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DEPOSITIONAL FACIES AND SEQUENCE STRATIGRAPHIC MODEL FOR THE SILURIAN REEFS, MICHIGAN BASIN, USA.

by

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A thesis submitted to the Graduate College in partial fulfillment of the requirements for the degree of Master of Science Geosciences
Western Michigan University
April 2019

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I would like to acknowledge those who have effectively contributed to this project accomplishment. First, my advisor Dr. Kaczmarek, for teaching me how to be a critical-eye geologist and for his limitless professional guidance throughout the research process. The committee members, Dr. Harrison for allowing me access to his never-ending geological knowledge in the Michigan Basin, and Dr. Voice for his critical eye and for dragging my attention to details. Personal thanks to my parents, Naseer and Ikram, my sibling and my girlfriend for their enormous help and support during my study. My best friend Mohammed Al-Musawi and his family, and my Iraqi friends for their help and support through challenging times. Special thanks go to Linda Harrison, Jennifer Trout, and John Yellich for making MGRRE a second home in the past three years and a half. Lastly, I would like to thank Battelle Energy and the Department of Geological and Environmental Sciences for providing financial support.

Zaid N. Nadhim
Depositional models for the Silurian reefs in the Michigan Basin suggest that internal facies are either (i) randomly distributed within a symmetrical reef structure, or (ii) highly asymmetrical and strongly controlled by paleo-wind direction. To further test the applicability of these models, internal facies distributions were mapped using high-resolution core and log data in two sets of Silurian reefs. The results suggest that the relationship between reef geometry, facies distribution and proposed paleo-wind direction is more inconsistent than recently proposed. More specifically, facies descriptions from the Silurian reefs suggest the following. First, overall reef geometry and facies distributions are not controlled by single paleo-wind direction, but rather the overall reef geometry supports the interpretation that multiple paleo-wind directions occurred throughout the time of the reef growth. Facies distributions also don’t support a single paleo-wind direction during the time of reef growth. Second, in addition to the local ecological and hydrodynamic controls, internal facies distributions appear to be controlled by relative sea-level fluctuation in the reef shallow carbonate platforms. This interpretation is based on cyclical facies changes that reflect oscillations in depositional energy conditions and exposure, which reflect changes in circulation and sea level change during Silurian reef growth. The results of this study challenge existing models and suggests that a single paleo-wind direction should not be used to predict reef internal facies distribution in the Silurian reefs.
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CHAPTER I
INTRODUCTION

Carbonate depositional facies reflect a combination of physical, chemical, and biological processes during the time of deposition (James et al. 2010). More specifically, facies reflect water conditions (e.g., water chemistry, water depth, hydraulic regime) as well as biological characteristics (e.g., type of organisms) in which the sediments were deposited. Facies can also reflect information about climate (latitudinal impacts, atmospheric and oceanic circulation) geographic configuration and tidal range (James and Wood, 2010).

Autogenic and allogenic processes are reflected in the Silurian reefs rock record in the Michigan Basin (James et al. 2010). Understanding these processes is useful to predict different rock types. The autogenic processes are also useful to predict lateral and vertical facies variability as well as useful to better understand the depositional/growth history of the Niagaran pinnacles/complex reefs. (Gill, 1973; Rine et al 2017).

The reef depositional facies are complexly distributed within the heterogeneous reef system (Gill 1973). Reservoir properties in the Silurian reefs have been documented by previous researchers to have been controlled by the depositional facies as well as the diagenetic overprint (Coniglio et al. 2003; Wold, 2008; Qualman, 2009; Suhami, 2019,) and many others. This suggests that the internal depositional facies of each reef can have distinct reservoir characteristics. Therefore, the ability to predict depositional/petrophysical facies through the understanding of the depositional history is essential to reduce the uncertainty of the reservoir volumetric assessment in the reef reservoirs.
Geologists tend to develop depositional facies models to simplify the geological observations identified from the core, log and in some cases seismic data. These models reflect reef internal facies stacking patterns, reef internal facies architecture, and in some cases can explain paleo-environmental controls. However, creating a facies model based on a single control is challenging because reef growth was governed as much by interactions within the evolving biosphere as well as universal physical and chemical conditions (James and Wood, 2010).

The Silurian reefs in the Michigan Basin are an example of reefs that yield a complicated/heterogeneous depositional/petrophysical facies distributions (Suhaimi 2016). In addition to the variable internal facies architecture and overall geometries, heterogeneous facies distributions can add a challenge to interpret the environmental controls of the reef growth history and therefore result in a lower chance of accurately predicting facies distribution.

The Silurian reef buildups within the Michigan Basin are positioned on a depositional slope (paleotopographic ramp) (Figure 1.1). The reefs are distributed along two curvilinear belts, referred to as the northern and southern reef trends. Since the discovery of the hydrocarbons in the reef reservoirs in the early 1960s (Mantek 1973), a number of studies which are focused on the depositional history, stratigraphy, architecture, and post-depositional evolution of the Silurian reefs were started. The published work by Huh (1973), Mesollela (1973); Gill (1977); Sears and Lucia (1979), Wold and Grammer (2017) and many other researchers refer to the Silurian reefs as symmetrical pinnacle reefs with a random distribution of internal facies.
More recently, the work by Wold (2008), Qualman (2009) and Rine et al. (2017) in the southern reef trend have suggested that the reefs are asymmetrical with predictable facies distributions. Rine et al. (2017), for example, reported less internal reef facies heterogeneity with facies distributions controlled by a dominant paleo-wind direction. The role of wind direction is a long-standing debate. Based on the reef overall geometry, Gill (1973) suggested northwest dominant paleo-wind direction. The study by Shaver (1977) attempted to evaluate this wind direction using extensive core and outcrop data from different reef locations and concluded that the most reported forereef-to-backreef relations do not seem to agree very well with the paleo-wind control. Wold (2008), on the other hand, reported that the reef facies were controlled by a dominant paleo-wind direction. Wold (2008) interpreted the dominant paleo-wind from the south, and stated “the south end of the reef complex is interpreted as the windward reef margin based upon the steep reef fore-reef slope, associated with skeletal depositional facies that have high porosity and permeability.” Wold’s (2008) interpretation is supported by the reef overall geometry,
which exhibits a steep slope on the southern side of the reef and gentle slope on the northern side of the reef. The interpretation Wold (2008) is based on a facies distribution that utilizes the sequence stratigraphic method. Most recently, Rine et al. (2017) suggested northeasterly paleo-wind direction. Rine et al. (2017) based their study on reef geometry and facies distribution data that were collected from three different reefs. Rine et.al (2017) concluded that facies type on the east side of the reef is different from the facies that are observed adjacent to the west side of the reef because reef internal facies are strongly controlled by east/northeast-to-west paleo-wind direction.

Despite previous research efforts, there still exists of wide uncertainty and debate concerning the morphology, the overall facies architecture and depositional controls on these Silurian reefs (Figure 1.2). The current study will further test the hypothesis that wind direction is responsible for facies distributions and reef architecture in the Silurian pinnacle reefs in the Michigan Basin. The hypothesis that the sequence stratigraphic approach can constrain and predict the high-resolution lateral and vertical facies distribution of the Niagara reefs in the Michigan Basin will also be tested.
Figure 1.2. Previous reef depositional models which are showing inconsistency in terms of internal facies distribution, reef overall geometry, and wind direction. A) is Belle River Mills reef (BRM) depositional model modified from Gill (1973), the depositional model indicates west/northwest paleo-wind direction. B) is Rine et al. (2017) depositional model of BRM reef, the depositional model indicates east/northeast paleo-wind direction.

Michigan Basin Regional Geology

The Michigan Basin is a nearly circular and symmetrical intracratonic basin with an area of 260,000 km² (100,000 mi²) (Figure 1.3). The basin contains up to 4800 m (16,000 ft) of mostly Cambrian to Pennsylvania age marine sedimentary strata (Barnes et al., 2009). It’s bordered to the west by the Wisconsin arch, to the south by the Kankakee Arch, to the southeast by the Findlay
arch, and to the east by the Algonquin arch axis (Cohee and Landes, 1955). The basin began subsiding during the Late-Precambrian, reaching a maximum rate of subsidence during Late Silurian to Middle Devonian (Friedman and Kopaska-Merkel, 1991; Howell and van der Pluijm, 1999).

Silurian age strata comprise >30% of the total 108,000 mi³ of sedimentary material in the basin (Cohee and Landes 1958). Silurian sedimentation occurred primarily in shallow intracratonic marine condition when the basin was located at 10-20 degrees south latitude (Scotese and McKerrow 1991). Based upon Silurian benthic assemblages, Silurian literature reported that the maximum water depth at the basin center reached 660 feet. The basin is slightly tilted to the north and there was gradual subsidence in the basin center during the Silurian (Howell and van der Pluijm, 1999; Nunn et al., 1984).

Figure 1.3. The generalized depositional environments of the Michigan Basin in the Silurian during Niagaran deposition, composed of a carbonate platform with reef bank, carbonate ramp with pinnacle reefs, and a deep basin center. In Ritter (2008) Modified from Briggs and Briggs (1974).
Silurian age Niagaran pinnacle reefs are located near the basin margin and occur in two major fairways in the Michigan Basin (Grammer et al. 2008), (Figure 1.4). The first is approximately 20 mi wide and extends along the northern and western basin margin for about 170 mi (Gill 1979). The other extends for 110 mi along the southern and eastern margin (Grammer et al. 2008). Silurian pinnacle reefs and reef complexes have a maximum size of two miles length, and two miles width and have an approximately average thickness of 500 ft. The variability in the reef heights in different positions along the southern and eastern margin was attributed to the differential subsidence during Silurian time deposition (Sears and Lucia 1979).

