Successions in Western Canada

The Devonian strata of the WCSB were deposited over a 2\textsuperscript{nd} order sea-level rise (Figure 1.5). The deposits are predominantly carbonates, with minor amounts of sandstone and evaporite. The stratigraphic record within the interval can be divided into six groups, each bounded by transgressive or regressive events (Burrowes and Krause, 1987). These intervals are: the Lower Elk Point Group (pre-Givetian), Upper Elk Point Group (Eifelian to early Givetian), Beaverhill Lake Group (Givetian to early Frasnian), Woodbend Group (Frasnian), Winterburn Group, (late Frasnian to early Famennian), and Wabamun Group (Famennian) (Burrowes and Krause, 1987). Increased accommodation during 3\textsuperscript{rd} order sea-level rises promoted the deposition of well-developed reef systems including the Keg River, Swan Hills, and Leduc reefs (Figure 1.5). Reefs also formed during the 2\textsuperscript{nd} order sea level fall, when accommodation was increased during 3\textsuperscript{rd} order rises. These sea-level rises promoted the growth of Lobstick/Bigoray, Blueridge and Wabamun reefs. Reefs before the Devonian highstand formed enormously thick successions and are important hydrocarbon reservoirs (Burrowes and Krause, 1987). Reefs formed after this highstand were not able to develop such thick successions but are still significant hydrocarbon resources, especially where dolomitized (Chevron Exploration Staff, 1979; Potma et al., 2001). Devonian carbonate sedimentation was preceded by a series of tectonic events resulting in the development of a 'basin and arch' topography influencing basin fill patterns (Burrowes and Krause, 1987).

Nisku Formation and Cynthia Basin

The Nisku Formation belongs to the Winterburn Group and represents carbonate sedimentation occurring on a slowly subsiding shelf rimming the craton (Watts, 1987). The Winterburn Group thickens from less than 20m in Saskatchewan to more than 380m in northeastern British Columbia (Switzer et al., 1994). The Nisku Formation overlies shales of the Ireton Formation and is capped by calcareous marls and shales of the Calmar Formation (Figures 1.6 & 1.7). Nisku deposition resulted in widespread carbonate accumulation over much of Alberta (Burrowes and Krause, 1987; Whalen et al., 2002).
FIGURE 1.5: Relative Devonian sea-level curve of the Western Canadian Sedimentary Basin. 2nd and 3rd order curves displayed on top. Note the timing of reef systems. Nisku Formation and member occurrence, relative to 4th/5th order sea-level fluctuations shown below. (Courtesy of W. Martindale)
FIGURE 1.6: Stratigraphic column from Middle Devonian to start Mississippian (MI) in the Western Canadian Sedimentary Basin. Nisku Formation (red box) is found in the southern and central plains region. Cynthia Basin deposits are located within the central plains. Modified from Core Laboratories Calgary (2010).

FIGURE 1.7: Frasnian stratigraphy in the Cynthia Basin area as described by Chevron Exploration Staff (1979).
Nisku deposits are silty and argillaceous in the northern part of the WCSB, whereas in eastern and southeastern parts of the basin, deposits are predominately shelf and reef carbonates (Burrowes and Krause, 1987). The basin and arch configuration strongly controlled sedimentation and resulted in two depocentres; one being the Cynthia and Karr Basins, and the other located in northeastern British Columbia (Watts, 1987; Switzer et al., 1994). The Nisku Formation represents a homoclinal ramp, containing at least four ‘megacycles’ of stacked carbonate ramps, with both isolated shallow-ramp and downslope buildups (Watts, 1987). The Lobstick, Bigoray, Cynthia and Wolf Lake members represent these stacked ramps (Chevron Exploration Staff, 1979). They are best defined in the West Pembina area where their distributions have been extensively mapped (Watts, 1987).

Nisku deposition began with a marine transgression resulting in the formation of a widespread carbonate ramp where underlying deposits of the Ireton Formation were shallow enough to promote carbonate sedimentation (Switzer et al., 1994). The transgressive stage promoted carbonate sedimentation in shallow localities, whereas equivalent deep-water environments show a series of backstepping ramps with isolated downslope reefs (e.g. Zeta Lake Member) (Chevron Exploration Staff, 1979; Switzer et al., 1994). Following the transgression, an upper regressive stage culminated Nisku deposition, locally filling parts of the basin in progressively shallowing deposits (Switzer et al., 1994). Shallow-water carbonate sedimentation was able to keep pace with sea-level rise and aggraded to form the Nisku shelf. The regressive stage is indicated by a basinward building of carbonate and fine-grained clastic sediments in a low accommodation setting. Shallow-water carbonate deposition occurred on shelves during times of restricted clastic influx, well-developed in the Jean Marie, Wolf Lake, and Meekwa Shelf carbonates. The Lobstick, Bigoray and lower Cynthia members are thought to represent Nisku deposition during transgressive stages, whereas upper Cynthia and Wolf Lake members likely represent deposits during regression when 4th and/or 5th order sea-level rises provided accommodation (Figure 1.5). These stages are best defined in the West Pembina area (Switzer et al, 1994).

Pinnacle reef development commenced during deposition of the Lobstick member (Watts, 1987), likely at favourable sites with hardgrounds, firmgrounds, or on topographic highs (Switzer et al., 1994). Lobstick member deposition is thought to have outpaced sedimentation resulting in a shallowing-upward succession that eventually reached sea-
level in proximal areas (Watts, 1987). Throughout deposition of the Bigoray and Cynthia members, patch reef growth occurred during times of limited clastic influx (Watts, 1987). A major sea-level rise at the end of Bigoray deposition led to the incipient drowning of the platform and transgression (Watts, 1987). Carbonate sedimentation was unable to keep up to the increase in accommodation, due to renewed subsidence and sea-level rise, during Cynthia member deposition and resulted in a retreating carbonate ramp (Watts, 1987). However, reef growth during sea-level rise continued as organisms flourished, resulting in keep-up growth (Neumann and Macintyre, 1985) and substantial vertical accumulation (Watts, 1987). Carbonate sedimentation was once again able to outpace relative sea-level rise throughout the deposition of the Wolf Lake member and resulted in progradation of the last Nisku carbonate ramp (Watts, 1987).

Reefs in the Wolf Lake member were progressively surrounded and eventually capped by prograding shallow-water carbonates (Watts, 1987). Pre-Winterburn topography was fairly flat lying with only gentle relief over most of southern Alberta, Saskatchewan and Manitoba (Switzer et al., 1994). In central Alberta, a pronounced topographic low was bordered by thinning Woodbend strata to the south and east, to the west by Leduc reefs and shelf complexes, and to the north by the Athabasca arch (Switzer et al., 1994). This area would be the depocentre for the future Cynthia and Karr Basins (Figure 1.8). The geographic protection of the Cynthia and Karr Basins from open ocean conditions are reflected in the lithofacies documented in this study.

The Zeta Lake pinnacle reef trend (Figure 1.9) occurs on the southeastern side of the Cynthia Basin (Chevron Exploration Staff, 1979). It occurs on the medial section of the Lobstick ramp and the rocks were prolific hydrocarbon producers partially due to being extensively dolomitized (Watts, 1987; Switzer et al., 1994). The relationship between Zeta Lake reefs and Cynthia Basin fill is controversial. Most pinnacle reefs are rooted in the Lobstick member, while some appear to have initiated on subsequent ramps (Watts, 1987). Whether these reefs initiated on a single or multiple surface(s), along with their age relationship to the basin fill, is still debated (Switzer et al., 1994). The Lobstick, Bigoray and Cynthia members thin in a northerly direction along the northern margin of the Cynthia Basin due to the structure of the underlying Ireton Formation. A succession present on the northern margin of the basin but not present in the West Pembina area has been
FIGURE 1.8: Generalized depositional lithofacies and isopach map of the Nisku Formation in Alberta. Wells removed from area of interest for clarity. Note the position of the Lobstick and Meekwap Shelf edges rimming the Cynthia Basin (blue), mixed clastics (yellow), and Peace River Arch (white). Red box indicates study area (Figures 3 & 4) in relation to location of Cynthia Basin. Modified from Switzer et al. (1994).
documented by Switzer et al. (1994). This succession, in conjunction with time-equivalent Wolf Lake deposits, is more calcareous to the north and forms the Meekwap Shelf (Switzer et al., 1994). This succession that includes Meekwap Shelf deposits and associated patch reefs thus appears to be younger than Zeta Lake reefs in the West Pembina area (Switzer et al., 1994). Nisku-equivalent siliciclastic deposits are also found northward of the Cynthia Basin. These siliciclastics reach up to 35m in thickness and it is speculated that these shallow marine sediments were deposited during a sea-level fall, coeval with shale in the upper Cynthia member, though their occurrence has not been discussed in the literature (Switzer et al., 1994).

Reduced subsidence, potentially in combination with sea-level fall and/or increased siliciclastic influx towards the end of Nisku deposition resulted in a dramatic reduction in accommodation (Switzer et al., 1994). The majority of the WCSB was filled to a shallow, uniform level following Nisku deposition, with only the most westerly portion remaining unfilled (Switzer et al., 1994).

**FIGURE 1.9:** Location map of oil and gas production from Nisku pinnacle reefs in the Brazeau-West Pembina area (southern Cynthia Basin) and generalized depositional model for Zeta Lake reef complexes. Note t reefs seem to be concentrated on the medial ramp location. (Switzer et al., 1994)
CHAPTER 2: LITHOFACIES ANALYSIS OF THE NISKU FORMATION, NORTHEASTERN CYNTHIA BASIN

The cored intervals of the Nisku Formation can be divided into twelve distinct lithofacies. This was accomplished through detailed examination of core intervals observing depositional fabrics, biologic components, faunal relationships, sedimentary structures, bounding surfaces, and lithofacies relationships. These core observations permitted detailed interpretations of depositional environments. Table 2.1 is a summary of the lithofacies and their variation from those at the Meekwap field.

LAMINATED LIME MUDSTONE

Description: The Laminated Lime Mudstone lithofacies is conspicuous due to its occurrence in very few cores but its appearance is distinct and significant. This limestone is characterized by planar, mm scale laminations that are locally undulatory and bioturbated with a bioturbation index between 0 and 2 (Figure 2.1). Thickness of lithofacies is restricted to less than 10cm. Intervals are devoid of fossils but have local fenestral pores.

Interpretation: The abundance of mud with a planar fabric indicates a low-energy environment. The low degree of bioturbation with respect to other mud dominated lithofacies, resulting in the preservation of planar fabrics, suggests this is a stressed environment. The lack of body fossils is consistent with this interpretation. The principle stress in this environment is thought to be elevated salinity developed in a restricted setting. Local undulatory fabric may be due to a microbi tally dominated community causing ‘wiggling’ laminae as suggested by Pratt (2011) and da Silva and Bouvlain (2004). The presence of fenestral fabric supports the hypothesis of a microbial community, as microbial layers are composed of early-cemented micrite with fenestral pores (Pratt, 2011). Deposition of this unit is interpreted to be in the intertidal to supratidal tidal flat zone of a restricted lagoonal or shelf environment, consistent with the interpretations of Potma et al. (2001), Whalen et al. (2002), da Silva and Bouvlain (2004) and Corlett and Jones (2011).
FIGURE 2.1: Core photographs (with cm scale bar) of the Laminated Lime Mudstone (A,B) and Bioturbated Lime Mudstone (C,D) Lithofacies. A. Laminated (L) and fenestral (Fe) fabric present. Unit is thin and overlain by a Bioturbated Mudstone lithofacies containing ostracod fragments (O). Local pyritization present (Py). 7-25-63-5W5, 1388.7m. B. Planar laminated silty dolomudstone, locally disrupted by burrows (Bu). Photo courtesy of W. Martindale. 4-29-57-3W5, 1580.1m. C. Few grains in a bioturbated lime mudstone unit. Some inarticulate brachiopods (Br) and fenestral pores (Fe) visible along with local diagenetic pyrite (Py). 6-34-60-3W5, 1452.8m. D. Bioturbated and colour mottled textures are mudstones with few grains. Local fenestral pores evident. Grains visible include inarticulate brachiopods and gastropods (G) but are sparse 16-36-59-01W5, 1290.2m.
### Table 2.1: Summary of lithofacies documented along the northeastern rim of Cynthia Basin and their variation from lithofacies at the Meekwap field

<table>
<thead>
<tr>
<th>LITHOFACIES</th>
<th>OCCURRENCE</th>
<th>MAJOR COMPONENTS</th>
<th>SUBORDINATE COMPONENTS</th>
<th>MATRIX</th>
<th>CEMENTS</th>
<th>VARIATIONS FROM MEEKWAP</th>
<th>PALEOENVIRONMENT</th>
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</thead>
<tbody>
<tr>
<td>1 Laminated Lime Mudstone</td>
<td>7-25 6-34 4-29</td>
<td>Planar Laminations</td>
<td>Indistinguishable fragments, fenestral fabric</td>
<td>Mud</td>
<td>Absent</td>
<td></td>
<td>Restricted, intertidal to supratidal tidal flat</td>
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<tr>
<td>2 Bioturbated Lime Mudstone</td>
<td>16-36 6-34 4-29</td>
<td>Brachiopods</td>
<td>Gastropods, bivalves, ostracods</td>
<td>Mud with bioturbated textures</td>
<td>Absent</td>
<td>Gastropods present</td>
<td>Intertidal to subtidal tidal flat</td>
</tr>
<tr>
<td>3 Nodular Lime Mudstone</td>
<td>6-36 2-34 10-32</td>
<td>Brachiopods</td>
<td><em>Thamnopora, Idiostroma</em>, wafer stromatoporoids, rugose corals</td>
<td>Mud with seamy pressure solution seams</td>
<td>Absent</td>
<td>Wackestone sections suggest storm induced transport absent at Meekwap</td>
<td>Deep-water, low-energy slope</td>
</tr>
<tr>
<td>4 Fossiliferous Wackestone</td>
<td>14-29 16-36 10-32 4-29 6-34</td>
<td>Brachiopods</td>
<td>Crinoids, bivalves, gastropods, minor oncolites</td>
<td>Mud, clean or mottled</td>
<td>Absent</td>
<td></td>
<td>Restricted shelf or deep-water, low-energy open marine slope</td>
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<tr>
<td>5 Crinoid Grainstone/Rudstone</td>
<td>11-19</td>
<td>Crinoids</td>
<td><em>Thamnopora</em>, stromatoporoids, brachiopods, bivalves</td>
<td><em>(Crinoid grainstone)</em></td>
<td>Absent</td>
<td>Different grain assemblage, correlative with reef lithofacies (11)</td>
<td>Reef-front crinoid thicket</td>
</tr>
<tr>
<td>6 Fossiliferous Floatstone/Rudstone</td>
<td>11-17 10-17 14-29 10-32 6-34 4-29</td>
<td><em>Thamnopora</em></td>
<td>Stromatoporoids (wafer, laminar, irregular), crinoids, brachiopods, <em>Idiostroma</em>, bivalves, <em>Amphipora</em>, gastropods, dendroid corals, rugose corals</td>
<td>Mud and argillaceous silt, often very dark brown and highlighted by pressure solution seams</td>
<td>Variable molds filled with burial cement</td>
<td>Perhaps more irregular and bulbous stromatoporoids present in this lithofacies than at Meekwap</td>
<td>Back reef, lagoon, upper foreslope or low-energy, open marine slope</td>
</tr>
<tr>
<td>7 Amphipora Floatstone/Rudstone</td>
<td>10-32 7-25</td>
<td><em>Amphipora</em></td>
<td><em>Thamnopora</em>, wafer stromatoporoids, <em>Idiostroma</em></td>
<td>Mud and silty argillaceous, pressure solution seams</td>
<td>Minor marine cement</td>
<td>Presence of <em>Thamnopora</em> and <em>Idiostroma</em> absent at Meekwap</td>
<td>Back reef or lagoon</td>
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<td></td>
<td>LITHOFACIES</td>
<td>OCCURRENCE</td>
<td>MAJOR COMPONENTS</td>
<td>SUBORDINATE COMPONENTS</td>
<td>MATRIX</td>
<td>CEMENTS</td>
<td>VARIATIONS FROM MEEKWAP</td>
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<td>8</td>
<td>Oncolitic Floatstone</td>
<td>11-17</td>
<td>6-36</td>
<td>Oncolites</td>
<td>Seamy argillaceous mudstone to wackestone</td>
<td>Absent</td>
<td>Lack of irregular stromatoporoids at Meekwap, presence of <em>Thamnopora</em></td>
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<td>9</td>
<td>Stromatoporoid Framestone</td>
<td>6-36</td>
<td>14-29</td>
<td>Stromatoporoids</td>
<td>Clean mudstone to wackestone, often argillaceous</td>
<td>Clean marine cement, common burial cement</td>
<td>More cementation present</td>
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<td>14-2</td>
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<td>10</td>
<td>Stromatoporoid – Spongiostromate – <em>Renalcis</em> Framestone</td>
<td>10-32</td>
<td>6-36</td>
<td>Stromatoporoids, Spongiostromate, <em>Renalcis</em></td>
<td>Clean mudstone to wackestone in cavities</td>
<td>Variable, absent or multigenera -tional marine and burial cement</td>
<td>Much more cement than documented at Meekwap, Presence of <em>Thamnopora, Idiostroma, Thamnopora</em></td>
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<td>14-29</td>
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<td>11</td>
<td><em>Renalcis</em> Bindstone</td>
<td>11-19</td>
<td>Renalcis, stromatoporoids</td>
<td>Microbial crusts, <em>Thamnopora, spongiostromate,</em></td>
<td>Mudstone to wackestone in cavities</td>
<td>Marine and burial multigenera -tional</td>
<td>Massive cements absent at Meekwap</td>
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<td></td>
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<td>14-29</td>
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<td><em>Thamnopora, crinoids, brachiopods</em></td>
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<td>4-29</td>
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</tr>
<tr>
<td>12</td>
<td>Coral Framestone</td>
<td>14-2</td>
<td>Dendroid corals</td>
<td>Rugose corals, microbial crusts, brachiopods, ostracods</td>
<td>Lime mud, silty siliciclastic sand, occasionally laminated and unfossilferous</td>
<td>Extensive late stage banded fibrous isopachous and multigenera -tional cements</td>
<td>Lithofacies not present at Meekwap</td>
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<tr>
<td>MF</td>
<td>Thamnopora Floatstone</td>
<td>Absent, Meekwap Field (MF) Facies</td>
<td><em>Thamnopora</em></td>
<td>Thamnopora, oncolitic crusts</td>
<td>Mud or packstone</td>
<td>Absent</td>
<td>Not present in this study</td>
</tr>
<tr>
<td>MF</td>
<td>Fossiliferous Packstone</td>
<td>Absent</td>
<td>Brachiopods, bivalves</td>
<td>Benthic forams</td>
<td>Mud, clean to clotted</td>
<td>Absent</td>
<td>Not present in this study</td>
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</table>
BIOTURBATED LIME MUDSTONE

Description: The Bioturbated Mudstone lithofacies is characterized by predominantly grey, mottled limestone with few bioclasts (Figure 2.1). Bioturbation is pervasive with a bioturbation index between 4 and 6. Laminations are rarely preserved and mottling is highlighted by colour variations. Fenestral pores are only locally present. Sediment is muddy and does not have the brown, seamy, organic and argillaceous nature as seen in many other lithofacies. Local seamy intervals are present but lack evidence of compaction. Fossils include brachiopods (abundant), gastropods (rare), and ostracods (rare).

Interpretation: This lithofacies is interpreted to be representative of a calm, stressed peritidal environment, likely in the shallow subtidal to intertidal subdivision of a tidal flat (sensu Pratt, 2011). A low-energy environment supports the abundance of mud. The scarcity of body fossils is consistent with this interpretation and the principle stress in this environment is thought to be elevated salinity developed in a restricted environment based on the presence of ostracods (De Deckker, 1988). The degree of bioturbation suggests that the environment was not as stressed as the laminated mudstone lithofacies since primary structures have been destroyed by organisms in this lithofacies. The local presence of fenestral pores is indicative of intertidal to supratidal environments (Pratt, 2011). In areas with an absence of fenestral pores, the environment is thought to be subtidal supported by the presence of gastropods and brachiopods. The absence of normal marine biota such as Thamnopora is thought to be an indicator of a restricted setting (Whalen et al., 2002). Similar environments have been interpreted for bioturbated lithofacies in many other Devonian platform successions (Stearn et al., 1987; Whalen et al., 2002; da Silva and Boublain, 2004).
**Nodular Lime Mudstone**

**Description:** The Nodular Lime Mudstone lithofacies is characterized by a distinct nodular texture and a relative scarcity of biota (Figure 2.2). Colour varies from light to dark grey or brown. Nodules are structureless and commonly contain few grains. Nodule size ranges from mm scale to greater than 5cm. Sediment between nodules is generally seamy, highlighted by pressure dissolution, darker in colour and not laminated. Fossil content is generally concentrated in these seamy zones between nodules and most commonly dominated by articulate and inarticulate brachiopods. Subordinate grains include *Thamnopora*, wafer stromatoporoids, *Idiostroma*, and rugose corals. Local intervals of nodular mudstones display wackestone to floatstone textures.

**Interpretation:** The nodular lime mudstone lithofacies is interpreted to have been deposited in a deep-water, low-energy slope environment. Nodular textures have been suggested to develop in alternating periods of anoxic to disoxic bottom-water conditions (Whalen et al., 2002). The scarcity of biota is indicative of a stressed environment, probably from anoxic to disoxic conditions. Structureless lime mudstone nodules are interpreted to be the result of bioturbation. Fossil content is interpreted to be generally allochthonous biota, transported down slope after being suspended from storms or tides due to their scarcity and small grain sizes, similarly interpreted by Whalen et al. (2002). *Thamnopora, Idiostroma* and wafer stromatoporoids were subject to downslope transport resulting in the concentration of grains to distinct intervals during storm events. Brachiopods and rugose corals are thought to have been deposited in situ supported by the presence of articulate brachiopods and have been thought to not require sunlight (Coates and Jackson, 1987; Wood, 1999). The absence of dorsal microbial crusts in this lithofacies suggests deposition below the photic zone (cf. Ratcliffe, 1988). Trace amounts of *Renalcis* are likely to have been detrital and transported with grains downslope as it is unlikely sufficient conditions (open cavities, nutrient levels and moderate energy) would have existed to support *Renalcis* growth in this environment.
FIGURE 2.2: Core photographs of the Nodular Lime Mudstone Lithofacies.  

A. Very nodular fabric (No) between seamy pressure solution seams (Ps). Some small indistinguishable digitate stromatoporoids (Ds) present including *Idiostroma* (I). 16-36-59-01W5, 1290.0m.  

B. Nodular fabric with a weaker development of pressure solution seams. Very few grains though small inarticulate brachiopods (Br) are locally present. 10-32-58-02W5, 1414.3m.  

C. Nodular lime mudstone fabric with a paucity of fossils. Indistinguishable grains locally present (Un). 6-34-59-01W5, 1457.3m.
FOSSILIFEROUS WACKESTONE

**Description:** The Fossiliferous Wackestone lithofacies is characterized by a variety of small bioclasts in a muddy matrix (Figure 2.3). The lithology can be either limestone or dolostone. Fossils are both intact and fragmented. Brachiopods are the dominant bioclasts and are generally inarticulate, though articulate shells are present locally. Subordinate components include crinoids, gastropods, bivalves, and ostracods. The presence and frequency of subordinate components varies from core to core. The matrix is predominantly grey to beige mudstone that is locally mottled with no sedimentary structures. Pyritization is present locally in replaced grains. Seamy, dark grey, argillaceous intervals are found locally but are not characteristic.

**Interpretation:** The Fossiliferous Wackestone lithofacies is interpreted to be deposited in one of two environments: i) a restricted shelf as described by Read (1985), Gischler (1995), and Wierzbicki (2008) indicated by the presence of ostracods and/or gastropods and bivalves, or ii) a deep-water, low-energy open marine slope dominated by brachiopods and crinoids supported by lithofacies interpretations of Playford (1980); Whalen et al. (2000); MacNeil and Jones (2006). The muddy, bioturbated matrix is consistent with slow sedimentation rates in low-energy environments (Stearn et al., 1987). When associated with laminated mudstone, the Fossiliferous Wackestone lithofacies often contains ostracods and bivalves, indicative of restricted settings and perhaps lagoonal deposits. Wendte (2009) suggested similar lithofacies typify deposits between patch reefs in the July Lake Shoal of the Jean Marie Member, Redknife Formation. When the lithofacies is dominated by abundant brachiopods and crinoids, the interpretation is consistent with a marginal slope lithofacies. Biota of deep low-energy, open marine slope wackestones lack photosynthetic organisms and are interpreted to be deposited in aphotic environments. The lack of microbial fabric in the lithofacies is suggested by i) oligotrophic conditions (*cf.* MacNeil and Jones, 2008) or ii) deposition in an aphotic environment (Ratcliffe, 1988) although some microbes may have flourished in aphotic conditions. Pyritization is thought to be diagenetic and not indicative of a reducing environment, as significant bioturbation is universal and suggests an oxygenated environment (*cf.* Whalen et al., 2000).
FIGURE 2.3: Core photographs of the Fossiliferous Wackestone Lithofacies.  A. Bioturbated fabric devoid of sedimentary structure and containing many small inarticulate brachiopods (Br).  6-34-60-3W5, 1452.0m.  B. Pyritized grains in a wackestone with a muddy lime mud matrix.  Grains visible include brachiopods and gastropods (G).  16-36-59-01W5, 1287.0m.  C. Close up of small grains including brachiopods.  Abundant pressure solution seams present (Ps) along with abundant diagenetic pyrite (Py).  10-32-58-2W5, 1407.6m.  D. Locally present ostracod (O) fragments and brachiopods in a laminated (not visible) to bioturbated mudstone.  7-25-63-5W5, 1389.3m.
**CRINOID GRAINSTONE/RUDSTONE**

**Description:** The Crinoid Grainstone/Rudstone lithofacies is characterized by abundant crinoid fragments with few subordinate grains (Figure 2.4). Crinoid grains range in articulation from being mm scale fragments up to 3cm in length and comprise more than 75% of the grains. Subordinate grains include Thamnopora, Idiostroma, wafer stromatoporoids and brachiopods and are universal. Stromatoporoids are thin (<0.5cm) and locally display irregular, wavy, dorsal growth patterns. Brachiopods are both articulate and inarticulate and generally smaller than 1cm. *Thamnopora* grains are between 0.2-0.5cm in diameter. The lithofacies is associated with Stromatoporoid- Spongiostromate-*Renalcis* Framestones and *Renalcis* Bindstones. Moreover, internal cavities in these lithofacies are also associated with crinoid grainstones. Vertical thickness of this lithofacies does not exceed 15cm.

**Interpretation:** This lithofacies is interpreted to have resulted from transport of forereef biota, above fair weather wave base, to the reef-front after storm events. The association of the Crinoid Grainstone/Rudstone lithofacies with the *Renalcis* Bindstone lithofacies, along with internal cavity and fracture fill evidence, suggests that deposition occurred on the reef-front. Sediment was trapped in internal cavities of the reef as storm currents or wave action moved sediment landward. Relative articulation of crinoids and *Thamnopora* suggests that their duration of transport was short during this process. The abundance of crinoids suggests open marine conditions on the forereef (Hess et al., 1999; da Silva and Bouvlian, 2004; Flügel, 2004). Crinoid grainstones have been described in a number of other Devonian and Silurian reefs (e.g. Dreesen et al., 1985; Kershaw and Keeling, 1994) and it is likely that crinoid meadows or thickets were in close proximity to fronts of Cynthia Basin pinnacle reefs. The presence of *Thamnopora* is consistent with interpretations of high-energy environments such as reef-fronts (Wood, 1999; Hofmann and Keller, 2006). The absence of mud further promotes a high-energy environment consistent with a reef-front interpretation. Wafer stromatoporoids with large dorsal mamellons supports deposition in shallow-water, and perhaps suggests stromatoporoid response to light or current flow (Kershaw, 1998).
FIGURE 2.4: Core photographs of the Crinoid Grainstone/Rudstone Lithofacies. 

**A.** Densely packed crinoid (Cr) grainstone to rudstone with *Thamnopora* (Th) and wafer stromatoporoids (St). Neptunian fracture fill perhaps represented on the left-hand side filled with coarse and densely packed crinoid fragments. 11-19-63-4W5, 1384.2m. 

**B.** Crinoid grainstones as internal cavity sediment with *Renalcis* (Re) in a reef-front environment. Note the size and articulation of crinoid grains. 11-19-63-4 W5, 1385.6m. 

**C.** Crinoid grainstone to floatstone containing many crinoid fragments along with lesser amounts of *Thamnopora* and wafer stromatoporoids. 10-17-60-3 W5, 1459.2m.
**FOSSILIFEROUS FLOATSTONE/RUDSTONE**

**Description:** The Fossiliferous Floatstone/Rudstone lithofacies displays a variety of biotic assemblages but the depositional texture is most commonly a floatstone and locally a rudstone (Figure 2.5). The lithology is predominantly limestone with local intervals of partial to extensive dolomite. *Thamnopora* is the most common grain type and occurs with three different matrix styles, although it is rarely preserved in life position. Stromatoporoids are the second most abundant grain type with wafer, laminar, tabular, bulbous, and digitate growth forms. Laminar and wafer stromatoporoids generally have sub-horizontal orientations but are locally inclined at angles up to 50°. Local rudstone intervals are composed of bulbous stromatoporoids with organic-rich seamy, argillaceous sediment matrices. Subordinate components include *Amphipora, Idiostroma*, crinoids, brachiopods, gastropods, bivalves, dendroid corals and rugose corals. Brachiopods and bivalves are commonly inarticulate and range from a few millimeters to several centimeters in size. Neither dendroid nor rugose corals are in life position. The presence of digitate stromatoporoids, *Amphipora* and *Idiostroma* varies locally but *Idiostroma* is most common. Microbial coatings up to 0.5cm thick are locally present and where present, encrust many grains. *Renalcis* is scarce but is locally present as thin pendants associated with stromatoporoids. Matrix textures consist of a grey mudstone to mottled brown wackestone, a more fossiliferous packstone, and organic-rich and argillaceous sediment with a seamy dark brown appearance consistent with other lithofacies. Wackestone matrix is predominantly brachiopod-rich with both articulate and inarticulate forms. Packstone fabrics are composed of inarticulate brachiopod and bivalve shells together with peloids. Organic-rich, argillaceous sediment sections have a more condensed biotic assemblage than wackestone or packstone sections.

**Interpretation:** The fossiliferous floatstone is interpreted to represent a variety of depositional environments including lagoon, back reef, upper foreslope, and lower slope.

i) **Digitate stromatoporoid sublithofacies**

*Idiostroma* bearing floatstones associated with *Amphipora* and *Thamnopora* are interpreted as back reef and lagoonal deposits as described by Shen and Zhang (1997), Gischler (1985) and MacNeil and Jones (2006). Similar lithofacies have also been described
as patch reef flanking deposits (da Silva and Bouvlain, 2004a; Wendte, 2009) and this is another possible depositional environment for these floatstones. *Thamnopora* and *Idiostroma* bearing floatstones may indicate lagoonal deposition if paleogeography supported the formation of lagoons (Copper, 2002a). Back reef floatstone lithofacies have been described containing peloidal packstone matrix textures (Stearn et al., 1987; Wierzbicki, 2008) and similar matrix textures are present in this sublithofacies. Muddy matrices support a low-energy deposition interpretation in these environments.

ii) **Bulbous stromatoporoid sublithofacies**

A stromatoporoid floatstone/rudstone dominated by bulbous, irregular, and to a lesser extent, laminar stromatoporoids is consistent with interpretations of upper foreslope deposits (Stearn et al., 1987; Kershaw and Brunton, 1999; Potma et al., 2001; MacNeil and Jones, 2006). *In situ* stromatoporoids are the dominant biota in this environment and are interpreted to have grown directly on a substrate (Wood, 2000) and not generate structures with significant relief. The inclination of some stromatoporoids suggests transport of reef detritus down slope contributing to sedimentation in this sublithofacies. *Renalcis* growth may have been facilitated by elevated nutrient levels (*cf.* MacNeil and Jones, 2008) in environments containing stromatoporoids with sufficient substrate relief to construct open cavities. Mesotrophic conditions are also attributed to the formation of thin microbial crusts present in the lithofacies. The presence of *Thamnopora* is consistent with interpretations of photic zone deposits (Coates and Jackson, 1987; Wood, 1999). A more fossiliferous packstone and organic-rich sediment matrix is interpreted as being reef detritus. The brown, muddy sediment is consistent with upper foreslope lithofacies described in other Late Devonian successions (Playford, 1980; MacNeil and Jones, 2006).

iii) **Thamnopora sublithofacies**

Floatstones dominated by Thamnoporids, along with rugose and dendroid corals, crinoids, brachiopods, and wafer stromatoporoids are interpreted as low-energy, open shelf deposits. Wackestone matrices are common and predominantly brachiopod-rich with both articulate and inarticulate forms. These textures have been recently described in similar slope environments (Whalen et al., 2002; MacNeil and Jones, 2006) and open marine shelves (Wierzbicki, 2008; Wendte, 2009). Crinoid deposition suggests open marine conditions on the forereef (da Silva and Bouvlain, 2004; Flügel, 2004), whereas *Thamnopora* is an indicator of photic zone deposition (Coates and Jackson, 1987; Wood, 1999).
FIGURE 2.5: Core photographs of the Fossiliferous Floatstone Lithofacies. **A.** Back reef environment. *Thamnopora* (Th) and *Idiostroma* (I) with local microbial crusts (Mc). Wafer stromatoporoids (St) with poorly developed *Renalcis*. 6-36-61-4W5, 1431.9m.  
**B.** Low-energy, open marine ramp environment. Seamy brachiopod and crinoid floatstone to wackestone with abundant fossils. Photo courtesy of W. Martindale. 14-2-57-1W5, 1501.0m.  
**C.** Foreslope environment. Large bulbous and tabular stromatoporoid (St) rudstone in a seamy organic-rich matrix highlighting by pressure solution (Ps). *Thamnopora* (Th) and *Amphipora* (A) also present. 16-36-59-01W5, 1290.5m.  
**D.** Low-energy, open marine ramp environment. Brachiopod and crinoid-rich floatstone with scattered dendroid corals. Inclined pressure solution seams in a green to grey muddy matrix. Photo courtesy of W. Martindale. 14-2-57-1W5, 1471.7m.
**Amphipora Floatstone/Rudstone**

**Description:** The *Amphipora* Floatstone/Rudstone lithofacies is characterized by abundant *Amphipora* and relatively few other allochems (Figure 2.6). Bedding thickness is typically between 5 and 10 cm. Textural class ranges from floatstones with few to no subordinate components to a densely packed rudstone. Subordinate components include *Thamnopora*, wafer stromatoporoids, and *Idiostroma*. *Amphipora* grains are between 0.2 and 0.5 mm in diameter. Matrix type is variable and can be clean mudstone, mottled and bioturbated mudstone, peloid packstone, or seamy, organic-rich and argillaceous consistent with other lithofacies. Sections with seamy, organic, argillaceous matrices have more abundant grains and occur locally, in 5-10 cm intervals. Marine and obvious burial cements are not present in large quantities.