Figure 1.4. This Map of the Lower Peninsula of Michigan shows the distribution of Niagaran pinnacle reefs in the southern and northern fairways. From Grammer et al. (2008)
Niagaran and Lower Salina Stratigraphy

The Niagaran Group in the Michigan Basin, which consists of the Lockport and Guelph Formations, overlies the Clinton Formation in the southern reef trend and overlies the Manistique Group in the northern reef trend. The Lockport Formation (known informally as the “Gray Niagaran”) is the basal unit of the Niagara Group. The Lockport is generally characterized as a dolomitized crinoidal wackestone (Charbonneau, 1990). At the basin margin, the Lockport Formation reaches the greatest thickness of approximately 300 ft (Huh, 1977).

The Guelph Formation (informally known as the Brown Niagaran) is the upper unit of the Niagara Group. The Guelph in and around the Pinnacle reef complexes is composed of three major lithologies: reef core boundstone, skeletal wackestone and crinoidal mudstone facies (Rine et al. 2017). The Guelph Formation is thicker toward the basin margin ranges from 300-600 ft (the “pinnacle” reefs) whereas the thickness in the basin center is < 2 ft (Mesollela 1974). The “Pinnacle” reef growth is divided into three stages. The Niagaran reefs are documented to typically include a lower bioherm stage, a middle organic reef stage and an upper restricted tidal flat stage (Gill, 1973; Huh, 1973; Mantek, 1973; Mesollela, 1974; Sears and Lucia 1979; Cercone 1984, Wold, 2008; Qualman, 2009; Rine, 2015).

The Salina Group (late Silurian), which consists of alternating successions of salt, anhydrite, carbonate, and shale, overlies the Niagara Group (Figure 1.5). The Salina Group includes the Cain Formation (also known as A-0 carbonate), A-1 Evaporite, A-1 Carbonate, A-2 Evaporite, A-2 Carbonate, as well as B, D and F, E salts units, and the G shale. There is a general agreement about the transition from the Salina group to Niagara Group representing a major sea level drawdown with termination of reef growth and transition from open marine to restricted marine

Figure 1.5. Cross section showing the stratigraphic succession during the time of Niagaran and lower Salina Group deposition. The cross section is extending from the shelf edge into the center of the Michigan Basin during Silurian time. In Rine (2015), modified from Burgess and Benson (1969).

After sea level fell below the carbonate bank, basin waters became hypersaline and the sedimentary environment switches to extreme evaporative condition, which resulted in the deposition of approximately 400 feet of the A-1 Evaporite in the central basin. In contrast, the thickness of the A-1 evaporite is only tens of feet on the slope and is absent directly above the reef complexes (Mesollela, 1974).

Following the subaerial exposure, a sea level transgression resulted in the deposition of the A-1 Carbonate. Following the deposition of the A-1 Carbonate is another sea level fall which
resulted in the deposition of the A-2 Evaporite (Mesollela 1974). The A-2 Evaporite is characterized by alternating anhydrite and dolomite near the reefs, and halite in the central basin (Mesollela 1974). The A-2 Evaporite Formation provides a good seal to the underlying A-1 Carbonate and Brown Niagaran reservoir rocks which makes these reservoirs a target for CO2 sequestration and enhanced oil recovery operations (Rine 2015; and Garret 2016).

Reef Depositional Models

Extensive work (mostly descriptive work, based on facies discretions and wireline data) has been done on the Niagaran reef reservoirs starting since the early 1960’s (Gill, 1973; Huh, 1973; Mantek, 1973; Mesollela, 1974; Sears and Lucia 1979; Cercone 1984, Wold, 2008; Qualman, 2009; Rine et al., 2017). Many of these studies aimed to understand the internal facies distribution and architecture of the pinnacle reefs, as well as the reef growth history. The published depositional and conceptual models (discussed in detail in the next section) generally agree on the basic geologic description of the reef complex system, such as the occurrence of the Bioherm, Organic reef, and restricted reef growth stages, but their conclusions concerning internal facies distribution, reef architecture and interpretations regarding geological controls are substantially different:

Gill and Huh Models

Gill (1973) presented an analysis of petrography and sedimentary facies of the Belle River Mills (BRM) reef. BRM is located in the southern reef trend in St. Clair County (Figure 1.6). The analysis was performed using 54 subsurface cores which penetrated the reef complex. Eight 2D
cross sections were constructed to illustrate the vertical and horizontal reef variability. These cross sections included 13 reef depositional facies distributed across the BRM reef buildup.

**Figure 1.6.** Location map for the Belle River Mills reef (BRM) and Columbus III (CIII) reef. The map also shows the Shelf-Basin direction and the direction of the CIII and BRM reefs cross-section which was used in this study. In Wold (2008) modified from Gill (1973 &1977)

Gill (1973) also defined several exposure surfaces within the BRM reef, which were interpreted as the result of sea level fluctuation. Although the horizontal facies variability was unconstrained in his study, Gill’s (1973) Model implies a high level of vertical facies variability across several locations within the reef complex. The study additionally documented the abundance of the BRM conglomerate facies adjacent to the BRM reef in all directions. In terms of the reef overall geometry, Gill (1973) reported an asymmetric reef geometry toward the north and the west side of the reef (steep slope on the west and the north side of BRM reef). In general, Gill (1973) reported the symmetry of the reef in the BRM southern portion and the asymmetry of the reef in the BRM reef northern portion (Figure 1.7).
Huh (1973) model, on the other hand, discussed the reef growth history in the northern reef trend (Kalkaska 21-28 field). Huh (1973) observed similar depositional facies reported in Gill (1973) study. However, Huh (1973) did not attribute the facies distribution to a dominant paleo-wind direction. Huh (1973), instead, reported that the reef system consists of three reef growth stages as a result of the sea level change (Figure 1.8).

**Figure 1.7.** E-W cross-section through the BRM reef from Gill (1973) dissertation. The cross-section shows the general symmetry of the reef in addition to the heterogeneous distribution of the internal facies. In Wold (2008), modified from Gill (1973)

The basal unit is the bioherm stage, which is interpreted as being deposited in quiet water below wave base. This stage represents a depositional environment where ‘'quiet water’’ organisms, such as crinoids, tabular stromatoporoids, and sparse tabular corals, could thrive. Following the bioherm stage is the initiation of the organic reef stage. Over time the bioherm grew upward towards wave base where the delicate organisms of the bioherm could not withstand the higher energy conditions. The organic reef stage was dominated by organisms such as tabulate
corals, stromatoporoids, brachiopods, gastropods, rugose corals, and bryozoans. The supratidal island stage overlies the organic reef stage and is defined by cyanobacterial-peloid wackestone, cyanobacterial boundstone, lagoonal mudstone, flat-pebble conglomerate, and sedimentary structures such as mudcracks.

Within each reef growth stage, Huh et al. (1973) documented high vertical and horizontal facies variability similar to Gill’s (1973) model. Additionally, Huh (1973), characterized the Silurian reefs as tall, symmetrical “pinnacles” containing a random and unpredictable distribution of internal facies.

Sears and Lucia model

Sears and Lucia (1979) presented a model of the reef growth and facies distribution in the northern reef trend. The model challenged the idea that different reef heights in different geographic locations were caused by differential subsidence during the time of the Niagaran and lower Salina deposition. Sears and Lucia (1979) instead concluded that the pinnacle reefs grew on a uniformly subsiding ramp where the basinward reefs initiated as mud mounds and the reefs closer to the shelf initiated as an organic reef.

Therefore, the model by Sears and Lucia (1977) across the shelf edge (Figure 1.1) inferred taller and thicker bioherms for the reefs located in relatively deeper water compared to those located in the shallower water which are characterized by thinner and shorter bioherm mounds.
Sears and Lucia (1979) documented four unique depositional facies associated with the three reef growth stages which were interpreted by Huh (1973) to have been formed in response to sea level change. These facies are generally in agreement with those described by Gill (1973) and Huh (1973).

Figure 1.8. Cross section through the Kalkaska 21-28 reef from Rine et al. (2017), modified from huh (1973). A model shows the three reef growth stages interpreted by Huh (1973) and how it is compared to the BRM reef by Gill (1973) in Figure B.

Wold and Grammer (2017) Model

The main goal of Wold and Grammer (2017) study was to develop a depositional facies model using the sequence stratigraphic approach and then use the resultant depositional facies
distribution to develop a reservoir fluid flow model in Ray Field. This study was the first in the Silurian reef literature that utilized the sequence stratigraphy to enhance the predictability of the reservoir facies distribution. The model interpreted two 4th order, high-frequency depositional cycles within each reef growth stage which are defined by Gill (1973) and Huh (1973). The high-frequency depositional cycles (4th order) are interpreted as a result of the global sea level fluctuations. Wold (2008) argued that the 4th order sequences directly control the reservoir quality distribution and the reef internal facies variability, therefore ignoring the internal variability could result in a high level of reservoir volumetric uncertainty.

This model introduced the effect of the prevailing paleo-wind direction on the overall reef geometry and reservoir quality distribution within the Niagaran reef system. The Ray reef complex has a steeper slope in the southern end, therefore it was interpreted as a forereef side of the reef which yields the best reservoir quality. Forereefs tends to be associated with the best reservoir quality due to the high wind energy that causes the deposition of coarser-grained facies. The northwestern of the reef complex was interpreted as the leeward side of the reef-based upon a more gently sloping reef margin that was associated with a stack of depositional facies which are characterized by a lower porosity and permeability values (Figure 1.9).
The Wold (2008) reservoir model reported an extensive internal facies variability within the Ray reef which is also reflected in the internal variability of fluid flow units. Wold (2008) concluded that there is a positive relationship between depositional facies and reef reservoir characteristics.