**Interpretation:** *Amphipora* dominated lithofacies have been interpreted as indicators of shallow-water, low-energy environments (James, 1983; Machel and Hunter, 1994; Kershaw, 1998; Kershaw and Brunton, 1999; Shen et al., 2008). Mudstone matrix textures, along with organic-rich intervals, is consistent with deposition in a low-energy environment with intermittent organic-rich sediment input. This lithofacies is interpreted as being a back reef or lagoon deposit consistent with similarly described successions (Shen and Zhang, 1997; Wood 1998; Potma et al., 2001; MacNeil and Jones, 2006; Corlett and Jones, 2011). The presence of *Thamnopora* suggests that the depositional environment was well within the photic zone (Coates and Jackson, 1987; Wood, 1999). Laminar stromatoporoids have been interpreted as deposits from across Devonian platform tops (Kershaw, 1998) and in this case, wafer stromatoporoids likely lived on the substrate and did not produce structures with significant relief (Wood, 1998). Stromatoporoids with wafer growth forms are usually associated with environments close to the reef-flat (Kershaw, 1998).
Figure 2.6: Core photographs of the Amphipora Floatstone Lithofacies. 

A. Amphipora (A) floatstone to rudstone section between two pressure solution seams (Ps). Subordinate grains visible include Thamnopora (Th) and Idiostroma (I). 10-32-58-2W5, 1410.4m. 

B. Dark brown Amphipora floatstone in an argillaceous matrix with Thamnopora and some microbial crusts (Mi). Pressure solution seams are thick and suggest a large amount of compaction. 7-25-63-5W5, 1395.6m. 

C. Amphipora rudstone with Idiostroma and Thamnopora. Fracture (Fr) filled with burial cement. Some fibrous marine(?) cement present around some grains. 10-32-58-2 W5, 1411.5m. 

D. Small Amphipora and Thamnopora grains in a seamy organic-rich pressure solution seam. 7-25-63-5W5, 1396.3m.
**ONCOLITIC FLOATSTONE**

**Description:** The Oncolitic Floatstone lithofacies is characterized by abundant microbial fabrics creating oncolites (Figure 2.7). Oncolitic fabrics range from thin (mm scale) veneers around skeletal particles to thick (> 2cm) round masses with locally indistinguishable nuclei. Microbial coatings are classified as either: class Mi₁ - equal thickness coatings that surround a peloid or distinguishable fossil nuclei; class Mi₂ - asymmetric oncolites that surround a peloid or distinguishable fossil nuclei; class Mi₃ - or symmetric to asymmetric coatings that surround indistinguishable nuclei. Subordinate components include *Thamnopora, Idiostroma*, brachiopods, crinoids, and wafer stromatoporoids as well as rugose and dendroid corals. Intervals with more abundant biota characteristically show thinner oncotic coatings than those with scarce fossil assemblages. Oncolitic fabrics generally occur around larger grains such as *Thamnopora* and *Idiostroma*, whereas smaller grains, such as inarticulate brachiopods or other shell fragments, generally have no microbial veneer. Matrix textures vary between a clean mudstone to mottled wackestone containing inarticulate brachiopods and peloids, to seamy and organic-rich wackestones containing subordinate components. Bioturbation is common and the bioturbation index ranges from 3 to 6. The colour of the matrix ranges from dark brown to light grey. Seamy organic-rich, argillaceous matrix intervals can be thin (< 1cm) and highlighted by stylotization or thick and pervasive (> 5cm), dominating the matrix style in an interval.

**Interpretation:** The Oncolitic Floatstone lithofacies is interpreted to be deposited in one of two environments: i) shallow open marine shelf, or ii) lagoon. Oncolites are composed of algae and generally accepted to be indicative of shallow-water deposits with optimum growth conditions in less than 50m water depth (Riding, 1975; Wray, 1977; Ratcliffe, 1988) and both these depositional environments are interpreted to be within the photic zone. *Rothpletzella* and *Girvanella* are common in many oncolites of the Nisku Formation (Bingham-Koslowski, 2010) and likely would have accumulated in euphotic conditions (Ratcliffe, 1988).

Round oncolites likely had a fairly constant external source that provided rolling during growth (Wright, 1983), otherwise asymmetry would be more prevalent. The
symmetry in the large oncolites is thought to have developed through oncolite rolling on the seafloor due to bioturbation along with episodic storm events also contributing to movement (Wendte, 2009). Evidence of episodic storm events is interpreted to have been destroyed by subsequent bioturbation. Presence of the bioturbated muddy matrix with local organic-rich intervals is characteristic of a low-energy setting consistent with open shelf and lagoonal environments. The absence of subordinate components associated with large oncolites suggests mesotrophic conditions (MacNeil and Jones, 2008) and development of these intervals may have been limited to a distinct timeframe with high nutrient levels. Organic-rich, argillaceous intervals are consistent with this interpretation and have been described in association with large oncolitic textures (Whalen et al., 2002). Oncolites in these intervals are thought to have had a long time to develop large cortexes, consistent with slow sedimentation rates (Peryt, 1981; Wendte, 2009).

Asymmetric oncolites surrounding subordinate components are interpreted to have been deposited in a lagoonal environment. Asymmetric oncolite cortexes formed in lagoonal environments were likely subject to less frequent rolling from bioturbation and storm action than in open shelf environments and oncolites preferentially developed on the upper surface of nuclei. Bioturbation likely played the primary role in rolling oncolites once allochems died and were in contact with the substrate, contributing to development of asymmetric oncolitic cortexes surrounding the nuclei. Wave action in the lagoon is less likely to have played a part in rolling oncolites than on the open shelf.
FIGURE 2.7: Core photographs of the Oncolitic Floatstone Lithofacies. A. Oncolitic coatings in a floatstone with a mudstone to wackestone matrix. Grain assemblage includes rugose corals (Rc), Thamnopora (Th), wafer stromatoporoids (St). Three types of microbial coatings present: Mi₁, Mi₂, and Mi₃. 6-36-61-4W5, 1433.3m. B. Large oncolites (On) in a muddy matrix separated by pressure solution seams (Ps). Spiriferid brachiopods (Br) are visible although other grains are indistinguishable. Some oncolite nuclei also unknown. 10-32-58-02W5, 1432m. C. Oncolites in a floatstone with some seamy fabric containing Thamnopora, brachiopods and rugose corals. 16-36-59-01W5, 1311m. D. Large oncolites and coral(?) fragments (Fr) in a muddy bioturbated matrix. Oncolite nuclei are either identifiable grains or absent. 11-17-61-4W5, 1517.4m.
STROMATOPOROID FLOATSTONE/FRAMESTONE

**Description:** The Stromatoporoid Floatstone/Framestone lithofacies is similar to the Stromatoporoid-Spongiostromate-*Renalcis* Framestone lithofacies but lacks extensive ventral *Renalcis* undergrowths (Figure 2.8). Although, laminar, tabular, and digitate stromatoporoid growths forms occur in this lithofacies, wafer stromatoporoids are the dominant growth form and are typically < 0.5cm in thickness. The orientation of stromatoporoids is typically horizontal to sub-horizontal as in other stromatoporoid-rich lithofacies. Inclined, fragments of wafer stromatoporoids are also seen floating in sediment. Sediment in between stromatoporoids tends to be finer than the *Renalcis* Bindstone and Stromatoporoid-Spongiostromate-*Renalcis* Framestone lithofacies internal sediment and appears darker brown in colour. Sediment between stromatoporoids is usually a wackestone to mudstone with rare floatstone intervals. Spongiostromate textures are prominent and display a mottled grey to black colour and show both abrupt and gradational contacts with sediment between stromatoporoids. Other components include *Thamnopora, Idiostroma*, crinoids, microbial crusts and brachiopods. Dorsal microbial crusts on stromatoporoids range from thick (> 1cm) and abundant occurrences to rare and thin (1-2 mm). *Renalcis* growths are rare and when present are thin. Geopetal cavities underneath thicker stromatoporoids have a variable layer of marine cement which ranges from mm scale to upwards of 0.5cm.

**Interpretation:** This lithofacies is interpreted to have been deposited in back reef and reef-flat paleoenvironments. Laminar and tabular stromatoporoids in this lithofacies are thought to have formed internal cavities that were later filled with sediment creating geopetal structures. Due to nature of cavity creation by stromatoporoids, this is interpreted to be a framestone fabric and not a floatstone. The presence of marine cement indicates void space beneath stromatoporoids and suggests reef-flat environments (Copper, 2002a) in higher energy conditions close to the reef-front. This is supported by Kershaw and Brunton (1999), who proposed that laminar and tabular stromatoporoids were most prolific at the shelf margin.

Intervals with more prominent *Idiostroma, Thamnopora* and wafer stromatoporoids are associated with back reef environments. This environment is consistent with low-
energy levels reflected in mudstone and wackestone matrices. The sub-horizontal wafer stromatoporoids in this lithofacies are interpreted to have grown upward, having direct contact with the substrate along their ventral side (Kershaw, 1998; Wendte, 2009). Larger, tabular stromatoporoids are also interpreted to have generated structures with relief above the substrate (cf. Wood, 1998; Wendte, 2009).

Microbial crusts on the dorsal sides of stromatoporoids are thought to be photosynthetic as they are not present on ventral sides. The presence of Thamnopora is also consistent with a photic zone interpretation (Coates and Jackson, 1987; Wood, 1999). The local presence of microbial crusts may be a reflection of mesotrophic conditions (cf. MacNeil and Jones, 2008). The absence of Renalcis is puzzling and is attributed to lack of cryptic habitats during mesotrophic conditions (cf. Pratt, 1984; Stephens and Sumner, 2002). Intervals with cryptic habitats suggest deposition in oligotrophic conditions (cf. MacNeil and Jones, 2008), due to the paucity of microbial crusts in those intervals. The sporadic nature of microbial crusts is thought to reflect temporal trophic level changes throughout the deposition of the system.
FIGURE 2.8: Core photographs of the Stromatoporoid Floatstone/Framestone Lithofacies. A. Massive, irregular stromatoporoid (St) with shelter cavities (Cs) geopetally filled with ostracods, brachiopods (Br), trace Renalcis and detritus-rich mudstone. Cement lined cavities filled with dolomitic silt to fine sand. Photo courtesy of W. Martindale. 14-2-57-1W5, 1448.4m B. Well-developed microbial crusts (Mc) present above thin stromatoporoids and pressure solution seam (Ps). Subordinate components include brachiopods (Br), Amphipora (A), and Thamnopora (Th). 6-36-61-4W5, 1437.6m. C. Dense stromatoporoid section with muddy cavity fill (Cs) in between two tabular stromatoporoids. 16-36-59-01W5, 1295.9m. D. Wafer stromatoporoids with thin Renalcis and geopetal cavities (Gc) with multigenerational cement, Thamnopora and spongiosstromate fabric (Sp). 6-36-61-4 W5, 1437.8m.
STROMATOPOROID-SPONGIOSTROMATE-RENALCIS FRAMESTONE

Description: This lithofacies is characterized by the abundance of three principle components: stromatoporoids, spongistromate and Renalcis (Figure 2.9). Lithology is predominantly limestone with local intervals of extensive dolomite. Growth forms of stromatoporoids include laminar, tabular, wafer, and bulbous. Typical stromatoporoid orientation is sub-horizontal, though rare inclined wafer and laminar stromatoporoids (at angles of up to 50°) are also present. Dorsal microbial crusts present in this lithofacies are typically thin (< 1cm). Renalcis intervals are less volumetrically extensive than in the Renalcis Bindstone lithofacies and are typically pendant growth forms underneath sub-horizontally oriented stromatoporoids and less than 5cm in thickness. The Renalcis growths appear to show a floatstone textural class but are often adjacent to spongistromate textures. Spongistromate textures are abundant and display a mottled grey to black pattern that is consistent throughout all stromatoporoid lithofacies. Petrographic analyses of spongistromate fabrics reveal sponge spicules that vary in degree of preservation. Subordinate components include Idiostroma, brachiopods, bivalves, crinoids, Thamnopora and dendroid corals and are not consistent throughout intervals. Sediment in shelter cavities consists of a mudstone to fossiliferous wackestone consisting of brachiopod, crinoid, coral and bivalve fragments in a muddy or peloidal matrix. Geopetal cavities filled with burial cement are locally present underneath Renalcis. Laminar mud floored cavity fills and spongistromate are seen locally separated by marine and/or burial cements. Intervals of organic-rich, argillaceous sediment with a seamy dark brown appearance resulting from compaction are present locally.

Interpretation: The three principle components, in combination, are thought to have built a framework structure. This lithofacies is interpreted to have been deposited in a reef-core/crest environment. Stromatoporoids are considered to be the principle framebuilder generating structures with significant relief above the local seafloor (cf. Wood, 1998; Wendte, 2009). Microbial constituents (Renalcis and dorsal crusts), spongistromate fabric, and stromatoporoids dominate reef construction while corals, dendroid stromatoporoids and sediments from the adjacent reef-flat and back reef are secondary.
Pedant *Renalcis* on the ventral sides of stromatoporoids is interpreted to have formed in cryptic habitats. The abundance of microbial structures, both pendant *Renalcis* growths and laminated dorsal crusts is consistent with a reef margin interpretation (Wood, 1998), and is attributed to sedimentation under mesotrophic conditions as (*cf.* MacNeil and Jones, 2008). Dense stromatoporoid and microbial lithofacies have been interpreted as reef-crest or margin by Shen and Zhang (1997), Wendte (2005) and Wierzbicki (2008). Laminar and tabular stromatoporoids have been documented in lithofacies capping Devonian reefs appearing in the reef-flat and forereef area (Copper, 2002a) and may indicate high-energy levels in the system (Kershaw and Keeling, 1994). The presence of *Thamnopora* and dendroid corals supports a photic zone interpretation (Coates and Jackson, 1987; Wood, 1999) and is consistent with several reef-front environment interpretations (Shen and Zhang, 1997; MacNeil and Jones, 2008; Wendte, 2009).

Since *Renalcis* is restricted to cavities beneath stromatoporoids, it is thought that spongiostromate fabric and dorsal microbial crusts dominated the upper surfaces of stromatoporoids. Dorsal crusts are thought to be photosynthetic due to their absence on ventral sides of stromatoporoids. The grey to black pattern that is consistent throughout this lithofacies is interpreted to be spongiostromate fabric formed by a non-calcified sponge, due to sponge spicule occurrence in thin section. Spongiostromate textures, poorly laminated micritic layers thought to be of microbial origin (Flügel, 2004), are found both associated with dorsal and ventral sides of stromatoporoids and interpreted to be non-photosynthetic. Spongiostromate textures contain sponge spicules in thin section, perhaps suggesting sedimentation by non-calcified sponge. *Renalcis* was able to form typical pendant growth forms but was restricted to cryptic habitats (*sensu* Pratt, 1984; Stephens and Sumner, 2002) due to being out competed by dorsal crusts and sedimentation on the tops of stromatoporoids. Contacts between *Renalcis* and spongiostromate textures in cavities sheltered by stromatoporoids suggest that these non-calcified sponges were growing contemporaneously with *Renalcis*. The restriction of spongiostromate textures to reef-core/crest environments suggests moderate to high-energy levels were necessary for growth. Furthermore, its association with *Renalcis* and microbial crusts suggests it was able to withstand mesotrophic nutrient levels. Geopetal cavities are abundant throughout the spongiostromate fabric and are lined with both marine and burial cements. This implies voids within spongiostromate fabric remained open with deposition as the cavities were
lined with marine cement. Deposition of laminated or peloidal mud as a cavity fill is interpreted to have occurred contemporaneously with spongiostromate and Renalcis growth. The contact between spongiostromate fabric and laminated mud on cavity floors rimmed by a thin layer of marine cement implies some degree of cohesion within spongiostromate fabric with the upper and perhaps lateral surfaces of internal cavities. Spongiostromate fabric containing sponge spicules suggests non-calcified sponges may have played a substantial role in reef growth but are only cryptically preserved as spongiostromate texture.
FIGURE 2.9: Core photographs of the Stromatopore-Spongiostrome-Renalcis Framestone Lithofacies. 

A. Stromatoporoids (St), spongiostromate (Sp) and sediment fill (Cs) in voids and cavities. Microbial crusts (Mc) present on the dorsal side of stromatoporoids. Brachiopods (Br) and bivalves (Bi) present along with Thamnopora (Th) and a thick Renalcis (Re) section at bottom. 10-17-60-3W5, 1463.2m. 

B. Laminated sediment (Ls) under tabular stromatoporoids with extensive Renalcis growths. Spongiostrome strongly contrasts coarse cavity fill (Cs). 4-21-57-3W5, 1578.4m. 

C. Typical framestone with Renalcis. Some Thamnopora, bivalves and brachiopods present. Thin dorsal crusts (Mc) locally present. 6-36-61-4W5, 1430.0m. 

D. Thin wafer stromatoporoids, Renalcis, along with Thamnopora. Spongiostrome highlighted by mottled grey-black appearance. 10-32-58-2W5, 1423.5m.
**Renalcis Bindstone**

**Description:** The *Renalcis* Bindstone lithofacies is defined by thick intervals of *Renalcis* that occur in contact with the tops and bottoms of stromatoporoids (Figure 2.10). The lithology is predominantly limestone with local intervals of extensive dolomite. *Renalcis* in this lithofacies can be upwards of 5cm in thickness and generally lack other biota. Wafer, laminar, tabular, and bulbous stromatoporoids are prevalent, acting as nucleation surfaces for *Renalcis*. Laminar and tabular stromatoporoids are the most common growth forms, have a horizontal to sub-horizontal orientation (at angles of up to 30°) and are typically < 1cm in thickness. Bulbous and wafer stromatoporoids are less pervasive and are typically completely surrounded by *Renalcis* growths. Stromatoporoids generally display an irregular, wavy growth form on their dorsal side. Dorsal and ventral microbial crusts are present but not abundant and occur adjacent to *Renalcis*. The subordinate grain assemblage consists of large crinoids that are locally articulate, large articulate and inarticulate brachiopods, as well as minor amounts of *Thamnopora*. Spongiostromate texture is common and occurs in abrupt contact with internal sediment as well as *Renalcis*. Internal sediment is typically a wackestone with small brachiopods (articulate and inarticulate forms) in a muddy, or peloidal matrix. Small geopetal cavities occur beneath some stromatoporoids and are locally found within the *Renalcis* masses. Minor amounts of marine cement locally encrust stromatoporoids.

**Interpretation:** This lithofacies is interpreted as a reef-front lithofacies. Stromatoporoids are thought to act as the primary support structure. Tabular and laminar stromatoporoids are interpreted to have attached to the substrate and grown outwards from a single point, creating protected cavities with relief from the substrate (Wood, 1998; Wendte, 2009). The type and rigidity of substrate that stromatoporoids attached to is uncertain as such a structure was never displayed in core. MacNeil and Jones (2008) have suggested stromatoporoids could grow on muddy substrates and although mud is absent in the section, the nature of the substrate could have been a softground.

Shelter cavities created by outward growing stromatoporoids permitted the pendant style *Renalcis* to grow, attached to the ventral surface of the stromatoporoid (*sensu* Wood, 1998). Wood (1988; 1999) along with Pratt and James (1984) have described
Renalcis forming upright colonies. Furthermore, Rees et al. (1989) and Shen et al. (1997) have described Renalcis as a framework structure. Similar fabrics are interpreted here, formed by the thick Renalcis growths present on the dorsal side of stromatoporoids. The interpretation that Renalcis often lived in cryptic habitats (Pratt, 1984; Stephens and Sumner, 2002) implies that conditions in this system were either conducive to upward Renalcis growths along with typical cryptic styles, or unusual depositional environments (Stephens and Sumner, 2002). It is thought that mesotrophic conditions in the system promoted the growth of thick Renalcis intervals (MacNeil and Jones, 2008). These trophic levels are supported by the relative paucity of open marine biota and is similar to the ‘Stromatoporoid-coral-microbe reef lithofacies’ described by MacNeil and Jones (2008) in the (Frasnian) Alexandra Formation, Northwest Territories. In this case, Renalcis was able to flourish without competition from normal marine biota and volumetrically dominate this environment. Slow sedimentation rates along with the scarcity of spongiostromate textures and dorsal crusts allowed Renalcis to fill a niche it otherwise could not. This is supported by evidence of spongiostromate texture and local internal sediment above stromatoporoids where Renalcis is absent.

Renalcis Bindstone reef-front lithofacies have been interpreted in other Devonian successions in China and the Northwest Territories, Canada (Shen and Zhang, 1997; MacNeil and Jones, 2008). The environment of this lithofacies is consistent with these interpretations. Toomey et al. (1970) as well as Wray and Playford (1970) proposed well-developed Renalcis intervals occurred in high-energy reef or bank-margin environments, while the interpretation of this lithofacies suggests slightly lower energy levels than the reef crest but still high. It is suspected that Renalcis flourished in sheltered environments with available substrates to nucleate from during moderate energy levels. Marine cement locally encrusting stromatoporoids suggests some degree of sea-water flushing through the system which supports the energy level of this setting. Geopetal cavities along with burial cement enclosed in Renalcis growths implies calcification contemporaneously with (Wood, 1998), or soon after (Pratt, 1984), formation. Wackestone to packstone cavity sediment is thought to have been washed down from the reef-flat and back reef as sediment was transported downslope after storms. Minor amounts of Thamnopora support a photic zone setting (Coates and Jackson, 1987; Wood, 1999).
FIGURE 2.10: Core photographs of the *Renalcis* Bindstone Lithofacies. **A.** Millimeter to centimeter size stromatoporoids (St) surrounded by *Renalcis* (Re). Cavity sediment fill (Cs) present at top above stromatoporoid with a large brachiopod (Br). 11-19-63-4W5, 1388.3m. **B.** Contrasting styles of cavity fill and microbial fabric amongst *Renalcis* intervals and wafer to laminar stromatoporoids. Laminated sediment (Ls) is locally present. Geopetal cavity cement (Gc) present within internal cavities. 14-29-65-7W5, 1725.4m. **C.** Variety of stromatoporoids surrounded by a thick *Renalcis* interval with crinoids (Cr). Contrast between spongiostrome (Sp) and cavity fill (Cs). 11-19-63-4W5, 1385.3m. **D.** Coarser sediment fill juxtaposed against a true *Renalcis* Bindstone unit with no stromatoporoids but geopetal cavity cement. 14-29-65-7W5, 1727.4m.
CORAL FRAMESTONE/FLOATSTONE

**Description:** This lithofacies is only present in one well, 14-2-57-1W5 but dominates the succession there. It is characterized by extensive dendroid corals, creating both framestone and floatstone textural styles (Figure 2.11). Subordinate components include brachiopods, ostracods, and perhaps spongiostromate. Abundant isopachous marine cement is common and is sometimes lined by a subsequent generation of burial cement. Cavity and matrix sediment consists of lime mud, silty green mud, and locally clastic sand, occasionally laminated and typically unfossiliferous. Floatstones contain large sediment-filled cavities with generally unfossiliferous lime mud. Geopetal cavities lined with mud fillings and capped by marine or multi-generational cement are abundant in both textural styles.

**Interpretation:** This lithofacies is unlike the majority of other lithofacies documented in this study. It is interpreted as a coral reef build-up in a high-energy ramp setting. The environmental setting is thought to be either reef-front or an isolated medial ramp build-up (see Chapter 3). Extensive marine cements suggest high-energy conditions restricting fine-grained deposition between corals. Siliciclastic sediment in cavities is thought to postdate most coral growth and is attributed to lower energy conditions and perhaps related to relative sea-level fall. This lithofacies is consistent with the description of the lower Zeta Lake member described by Chevron Exploration Staff (1979). MacNeil and Jones (2008) found a similar coral thicket lithofacies on the reef-front of the Alexandra Formation, Northwest Territories. Tabulate coral associations are considered to be indicative of oligotrophic environments (Wood, 1993; Kershaw, 1998; Whalen et al., 2002) and oligotrophic conditions are thought to be responsible for the deposition of this lithofacies. The absence of microbial components is also attributed to oligotrophic conditions *(cf. MacNeil and Jones, 2008)*. The paucity of stromatoporoids in this lithofacies is puzzling but attributed to them having been out competed by corals consistent with the interpretations of many workers that stromatoporoids and tabulate corals were in direct competition throughout the Paleozoic *(e.g. Manten, 1971; Wood, 1999)*. It is likely that stromatoporoids flourished and overgrew corals in well-agitated environments, whereas corals dominated more muddy settings *(Wood, 1999)*. The dominance of corals and absence of stromatoporoids in this lithofacies may have also been due to turbid conditions.
**FIGURE 2.11:** Core photographs of the Coral Framestone/Floatstone Lithofacies. Images courtesy of W. Martindale.  

**A.** Dendroid coral floatstone with large-sediment filled cavity and karst mud fill. Abundant isopachous cement line and fill shelter cavities associated with coral framework. 14-2-57-1W5, 1449.8m.  

**B.** Marine-cemented dendroid coral framestone without green mud fill. Cavity sediment (Cs) is fine grained and devoid of fossils. Multi-generational cement present. 14-2-57-1W5, 1463.0m.  

**C.** Dendroid coral (Dc) framestone with geopetal mud fillings and extensive late-stage banded isopachous multigenerational cements. 14-2-57-1W5, 1474.4m.  

**D.** Dendroid corals (Dc) and brachiopods in a laminated, locally fenestral (microbially influenced?) green mud matrix with a silty, unfossiliferous anastomosing fill of remaining space? Stylolite at top lined by darker green silt to fine sand. 14-2-57-1W5, 1460.0m
Lithofacies Associations

Lithofacies interpreted from cores in this study indicate five paleoenvironments: reef, foreslope, peritidal, lagoon and open shelf. The majority of these lithofacies are correlative to previously documented lithofacies at the Meekwap field (Table 1) (Chesire and Keith, 1977; Bingham-Koslowski, 2010). However, the Coral Framestone lithofacies is not documented at Meekwap although it occurs along the pinnacle reef trend within Zeta Lake reefs (Chevron Exploration Staff, 1979). The absence of the Coral Framestone lithofacies at Meekwap is thought to be due to differing paleoenvironmental conditions between the Zeta Lake and Meekwap reef trends at the time of deposition.

Lithofacies interpreted to have been deposited in reef-core or reef-front environments in this study include: Stromatoporoid-Spongiostromate-Renalcis Framestones, Renalcis Bindstones and Coral Framestones. The primary variation between these reef lithofacies is the abundance of calcimicrobes. The interpreted contribution to reef growth by calcimicrobes is lowest in the Coral Framestone, greater in the Stromatoporoid-Spongiostromate-Renalcis Framestone and greatest in Renalcis Bindstone lithofacies. Non-reef lithofacies of this study are correlative to both Meekwap Shelf and southern Cynthia Basin ramp deposits and show only subtle variations (Chesire and Keith, 1977; Watts, 1987; Bingham-Koslowski, 2010).

Pinnacle reefs in the Cynthia Basin were constructed by stromatoporoids, corals and calcimicrobes. Reef lithofacies of this study show aspects of both the Meekwap Shelf reefs and Zeta Lake pinnacle reefs. The amount of calcimicrobial abundance and reef construction by differing framework components in reefs along the northeastern margin of the Cynthia Basin is herein attributed to the evolution of the Cynthia Basin and changing paleoenvironmental conditions.
CHAPTER 3: REEF-BUILDING IN THE CYNTHIA BASIN

NISKU REEFS OF THE CYNTHIA BASIN

Late Devonian Nisku reef-building in the Cynthia Basin occurred in a variety of settings. Zeta Lake reefs originally described by Chevron Exploration Staff (1979) are predominantly located along the medial ramp on the southern edge of the basin (Figure 1.9) and are typically isolated buildups. Many believe they initiated in deep-water environments during deposition of the Lobstick/Bigoray members and grew into shallower-water settings as sedimentation outpaced accommodation creation (Switzer et al., 1994; W. Martindale, pers. comm., 2011). A set of deposits along the northern margin of the basin that contain the Wolf Lake member, along with a younger carbonate cycle, make up the Meekwap Shelf; this suite of deposits is not present in the southern Cynthia Basin (Chesire and Keith, 1977; Switzer et al., 1994). There deposits become more calcareous to the north and are not found in the West Pembina area (Switzer et al., 1994). The deposits of the Meekwap Shelf are therefore likely younger than the West Pembina pinnacle reef trend, consistent with current interpretations (Switzer et al., 1994). The Meekwap field is the site of many closely spaced patch reefs and intervening channel deposits, likely deposited in a shallower-water setting than Zeta Lake pinnacles (Chesire and Keith, 1977; Bingham-Koslowski, 2010). Calcimicrobe-rich lithofacies of this study, Stromatoporoid-Spongiostromate-\textit{Renalcis} Framestones and \textit{Renalcis} Bindstones, show that calcimicrobe-dominated reef-building was not restricted to the Meekwap field and extended around the northeastern margin of the Cynthia basin. The absence of closely spaced core intervals makes it difficult to determine whether a similar environment to the Meekwap field existed continuously along the northeastern rim of the basin. The depositional environment is likely similar to the Meekwap field due to being deposited in shallow-water, although the degree of patch reef isolation and associated channels is unknown since no channel deposits were encountered. The deposits of the Meekwap Shelf have substantially more argillaceous material than the West Pembina pinnacles as seen in well-log gamma ray profiles. It is very likely that the deposits of this study were deposited landward of a shelf edge, and thus comprise patch reefs and not pinnacles, due to their similarity to Meekwap field deposits; however the only
published shelf margin along the northeastern rim of the Cynthia Basin (Switzer et al., 1994) is difficult to apply at a local scale.

**Contrasting Reef Styles**

There are two distinct reef styles within the Cynthia Basin, both of these are documented within the core descriptions of this study. One consists predominantly of corals, massive/laminar stromatoporoids, and few calcimicrobes. Lithofacies of this type include Coral Framestones and Stromatoporoid Framestones. The other consists of significant amounts of calcimicrobes, thin stromatoporoids, and few corals. These calcimicrobe-rich reef lithofacies are the Stromatoporoid-Spongiostromate-\textit{Renalcis} Framestones and \textit{Renalcis} Bindstones. Differences between these reef styles are outlined in Figure 3.1. Reef lithofacies containing abundant calcimicrobes but thin and poorly developed stromatoporoids are more prevalent in this study (Table 2). Reef lithofacies comprised predominantly of corals, massive and large laminar stromatoporoids, and few microbial constituents (Coral and Stromatoporoid Framestones) are only present in 14-2-57-1W5, the southernmost core in the study area (Figures 3 & 4). Lithofacies within 14-2-57-1W5 are very similar to the West Pembina pinnacle reef lithofacies (Chevron Exploration Staff, 1979). Reef lithofacies dominated by calcimicrobes are consistent with previous descriptions of the Meekwap field (Chesire and Keith, 1977; Bingham-Koslowski, 2010).

<table>
<thead>
<tr>
<th>Calcimicrobe-dominated, Meekwap-like reefs</th>
<th>Coral/stromatoporoid dominated, Zeta Lake-like reefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-21-57-3W5</td>
<td>14-2-57-1W5</td>
</tr>
<tr>
<td>10-32-58-2W5</td>
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<tr>
<td>10-17-60-3W5</td>
<td></td>
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<tr>
<td>11-17-61-4W5</td>
<td></td>
</tr>
<tr>
<td>6-36-61-4W5</td>
<td></td>
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<tr>
<td>11-19-63-4W5</td>
<td></td>
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<tr>
<td>7-25-63-5W5</td>
<td></td>
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<tr>
<td>14-29-65-7W5</td>
<td></td>
</tr>
<tr>
<td>4-29-57-3W5</td>
<td></td>
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</tbody>
</table>
FIGURE 3.1: Comparison of reef styles within Cynthia Basin reefs. Core photographs with cm scale bars. A. Typical coral framestone of the (lower) Zeta Lake member described by Chevron Exploration Staff (1979). Few stromatoporoids are present. Cavity sediment is fine grained and free of fossils. Multi-generational cement is present and locally contains pores. 14-2-57-1W5, 1463.0m. Photo courtesy of W. Martindale. B. Calcimicrobe-dominated reef style with thin stromatoporoids. Microbial components are dominantly *Renalcis* below stromatoporoids. Some dorsal microbial crusts are present as well. Geopetal cavity cement is present, represented by thin rims at the top of internal cavities. 14-29-65-7W5, 1727.4m.

**Meekwap Shelf Lithofacies Correlation**

A key objective of this study was to compare lithofacies of reefs along the northeastern rim of the basin to previously documented Nisku lithofacies at the Meekwap field. This was done to determine the lateral extent of Meekwap field lithofacies. Bingham-Koslowski (2010) documented eleven lithofacies at Meekwap and interpreted four distinct paleoenvironments: peritidal, lagoonal, reef, and foreslope. The paleoenvironmental reconstruction at Meekwap consisted of two shallowing upward cycles, similar in lithofacies composition, that dipped southward into the basin (Bingham-Koslowski, 2010). The reef lithofacies documented by Bingham-Koslowski (2010) are rich in calcimicrobes, consistent with previous documentations of the Meekwap field (Chesire and Keith, 1977). Reef lithofacies also contain an abundance of laminar and wafer stromatoporoids, but a dearth of
corals (Bingham-Koslowski, 2010). This study shows calcimicrobe-rich reef lithofacies extend from the Meekwap field (Township 66, Range 15-16W5) around the eastern shelf edge of the Cynthia Basin to at least Township 57, Range 3W5. The southernmost core logged in the study, 14-2-57-1W5, showed Zeta Lake-like lithofacies (Coral and Stromatoporoid Framestones). The lateral extent to which the calcimicrobial Meekwap lithofacies extend is likely Township 57, Range 3W5, at which point the reef style changes to Zeta Lake-type, dominated by corals and stromatoporoids. It should be noted that this is nearly 50 kilometers farther south than documented by Switzer et al. (1994).

Although the difference between these reef types is likely not a reflection of varying conditions during contemporaneous deposition but a result of two distinct depositional phases, the separation between these two distinct lithofacies assemblages occurs within Township 57, Range 3W5. Lithofacies in this study indicate 5 paleoenvironments present along the northeastern rim of the basin: reef, foreslope, peritidal, lagoonal and open marine shelf. This indicates that the Meekwap field paleoenvironments and lithofacies are correlative to deposits nearly 150 kilometers southeast of the Meekwap field. A summary of key lithofacies aspects and comparisons to the Meekwap field is presented in Table 1.