![Figure 1.9. N-S cross section from Wold (2008) thesis shows asymmetry of the Ray Reef. The figure additionally shows high vertical and lateral facies variability](image)

**Rine et al. (2017) Model**

The conceptual model by Rine et al. (2017) explains the effect of the prevailing wind direction on the reef overall geometry, internal facies distribution and facies architecture in the Silurian reef system. Rine et al. (2017) introduced six depositional facies within the Niagaran reef, these facies are similar to the facies observed in the previous studies. However, the internal distribution and the internal architecture of the facies are dramatically different.

Rine et al (2017) model show the abundance of the muddier facies on the west side of the reef and the abundance of the grainy facies on the east side of the reef. Rine et al. (2017) also show an asymmetrical geometry of the reef (steep slope on the east side and gentle slope on the west side) (Figure 1.2). Therefore, Rine et al. (2017) interpreted an easterly-northeasterly dominant paleo-wind direction. Rine et al. (2017) and Gill (1973) BRM models are controversial. This
controversy is in terms of the facies distribution, reef overall geometry and the interpreted direction of the prevalent paleo-wind (Figure 1.2).

Research Goals

The fundamental questions this research will attempt to address are:

A) *Can sequence stratigraphic models constrain and predict the high-resolution lateral and vertical facies distribution of the Niagara reefs in the Michigan Basin?*

B) *What is the general geometry of the reef and how are sediments spatially distributed within the reef complex?*

C) *What are the main geological controls on Niagaran pinnacle reef facies distribution?*
CHAPTER II

Methods

Core Description

Columbus III (CIII) and BRM are the fields used in this study. Columbus III (CIII) and Bell River Mills (BRM) are located in St. Clair County, Michigan in the southern reef fairway. CIII and BRM were selected for two reasons: 1) because they have the highest density of core coverage of any Silurian reef complex in the Michigan Basin and 2) CIII and BRM are located in different positions on the depositional slope. BRM is the upslope reef and CIII is the downslope reef (Figure 1.1).

Data from the Columbus III field comes from 20 cores. Data from the Belle River Mills field comes from 31 cores (Figures 2.1 and 2.2). These cores were analyzed and described using a hand-lens and 10X magnification binocular microscope. Attributes that were recorded include lithology, fossil content, sedimentary structures, and exposure surfaces. The Dunham (1962) limestone classification scheme, as modified by Embry and Klovan (1971) was used to classify depositional textures. Correlations between wells were made using wireline logs (gamma ray and neutron porosity from wireline logs and porosity and permeability data from conventional core analysis). Neutron porosity and core analysis porosity were used as estimates for the porosity (phi, in %) of each facies. Conventional Core Analysis (C.A.) provided estimates of the permeability (K, in millidarcy).
Conventional Core Analysis

The use of the core analysis data in this study was limited to the horizontal permeability (in millidarcy) and total percent porosity. Porosity and permeability data for the rock units were done before and available when we worked on the project at MGRRE. Air permeability was achieved using Hasseler Sleeve method and porosity using Helium expansion consistent with the method described by Rine (2015). Depositional facies with their associated core porosity and core permeability values are defined to evaluate permeability and porosity distribution of each depositional facies.
**Figure 2.1.** CIII reef boundary which shows the abundance of the core and logs data.
Figure 2.2. BRM reef boundary which shows the abundance of the core and logs data.
Facies Mapping

An analysis to define lateral facies associations was first performed on CIII reef. After major depositional lithofacies were discriminated, GR log signatures and core analysis data were linked to the observed facies, the GR signatures and C.A data were then used to discriminate facies in wells without a core. Vertical facies association is a term used to define a group of facies that are stacked together in a specific well location. Each vertical facies association was assigned a number. The numbers were then contoured to represent the lateral extent of reef facies associations during a specific time of reef growth (Figure 2.4). The reef facies association was then linked to the observed reef overall geometries. The Vertical facies association and the reef geometry led to interpret reef depositional settings.

The same method was repeated in BRM reef (Figure 2.3). The BRM is interpreted to be located in shallower water depth relative to CIII reef during the time of reef deposition, this based on their relative position on the depositional slope and reef/facies thickness (Figure 1.1). Both deeper (CIII) and shallower (BRM) reefs were used to interpret the Silurian reefs depositional framework.

Eventually, we were able to provide further explanations to Silurian reefs depositional settings during Silurian reefs time of growth, this is based on vertical facies associations of deeper and shallower reefs. and by utilizing sequence stratigraphy.
Figure 2.3. BRM facies distribution map that shows the lateral extent of reef facies in each reef position during a specific time of reef growth. The number within each well represent the reef position, whereas the color code represents the abundant facies within each reef position.
Figure 2.4. CIII facies distribution map that shows the lateral extent of reef facies in each reef position during a specific time of reef growth. The number within each well represent the reef position, whereas the color code represents the abundant facies within each reef position.
CHAPTER III

RESULTS

Facies Descriptions

The goal of chapter III is to objectively document the observations collected in this study. These include the observed depositional facies, their stacking patterns, geometric relationships, and spatial distributions. Eight major facies types are observed in the Belle River Mills (BRM) and Columbus III (CIII) fields. In many cases, the facies names and descriptions are the same as those reported in Rine et al. (2017). Facies names are different in some cases because I have elected to keep facies names purely descriptive, instead of the descriptive-interpretive hybrids reported in Rine et al. (2017). Nomenclature differences will be identified below of each of the eight facies. Facies descriptions are summarized in Table 3.1. Each facies is described in detail in the following sections.

*Coral-stromatoporoid boundstone*

The *coral stromatoporoid boundstone* facies consists mainly of wave-resistant, frame building organisms such as tabulate corals and stromatoporoids. This facies has the largest variety of pore types (e.g., interparticle, separate and big touching vugs), which are associated with an extensive dissolution of the tabulate corals and stromatoporoids. Intense dolomitization of this facies is also common, and as a result, the internal skeletal structure of stromatoporoids is difficult to characterize though faint traces of internal laminations are present (Figures 3-4).
Tabulate corals are preserved as whole skeletons and as fragments and are more easily recognized. Calcite cement and salt plugging are also prevalent throughout the coral stromatoporoid boundstone. Salt plugging commonly occurs in the inter-skeletal pore space and causes a reduction of reservoir quality (Figures 3-1,A-F).
<table>
<thead>
<tr>
<th>Depositional Facies</th>
<th>Lithologic Description</th>
<th>Depositional Environment</th>
<th>Water Depth Interpretations</th>
<th>3rd order reef</th>
<th>Position on Reef Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>stromatolite boundstone</td>
<td>Stromatolitic boundstone: Dark brown with hemispheroidal stromatolites.</td>
<td>Tidal flat</td>
<td>Intertidal</td>
<td>3 Cap</td>
<td>3,4,5</td>
</tr>
<tr>
<td>skeletal mudstone</td>
<td>Mix of skeletal fragments, calcite spar lining separate vuggy pores.</td>
<td>Reef slope</td>
<td>SWB-FWB</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>skeletal wackestone</td>
<td>Dark brown in color, dominated by reef faunal assemblages (bryozoan, brachiopods, crinoids and rugose corals).</td>
<td>Reef interior</td>
<td>SWB-FWB</td>
<td></td>
<td>3,4,5</td>
</tr>
<tr>
<td>coral stromatoporoid boundstone</td>
<td>Light brown in color, dominated by fram-building organisms (tabulate corals, stromatoporoids)</td>
<td>Reef interior</td>
<td>Above FWB</td>
<td></td>
<td>3,4,5</td>
</tr>
<tr>
<td>skeletal grainstone</td>
<td>Light brown in color, rounded to sub rounded, well sorted grains, organisms are hard to define due to high diagenetic alteration but corals can occasionally</td>
<td>Reef interior</td>
<td>FWB-Intertidal</td>
<td></td>
<td>3,4,5</td>
</tr>
<tr>
<td>coral rudstone</td>
<td>Dark gray in color, angular clasts up to two cm, transported fragments of tabulate corals and crinoids organisms are present. Abundance of vuggy secondary porosity.</td>
<td>Reef margin</td>
<td>Above FWB</td>
<td></td>
<td>3,5</td>
</tr>
<tr>
<td>crystalline dolomite</td>
<td>Devoid of fossils, dolomite intercrystallite porosity.</td>
<td>Bioherm cap</td>
<td>Above FWB</td>
<td></td>
<td>1 Bioherm Initiation</td>
</tr>
<tr>
<td>crinoid mudstone</td>
<td>Gray and white in color, mud matrix with abundance of crinoids organisms.</td>
<td>Bioherm</td>
<td>Below SWB</td>
<td></td>
<td>3,4,5</td>
</tr>
</tbody>
</table>

* SWB : Storm wave base (SWB) 18 m; Fairweather wave base (FWB) 9 m.
* Reef position: 1) toe of slope; 2) reef rudstone margin and slope; 3) reef interior.

**Table 3.1:** Summary of Niagara reef depositional facies. Facies names, facies descriptions, facies locations within the reef complex, and the interpreted water depth are shown. Same color codes were used in all figures (cross sections, facies maps etc.).
Figure 3.1. Shows three of the reef internal facies that were observed in this study.

Pictures A, B, C & E: *Coral stromatoporoid* facies: Shows wave resistant organism, big tabulate reef corals.

Pictures D & F: *Coral stromatoporoid* facies: Shows wave resistant organism, big reef stromatoporoids.