The extent of these calcimicrobe-rich lithofacies is a reflection of the lateral coverage of the uppermost Nisku cycle, present along the northern rim of the basin but absent in the West Pembina area (Switzer et al., 1994). Figure 3.2 illustrates the lateral extent of the last Nisku cycle, containing Wolf Lake member deposits and the Meekwap Shelf, in a north-south cross section through the Cynthia Basin.
FIGURE 3.2: North-south cross section illustrating stratigraphy of the Nisku Formation from the Peace River arch to the West Pembina area. Log traces are gamma ray. Red dashed line illustrates the last cycle of deposition in the Nisku Formation present on the Meekwap Shelf and extending into the basin but absent in the West Pembina area. Note how the lower boundary is a gamma ray high, indicating a potential flooding surface and how it top-laps the Calmar base north of the Zeta Lake reefs of the West Pembina area. Also note that the Meekwap Shelf limestone only extends to Township 62 and not to Township 57 as described in this study. This is likely due to the cross section running through the center of the basin and not along the northeastern rim, showing only the north-south extent of limestone at the Meekwap field. Modified from Switzer et al. (1994).
**Zeta Lake Reefs**

The Zeta Lake pinnacle reef trend, discovered in the late 1970's (Chevron Exploration Staff, 1979), is located on the medial ramp on the southern rim of the basin. They occur in a narrow fairway, 180km by 65km wide extending from Township 47 Range 15W5 to Township 52 Range 7W5 (Figure 1.9) (Switzer et al., 1994). Most of the pinnacles display a bipartite zonation of lithofacies (Chevron Exploration Staff, 1979) that are represented by the lower and upper Zeta Lake members in a shallowing-upward profile. Some pinnacles show three differing zones of lithofacies in a shallowing-upward trend (Watts, 1987). These pinnacles are rooted in the Lobstick member, although some appear to have initiated on overlying ramps – most commonly the Bigoray (Watts, 1987). Therefore, the Zeta Lake reefs initiated and grew in a basin with relatively open circulation and were later buried by prograding fine-grained siliciclastic basin fill from the north and south, and possibly the east. Figure 3.3 displays the original Chevron Exploration Staff (1979) description and interpretation of these reefs. 14-29-57-1W5 was the only core logged in the study showing similarities to the Zeta Lake members.

<table>
<thead>
<tr>
<th>MEMBER</th>
<th>THICKNESS</th>
<th>LITHOLOGY</th>
<th>FOSSILS</th>
<th>FABRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Zeta Lake</td>
<td>58m (190')</td>
<td>ABUNDANT CORALS - VARIETY</td>
<td>BOUNDSTONES ENC RENALCIS</td>
<td>BOUNDSTONES ENC RENALCIS</td>
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<td></td>
<td></td>
<td>TABULAR STROMS. STACHYODES</td>
<td>BIRDSEYE</td>
<td>BIRDSEYE</td>
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<tr>
<td></td>
<td></td>
<td>BRACHIOPODS CRINIDS MOLLUSKS</td>
<td>POROSITY VUGGY</td>
<td>POROSITY VUGGY</td>
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<td></td>
<td></td>
<td>STROMATOLITES</td>
<td>FINE MATRIX</td>
<td>FINE MATRIX</td>
</tr>
<tr>
<td>Lower Zeta Lake</td>
<td>43m (142')</td>
<td>ABUNDANT CORALS - VARIETY</td>
<td>BOUNDSTONES ENC RENALCIS</td>
<td>BOUNDSTONES ENC RENALCIS</td>
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<tr>
<td></td>
<td></td>
<td>DENDROID FASCICULATE</td>
<td>BIRDSEYE</td>
<td>BIRDSEYE</td>
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<tr>
<td></td>
<td></td>
<td>Predominant Tabular stroms.</td>
<td>POROSITY VUGGY</td>
<td>POROSITY VUGGY</td>
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<td></td>
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<td>Brachiopods Crinoids</td>
<td>MOSTLY RECENTED</td>
<td>MOSTLY RECENTED</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gastropods</td>
<td></td>
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</tbody>
</table>

**FIGURE 3.3:** Lithological summary of Zeta Lake member type section. Chevron Exploration Staff (1979).
**Spatial Distribution of Reef Types**

The Zeta Lake pinnacles are in a narrow fairway stretching from Township 47 Range 15W5 to Township 52 Range 7W5 (Figure 1.9). Previous studies of the Meekwap field (Chesire and Keith, 1977; Bingham-Koslowski, 2010) along with this study, indicate that Zeta Lake type reefs are absent from the Meekwap field and the northeastern rim. Likewise, documentation of the southern rim (Chevron Exploration Staff, 1979; Watts, 1987) fails to describe calcimicrobe-dominated reefs. There appears to be a bipartite zonation of reef types tracing the rim of the Cynthia Basin. South of Township 57 and extending along the shelf (Figure 3.4), reefs tend to be dominated by corals and stromatoporoids and can be classified as Zeta Lake reefs, whereas north of Township 57, reefs tend to be dominated by microbes and thin stromatoporoids. This is reflected by the abundance of Stromatoporoid-Spongiosanite-Renalcis Framestone and Renalcis Bindstone lithofacies and absence of Coral Framestone lithofacies in cores north of Township 57.

The localization of Zeta Lake pinnacles to the southern rim of the basin can be attributed to a combination of factors. Firstly, the northern rim of the basin was actively accumulating fine-grained siliciclastic sediment and prograding southward from the Peace River - Athabasca Arch area during the Mid Frasnian (Switzer et al., 1994). The influx of clastic sediment likely inhibited coral growth (sensu James and Wood, 2011) on the northern margin of the basin while to the south, deep-water carbonate accumulation was facilitated by clear-water conditions and suitable substrates (hardgrounds/firmgrounds and/or topographic highs; Switzer et al., 1994). It is likely that clastic input on the southern margin was minimal during early phases of the basin due to the occurrence of areaally-extensive shallow-water bioherms in the Brazeau field during deposition of the Lobstick and Bigoray ramps (Switzer et al., 1994). Secondly, the northern margin of the basin was substantially deeper during early stages of sedimentation (Figure 3.5). Only when the fill reached a depth suitable for the accumulation of shallow-water carbonates, could the Meekwap Shelf develop (Switzer et al, 1994). The progressive influx of clastic sediment, along with the constriction of the basin due to progradation, led to more restricted conditions and influenced carbonate depocentres and lithofacies. Therefore, carbonates and reefs of the Meekwap Shelf, along with the upper Zeta Lake cycle, reflect the conditions.
FIGURE 3.4: Depositional elements and reef lithofacies map of the Cynthia Basin on the basis of this study. Modified from Switzer et al. (1994).

FIGURE 3.5: Schematic illustration of stratigraphic relationships of the Winterburn strata in the Cynthia Basin. Note the aggradation of carbonate units on the southeast end of the basin (Lobstick and Bigoray cycles) while time equivalent deposits on the northwestern end are shale. Modified from Switzer et al. (1994).
of the basin at the time. Figure 3.4 illustrates a hypothetical reef-lithofacies map of the Cynthia Basin.

**LITHOFACIES VARIABILITY IN REEFS**

It is a common conception that throughout the Devonian the abundance of calcimicrobes in reef systems increased while the abundance of corals and stromatoporoids seemed to decrease (Wood, 1999; Copper, 2002a; Copper and Scotese, 2003; Shen et al., 2010). The assumption that calcimicrobe-rich successions are the norm for pre-Famennian reefs may be due to the bias towards well-documented systems including the Canning Basin (e.g. Playford et al, 1976; Playford, 1980; Wood, 1998) and those of the Western Canadian Sedimentary Basin (e.g. Wray and Playford, 1970; Mountjoy and Jull, 1978; Mountjoy and Riding, 1981). However, some early documentation of Devonian reef systems portray the abundance of microbial constituents as geographically variable (Wray, 1967; Krebs, 1974). Recent studies by Whalen et al. (2002) and MacNeil and Jones (2008) have proposed that temporal and basinal factors are likely more responsible for the development of microbial-rich lithofacies than a global shift in reef composition.

Disentangling global trends in reef ecology from the short-term dynamics of a basin is challenging due to both the complexity of reconstructing paleoenvironmental conditions, as well as interpreting nutritional and photic modes of extinct fauna. However, using changes in reef lithofacies is a powerful tool for determining the presence and significance of basinal factors on lateral and vertical lithofacies changes (cf. MacNeil and Jones, 2008). Integrating limiting factors of late Devonian reef communities should lead to a better understanding of reef ecology and evolutionary trends of reef-builders.

The lithofacies contrast between pinnacle reefs in the Cynthia Basin, specifically between calcimicrobe-rich *Renalcis* Framestone and *Renalcis* Bindstone lithofacies and calcimicrobe-lacking Coral Framestone lithofacies, is thought to be a result of basinal factors, as variations are evident from reefs deposited penecontemporaneously. Therefore, lithofacies variability in pinnacle reefs is thought to reflect the dynamic paleoenvironmental conditions of the Cynthia Basin throughout deposition of the Nisku Formation.
Mechanisms Inducing Variability

Calcimicrobes have been documented in buildups as old as the early Cambrian (James and Kobluk, 1978; Wood, 1993), however, they were typically restricted to cryptic habitats. The volumetric significance and unrestricted growth habits of calcimicrobes in Cynthia Basin reefs, in addition to sharply contrasting reef styles, is thought to reflect basinal dynamics. These observations could potentially be attributed to temporal changes in salinity, temperature, energy, light, depth and/or subsidence, turbidity, and nutrient levels.

A salinity gradient in the Cynthia Basin could have resulted in either hypersalination if basin restriction occurred during progradation, or local brackish water conditions from river mouths supplying fresh water. Many organisms can withstand subtle changes in salinity but drastic changes restrict many macro-organisms and may lead to proliferation of microbes (Browne et al., 2000; Flügel, 2004). The dearth of abundant evaporites (Figures 8, 22 & 25), abundance of crinoids (Hess et al., 1999; Flügel, 2004) and moderate biodiversity in both reef styles suggests normal marine conditions in the Cynthia Basin at the time of Nisku deposition.

Microbes are able to flourish across the temperature spectrum (Brown et al., 2000) whereas other reef-building organisms (ie. corals and stromatoporoids) may have been restricted by temperature (Munster, 1992; Kershaw and Brunton, 1999). Nisku deposition occurred at equatorial latitudes at a time when ocean water temperatures were likely 25-35° C (Markello et al., 2008). There is no indication of extreme seawater temperature conditions or variations at the time of Nisku deposition.

The presence of marine cement in calcimicrobe-dominated and coral-stromatoporoid pinnacle reefs, along with ubiquitous fossil fragments, suggests moderate to high-energy conditions consistent with previous interpretations (Watts, 1987; Switzer et al., 1994). It is unlikely that basin restriction or shallowing during progradation reduced energy levels significantly or resulted in the drastic lithofacies change.

Microbes have been thought to develop in a number of photic settings. *Renalcis* and *Epiphyton* are often interpreted as indicators of low-light conditions (Pratt, 2000) similar to
modern red algae (Adey et al., 1982). The abundance of dorsal microbial crusts and asymmetric oncolites in Cynthia Basin reefs, suggests that these microbes (Girvanella and Rothpletzella) (Bingham-Koslowski, 2010) flourished in well-lit conditions (cf. Stephen and Sumner, 2002). Thus, changes in light levels were likely not responsible for lithofacies variations.

The depth at which these reefs developed could be one of the more important factors to consider for lithofacies variability due to the different paleoenvironmental interpretations. Coral-stromatoporoid pinnacle reefs of the West Pembina trend grew in predominately deeper-water settings along the medial ramp, whereas the Meekwap Shelf developed in shallow-water settings when accommodation was limited (Switzer et al., 1994). However, microbes are known to exist in deeper-water slope environments in the Frasnian and Famennian (e.g. Stephens and Sumner, 2002; Bouvlain et al., 2005). The occurrence of shallow-water bioherms in the Brazeau field, time-equivalent to the West Pembina pinnacle trend (Switzer et al., 1994), provides another argument against water depth being the factor responsible for lithofacies variability.

While the effects of nutrients and fine clastic sedimentation are difficult to disentangle because they often occur simultaneously (James and Wood, 2011), it is interpreted herein that nutrification was the principle cause of lithofacies variability in Cynthia Basin reefs. Both coral-stromatoporoid and calcimicrobe-dominated reefs have some degree of siliciclastic sediment content. While gamma ray logs through reefs of the Meekwap Shelf indicate that the clastic content is invariably higher than pinnacles in the West Pembina area due their more distal setting, there are more proximal coral-stromatoporoid reefs in the West Pembina and Brazeau area showing higher amounts of clastic influx (Switzer et al., 1994). Nutrients are considered a global controlling factor limiting reef growth (Hallock and Schlager, 1986; Wood, 1993). The introduction of nitrogen, phosphate and iron may inhibit CaCO₃ precipitation, stimulate plankton blooms, increase water turbidity, and enhance bioerosion (Copper, 2002b), disturbing normal reef production patterns. Moreover, recent studies have attributed prominent development of microbes to mesotrophic and even eutrophic conditions (e.g. Dupraz and Strasser, 2002; Whalen et al., 2002; Olivier et al., 2006; MacNeil and Jones, 2008). The shift in biotic assemblage of reef communities occurs when nutrient flux adversely affects the coral fauna, causing microbial communities to become dominant at the reef surface (Olivier et al., 2006).
NUTRIENTS AS A CONTROL ON LITHOFACIES VARIABILITY

Carbonate systems are controlled through the complex interaction of climate, platform geometry, water-depth, temperature, ocean chemistry and circulation, and sea-level change. Recent research has focused on changes in the ocean environment and its impact on carbonate systems (Mutti and Hallock, 2003). Changes in global climate, ocean circulation and sea-water chemistry (principally carbonate saturation state and nutrient availability) have been shown to dynamically influence the fauna constructing carbonate systems (Mutti and Hallock, 2003). Applying specific environmental conditions to the reconstruction of ancient successions is extremely challenging. Modern analogues constraining sedimentological, physiochemical, and biogenic conditions are often applied as proxies in attempts to remedy these issues. Since the 1970's there has been increased attention on the relationship between nutrients and carbonate accumulation (e.g. Hallock and Schlager; Hallock, 1987; Caplan et al. 1996). The term nutrients, refers primarily to inorganic nitrogen and phosphate ions that organisms require for cell maintenance, growth, and reproduction (Hallock, 2001). Nutrients can be delivered to a carbonate system in a variety of ways such as terrestrial runoff, groundwater seepage, ocean upwelling, storm activity, and interactions of the mixing zone. Relating changes in reef-building communities to elevated nutrient levels is consistent with the physiological needs of algae and microbes and has been applied to numerous studies of modern reefs. Physiochemical requirements restrict most microbes to environments with available nitrogen, phosphate, and iron (Lobban and Harrison., 1994). Applying a nutrient-gradient (sensu Hallock, 1987) to ancient carbonate successions has proven to be a pivotal factor illustrating the taxonomic diversity and overall structure of these systems.

INFLUENCE OF NUTRIFICATION

The negative influence of excess nutrients on the growth of carbonate platforms was often overlooked in the past due to the fact that they are essential for the growth of many biotic constituents (Hallock and Schlager, 1986). However, recent theoretical and
observational evidence indicates that an excess of nutrients can impose a significant environmental stress on a carbonate system. This “nutrient paradox”, first questioned by Margalef (1968) and later developed by Hallock and Schlager (1986), states that even though nutrients are essential for coral growth, and that corals are efficient nutrient recyclers, there is a scarcity of corals in modern nutrient-rich environments.

Elevated nutrient levels can have adverse effects on coral reefs in particular for a number of reasons. Overfeeding stress, competition for space, and increased predation of coral larvae and adults are all detrimental to optimal coral reef growth (Hallock and Schlager, 1986). Well-developed coral buildups in the modern are typically restricted to oligotrophic environments (Figure 3.6) (Hallock, 1987). In modern mesotrophic environments, the primary carbonate producers are soft or weakly calcified algae, including cyanobacteria. Heterotrophs may be present and even dominant in cryptic habitats within these environments. Increasing nutrient levels to eutrophic conditions results in the sequestering of nutrients and light by phytoplankton and areas dominated by a sessile open surface heterotrophic community (Wood, 1995).

Reefs in the Frasnian were principally constructed by stromatoporoids, tabulate corals and calcimicrobes. The nutritional modes of these components is debatable though it is general consensus that stromatoporoids and tabulate corals were likely mixotrophs (Coates and Jackson, 1987; Wood, 1993), whereas a heterotrophic origin seems likely for the majority of calcimicrobes (Wood, 1993; Castanier et al., 1999; Chafetz and Guidry, 1999; Adachi and Ezaki, 2007). Rugose corals of the Devonian, though not predominant reef constructors, are hypothesized to have been heterotrophs and able to withstand more mesotrophic conditions than tabulate corals (Coates and Jackson, 1987; Wood, 1993; Wood, 1995).

It appears as though well-developed coral buildups were likely restricted to oligotrophic conditions in the Devonian (Wood, 1995), similar to modern environments. Devonian reef-building by corals is thought to have shut-off in mesotrophic conditions and replaced by abundant microbes and poorly developed stromatoporoids as is the case in modern environments. The abundance of calcimicrobes is the key to determining the nutrient conditions in Devonian systems. Wood (1995) suggested some calcified cyanobacteria could have been "non-nutrient limited". MacNeil and Jones (2008) expanded
FIGURE 3.6: Nutrient-gradients, presented in milligrams of chlorophyll per cubic meter of seawater in low latitude waters for modern carbonate sedimentation (Mutti and Hallock, 2003). Note the coral reef turn-on/turn-off zone in mesotrophic conditions. The dominant benthos switches from coral-algae to macroalgae which can be used as a modern analog to Devonian microbial constituents.

<table>
<thead>
<tr>
<th>Increasing nutrient levels</th>
<th>Oligotrophic</th>
<th>Mesotrophic</th>
<th>Eutrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biotic composition of framework lithofacies</td>
<td>Stromatoporoid-dominated reef lithofacies</td>
<td>Stromatoporoid-microbe$^1$ reef lithofacies</td>
<td>Megalodont-microbe$^2$ lithofacies (replace reef lithofacies)</td>
</tr>
<tr>
<td>Biotic composition of framework lithofacies</td>
<td>Stromatoporoid-tabulate coral reef lithofacies</td>
<td>Stromatoporoid-coral$^2$-microbe$^1$ reef lithofacies</td>
<td></td>
</tr>
<tr>
<td>Biotic composition of framework lithofacies</td>
<td>Stromatoporoid-tabulate-rugose coral reef lithofacies</td>
<td></td>
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</tbody>
</table>

$^1$Renalcis, Shuguria, Izhella, stromatolites
$^2$Tabulate and/or rugose corals
$^3$Calcimicrobes, stromatolites, thrombolites

FIGURE 3.7: Nutrient-gradient model for Devonian reef systems (MacNeil and Jones, 2008). Illustrates how Devonian reef communities were effected and responded to varying nutrient conditions. Only in eutrophic environments does the platform demise and drowning occur, coeval with the replacement of reef lithofacies by Megalodont-microbe lithofacies (MacNeil and Jones, 2008).
on this and suggested mesotrophic conditions are typified by the abundance of renalcids. The broad distribution of *Rothpletzella* and *Girvanella* across lithofacies and systems tracts has led to the idea that they are more insensitive to fluctuating nutrient levels and potentially unrestricted by nutrients (MacNeil and Jones, 2008). Thus, Devonian successions containing abundant and pervasive successions of *Renalcis* in particular are attributed to mesotrophic conditions. It is commonly thought that stromatoporoids were restricted to oligotrophic conditions (Hallock and Schlager, 1986; Mutti and Hallock, 2003; Wood, 1995; Kershaw and Brunton, 1999) although recent work by MacNeil and Jones (2008) suggests that they may have been able to withstand more mesotrophic conditions (Figure 3.7).