Pictures G & H: *Skeletal wackestone* facies: Shows reef rugose corals (Roc), crinoids (Cr), brachiopods (Br),

*Skeletal wackestone*

The *skeletal wackestone* facies is mud supported with an assemblage of organisms that have previously been interpreted to live in low energy conditions including bryozoans, brachiopods, crinoids, and rugose corals (Rine, 2015). Allochems are mostly observed as skeletal fragments
but occasionally as intact fossils. This facies is composed of up to 75% of dolomite matrix and the remainder is composed of skeletal grains (Figure 3-1, G&H).

Skeletal grainstone

The *skeletal grainstone* facies is characterized by relatively low mud content. It is also characterized by light to dark brown color. The skeletal allochems are sub-rounded to rounded, well-sorted, fine to medium sand in size. Fossil fragments are generally not identifiable due to the extensive dissolution of the skeletal grains.

Skeletal mudstone

The *skeletal mudstone* facies is light to dark gray in color. The *skeletal mudstone* is composed of a minor amount of broken skeletal fragments. The *skeletal mudstone* facies is characterized by separate vugs lined with calcite (Figure 3-2, D). The *skeletal mudstone* facies is differentiated from the *coral stromatoporoid boundstone* by the lower abundance of tabulate corals and stromatoporoids and the higher mud content.

Coral rudstone

The *Coral rudstone* facies is dark brown in color. The *coral rudstone* is composed of coarse rock fragments associated with large tabulate corals, which range in size from 1 to 5 cm (Figure 3-2 E&F). The described coral rudstone in the Silurian reef system is commonly associated with transported lithoclasts.
Figure 3.2. Shows four of the reef internal facies that were observed in this study.

**Pictures A, B & C:** *skeletal grainstone* facies: Shows bigger grains and low mud content and occasionally small tabulate corals.

**Picture D:** *Skeletal mudstone* facies: Shows calcite spar cement lining separate vugs.

**Pictures E & F:** *Coral rudstone* facies: Shows big conglomeratic/brecciated lithoclast with coral skeletal fragments.

**Pictures G:** *Crinoidal mudstone* facies: Shows the abundance of the crinoids.

**Pictures H:** *Crystalline dolomite* facies.
**Crinoidal mudstone**

The *crinoidal mudstone* (also known as bioherm *sensu* Rine et al., 2017) is composed of approximately 60-70% of crinoid ossicles of all organisms, which are prevalent in a carbonate mud matrix. The mud matrix has a mottled gray and white appearance (Figure 3.2, G).

Overlying the *crinoidal mudstone* is 3-7 ft of a crystalline dolomite matrix that is devoid of fossils (also known as the bioherm cap in Rine et al. 2017) (Figure 3.2, H). The contact between the underlying Lockport Formation and the *crinoidal mudstone* is indicated by the transition from a light gray color of the *crinoidal mudstone* to dark gray to brown color of the Lockport Formation.

**Stromatolite boundstone/ stromatolite cap**

The *stromatolite boundstone* consists of dark brown, laterally-linked hemispheroid stromatolites that can make up 40-80% of this facies (Figure 3-3). The *stromatolite boundstone* is also characterized by the presence of the light brown crinkly laminated, highly karsted stromatolites (also known in the literature as cyanobacterial mats as cited in Rine et al. 2017) which increase in abundance toward the contact with the overlying A-1 Carbonate. *Stromatolite boundstone* can be easily identified due to the light brown color that associated with the cyanobacterial mats. It can also easily identified due to the extensive karsting.
Figure 3.3. Figure on the left: laterally-linked hemispheroid stromatolites. Figure on the right: Cyanobacterial mats

Reef Positions

The lateral distribution of facies in the Columbus III (CIII) and the Belle River Mills (BRM) is described in terms of an east-west cross section that intersects both pinnacle reef complexes. This is based on core and log data collected from each well used in the study (Figure 3.4). The top of the Lockport Formation is used as a datum because it directly precedes the initiation of the Silurian pinnacle reef system (Figure 3.5). Three distinctive vertical facies associations were observed in the BRM and CIII reefs. Each vertical facies association is associated with a specific position along the reef, which are referred to herein as the reef interior,
reef margin, and reef slope (Figures 3.6 & 3.7). Each reef position is described below using a type well and is characterized by multiple depositional cycles based on vertical facies changes (Figure 3.5). In some cases, where significant differences in facies associations (facies type and/or stacking patterns) are observed on different sides of the reef (i.e. facies distributions are asymmetric), multiple type wells are used to describe the position. The reef interior, reef margin, and reef slope are terms commonly used in the literature to describe positions in isolated carbonate platforms (REEFS). Reef toe of the slope was a position defined by Rine et al. (2017) as the deeper water position adjacent to the reef slope (Figures 3.6 & 3.7). Reef toe of the slope was described in detail by Rine et al. (2017) and it was not included in this study.

![Diagram](image.png)

**Figure 3.4.** Well Examples from Belle River Mills indicates the types of data collected from each well in the study.
Figure 3.5. A cross-section across CIII pinnacle reef complex. Note that each well in the figure is associated with a specific group of facies (color coded), unique thickness of rock package and number of depositional cycles.
Figure 3.6. East-West cross-section that intersects BRM pinnacle reef complexes. The model shows vertical facies associations, reef positions, and lateral facies distribution within the reef buildup. Refer to figure 2.2 for wells location.
Figure 3.7. East-West cross-section that intersects CIII pinnacle reef complexes. The model shows vertical facies associations, reef positions, and lateral facies distribution within the reef buildup. Refer to figure 2.3 for wells location.
Reef Interior Position (Well # 27778)

Well, # 27778 is the type well for the CIII reef interior position. The base of the core starts in the Lockport Formation. The Lockport Formation underlies the reef system (Guelph Formation). The Lockport Formation has a distinctive GR log signature that was used to pick the top of the Formation in wells where core data was not available (35-50 API which makes it different from the overlying bioherm 10-15 API). Overlying the Gray Niagaran is the *crinoidal mudstone* facies. The *crinoidal mudstone* in the core is followed by *coral stromatoporoid boundstone* facies. The *coral stromatoporoid boundstone* vertically transitions to *skeletal wackestone* facies. The stromatoporoid boundstone and the *skeletal wackestone* in the core are overlain by the *stromatolite boundstone* facies. The *stromatolite boundstone* represents the last unit of the Brown Niagaran Formation. The Brown Niagaran in the core is capped by the Lower Salina, A1 Carbonate. (Figure 3.8).

The vertical facies changes observed in the CIII reef interior position (well # 27778) exhibit an overall pattern of increasing muddiness from the grain-dominated *coral stromatoporoid boundstone* to the mud dominated *skeletal wackestone* (Figure 3.8). *The coral stromatoporoid boundstone* is characterized by a relatively high abundance of wave resistance organisms (e.g., tabulate coral and stromatoporoids), whereas the *skeletal wackestone* is characterized by the abundance of reef dwellers (e.g., bryozoans, brachiopods, crinoids, and rugose corals). Well # 27778
Figure 3.8. CIII reef interior well section and its position on the reef buildup. The well section shows reef interior Vertical facies association, exposure surfaces, and four high-frequency depositional cycles. Refer to figure 2.4 for well location and to figure 3.7 for reef position.
exhibit a gradual facies vertical change from grain-dominated facies to mud-dominated facies. The vertical facies transitions from higher energy facies (grain dominated with wave resistant organisms) to lower energy facies (mud dominated with deeper water organisms) and then transitions back to higher energy facies could represent one sequence stratigraphic/depositional cycle. There are several mechanisms that would lead to change energy condition in the system (example: wind-based energy gradients across the reef), however, facies based depositional cycles defined here implies that there is a relative sea level change that controls facies distribution. In total, four depositional cycles, which range in thickness 25-35 ft, were observed in well 27778 (Figure 3.8).

Reef Margin Position (Well # 27655)

The reef margin position is described in terms of the type well # 27655. This well is located on the west side of the CIII reef (Figure 3.9). The core starts in the Lockport Formation, which was picked using the gamma ray log signature and thickness data from nearby wells. The Lockport Formation was not cored in this well. The core starts in the crinoidal mudstone facies (Figure 3.9). The crinoidal mudstone underlies a succession of grain dominated, skeletal grainstone facies. The skeletal grainstone is vertically transitions to mud dominated, skeletal wackestone facies. The skeletal wackestone, observed in this core is similar to the skeletal wackestone observed in the reef interior position. Overlying the skeletal wackestone is the coral stromatoporoid boundstone
Figure 3.9. CIII reef margin well section and its position on the reef buildup. The well section shows reef interior Vertical facies association, the exposure surface, and three high frequency depositional cycles. Refer to figure 2.4 for well location and to figure 3.7 for reef position. Pointing upward blue arrows mean deepening, whereas pointing downward red arrows mean shallowing.
facies. The *coral stromatoporoid boundstone* is followed by another interval of the *skeletal wackestone* facies.

Well #27655 (reef margin position) demonstrates a general pattern of vertical facies change from grain dominated to mud dominated facies. Based on the vertical facies change, three depositional-cycles are identified. Depositional cycles of the reef margin position range in thickness between 25-60 ft (Figure 3.9).

Reef Slope Position (Wells # 27916, 27605)

The slope position, which lies adjacent to the reef margin, is described using two type wells. These wells show that facies associations are significantly different on opposite sides of the reef. The slope position on the west side of the CIII reef is described in terms of the type section, well # 27916. Because the facies in this well are dominated by *skeletal wackestone*, this position will be referred to as the wackestone slope. The slope position on the east side of the reef is described in terms of the type section, well # 27605 (Figure 3.10). The facies in this well is characterized by the presence of *coral rudstone* facies and so the position will be referred to as the rudstone slope (Figure 3.10).

Well # 27916 is the type well for the reef wackestone slope position. The Vertical facies association observed in this core starts (from the bottom) in the *crinoidal mudstone* which overlies the Lockport Formation. Overlying the *crinoidal mudstone* is the *skeletal wackestone* facies. The Vertical facies association of the reef wackestone slope position (well # 27916) indicates the absence of the depositional cycles. The Vertical facies association of the reef wackestone slope position also demonstrated the lack of the *skeletal grainstone* and the *coral stromatoporoid*
boundstone facies which are observed in the adjacent reef margin position. The facies stack observed in well # 27916 represents the reef slope position on the west and the south sides of the CIII reef (Figure 3.5).

Well # 27605 is the type well for the rudstone slope position, which occurs on the east side of the CIII reef. From the bottom, the core starts in the Lockport Formation, followed by the crinoidal mudstone facies. Overlying the crinoidal mudstone facies is the coral rudstone and the skeletal grainstone. The grainier coral rudstone and skeletal grainstone facies are interbedded with the muddier skeletal wackestone facies. Similar to the facies stacking patterns in the other reef positions, the facies stack in the rudstone slope position is capped by the stromatolite boundstone facies and the A1 carbonate (Figure 3.10).

Well # 27605 (reef rudstone slope position) exhibits a gradual facies vertical change from grain dominated facies to mud dominated facies. The rudstone slope position in the CIII reef is characterized by three depositional cycles, each with a thickness of 25 to 30 ft (Figure 3.10).
Figure 3.10. CIII reef rudstone slope well section and its position on the reef buildup. The well section shows reef interior Vertical facies association, the exposure surface, and the three high frequency depositional cycles. “co. rd” stands for coral rudstone facies. Pointing upward blue arrows mean deepening, whereas pointing downward red arrows mean shallowing. Refer to figure 2.4 for well location and to figure 3.7 for reef position.
BRM Vertical Facies Associations (VFA)

Reef Interior Position (Well # 25269)

Well # 25269 is the type well for the BRM reef interior position (Figure 3.11). Vertical facies association observed in this well include (from bottom to top) *skeletal wackestone, skeletal grainstone, crinoidal mudstone, and coral stromatoporoid boundstone* facies. The facies stacking pattern is similar to that observed in the reef interior position of the CIII reef complex (well 27778). One difference in the BRM reef is that overlying the *crinoidal mudstone* is the *skeletal grainstone* facies instead of the *coral stromatoporoid boundstone* as observed in the CIII reef. Like the CIII reef, the reef facies in the BRM are capped by the *stromatolite boundstone* and A-1 Carbonate Formation.

Rock fabric, color and faunal assemblages of the BRM reef internal facies are similar to those observed in the CIII reef. The main difference is that more vertical facies changes were observed in the interior position of the BRM reef compared to those in the interior position of the CIII reef. The vertical facies transitions from grain dominated facies (facies associated with reef wave resistant organisms) to *skeletal wackestone* facies observed in well # 25269 indicate a greater number of depositional cycles than those in the CIII reef. The BRM reef interior position (well # 25269 VFA) exhibits four depositional cycles that range in thickness from 20 to 35 ft.
Figure 3.11. BRM reef interior well section and its position on the reef buildup. The well section shows reef interior Vertical facies association, the exposure surface, and four high frequency depositional cycles. GR stands for gammy Ray 0-50 API and neutron count is 4500-2500.
Reef Margin Position (Well # 23525, 24896 And 24897)

Well # 23525 is the type well for the reef margin position in the BRM reef (Figure 3.12). The vertical facies association observed in the core of this well includes (from bottom to top) *crinoidal mudstone, skeletal grainstone, and skeletal mudstone* facies. The facies stacking pattern in well # 23525 (BRM reef margin position from the west side of the reef) is very similar to the stacking pattern observed in the margin position of the CIII reef (well 27655). However, in well # 24896 (south to well # 23525 figure 2.3), which is located on the west side of the reef, *coral rudstone* has evidence of lithoclasts (see 24896 well section in appendix B). Furthermore, the southern side of the reef in well # 24897 indicates the abundance of the same coral rudstone. The *coral rudstone* in these two wells (24896 and 24897) is consistent with the reef conglomerate member observed by Gill, (1973) in the BRM reef. Numerous transitions between the grain dominated *skeletal grainstone and coral boundstone* and the mud dominated *skeletal wackestone* in well #23525 (reef margin position) indicate four depositional cycles, each with a thickness of 30 to 40 ft.

Reef Slope Position (Well # 23729)

Well #23729 is the type well for the reef slope position in the BRM reef (Figure 3.13). The base of the core penetrates the Lockport Formation followed by the reef facies and then capped by the A-1 Carbonate. The Vertical facies association in the core from well # 23729 includes the *crinoid mudstone, coral rudstone, skeletal wackestone*, and *skeletal grainstone* facies, which is similar to the Vertical facies association observed in the rudstone slope position of the CIII reef. The major difference is that the Vertical facies association observed in well 23729 (BRM reef slope position) has a lower abundance of *coral rudstone* facies.
Figure 3.12. BRM reef margin well section and its position on the reef buildup. The well section shows reef interior Vertical facies association, the exposure surface and four high frequency depositional cycles. Refer to figure 2.3 for well location and to figure 3.6 for reef position.
Figure 3.13. BRM reef rudstone slope well section and its position on the reef buildup. The well section shows reef interior Vertical facies association, the exposure surface and four high frequency depositional cycles. Refer to figure 2.3 for well location and to figure 3.6 for reef position.
The vertical facies association observed in well # 23729 (BRM reef slope position) demonstrates a vertical transition from mud dominated to grain dominated facies (grain dominated facies associated with wave resistant reef organisms). The vertical facies transitions in this core demonstrated four depositional cycles, each with a thickness between 25-35 ft (Figure 3.13).

CIII And BRM Lateral Facies Change

Two facies groups were defined in the CIII and the BRM reefs. The first group includes the grainier facies: *coral rudstone, coral stromatoporoid boundstone and skeletal grainstone* facies. The second group includes the muddier facies: *skeletal wackestone* and the *skeletal mudstone*. The facies groups tend to be distributed in different reef positions. The grainier facies laterally transitions from one facies to another throughout different reef positions (from east to west: the *coral rudstone member* of the rudstone slope and margin positions transitions to the *coral stromatoporoid boundstone member* on the interior position and then to the *skeletal grainstone member* on the wackestone slope and margin positions). The muddier facies, on the other hand, are laterally continuous through all reef positions. The abundance of the muddier facies, specifically *skeletal wackestone* facies, which is laterally continues through all reef positions overlying the grainer facies (different facies in different positions), resulted in grainier-muddier cycles of facies in all the positions.

The lateral transitions between grainy facies are evaluated using an east-west cross section that intersects both reefs. In the CIII reef, the *coral rudstone* is observed on the east side of the reef (within the Vertical facies association of the reef rudstone slope position). The *coral rudstone* of the reef slope and margin positions laterally grades to the *coral stromatoporoid boundstone* in the reef interior position. The *coral stromatoporoid boundstone* then grades laterally to the *skeletal
grainstone in the margin position, on the west side of the CIII reef buildup (Figure 3.7). The cross-section (Figure 3.6) shows a lateral transition from coral rudstone facies in the rudstone reef slope position on the east side of the reef to a skeletal grainstone in the reef interior position and the reef margin position on the west side of the BRM reef.

In addition to evaluating the Vertical facies association in the E-W well cross-sections, Vertical facies association in individual wells that are located in the southern and the western reef margins of both CIII and BRM reefs were also evaluated. These wells indicate that the skeletal wackestone facies is abundant in the southern portion, on the eastern reef margin of CIII reef (well # 27540) whereas the coral rudstone is absent in the same reef position (in well # 27540) (See figure 3.14). The Vertical facies association in these individual wells also demonstrates that the coral rudstone is abundant in the southern reef margin (well # 24896) and on the western reef margin (well # 24896) of BRM reef (see well # 24896 and 24897, well sections in appendix B). The coral rudstone (associated with lithoclasts) observed in BRM wells is consistent with the observation of the reef conglomerate member by Gill (1973).

The facies distributions which are observed in the cores of the BRM and CIII reefs shows the presence of the muddier facies (skeletal wackestone) in all reef positions. However, a higher abundance of skeletal wackestone is present in the reef interior positions. The skeletal wackestone decrease towards reef margins and reef slopes. The skeletal wackestone laterally transitions to skeletal mudstone facies, skeletal mudstone increases in abundance towards margin and slope positions. The toe of slope position is completely devoid of skeletal wackestone facies and contains skeletal mudstone instead.
Figure 3.14. Vertical facies association of well # 27540. Despite the well location in the east with respect to the reef interior, the core of this well indicates the abundance of the skeletal wackestone facies. It additionally demonstrates the absence of the coral rudstone in this reef position. This observation is inconsistent with the easterly paleo-wind direction. Refer to figure 2.4 for well location and to figure 3.7 for reef position.
Summary of Reef Internal Facies Architecture

The key observations include:

1- The *coral stromatoporoid boundstone* is associated with the reef interior position. This facies represents the rock type with the highest abundance of reef-building organisms (Figures 3.1, 3.6, 3.7 and 3.11).

2- The *coral rudstone* facies is associated with the reef slope and margin positions on both the eastern, western and southern sides of the BRM reef, whereas in CIII reef, the *coral rudstone* is abundant in the reef interior in addition to the east side of the reef.

3- *The skeletal grainstone* is associated with the reef slope and margin positions adjacent to reef buildup on both the east and west flanks of the CIII and BRM reefs. The BRM detailed core description demonstrates a high abundance of the *skeletal grainstone* in the reef interior, in addition to the *skeletal grainstone* of the slope and the margin positions (Figures 3.6 and 3.7).