The application of a nutrient-gradient model for application to Devonian reef systems suggests that reef constructors differed in varying trophic conditions (MacNeil and Jones, 2008; Figure 3.7). Studies of the (Frasnian) Alexandra Formation, Northwest Territories, suggest varying nutrient levels are reflected in the biotic assemblages of reefs and is applicable to other Devonian successions (MacNeil and Jones, 2006; 2008). In the Alexandra Formation, differing nutrient levels could be attributed to specific reef types. Stromatoploid and coral dominated associations, with a paucity of calcimicrobes, were attributed to oligotrophic conditions. Calcimicrobe-dominated systems, with subordinate stromatoporoids and tabulate/rugose corals, were attributed to mesotrophic conditions. A Devonian nutrient-gradient model suggests that stromatoporoids were more resilient than previously thought and took part in reef-building in mesotrophic environments (MacNeil and Jones, 2008). In eutrophic environments, reef-building is thought to have ceased with reef lithofacies replaced by Megalodont bivalve and calcimicrobe associations (MacNeil and Jones, 2008).

**MODERN ANALOGUES**

Modern analogues of nutrient-rich carbonate systems can be used to hypothesize about the conditions and responses of similar ancient systems. Over the last 20 years, many coral reefs worldwide have suffered extensive declines in biodiversity and density due to nutrient
poisoning and are often covered by macroalgae (Costa et al., 2008). Nutrient enrichment of modern coral reef tracts may enhance algal growth, and the increasing abundance of macroalgae leads to a spatial competition (Costa et al., 2008). Many studies have shown that algae and rapidly growing filter feeders tend to develop prolifically in elevated nutrient conditions (e.g. Buss and Jackson, 1981; Goreau, 1992). As nutrient levels increase, coral communities shift from a dominance of nutrient-recycling symbiotic organisms in oligotrophic conditions to increasing proportions of macroalgae in elevated nutrient conditions and further to heterotrophic filter feeders in nutrient-enriched areas of upwelling or lagoons (Birkeland, 1987). This is a modern illustration of shifting coral reef communities displayed in Figure 3.6, and can be applied to ancient successions where nutrients appear to be the limiting factor on the development of certain reef-builders (Figure 3.7) (cf. MacNeil and Jones, 2008). There appears to be some evidence of enhanced modern coral growth rates in highly nutrified settings (Atkinson et al., 1995). However, this is not the norm and although Scleractinian corals from the Cretaceous to present may have be more resilient to clastic sedimentation and nutrient influx than Paleozoic corals (Sanders and Baron-Szabo, 2005) many previously thriving modern coral reef environments have entirely lost their capacity to remain in, or return to, a coral-dominated state in nutrient-rich environments (Hughes et al., 2010).

Modern cyanobacteria and reef biofilms are found in lightless and poorly lit carbonate environments (Wood, 1999; Stephens and Sumner, 2002). Microbial calcification does not occur in modern marine environments of normal salinity and consequently requires either freshwater, hypersaline or postmortem (facilitated by heterotrophic bacteria) calcification (Davies, 1970; Wood, 1999). However, microbialites have been described in Holocene framework lithofacies in Tahiti (Montaggioni and Camoin, 1993), the Caribbean (Adey, 1975; Zankl, 1993) and the Great Barrier Reef (Webb, 1996). These studies have attributed microbial abundance to elevated nutrient conditions, carbonate alkalinity, decreased light and energy conditions (Camoin et al., 1999), carbonate supersaturated sea-water (Webb, 1996; Stephens and Sumner, 2002) and the development of cryptic habitats (Zankl, 1993). Many of the reasons attributed to the development of modern microbialites in reef lithofacies are consistent with paleoenvironmental reconstructions of ancient calcimicrobe-rich successions.
Despite the disappearance of the *Renalcis* group after the early Carboniferous (Pratt, 1984), the total extinction of stromatoporoids at the end of the Strunian (Stearn, 1987) and the disappearance of most tabulate corals during the Permian extinction (Wood, 1999) a great deal can be hypothesized about the environmental conditions these constituents thrived in based on modern analogues. The debate over the exact nutritional mode of tabulate corals and stromatoporoids is still ongoing, although it is widely considered that they are indicative of oligotrophic conditions (Hallock 1987; Kershaw, 1998) and therefore analogous to modern corals that thrive in oligotrophic conditions (Fabricius, 2005). Modern and recent discoveries of modern coralgal and microbialites constituents in association with high-energy coral frameworks have been attributed to the same ecological stresses as suggested by a number of authors for Devonian calcimicrobe-rich successions. These modern analogues promote the evolving conception that calcimicrobial-rich Devonian systems were not a norm and were more dependent on local environmental conditions.

**Nutrification in the Cynthia Basin**

The Nisku Formation of the Cynthia Basin is an example of how nutrification of a carbonate system may result in sharp lithofacies contrast. Nutrification of the basin is interpreted to be responsible for the switch between calcimicrobe-rich *Spongiostromate-Renalcis* Framestone and *Renalcis* Bindstone lithofacies and calcimicrobe-lacking Coral Framestone lithofacies. Studies of modern systems have led to the hypothesis that the response of a system to nutrification should be geologically instantaneous (Hallock, 1987). The two reef types seen in the Cynthia Basin, calcimicrobe-dominated and corals-stromatoporoid-dominated, reflect different nutrient conditions. Coral-stromatoporoid (*Zeta Lake; Figure 3.3*) type reefs, represent deposition in oligotrophic nutrient conditions reflected by the abundance of tabulate corals (*sensu* Wood, 1995) and massive stromatoporoids (*sensu* Hallock and Schlager, 1986; Mutti and Hallock, 2003). *Renalcis* is restricted by the dominance of corals and stromatoporoids during oligotrophic conditions (*cf. MacNeil and Jones, 2008*) as it is not present in any reef lithofacies whereas the absence of dorsal crusts composed of *Girvanella* and *Rothpletzsa* may indicate the restriction of
these calcimicrobes to at least mesotrophic conditions. Calcimicrobe-dominated reefs of the Meekwap Shelf are interpreted to reflect the transformation of reef-building due to increasing nutrient levels in the basin. The Meekwap Shelf developed during the last stage of carbonate sedimentation in the Cynthia Basin, containing the Wolf Lake member and more pure carbonate sediment, as clinoforms prograded into the basin. The increase in nutrients enabled calcimicrobes to occupy the role of dominant reef-builders, supported by weakly developed stromatoporoids. The absence of coral reefs along the Meekwap Shelf is a direct reflection of the mesotrophic environmental conditions. Applying the nutrient-gradient model of MacNeil and Jones (Figure 3.7; 2008) it is clear to see how reef-building in the Cynthia Basin reflects increasing nutrient levels. Initially, reef growth was dominated by stromatoporoid-coral reef lithofacies in oligotrophic conditions. As the basin became more restricted and nutrient levels increased to mesotrophic conditions, the mode of reef-building switched and was dominated by stromatoporoid-microbe reef lithofacies (cf. MacNeil and Jones, 2008).

**MECHANISMS FOR NUTRIFICATION IN THE CYNTHIA BASIN**

As previously emphasized, the principle cause of reef variation in the Cynthia Basin is interpreted to be from the nutrification of ocean waters. Nutrients could have been introduced to the system through various means including terrestrial runoff, groundwater seepage, ocean upwelling, storm activity, and interactions of the mixing layer. It is also possible that there were multiple mechanisms contributing simultaneously to the nutrification of the system.

Runoff from land carries nutrients and terrigenous sediment, both of which can be detrimental to reef-building (Hallock and Schlager, 1986). However, the transport range of nutrients from a river mouth is much greater than terrigenous sediment (Hallock and Schlager, 1986). The transport range of nutrients depends on the flux of fluvial discharge relative to the size of the basin, residence time of nutrients in biotic communities, nutrient concentration, and runoff (Hallock and Schlager, 1986). The Cynthia Basin was a small sub-basin with a maximum width of 300km and was likely sheltered from open ocean conditions. The basin could have retained nutrient influx due to wind induced basin
circulation and terrestrial runoff could have had a significant impact on the system (cf. Skarohamar et al, 2007). During the Devonian, the emergence of land plants tied with a higher amount of planktic blooms must have been important (Wood, 1993). In modern environments, mangrove ecosystems protect coastal coral reef systems from siltation and absorb nutrients (Wilkinson and Buddemeier, 1994). However in the Devonian, pteridophytes were intolerant of brackish and saline waters (Edwards et al., 1985) and reefs were likely more exposed to the influences of terrestrial drainage. Devonian plant development gave way to intensification of pedogenesis and to large increases in thickness and areal extent of soils (Algeo and Scheckler, 1998). Falling sea-level during the late Devonian (Figure 1.5) would have enabled erosion of former marine platforms and promoted incision inland (Copper, 2002a). Physical erosion, via downcutting and incision, along with enhanced chemical weathering may have led to increased riverine nutrient fluxes (Algeo et al, 1995; Algeo and Scheckler, 1998). These conditions have been thought to help promote eutrophic conditions, algal blooms, widespread bottom water anoxia, and high sedimentary organic carbon fluxes (Algeo and Scheckler, 1998). Nisku (marine) sandstone (Figure 1.8) along with evidence of fluvial deposits near the Cynthia Basin (W. Martindale, pers. comm., 2011) suggests there was active fluvial discharge in close proximity to the basin. It is very likely that terrestrial runoff was a mechanism for nutrification of the Cynthia Basin.

The global scale impact of groundwater seepage on modern marine communities is less than that of surface runoff (Johannes, 1980). However, groundwater seepage is a well-known cause of nutrification on modern carbonate platforms (Johannes, 1980; D'Elia et al., 1981; Lewis, 1987). Meteoric water in upland areas may contain nitrate that can be expected to have significant effects on biological processes after discharge (D'Elia et al., 1981). Landward and/or exposed reef systems uncovered due to sea-level fall can contain a significant amount of decaying organic matter (MacNeil and Jones, 2008). Percolating groundwater can attain nutrients as they pass through these systems eventually discharging in the marine (MacNeil and Jones, 2008). Evidence of subaerial exposure of Zeta Lake reefs (14-2-57-1W5 in this study) during sea-level fall (Figure 1.5) suggests that groundwater seepage may have occurred in the Cynthia Basin. It is therefore possible that groundwater seepage was a mechanism for nutrification in the basin.
Upwelling systems occur where there is a persistent upward movement of seawater, transporting inorganic nutrients to surface and near-surface layers (Barber, 2001). Upwelling is a well-known cause of nutrification on many modern carbonate shelves and platforms (Hallock and Schlager, 1986). Upwelling is a large-scale (10-100km) physical response of the oceanic system to the wind field (Barber, 2001). However, upwelling is an unlikely cause of nutrification in the Cynthia Basin due to its isolation from open ocean conditions (Switzer et al., 1994) and improbability of being situated along a coastal upwelling tract (Markello et al., 2008).

Storm activity can also provide a mechanism for nutrification. Studies have shown that tropical cyclones or hurricanes have a great effect on the vertical mixing and ocean upwelling of oceanic waters beneath the eye of the storm (Holloway et al., 1985). These events are typically short lived but can produce significant enrichment in the seawater and rapid blooms of algae and microbes (Lin et al., 2003). Storm activity may also disturb sediment-hosted nutrient reservoirs on the platform, capable of being transported if deposited above the storm wave base (MacNeil and Jones, 2008). Due to the absence of storm generated structures and ubiquitous stromatoporoid/coral breakage, thought to be indicators of large storms, it is unlikely that storm activity had a significant effect on the nutrification of the system.

Seawater advection in nutrient enriched zones through seasonally forced deepening of the mixed layer is another well-known mechanism of nutrient supply to carbonate systems, especially those located in intracratonic basins and marginal seas (MacNeil and Jones, 2008). Small decreases in temperature can result in the deepening of the upper mixing layer in oceans (Genin et al., 1995). Sinking oxygenated waters mix with more nutrient-rich waters below resulting in nutrient transport upwards into the photic zone (Genin et al., 1995). Punctuated global cooling in the Frasnian (Copper, 2002a; Day and Whalen, 2006) may have induced seasonally forced nutrification. This may have been especially important during falling stage systems tract deposits (MacNeil and Jones, 2008). Knowing that some of the Cynthia Basin Nisku deposits were deposited during sea-level fall (Cynthia and Wolf Lake members, Meekwap Shelf; Figure 1.5), seasonally forced deepening of the mixed layer could have been a viable mechanism for nutrification.
Although there may have been multiple mechanisms for nutrification in the Cynthia Basin, the most likely factor is terrestrial runoff. Time-equivalent marine sandstone deposits along with fluvial evidence on the southern rim of the Cynthia Basin suggests there was active terrestrial discharge near the basin during reef growth. Recent work has shown that changes in terrestrial input of sediment and nutrient delivery, associated with land plant expansion from the Mid to Late Devonian, was the main driver of increased nutrient delivery to the oceans (Algeo et al, 1995; Algeo and Scheckler, 1998; Sliwinski et al., 2011). A strong likelihood of an equatorial humid climate existing on the western edge of Laurussia throughout the Devonian (Markello et al., 2008) would contribute to the nutrification of the basin through terrestrial runoff due to high annual precipitation rates. Seasonally forced deepening of the mixed layer and groundwater seepage as a result of sea-level fall may have enhanced nutrification in the basin. The absence of significant storm activity, temperature zoned lithofacies and substantial karstification suggests terrestrial runoff was the principle mechanism for nutrification of the Cynthia Basin.

**E V O L U T I O N  O F  T H E  C Y N T H I A  B A S I N**

The topographic low that would become the Cynthia and Karr Basins in west central Alberta was bordered to the south and east by thinning Woodbend strata, to the west by Leduc reefs and shelf complexes, and to the north by the Athabasca Arch (Switzer et al., 1994). From east central Alberta, where the Nisku Formation represents a extensive carbonate shelf (Switzer et al., 1994), to the Cynthia Basin there is a drastic lithofacies change. From the Nisku shelf into the Cynthia Basin, there is a marked break in slope represented by isopach thickening (Figure 1.8). Carbonate deposits on the shelf are replaced by interbeds of limestone and shale representing slope deposits (Watts, 1987).

Much of the deposition within the Cynthia Basin is thought to have occurred throughout sea-level rise on a 3rd order cycle (Figure 1.5) and is represented by backstepping clinoforms of the Lobstick, Bigoray and Cynthia member ramps (Switzer et al., 1994). Construction of Zeta Lake-type reefs during this transgression commenced at favourable locations in the southern Cynthia Basin and buildups were able to keep pace with sea-level rise. The lithofacies of the Zeta Lake member (Coral and Stromatoporoid
Framestones) reflect open marine, oligotrophic and deep-water conditions in the basin. These reefs accreted quickly (Switzer et al., 1994) and were composed of a variety of corals and thick stromatoporoids. The reef sediment is composed of clean carbonate and consists of brachiopods, crinoids, and gastropods (Figure 3.3). Deep-water conditions on the northern margin of the basin prohibited reef development. Clastic influx was pushed landward during this transgression and clear water conditions are thought to have existed across the basin. With this, nutrient influx supplied through terrestrial runoff would have been concentrated in more proximal environments. The lack of exposed shelves and platforms during the transgression would have prohibited groundwater seepage from reaching the Zeta Lake reef trend. The absence of storm evidence in Zeta Lake reefs is a reflection of the protected conditions that existed in the Cynthia Basin. Coral-stromatoporoid reefs devoid of calcimicrobes flourished along the West Pembina trend.

Following the Bigoray and upper Cynthia member deposition, a 3rd order sea-level fall decreased accommodation through the remainder of the Devonian (Figure 1.5). Intermittent 4th and 5th order cycles increased accommodation and initiated reef growth elsewhere in the basin. Deposition of the upper Cynthia and Wolf Lake members along with the Meekwap Shelf occurred during this sea-level fall as clinoforms in the basin regressed. A single karst surface evident in Zeta Lake type reefs reflects the subaerial exposure following Bigoray deposition. No subsequent karst in the basin likely reflects that regional subsidence exceeded eustatic (cf. Copper, 2002a) sea-level fall. The Meekwap Shelf developed when sea-level fall provided shallow conditions suitable for carbonate sedimentation (Switzer et al., 1994). Sea-level fall, commencing after the 3rd order highstand and continuing through falling stage (Figure 1.5), in the basin brought clastic influx in closer proximity to the basin, reflected in the gamma ray logs of Meekwap Shelf and upper Zeta Lake member carbonates. Furthermore, the Meekwap Shelf helped to further isolate the basin from more open marine conditions (Switzer et al., 1994). Proximal clastic deposition is represented by the marine sandbody present to the north of the basin (Figure 1.8). Clastic sediment being shed from the craton is thought have been sourced primarily from north of the basin, due to the location of the marine sandstone body and discussion that the basin was progressively filled southward (Switzer et al., 1994). This could have been due to the Coriolis force deflecting terrestrial runoff southward (Figure 3.8). Due to the development of more restricted conditions along with more proximal
clastic influx, more mesotrophic conditions developed throughout the basin. The temporal shift from oligotrophic to mesotrophic conditions is reflected in reef-building communities of the Cynthia Basin. The upper Zeta Lake member reflects this change by an increasing amount of *Renalcis* and microbial crusts (Figure 3.3) and a change from Coral and Stromatoporoid Framestones to Stromatoporoid-Spongiostromate-*Renalcis* Framestones. Even higher nutrient levels are thought to have existed along the Meekwap Shelf. Lithofacies of the Meekwap Shelf, developed during mesotrophic basinal conditions, are devoid of coral frameworks but contain poorly developed stromatoporoids and abundant calcimicrobes. Spongiostromate-Stromatoporoid-*Renalcis* Framestones and *Renalcis* Bindstones of the Meekwap Shelf reflect the nutrient enrichment of the northern and eastern margins of the basin.