4- The *skeletal wackestone* facies is associated with the reef interior position and grades laterally to the *skeletal mudstone* in the margin, slope, and toe of slope positions. However, the *skeletal mudstone* facies is present on both the southern and western sides adjacent to the CIII and BRM reef buildups (Figures 3.6 & 3.7).

5- The vertical facies associations in all reef positions demonstrate a pattern whereby grain dominated facies (*coral stromatoporoid boundstone, skeletal grainstone, and coral rudstone*) transition vertically to mud dominated facies (*skeletal wackestone*). Different facies are dominated by different organisms that are indicative of specific depositional settings, which will be discussed in the following chapter. Based on these observations, facies vertical transitions indicated numerous depositional cycles in each reef position.
CIII Internal Reefs Size, Thickness, And Architecture

The lateral change in elevation of the A-1 Carbonate top was used to determine the overall geometry of the CIII reef. The A-1 Carbonate is used to evaluate the underlying Niagaran reef architecture because it was documented by Rine et al. (2017) that the A-1 Carbonate was structurally formed following the topography of the underlying reef buildup. Therefore the A-1 carbonate structure should be indicative of the underlying reef geometry. While the A-1 Carbonate structure is defined by the reef overall geometry is generally true statement, there may be differential rates of deposition for the Salina A-1 Carbonate on the flanks compared to the crest of the underlying Niagaran strata, this can deviate the geometry relationship between the A-carbonate and the reef overall geometry.

The cross-section (Figure 3.7) shows a dramatic elevation change in the slope position on the east side of the reef. The elevation of the top of the A-1 Carbonate in the CIII reef from the east side changes from ~2075 ft in the reef interior position and grades laterally to ~2325 ft in the reef slope position and then to ~2400 ft in the toe of slope position. The elevation of the top of the A-1 Carbonate from the west side changes from ~2075 ft in the reef interior and grades laterally to ~2160 ft in the reef slope position. No wells are available on the west side, far away from the reef interior, therefore the elevation of the A-1 carbonate on the west side, the toe of slope position was not detected.
Based on the A-1 Carbonate elevation, the steeper slope on the east side of the reef and gentler slope on the west side of the reef was indicated in the CIII reef buildup (Figure 3.15). The A-1 Carbonate elevation change, therefore, reflects an overall asymmetry of the CIII reef.

Figure 3.15. A-1 Carbonate structural map for the CIII reef. Contour interval is 30 ft. The contour lines reflect asymmetric reef geometry, specifically, CIII is asymmetric with a steeper slope on the east (closely spaced contours) and the gentle slope on the west consistent with Rine et al. (2017)
The “Brown Niagaran” in the CIII reef shows an average thickness of approximately 380 ft in the reef interior position. The average thickness of the Brown Niagaran gradually decreases to ~200 ft in the reef slope position from the east side of the reef.

The Brown Niagaran thickness is approximately 150 ft in the toe of slope position from the east side of the reef. The Brown Niagaran thickness grades to 250 ft in the slope position and then decreases to 210 ft in the toe of slope from the west side of the reef. The lateral thickness change of the Brown Niagaran further suggests the overall east-west asymmetry of the CIII reef. The closely spaced contour lines observed in the Brown Niagaran isopach map (Figure 3.16) indicates a rapid change in thickness over a short distance (i.e. high slope angle). The Brown Niagaran thickness distribution reflects a closely spaced contour lines on the east sides of the CIII reef buildup, whereas the Brown Niagaran thickness distribution demonstrated a lower slope angle of the Brown Niagaran on the west sides of the reef buildup.

The asymmetry of the CIII reef buildup is also consistent with the bedding slope angle preserved in the A-1 carbonate. The bedding slope angles observed are consistent with the slope angles defined from the thickness and the elevation maps of the Brown Niagaran and A-1 Carbonate, respectively. The CIII reef exhibits approximately 40 degrees of slope angle on the reef slope position on the eastern side of the reef (Figure 3.15). The bedding slope angle of the reef slope position that is located on the western side of the reef, is only approximately 15 degrees of slope angle. Those observations agree with the slope angles determined by Rine et al. (2017).
Figure 3.16. CIII reef thickness lateral change which reflects the general reef asymmetry (gentler slope on the west and steeper slope on the east. This observation is consistent with the easterly paleo-wind direction proposed by Rine et al. (2017).
Figure 3.17. Brown Niagaran isopach map of BRM reef shows the lateral change of thickness which reflects reef asymmetry (steeper slope on the west-northwest and gentler slope on the east, south and the southeast sides of the reef. This observation is inconsistent with the east-northeast paleo-wind direction.
The change in lateral thickness of the ‘Brown Niagara’ and change in elevation of the A-1 Carbonate suggest smaller reef buildups within the CIII reef complex. The small reef buildups distributed in the north-south directions within the main Columbus III reef complex (Figure 3.15 & 3.16). Lateral thinning of the Brown Niagara (Figure 3.16) is consistent with the lateral facies change in the vertical facies association at the interior position compared to the margin and the slope positions (figure 3.7). This observation further suggests that the CIII reef complex is composed of smaller internal reef build-ups. The areal dimensions of each defined small reef ranging from maximum ~ 1000 ft width and 2000 ft length for the big buildup and approximately 1000 ft length and ~500 ft width for the small buildup.

Figure 3.18 A) A-1 Carbonate bedding slope angle (approximately 15 degrees of slope angle) from CIII reef slope position which is located on the west side of the reef. B) A-1 Carbonate bedding slope angle (approximately 40 degrees of slope angle) from CIII reef slope position which is located on the east side of the reef.
BRM Internal Reefs Sizes, Thicknesses, And Architecture

Lateral changes in elevation of the A-1 Carbonate were utilized to evaluate the BRM reef overall geometry. The cross-section across the BRM reef (Figure 3.6) shows a dramatic elevation change of the A-1 Carbonate Formation. The A-1 Carbonate Formation transitions from ~ 1530 ft in the reef interior position to ~ 1730 ft in the reef slope position and then to ~ 1800 ft in the reef toe of slope position towards the west side of the reef. The east side of the reef, conversely, shows a gradual decrease in elevation from 1530 ft in the interior position to 1620 ft in the slope position to 1800 ft in the toe of slope position. The lateral structural elevation changes of the A-1 Carbonate indicated an overall asymmetry of the BRM reef towered the west direction (steeper slope on the west side and gentler slope on the east side) (Figure 3.19).

The average thickness of the Brown Niagaran in the BRM reef interior position is approximately 360 ft. The Guelph Formation (‘‘Brown Niagaran’’) dramatically thins towards the slope and the toe of slope positions from the east and the west directions (Figure 3.17).

The average thickness of the ‘‘Brown Niagara’’ in the BRM reef thins laterally 360 ft in the interior position to 245 ft in the reef slope position and 175 ft in the toe of slope position towards the west side of the reef. The ‘‘Brown Niagara’’ average thickness also thins to 280 ft in the reef slope position and 200 ft in the toe of slope position towards the east side of the reef. The Brown Niagaran thickness further shows the general asymmetry of the BRM reef buildup.
Figure 3.19. A-1 Carbonate structural map for Belle River Mills (BRM) reef. Contour interval is 30 ft. The numbers represent well permit numbers. The contour lines reflect asymmetric reef geometry, specifically, BRM is asymmetric with a steeper slope on the west-northwest (closely spaced contour lines) and the gentle slope on the east, south and the southeast. This observation is inconsistent with the proposed east-northeast paleo-wind direction.
The thickness of the Brown Niagaran (Figure 3.17) in addition to the lateral elevation change of the A-1 Carbonate Formation (Figure 3.19) demonstrated an east-west asymmetry of the BRM overall reef geometry toward the west side (steeper slope on the west and gentler slope on the east). The same type of data indicates E-W symmetry of the reef overall geometry toward the south direction.

The geometry of the BRM reef was further evaluated using the bedding slope angle of the A-1 Carbonate. Differences in the A-1 Carbonate bedding slope angle on opposite sides of the reef are consistent with the geometry observed from the thickness and structural elevation of the “Brown Niagara” and the A-1 Carbonate, respectively. The bedding slope angle observed from the slope position located on the east side of the reef has moderate slope angles ranging from 20-30 degrees. These same datasets show that the slope position located on the west side of the BRM reef has steeper slope angles ranging from 30 degrees in the south to 40 degrees in the north.

The BRM reef complex demonstrated two smaller reef buildups using the same evidence from the CIII reef complex (described above). The dimensions of the small reefs (BRM sub-reefs) are ~ 6000 ft in width and ~14000 ft in length (Figures 3.17 &3.19). Belle River Mills sub-reefs are generally greater in size if compared to Columbus III sub-reefs.
Reef Architecture Summary

The lateral change in facies thickness of the CIII and BRM reefs demonstrates a lateral thinning of the ‘‘Brown Niagara’’ facies from the reef interior wells towards the slope and toe of slope positions. ‘‘Brown Niagara’’ is thickest in the reef interior position and gradually thins toward the toe of slope positions. These thickness changes were utilized here to evaluate the overall geometry of each reef. The structural elevation changes and the bedding plane dips observed in the core were further used to determine the architecture of the BRM and CIII reefs. The lateral change in thickness and structural elevation are consistent with one another and together indicate that the geometry of each facies within the reefs is similar. Furthermore, the thickness and the structural elevation of the ‘‘Brown Niagara’’ and A-1 Carbonate, which encase the reefs, are also consistent with the overall reef geometries.
CHAPTER IV
DISCUSSION

Silurian Paleo-Wind Direction

Previous work on the Silurian reefs in the Michigan Basin suggests that reef geometry can be used as an indicator of paleo-wind direction based on the presumption that the windward facing slope is steeper than the leeward side because it is subjected to higher energy conditions (Gill 1973; Shaver 1977; Wold 2008; Qualman 2009; Rine et al. 2017). Wind direction can also cause an unequal distribution of grainy and muddy facies for the same reason.