Spatial variability in nutrient levels is also thought to have existed throughout later phases of deposition (development of the Meekwap Shelf) in the basin. Spatial variability of nutrient levels in modern lagoons and estuaries is the result of a complex interaction between hydrodynamic, chemical, and biological processes (Lillebo et al., 2005; Gikas et al., 2009). Although it is likely impossible to reconstruct the exact spatial variability of nutrients after discharge into the basin, it is reasonable to assume that concentrations would not be uniform across the system, with variability only reflected in reef lithofacies. Nutrient levels were likely more mesotrophic on the northern rim of the basin, playing a significant role on the composition of Meekwap Shelf reefs. This is reflected by the increasing abundance of calcimicrobes (in Stromatoporoid-Spongiostromate-*Renalcis* Framestone and *Renalcis* Bindstone lithofacies) northward towards the Meekwap field and the absence of Zeta Lake-type reefs north of Township 57. Terrestrial runoff as a primary source of nutrients is consistent with a spatial variability in lithofacies as runoff was likely more prominent in the northern end of the basin. The occurrence of the marine sandstone is consistent with this hypothesis, although the exact location of discharge is unknown and likely east of the Nisku subcrop (Figure 1.8). Evidence of fluvial discharge is present along the southern rim of the basin (W. Martindale, *pers. comm.*, 2011), though it may have been insignificant in comparison to the influx from the north or deflected westward due to the Coriolis force. Calcimicrobial reefs, principally Stromatoporoid-Spongiostromate-*Renalcis* Framestone and *Renalcis* Bindstone lithofacies in this study, prominent in the Meekwap field and along the northeastern basin rim, continued accreting until the end of the Frasnian...
FIGURE 3.8: Schematic illustration of Cynthia Basin evolution. A. During the Mid-Frasnian, high sea-level restricted carbonate deposition to the Zeta Lake reef trend, where suitable substrates and shallower environments existed. B. During the Late Frasnian, sea-level began to fall bringing terrestrial runoff closer to the basin. Carbonate development commenced along the Meekwap Shelf in shallow-water, nutrified environments. C. By the end Frasnian, terrestrial runoff had resulted in the nutrification of the Cynthia Basin, resulting in increasing calcimicrobial abundance along the Meekwap Shelf, as well as shallow marine sandstone deposits north of the basin. After MacNeil and Jones (2008), Switzer et al. (1994) & Whalen et al. (2002).
in a low accommodation setting (cf. Watts, 1987), never building reefs as vertically extensive as the Zeta Lake pinnacles. The absence of karstification suggests that these reefs were never subaerially exposed. Zeta Lake reefs continued accreting until the end of Frasnian as well, incorporating calcimicrobial constituents into their reef framework (Figure 3.3). The end of the Frasnian marks one of the most severe Paleozoic extinction events, eliminating most stromatoporoids, and tabulate corals (Stearn, 1987; Copper 2002a; Morrow et al., 2011) and terminating reef growth in the Cynthia Basin.

The Calmar Formation, which overlies both the Zeta Lake and Meekwap Shelf reefs, consists of fossiliferous green siltstones and shales deposited during a time of maximum sea-level lowstand when clastic influx was extremely high, prohibiting reef growth (Switzer et al., 1994; W. Martindale, pers. comm., 2011).
CHAPTER 4:  DYNAMICS OF DEVONIAN REEFS

Although the Devonian is often recognized as the acme of reef-building during the Paleozoic (Copper, 2002b), there has been some criticism as to the lack of “good data” pertaining to these systems (Wood, 1993; Kiessling et al., 1999). Reef-building in the Devonian was facilitated by the prominence of stromatoporoids, corals and calcimicrobes. The Devonian is also characterized by three peaks in extinction intensity, spanning approximately 30 Ma (Morrow et al., 2011). These are referred to as the Taghanic, Kellwasser, and Hangenberg events, occurring between 392 and 359 Ma (Morrow et al., 2011). Regardless of the causes, these biotic crises severely reduced the abundance of metazoan constructed reefs from the early Givetian into the Tournaisian. It appears remaining stromatoporoids continued constructing reefs in the Famennian despite being decimated at the end of the Frasnian (Stearn, 1987), albeit on a much reduced scale compared to those in the Givetian and Frasnian (Stearn et al., 1987; Morrow et al., 2011) and calcimicrobial reefs rose to dominate the Famennian (Playford, 1980; Copper, 2002a). However, calcimicrobes are documented as a primary constituent in many Frasnian reef systems in Western Canada, Australia, Belgium, Russia, and China (Wood, 1998; Whalen et al., 2000; Copper, 2002a; da Silva and Bouvlain, 2004; MacNeil and Jones, 2008; Shen et al., 2008; Shen et al., 2010). While there may be a global trend in the increase of calcimicrobes towards the end of the Devonian (Wood, 1999; Copper, 2002a; Shen et al., 2010), Devonian reefs were complex systems that responded to local environmental variations (cf. MacNeil, 2011).

DEVONIAN FACIES MODELS

It is common in studies of Devonian systems to include pre-Famennian facies models which describe stromatoporoid-microbe reef lithofacies as a global trend (e.g. Heckel, 1974; Machel and Hunter, 1994; Wood, 1999). Shen et al. (2010) suggested that “calcimicrobes came to dominate shallow reef environments well before the end of the Frasnian globally as stromatoporoid diversity declined”. Devonian carbonates were
deposited in an ocean supersaturated with respect to calcite (Copper, 2002a), promoting the calcification of microbial constituents (Riding, 2000), so the extensive calcification of microbial constituents in Devonian reefs should not be a surprise. Stromatoporoid diversity severely declined towards the end of the Devonian following a series of biotic crises (Morrow et al., 2011). However, microbial constituents are not described in every late Devonian succession and thus should not be considered a norm for the period. Several Frasnian successions have been documented with an absence of calcimicrobes; various studies of Frasnian Western Canadian Sedimentary Basin strata in particular (e.g. Fischbuch, 1968; Dolphin and Klovan, 1970; Noble, 1970; Fejer and Narbonne, 1992; MacNeil, 2011) have not identified *Renalcis* or any related forms as present in Late Devonian reef lithofacies. It appears that calcimicrobes of Devonian reefs are more dependent on local environmental factors than an overarching global trend in reef growth. Recent studies (Whalen et al., 2002; MacNeil and Jones, 2008) have shown that stromatoporoid-coral- and calcimicrobe-dominated lithofacies in Frasnian reefs could change very quickly with their occurrence being dependent on environmental factors. Community variation in ancient reefs can be attributed to variations in nutrient levels as evident from modern environments (Birkeland, 1987; Mutti and Hallock, 2003). Reefs of the well-studied Canning Basin containing an abundance of calcimicrobes bias lithofacies models for the time as Canning Basin reefs were almost certainly nutrified (Wood, 2000). WCSB reefs containing an abundance of calcimicrobes (e.g. Chow et al., 1995; MacNeil and Jones, 2008; Wierzbicki et al., 2008; Wendte, 2009) likely also reflect nutrified environments. Devonian lithofacies models should not, therefore, include calcimicrobes as a universal reef-builder as they likely did not develop in every reef environment. The application of nutrient-gradiente to Devonian facies models in order to recognize and interpret variations in reef lithofacies is a critical step for further understanding these systems (cf. MacNeil and Jones, 2008).

**IMPLICATIONS FOR DEVONIAN SUCCESSIONS**

Applying nutrient controls to ancient successions has likely been understated for a number of reasons. There is likely a bias for preservation of oligotrophic environments in
the fossil record due to the diversification of corals (Hallock, 1987) and stromatoporoids (Kershaw, 1998) along with the non-calcification and low preservation potential of mesotrophic thriving organisms (Hallock, 1987). The increasing proportion of calcimicrobes incorporated into reef environments towards the end of the Devonian may be a reflection of changing environmental conditions worldwide.

Algeo et al. (1995) presented the hypothesis that the Mid to Late Devonian biotic crisis, and related marine events, were initiated by the evolutionary development of vascular land plants. Although some land plants have been identified in successions as early as the Ordovician, rapid development in the Devonian triggered long-term changes in subaerial weathering processes, modes of landscape stabilization, and in river sediment processes and nutrient fluxes (Algeo and Scheckler, 2003). Understanding the connection between terrestrial evolution and marine processes in the Devonian is not well understood (Algeo and Scheckler, 2003). A critical link between these two environments is likely the flux of solutes (specifically biolimiting nutrients) from soils, which would have increased due to enhanced pedogenesis through mineral leaching and fixation of nitrogen by symbiotic root microbes. Riverine nutrient fluxes would have increased and promoted the nutrification of semi-restricted epicontinental seas, stimulating algal blooms and depleting bottom-water oxygen (Algeo and Scheckler, 2003). Increasing calcimicrobial abundance in reefs worldwide (Caplan et al, 1996; Shen et al., 2010) supports the arguments of Algeo et al. (1995), Algeo and Scheckler (2003) and Slinwinski et al. (2011) that nutrified environments increased in abundance worldwide due to the evolution of terrestrial processes.

Anoxia is a popular hypothesis for the late Devonian mass extinction (Joachimski and Buggisch, 1993) and would have been amplified if nutrification due to land plant evolution was a global trend. Phytoplankton blooms in nutrified environments absorb and utilize light as well as oxygen, promoting disoxic and anoxic conditions (Hallock, 1987). Increasing nutrient levels may have promoted the decline in coral and stromatoporoid diversity from the Middle Devonian onward as observed in WCSB reefs (Bingham-Koslowski, 2010). Nutrification of marginal-marine and marine environments may have promoted such anoxia and contributed to the Frasnian-Famennian (Kellwasser) extinction event.

Despite a global trend of increasing abundance of nutrified environments, Devonian
carbonate systems were complex entities and responded to varying environmental conditions at much shorter time-frames than the Kellwasser extinction (3-5 Myr; Joachimski and Buggisch, 1993). As demonstrated by Kiessling (1999), Whalen et al. (2002), MacNeil and Jones (2008) and this study, carbonate systems of the Devonian were able to adapt to changing nutrient levels without being susceptible to drowning (sensu James and Wood, 2011). Whalen et al. (2002) attributed elevated nutrient conditions to regressive intervals during highstand for the Miette and Ancient Wall deposits, which is an incorrect assumption for every succession as conditions are more dependent on local factors and not relative sea-level. MacNeil and Jones (2008) found that lithofacies of the falling-stage and lowstand systems tracts contained a greater abundance of calcimicrobes and reflected mesotrophic conditions. Cynthia Basin reefs reflect increasing nutrient levels during highstand and falling stage, promoted by nutrification via terrestrial runoff. Kiessling et al. (1999) suggested Canning Basin reef systems developed in mesotrophic conditions promoted by their close proximity to a region susceptible to upwelling. Using these examples, it is evident that nutrient levels are somewhat independent of systems tracts and dependent on the mechanism of nutrification present locally, or throughout the basin. Lithofacies variations can occur due to changes from oligotrophic to mesotrophic conditions as demonstrated by this study, Whalen et al. (2002) and MacNeil and Jones (2008) as well as from mesotrophic to oligotrophic conditions as shown by MacNeil and Jones (2008). A broad implication of this concept suggests that Devonian systems were not as susceptible to drowning as previously thought due to variations in nutrient levels, except for in the extreme case (MacNeil and Jones, 2008), but adapted because oligotrophic lithofacies could be replaced by mesotrophic assemblages and vice versa. Additionally, reef lithofacies can be used to determine the nutrient levels present throughout the deposition of Devonian systems. Finally and most importantly, the increasing abundance of calcimicrobial Devonian reef lithofacies can be, at least partially, attributed to the evolution of riverine nutrient fluxes promoting the nutrification of semi-restricted epicontinental seas, strongly influencing the style and development of carbonate systems.
CHAPTER 5: CONCLUSIONS

1. Late Devonian (Frasnian) Cynthia Basin reefs were constructed primarily by calcimicrobes, stromatoporoids and corals. Three of the twelve lithofacies documented in this study are interpreted to have been deposited in a reef paleoenvironment. The remaining lithofacies comprise foreslope, peritidal, lagoonal and open marine shelf paleoenvironments.

2. Calcimicrobial-rich lithofacies of the Meekwap Shelf extend to at least Township 57 following the Cynthia Basin shelf break southeastward from the Meekwap field towards the West Pembina area. A similar paleoenvironment to Meekwap, comprising a calm marine shelf with numerous patch reefs, is inferred to have developed around the entire northeastern rim of the basin.

3. Reef development in the Cynthia Basin indicates a transition from oligotrophic to mesotrophic conditions reflected by the switch from coral-stromatoporoid-dominated lithofacies to calcimicrobe-dominated lithofacies.

4. Terrestrial runoff during late highstand and falling stage is interpreted to have been the principle mechanism for nutrification and the transition from oligotrophic to mesotrophic conditions in the basin. Relative sea-level fall during deposition brought fluvial drainage systems closer to the Cynthia Basin, increasing terrestrial runoff and nutrient levels. Seasonally forced deepening of the mixed layer and groundwater seepage as a result of sea-level fall may have enhanced nutrification in the basin.

5. A spatial variation in the volumetric abundance of calcimicrobes exists along the Meekwap Shelf. The abundance of calcimicrobes increases northward and westward toward the Meekwap field from the West Pembina trend. This spatial variation reflects increasing nutrient levels closer to terrestrial sources of nutrients.
6. Cynthia Basin reef evolution indicates that Devonian carbonate systems were complex entities that were able to rapidly respond to changes in nutrient levels at high-frequencies. Local variations in nutrient levels likely had a larger effect on these systems than has been previously documented.

7. Reef lithofacies of the Cynthia Basin further promote the concept that calcimicrobial fabrics should not be included in a universal facies model for Devonian reefs and that the occurrence of calcimicrobes is at least partially dependent on local or basinal nutrient levels.

8. This study supports the concept that a shift in reef communities to incorporate calcimicrobial fabrics throughout the Devonian may have been enhanced by the evolution of land plants. An increasing flux of solutes from soils likely contributed to the nutrification of many semi-restricted epicontinental seas.
REFERENCES


89


APPENDICES

APPENDIX A – CORE DESCRIPTIONS

The following appendix compiles core descriptions in digital log form for core intervals examined in this study. Digital logs were created in Adobe Photoshop CS2 based on a template originally created by Dr. William Martindale. Digital logs present basic well information including the well name and location as well as the date logged. Core descriptions contain information on the lithology, biological components, depositional textures, sedimentary structures, grain size, colour and diagenetic fabrics. Additionally, the location of core photographs is noted along with general comments on the succession are presented. Core descriptions correspond to the Core Logging Symbol Key. Digital logs are organized from the southernmost to northernmost well locations.
CORE LOGGING SYMBOL KEY

**Fossils - Flora**
- Microbial Lamination

**Fossils - Fauna**
- Non-specific Fossil
- Brachiopod Articulated
- Brachiopod Disarticulated
- Gastropod
- Ostracod
- Bivalve
- Sponge Spicule
- Crinoid
- Non-specific Branched Fossil
- Amphipora
- Stachyodes
- Idiostroma
- Bulbous Stromatoporoid
- Hemispherical Stromatoporoid
- Thin Tabular Stromatoporoid
- Thick Tabular Stromatoporoid
- Wafer Strom
- Thamnopora
- Solitary Rugosa Coral
- Dendroid Coral
- Renalcis
- Spongiosome

**Grain Types**
- Oncloid
- Peloid
- Lithoclasts
- Intraclasts

**Sedimentary Structures**
- Nodular Bedding
- Bioturbation
- Geopetal
- Fenestral Fabric
- Hardground
- Sediment Filled Cavity
- Horizontal Cavity
- Inclined Cavity
- Laminated Sediment

**Diagenetic Fabrics**
- Stylolite
- Vertical Fracture
- Horizontal Fracture
- Fracture Network
- Radial Fibrous Cement
- Isopachous Cement
- Pyritization
Well Name: LP2 Majeau  
Location: 4-21-57-3 W5

Formation: Nisku  
Core Interval(s): 1572.5 - 1580.5m

Logged By: Dylan Johns  
Date: May 3/4, 2011

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<th>Gamma Ray</th>
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Formation Nisku is characterized by: 
- Sedimentary and structural features
- Biogenic components
- Diagenetic features
- Textural class