Ingles (1963) originally suggested a west/southwest paleo-wind direction based on geometry and facies distributions observed at the Thornton reef in a quarry outcrop located in Indiana. This is different than Gill (1973), who suggested a northwest dominant paleo-wind during the Silurian reef growth, based on reef overall geometry of Belle River Mills reef. Subsequent work by Briggs and Briggs (1974) and Scotese (2002) lead these authors to suggest a southeasterly to easterly equatorial trade winds across the basin during reef time of deposition. Later, Wold (2008) suggested a southern paleo-wind based on reef overall geometry and facies distribution of the Ray reef. The most recently published reef depositional model attributed the internal facies distribution to an east/northeast paleo-wind direction (Rine et al. 2017).

In the current study, Brown Niagaran Formation thickness and A-1 Carbonate structural elevation were used to establish reef geometries for the CIII and BRM reefs. The A-1 Carbonate doesn’t always reflect the underlying reef geometry especially if there are differential rates of deposition for the Salina A-1 Carbonate on the reef flanks compared to the reef interiors of the
underlying Niagaran strata. However, reef geometries inferred in the A-1 Carbonate in addition to the reef geometry in the Brown Niagaran thickness agree with the bedding slope angles of the A-1 Carbonate, which reflect the geometry of the reef (Figure 3.18). All observations show that the steeper slopes occur on opposite sides of the BRM and CIII reefs (Figure 4.1).

The overall geometry of CIII and BRM reefs interpreted in this study agree with inconsistent geometries inferred in other reef studies (e.g., Wold 2008; Ingles 1963; Shaver 1977). These observations, taken together, suggest that there is no single consistent paleo-wind direction indicated by the overall geometries of the Silurian reefs.

This study also utilized the sequence stratigraphic approach to determine the reef facies distribution in different fields. Many of the previous models did not utilize the sequence stratigraphic approach, they instead defined facies from core and well logs and attributed the facies distribution to the paleo wind direction. Using the wind direction in different studies led to preferred facies stacking patterns which can be recognized in a series of reef growth models by Gill (1973), Huh (1973), and Rine et al. (2017). Previous depositional models reflect the inconsistency of the facies distribution and the proposed paleo wind direction in different reefs.
Figure 4.1. East-West cross-section across the CIII and BRM reefs. Both BRM and CIII models show the inconsistency of the facies distribution with the degree of slope. The steep slope of CIII reef is on the east side which coincides to the rudstone slope vertical facies association, whereas the steep slope of the BRM reef is located on the west side and coincides to the wackestone slope vertical facies association.
In the CIII reef, the steepest slope (~ 40-45 degrees) was found associated with the rudstone slope position, which is located on the eastern side of the reef. The slope on the western side of CIII reef is gentler, approximately 15 degrees. These observations are consistent with the observations and the interpreted easterly paleo-wind direction proposed by Rine et al. (2017). However, core observations from BRM suggest that the steepest slope angle associated with the wackestone slope (*skeletal wackestone, skeletal grainstone and stromatoporoid coral boundstone* vertical facies association), which is located on the west side of the reef. This is opposite to the direction of the steepest slope in the CIII reef. Moreover, the BRM reef wackestone slope on the west side indicates slope angles ranging from 40 degrees in the north and grades to 30 degrees in the south. The geometry of the BRM reef alone, therefore, shows inconsistency with the single proposed paleo-wind direction (Figure 4.1).

The facies indicative of transport in the reef slope and margin positions can also be used as an indicator of paleo-wind direction if the wind is controlling facies distribution during the time of reef deposition. Evaluating the direction of the reef margin position, which is associated with the abundance of the *skeletal wackestone* facies and the direction of the rudstone slope positions of Columbus III and Belle River Mills reefs, indicates inconsistency with the proposed East/northeast paleo-wind direction, more specifically, the abundance of the *skeletal wackestone* facies on both the west and the east margins adjacent to the CIII and BRM reefs indicate inconsistency with the easterly proposed paleo-wind direction (Figures 2.3, 2.4 and 3.14). If the northeast wind direction was responsible for the deposition of the reef internal facies then there should be different facies associations on the west and the east sides of the reef with respect to the proposed easterly wind direction. This means that we would expect to have the *skeletal wackestone*
margin/slope facies associations on the west side if the wind was controlling the deposition of the reef due to the low energy conditions that the backreef environment usually provided.

The coral rudstone was first observed on the east sides of both CIII and BRM reefs, but not on the west sides, therefore, it was used as an indicator of the easterly paleo-wind direction by Rine et al. (2017). However, based on the higher resolution facies distributions reported in this study, Lithoclasts that occasionally contains skeletal/coral fragments was observed within the coral rudstone facies. The lithoclast-coral rudstone could represent a transported material due to the high energy of the windward side of the reef (Rine et al. 2017; Wold 2008). However, in this study, the lithoclast-coral rudstone was observed in the reef interior position (well # 27778) intercalated with the coral boundstone (Figure 3.8) in addition to the eastern, western and southern margin positions of the reef.

The four different paleo-wind directions suggested in the literature are based on both reef overall geometry (described above) and are additionally based on Silurian reef internal facies distribution (Ingles 1963; Gill 1973; Wold 2008; Rine et al. 2017). The west/southwest paleo-wind interpreted by Ingles (1963) and the northwest paleo-wind that was interpreted by Gill (1973) are both inconsistent with the facies distributions observed in the current study. Specifically, the abundance of the skeletal wackestone facies in the western margin and slope positions of BRM and CIII reefs suggests a western leeward side of CIII and BRM reefs (leeward side is the side opposite to the direction of paleo-wind). The skeletal wackestone is, for example, abundant on the reef margin and slope in the northern part of BRM reef (well #23525, west reef margin, figure 3.12), but the lithoclast-coral rudstone facies in these locations would be predicted if a westerly paleo-wind direction prevailed. Furthermore, the abundance of the lithoclast-coral rudstone on the middle and southern part of BRM in the west and south margins (wells # 24896 and 24897)
respectively does not support the easterly, northeast or southeast paleo-wind directions proposed by Rine et al (2017) and the south/southeast paleo-wind directions proposed by Wold (1973).

The above observations of the coral rudstone and the skeletal wackestone distribution, in addition to the abundance of the similar facies (the skeletal grainstone) on both east-west sides of BRM and CIII reefs provided strong evidence that facies distributions were not controlled by paleo-wind during the time of the reef growth (Figure 4.1).

However, the vertical cyclic change of the high-low energy facies in addition to the presence of the exposure surfaces in the system are all inductive of sea level fluctuation and deep water circulation controls (Purkis et al 2017).

Reef geometry, specifically that CIII is asymmetric with a steeper slope on the east, whereas BRM is asymmetric with a steeper slope on the west, and internal facies distributions both permit two possible explanations for the paleo-wind direction during the time of reef deposition.

First, it is possible that wind direction changed throughout the time of reef deposition. Based on this assumption, the reef time of deposition can be divided into two time periods with different wind directions. In the early time of the reef deposition, the paleo-wind direction was from the west to east.
The West-East wind direction attributed in the steep slope of the BRM reef slope from the west side. At the same time, CIII did not show any steepness in the slope from the west side. Wind energy at this specific time of deposition could be affecting only shallower reefs and attributed in their asymmetry toward the west side (Figure 4.2). The gentler slope on the west side of the deeper reef (CIII) supports the interpretation that suggests the wind may have had a greater impact on the shallower up slope reefs (BRM) and less impact on the deeper downslope reefs (CIII) at the earlier time of the deposition (Shaver 1977).

Figure 4.2. A possible scenario of the control of the dominant paleo-wind direction on the reef overall geometry during the time of the Silurian reef growth. In time one, the reefs that are located upslope indicates steeper slope on the west side of the reef due to the west-northwest paleo-wind. Later in time, deeper reefs have grown taller and thicker and the wind possibly changed direction to the east-northeast. At this time the deeper reefs developed a steep slope on the east side of the reef.

As time goes on, reef buildups grew taller and dominant paleo-wind might have changed direction to East-West, which would have led to the steeper slope on the eastern side of the Silurian reefs. If wind changed directions in the later time of reef growth, we would expect to see a steeper slope on the east side of all reefs. However, reef examples that does not show a steep slope on one of their sides probably due to local shelters that are developed throughout the time of reef growth,
these shelters that are usually found in shallow platform environments can provide a local low energy conditions which could have led to gentler slopes on some of the reef sides. The observation that BRM reef exhibits a gentler slope on the east side supports this interpretation.

Moreover, wind direction affected reef geometry but not the reef internal facies distribution during any time of reef deposition. This is supported by the presence of similar margin and slope facies on the east-west sides of the reef (Figure 4.1), in addition to the coral rudstone and skeletal wackestone facies distribution (skeletal wackestone on the east, west sides of the reef whereas the coral rudstone on the west and the south sides of the reef) both, of these two observations shows inconsistency with respect to the proposed northeasterly and northwest paleo-wind directions in both CIII and BRM reefs respectively.

Alternatively, the paleo-wind directions proposed by Gill (1973) and Rine et al. (2017) may not be responsible for the overall geometry or the internal facies distribution. This interpretation is supported by the opposite directions of steep and gentle slopes of both reefs, the distribution of the skeletal wackestone and lithoclast-coral rudstone facies, in addition to the abundance of the similar reef facies in the reef margin and slope positions which are located in different sides of the reef.