Comments: 
- Sedimentary and structural features include the presence of biogenic components, with some fossils. Large branches and vasculars, thrombopores, skeletons, and larger features noted. 
- Diagenetic features indicate significant changes in the rock's properties.
- Textural class suggests a specific type of sedimentary rock.
- Colour notes indicate variations in rock appearance.
- Photos 31, 32, and 33 provide visual evidence of the described features.
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<th>Unit</th>
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<th>Biogenic Components</th>
<th>Diagnostic Features</th>
<th>Textural Class</th>
<th>Colour</th>
<th>Notes</th>
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<td>Low</td>
<td>Marine current set with some current ripples.</td>
<td>Ammonites</td>
<td>Heavy bioturbation with a wackestone matrix. Muddy matrix and some small brachiopods.</td>
<td>Wackestone</td>
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<td>Wackestone</td>
<td>Brown</td>
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Notes:
- Heavy bioturbation with a wackestone matrix. Muddy matrix and some small brachiopods.
- Heavy bioturbation with a wackestone matrix. Muddy matrix and some small brachiopods.
- Heavy bioturbation with a wackestone matrix. Muddy matrix and some small brachiopods.
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- Heavy bioturbation with a wackestone matrix. Muddy matrix and some small brachiopods.
**Formation: Nisku**

**Core Interval(s): 1407.5 - 1434.5m**

**Logged By: Dylan Johns**

**Date: May 6, 2011**

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<th>Sedimentary &amp; Structural Features</th>
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<th>Diagenetic Features</th>
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</table>

- **98**

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**NISKU**

- **March megafauna dominantly with fragments being the dominant grains type as opposed to trona in the previous unit. Matrix appears to be bioclastic. Silt-sized grains decrease through the unit.**
- **Elm microfossil overgrowths can be seen surrounding foraminifera.**
- **Lack of muds in this unit as seen in previous unit. Some mudstone bedding throughout unit, along with a bit of porosity. Some laminar bedding noted down.**
- **Some rare matrix ooze grains can be seen at the bottom of the unit.**

- **Dark brown fluorite matrix lacking the grain distribution of the previous unit. Some fossils are preserved in the matrix.**
- **Some lagosa fossils are present at the top of the unit.**
- **Despite the frequency decrease of the same section.**
- **Some lagosa fossils appear a little bit below top 2-3m in section.**
- **Microwave siltstone is seen surrounding many grains giving an encrustation texture.**
- **Some matrix grains contain more grains than the other sections.**
- **Chalcedony fluorite with a smoothness/waxiness mantel.**
- **Continuation of rare amorphous fluorite. Laminites crosscutting seems to increase a bit at bottom of section.**
- **Tight matrix, hard to see most grains more quite metastable.**
- **Some really nice big eoliths seen through allochthonous sections.**
<table>
<thead>
<tr>
<th>Formation</th>
<th>Unit #</th>
<th>Depth (m)</th>
<th>Lithology</th>
<th>Gamma Ray</th>
<th>Sedimentary Structural Features</th>
<th>Biogenic Components</th>
<th>Diagenetic Features</th>
<th>X-ray &amp; Green Size of Matrix</th>
<th>Textural Class</th>
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</table>

**Comments:**
- Very muddy, feel gritty, green wash, in situ and fining up shale, firm and nodular indicating bitumen. Yields include small beads or Sibbit Boswell, conchoïds, gastropods, and bitumen. Grains abundant, is quite low. Grains seem to be cemented in areas where colour appears lighter. Some pyritisation present in very fine grains of the matrix and as a replacement matrix.
<table>
<thead>
<tr>
<th>Unit #</th>
<th>Depth (m)</th>
<th>Lithology</th>
<th>Gamma Ray</th>
<th>Sedimentary &amp; Structural Features</th>
<th>Biotogenic Components</th>
<th>Diagenetic Features</th>
<th>X-ray or Grain Size of Matrix</th>
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**UNIT LOST**

**NISKU**

- Unit starts with crinoids and a variety of sizes of belemnite: 1-2 mm. A variety of sizes of belemnite and crinoids is found in the Nisku Formation. Belemnites are common and occur in various sizes and shapes, often with the belemnites still attached to their original position.
- Belemnites and other shell debris are common throughout the Nisku Formation, indicating a marine depositional environment.
- Belemnites are also common in the Nisku Formation, often found in association with other marine fossils such as crinoids and bivalves.
- The belemnites are typically well-preserved, with some showing evidence of internal structures.
- Shell debris is common in the Nisku Formation, often found in association with other marine fossils such as crinoids and bivalves.
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Articulate belemnite with thin marine cement on interior.

Very dark brown argillaceous limestone-wackestone (mostly a shalestone). Primary fabrics are weak with minor carbonates and organic remains. Oncolitic fabrics can be seen with crinoid stems. Articulate and Belemnite belemnites can be seen throughout unit. Some nodule arrays still present. Micromineral grains can also be seen. Grains occur throughout section and are not concentrated in intervals. Oncolites increase in abundance as you move down section.
<table>
<thead>
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<th>Sedimentary &amp; Structural Features</th>
<th>Biogenic Components</th>
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- Formations: Nisku
- Core Interval(s): 1449.3 - 1463m
- Logged By: Dylan Johns
- Date: May 17, 2011
- Location: 6-34-60-3 W5
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**Comments**:  
16. Transition into a more horsted unit with increased indices. Silt layers are more distinct. 
18. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
19. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
20. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
21. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
22. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
23. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
24. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
25. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
26. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
27. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
28. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
29. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms. 
30. A muddy unit with variable fine grains at top and matrix below. Some art and diatoms.
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<th>Textural Class</th>
<th>Kal or Green Size of Matrix</th>
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<td></td>
<td></td>
<td>Fine grained fluvial with relatively few grains throughout. Smooth and elongated lenticular features weakly defined. Some small sandstone lenses present. Phytoliths seem to be the dominant grain type. Roots and root casts are also present.</td>
</tr>
<tr>
<td>2</td>
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<td>0-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Coarse-grained fluvial with low grain density. Some thin lenses of sandstone and wackestone. A thick interval with strongly identifiable grains except for a few minor that have been dissolved away. Very light colour with some red (in place) staining.</td>
</tr>
<tr>
<td>3</td>
<td>4428</td>
<td>0-10</td>
<td>0-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Looks like a dehydrated fluvial with low grain density. Some thin lenses of sandstone and wackestone. A thick interval with strongly identifiable grains except for a few minor that have been dissolved away. Very light colour with some red (in place) staining.</td>
</tr>
<tr>
<td>4</td>
<td>4429</td>
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<td>0-10</td>
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<td></td>
<td></td>
<td></td>
<td>A rare typical red clay consisting of a variety of grain types (sandstone and siltstone) and thin sandstone lenses. Some thin cracks visible in some intervals. Light grey colour with some red (in place) staining.</td>
</tr>
<tr>
<td>5</td>
<td>4530</td>
<td>0-10</td>
<td>0-10</td>
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<td></td>
<td>Back to a fluvial unit with many layers being the dominant grain type. Lenticular features can also be seen and are bigger than wackestone lenses that also shows the red color. Some wackestone lenses are still present. Phytoliths are seen surrounded by many grains and have a light orange colour.</td>
</tr>
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<td>Brown/pink fluvial with some thin sandstone lenses. Some nodules and tufa, root casts, and other debris.</td>
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<td>Dark brown fluvial unit with a bed of lower argillaceous fabric. Thick microbial coatings around many lenses. Variety of inclusions along with the other grains, such as bones become increasingly abundant, having dominant in the unit.</td>
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<td>Unit #</td>
<td>Depth (m)</td>
<td>Lithology</td>
<td>Gamma Ray</td>
<td>Sedimentary &amp; Structural Features</td>
<td>Biogenic Components</td>
<td>Diagnostic Features</td>
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<td>Unique gruvels, likely gastropods. Pale art forms coated with microbes forming exudative fabrics.</td>
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<td>Very micrally dominant foraminifera with sections of varying grains being more abundant. Quiescent holes with intervals of many argillaceous features that look like the typical skeletal features. Grains are usually very small in these sediments.</td>
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<td>1436.5</td>
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<td>19</td>
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<td>,Objective foraminifera with minor angular-shaped exudates.</td>
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<td>A stromatolite carbonate with some spongo-osteocytes and tabular stromatolitic features. Sections with some spongo-osteocytes devoid of stromatolitic features. Ammonium deposits of calcium filled with both marine and bacterial secretions. 3D fabrics filled with bacterial secretions. Some spongo-osteocytes (fabric appear intact and would suggest why there are more massive carbonates held being filled with cement. No remains seem to be present in this unit.</td>
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<td>Diageneric Features</td>
<td>Calcite &amp; Dolomite Size of Matrix</td>
<td>Textural Class</td>
<td>Colour</td>
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| 2     | 1384      |           |           |                                  |                    |                     |                           |                |        |       | Astromephalic bioclastic unit with large irregular shaped stones and massive calcite. Minor matrix stain in the previous and some fine-grained matrix fragments. Minor to moderate development throughout this section. No fine sandstone and very poor.
| 3     | 1385      |           |           |                                  |                    |                     |                           |                |        |       | Black calcite breccia unit with small, flowing, absolutely dominant the interpal elements of the rock. Fully thick and varied with sediments filling some above black, dark deposits and below breccias. Much of the sediment in this section is filled with granular fragments. Water staining and large angular breccias are surrounded by mineral replacements. Lack of angular breccia debris that is seen in other similar facies. Often unapparent shore the wavy, irregular growth form. |
| 4     | 1386      |           |           |                                  |                    |                     |                           |                |        |       | Articulates and disarticulates blocks in the unit have been washed away. |
| 5     | 1387      |           |           |                                  |                    |                     |                           |                |        |       |          |
| 6     | 1388      |           |           |                                  |                    |                     |                           |                |        |       |          |
| 7     | 1389      |           |           |                                  |                    |                     |                           |                |        |       |          |
| 8     | 1390      |           |           |                                  |                    |                     |                           |                |        |       |          |

**Formation:** Nisku  
**Core Interval:** 1383 - 1395.6 m  
**Logged By:** Dylan Johns  
**Date:** May 19, 2011  
**Location:** 11-19-63-4 W5
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### Well Name: Quasar Dorchester  
Location: 7-25-63-5 W5

Formation: Nisku  
Core Interval(s): 1384 - 1408.1m

Logged By: Dylan Johns  
Date: May 24, 2011

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**Notes:**
- Some minor annular textures present along with what looks to be horizontal burrows.

**Remarks:**
- Highly bioturbated mudstone with many bioturbated burrows. Large amount of grainstone observable. Colour ranges from bluish grey to tan and varies throughout. Much of the matrix is poorly preserved. Some internal microfacies can be seen and are thought to show the haarron structure. The mud seems to have a large amount of matrix and it shows no to no strong preferred orientation, making it a non-stratified feature area showing calcite spar nodules.
**Well Name:** CNRL e-1 Archie  
**Location:** 14-29-65.7 W5

**Formation:** Nisku  
**Core Interval(s):** 1722 - 1739.5m

**Logged By:** Dylan Johns  
**Date:** May 24-25, 2011

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<th>Sedimentary &amp; Structural Features</th>
<th>Biogenic Components</th>
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- **Textual:**  
  - First unit shows a moderately well sorted/fine-grained sandstone. Fades bog with large sections of internal sediment. Some minor-grade porosity within units may indicate small fluctuation in sea level. Some mesoporous presence but not enough to effect with acid. Typical rounded siltstones are seen and internal sediment fill between internal sedimentary units of similar age. Suspended sediment can sometimes be seen in cavity fills, as well as top filling contact. Quasi-bioturbated and non-bioturbated event can be seen in places.

- **Visual:**
  - **Unit 1 (1722-1723):**  
    - Lithology: Sandstone  
    - Sedimentary & Structural Features: Fades bog  
    - Biogenic Components:  
    - Diagnostic Features:  
    - Textural Class:  
  
  - **Unit 2 (1724-1725):**  
    - Lithology: Sandstone  
    - Sedimentary & Structural Features:  
    - Biogenic Components:  
    - Diagnostic Features:  
    - Textural Class:  
  
  - **Unit 3 (1726-1727):**  
    - Lithology: Sandstone  
    - Sedimentary & Structural Features:  
    - Biogenic Components:  
    - Diagnostic Features:  
    - Textural Class:  
  
  - **Unit 4 (1728-1729):**  
    - Lithology: Sandstone  
    - Sedimentary & Structural Features:  
    - Biogenic Components:  
    - Diagnostic Features:  
    - Textural Class:  

- **Unit 5 (1730-1731):**  
  - Lithology: Sandstone  
  - Sedimentary & Structural Features:  
  - Biogenic Components:  
  - Diagnostic Features:  
  - Textural Class:  

  - **Scenario:**  
    - Large sediment fill cavity with no debris path, small grains and some minor matrix material either side.  
    - Hinge contact into manganic boundstone.  
    - Minor biofabric, few other fabrics and large sediment fills.  

- **Unit 6 (1732-1733):**  
  - Lithology: Sandstone  
  - Sedimentary & Structural Features:  
  - Biogenic Components:  
  - Diagnostic Features:  
  - Textural Class:  

  - **Scenario:**  
    - Massive +5mm ooids.

- **Unit 7 (1734-1735):**  
  - Lithology: Sandstone  
  - Sedimentary & Structural Features:  
  - Biogenic Components:  
  - Diagnostic Features:  
  - Textural Class:  

  - **Scenario:**  
    - Highly bioturbated limestone and sediment filled cavity.

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<th>Depth (m)</th>
<th>Lithology</th>
<th>Gamma Ray</th>
<th>Sedimentary &amp; Structural Features</th>
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<td>Lost dark brown colour into a grayish with much less voids. More of a flintstone type unit with less structure and fewer remnants. There are massive burial cements.</td>
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<td>Much more sediment dominated, some sporadic small fossils, fewer remnants.</td>
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<td>Appearing argillaceous 4cm interval.</td>
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<td>Mostly size geometrical cavities.</td>
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<td>Thick burial cement in cm scale under remnants. Lots of internal sediment, fossiliferous fossils. Fewer remnants than above generally.</td>
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<td>Thick remnants flintstone internal with fewer stems and lots of thick burial cement.</td>
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<td>Strange cavity filled withnames \outside remnants.</td>
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<td>Sediment dominated section, some remnants intervals but they are thin.</td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Formation: Nisku**

**Core Interval(s): 1797.8 - 1808.2m**

**Logged By: Dylan John**

**Date: May 25, 2011**

**Notes:**
- Did not log Calmar section. Appears banded with fine grained silt and intercalated silt layers.
- Quite a grumpy, tan to gray unit with some amorphous but mostly fine-grained calcite. Debris grains seem to be the remnants of a fluvial setting.
- Some amorphous debris grains are visible. Does not look like much mud or bentonite is involved.
- A large amount of foraminifera/ciliates that are easily identifiable. Some irregularly shaped foraminifera are also seen. Test sections are seen in the upper left.
- Some aragonite test sections are seen.
- Overall contact into basement unit.

**Nisku:**

- Dark brown to grey matrix unit with many argillaceous intervals.
- Large raas-like intervals.
- Nodular and sandy intervals.
- Section of very small grains leaning towards mudstones.
- Poorly sorted.
Formation: Nisku
Core Interval(s): 1797.8 - 1808.2m
Logged By: Dylan Johns
Date: May 25, 2011

Comments:


14. Going towards a wackestone again.

15. Very few grains, quite nodular. Grains are thin-scaled.

16. Section shows the same branching, monosaccate pattern seen above.
APPENDIX B – SUPPLEMENTARY CORE DESCRIPTIONS

The following appendix compiles cores description in digital log form for core intervals observed in this study. The logs were created by Dr. William Martindale following core logging in May, 2005.
### Basal Contacts

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Interval 1</th>
<th>Interval 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>100</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>200</td>
<td>300</td>
<td>400</td>
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### Gamma Log

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<th>Gamma Value</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>200</td>
<td>300</td>
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</table>

### Neutron Density

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<tr>
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<td>0.1</td>
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<tr>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>200</td>
<td>0.3</td>
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</tbody>
</table>

### Lithol.

<table>
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<tr>
<th>Depth (ft)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Sandstone</td>
</tr>
<tr>
<td>100</td>
<td>Mudstone</td>
</tr>
<tr>
<td>200</td>
<td>conglomerate</td>
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</table>

### Core Pores

<table>
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<tr>
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<tbody>
<tr>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>200</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Core Perm.

<table>
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<th>Core Perm.</th>
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<tbody>
<tr>
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<td>0.1</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>200</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Core Areal

<table>
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<tr>
<th>Depth (ft)</th>
<th>Core Areal</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>200</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Fossil Types

- **Fossil 1**: Present in Interval 1, absent in Interval 2.
- **Fossil 2**: Present in Interval 2, absent in Interval 1.

### Comments

- Interval 1 is characterized by fine-grained sandstones with occasional siltstone horizons.
- Interval 2 contains thicker sandstone layers with interbedded shale intervals.

### Interp.

- Interval 1 is interpreted as a lower shoreface deposit.
- Interval 2 is interpreted as an upper shoreface deposit.

### Project Details

- **Project Name**: Encana, Mokwup Project
- **Date**: 5/4/05

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**Author**: Martindale

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**Textual Content**

1. Interval 1 is characterized by fine-grained sandstones with occasional siltstone horizons.
2. Interval 2 contains thicker sandstone layers with interbedded shale intervals.
3. Interval 1 is interpreted as a lower shoreface deposit.
4. Interval 2 is interpreted as an upper shoreface deposit.

---

**Further Details**

- The sandstone beds in Interval 1 are fine-grained and contain varying amounts of silt and clay, indicating a mixed-energy environment.
- Interval 2 shows a transition to more mud-rich deposits, suggesting a shallowing-upward sequence.

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**Key Points**

- The transition from Interval 1 to Interval 2 suggests a significant change in depositional setting from a deeper to a shallower environment.
- The presence of siltstone and shale layers in Interval 1 and 2 indicates a complex sedimentary history.

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**References**

- Additional references for detailed stratigraphic analysis and sedimentology.

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**Figures**

- Figures showing seismic reflections and core descriptions.

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**Tables**

- Tables summarizing lithological data, gamma log values, and core porosity measurements.

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**Additional Notes**

- Further notes on the sedimentology and facies analysis.