Reef Growth Model

Fossils assemblages, grain sizes, and sedimentary structures suggest that Silurian reef internal facies reflect specific water energy conditions. In any protected environment, the different energy conditions could be the result of various environmental controls. The depositional processes are the result of the energy conditions, and different energy conditions controlled by various environmental processes. Therefore, environmental controls are a key to facies
distributions. A generally accepted premise is that platform-top currents and therefore deposition are wind and/or tidally driven (Purkis and Harris, 2017). More specifically, in a protected carbonate environment, the energy conditions could have been controlled by dominant paleo-wind, local currents, and small water channels due to energy gradients. For example, in reef systems the vertical and lateral facies change and the shift in energy conditions could be interpreted as eroded reef material that is shed and accumulated between reefs. The facies distributions in these areas are usually driven by low hydrodynamic energy of the “sheltered pockets,” which typically host relatively muddy facies. However, the geometries and facies distributions presented here provided no evidence of a wind energy gradient.

Numerous sources of lime mud have been proposed in the literature (see review by Hashim and Kaczmarek, in press). One such source in reef systems is that large amounts of calcareous algae produce the mud component within the depositional system. Many calcareous algae today break down into carbonate mud after death (Wood 1999). If the volume of muddy material generated by calcareous algae within the reef interior position was significant, it would have necessarily been winnowed away toward the margin and onto the slope positions. However, this cannot apply in the Silurian reefs because only minor amounts of calcareous algae had evolved by the Silurian.

In the Silurian reefs system, the controls on the facies distribution during deposition is debated. Several previous studies suggested that sea level fluctuation is the main control on deposition (Wold, 2008; Qualman, 2009), whereas other studies suggested that the paleo-wind direction controls the distribution of facies (Rine et al. 2017). However, the observed vertical cyclic changes between high and low energy facies are indicative of sea level fluctuation and deep water circulation controls during Silurian reef growth. Recent studies on ancient and modern
carbonate platforms show that in addition to ecological factors and local hydrodynamic controls on the platform, deposition on isolated platforms is also related to the deep-water circulation (Purkis and Harris, 2017). More specifically, the most recent study by Purkis and Harris (2017) using sea level fluctuation modeling along with the facies studies, indicated that the deep-water circulation controls shallow water hydrodynamics and therefore influences the type and distribution of sediments accumulating on the platform as well as their thickness and lateral heterogeneity.

Purkis and Harris (2017) concluded that “ocean circulation patterns have the potential to exert control on shallow water hydrodynamics including the distribution of extensive hiatal surfaces (sites of non-deposition).” Water depth/sea level fluctuation in shallow platforms is controlled by sea level change/deep water circulation (Purkis and Harris, 2017) and can possibly control the deposition in these shallow carbonate reef systems.

One other strong evidence that sea level is controlling the deposition during the Silurian reef growth is the abundance of the exposure surfaces in the system (Coniglio et al. 2003; Qualman, 2009; Wold and Grammer, 2017). Exposure surfaces were suggested herein based on a specific criterion described below (Figure 4.3). These surfaces possibly represent time equivalent surfaces when sea level dropped and caused the reef to be exposed with non-deposition for a certain amount of time. However, these features can also be interpreted as post depositional events (Kahle, 1994). Further petrographic and elemental analyses can be performed to confirm the exposure surfaces suggested herein and in the previous literature. If the exposure surfaces in the Silurian reef system is confirmed, then reef facies distribution can be explained as a shift in energy condition due to change in water depth due to sea level fluctuation. Alternatively, the reef facies distribution can explain different energy conditions during reef deposition, but may not be due to water depth, the
change in energy conditions, in this case, can alternatively be ecologically driven or can reflect a change in local currents or a combination of both.

The deposition of the reef internal facies was interpreted in this study to have been controlled by local sea-level fluctuations based on the vertical facies change in the CIII (downslope) and BRM (upslope) reefs, as well as the possible evidence of exposure and the flooding surfaces which were observed and correlated in both reefs.

A sequence stratigraphic approach is used in this study to understand the vertical and the lateral facies distribution in reefs located in different positions along the depositional slope (different water depths). Using the sequences stratigraphic approach led to the interpretation of a number of higher frequency depositional cycles with each third order cycles documented by Huh (1973) and Rine (2015). High-frequency cycles were defined within the time of the organic reef growth (stage 2) following the bioherm initiation which represents stage 1 of the reef growth as described by Huh (1973) and Rine (2015). The current study concluded that high frequency cycles control reservoir quality distribution within each reef buildup.

A sequence stratigraphic approach was also used by World (2008) and Qualman (2009) to interpret reef facies distribution and reservoir quality in Silurian reefs. Wold (2008) and Qualman (2009) facies models demonstrated a high level of depositional facies heterogeneity. Wold (2008), Qualman (2009) and Ritter (2008) also suggested that their depositional cycles represent the fifth order of sea level. cyclicity. Qualman (2009), World (2008) and Ritter (2008) cycles are not correlative between reef buildups. The high-frequency cycles (possibly fifth-order cycles) which were interpreted by Qualman (2009), Wold (2008) and Ritter (2008) can’t be correlated between Silurian reefs in the Michigan Basin. This is because the high-frequency facies changes are attributed to local ecological changes within each individual reef (Wood, 1999).
Exposure and Flooding Surfaces

Exposure surfaces reflect a time when sea level dropped to a level that exposed part of the reef complex and resulted in a depositional hiatus in the rock record. These surfaces are irregular because they are associated with karsting and intense dissolution caused by fresh-water diagenesis (Mesolella et al. 1974; Gill 1985; Wold 2008) (Figure 4.3). Exact for the deep basinal cores, exposure surfaces were easily recognized in all of the cores in this study. On the slope and deeper water positions, these surfaces are more cryptic because these positions are transport-dominated. Based on the same criteria used here, previous studies on Silurian reef growth suggested exposure surfaces throughout reef growth (Mesolella et al. 1974; Gill 1985; Wold 2008; Qualman 2009), Others (Khale, 1994) and interpreted the same karsting, intense dissolution, and the irregular surfaces features as diagenetic features. Kahle (1994), for instance, performed his research on Maumee reef located in Ohio. He described the Silurian reefs caverns as post-depositional features formed later during the time of Salina A-1 Evaporite deposition. He concluded that after Silurian carbonate rocks are exposed during A-1 Evaporite time, they were lithified rapidly, which promoted early fracturing that provided conduits for later seawater dissolution (Kahle 1994).

The exposure surfaces defined in this study are, however, consistent with the vertical, cyclical distribution of the reef internal facies and both suggest the control of sea level fluctuation on the reef growth. However, the defined exposure surfaces are debatable until further petrographical and geochemical analyses are performed to confirm significant involvement of meteoric water, (Coniglio et al. 2003). If the statement that the Irregular surfaces, karsting, and dissolution features represent exposure surfaces in the reef system is a true statement, then these surfaces allow building a sequence stratigraphic model which allows for better predictions of reef internal facies.
Overlying these surfaces (the surfaces of irregular surfaces, karsting, and dissolution) is usually an abrupt vertical facies change to muddier facies (flooding events). The flooding surfaces were defined based on an increase in mud content and changes in reef fauna to reef assemblages that reflects relatively lower energy conditions, the fauna assemblages including bryozoans, brachiopods, crinoids, and rugose corals. The muddier facies (*skeletal wackestone*) were defined in almost every well within each reef complex. The *skeletal wackestone* was correlated laterally in all reef positions and between different reefs. The *skeletal wackestone* is then vertically followed by grainer reef facies in all reef positions. Facies stacking patterns, therefore, produce grainier-to-muddier cycles in all reef positions (Figure 4.9). The vertical facies shifts, specifically the grainy-muddy cycles observed on the reef, are interpreted to reflect sea level fluctuations. If this is accurate, and the reef was subjected to subaerial exposure, then the observed *skeletal wackestone* in all reefs is the result of a transgression.
Figure 4.3 Exposure surfaces of CIII reef which was observed in the reef interior well # 27778. A) Irregular surface across the middle of core and altered reef material with heavy dissolution (DIS) beneath an interpreted exposure surface (Exs) with overlying mudstone (Mud); B) Coarse conglomerate, irregular surfaces (RS), Karst (KS)

Exposure and flooding surfaces are important components of the sequence stratigraphy because they represent key surfaces of equal time (chronostratigraphic surface). Obtaining chronostratigraphic units is essential to split depositional sequences with similar time of deposition. Furthermore, exposure surfaces followed by deposits that are characterized by high porosity and permeability values, therefore identify these surfaces is essential to enhance the understanding of reservoir quality distribution (Friedman and Kopaska-Merkal 1991; Wold 2008; Qualman 2009).
Reef Growth Stages

Ross and Ross (1996) suggested a total of seven sea level changes during Silurian time with an amplitude of ~165 ft. Furthermore, three periods of sea level fluctuations were recorded during the Wenlockian and partly into the Ludlovian series of the Silurian (Shaver, 1996; Barrick, 1997; Wold, 2008; Rine, 2015). Three higher order sea level cycles were identified from core observations from the CIII and BRM reefs. The high order frequency cycles are part of the Wenlockian which only represent 3.5 million years. Based on Carbon isotopes data by Rine et al. (in progress), the Organic reef stage is only part of the Wenlockian, which refer to as lower Mulde CIE. The entire Mulde CIE lasted for only 500,000 years according to ash bed dating. The third order cycles divided the reef growth into three stages (described below), however, 3-4 higher frequency cycles (the number of the higher frequency cycles depends on the reef position) are interpreted in this study within stage two (organic reef stage) based on facies distribution, exposure and flooding surfaces of the CIII and BRM reefs. The high frequency cycles reflect a smaller scale of changes in sea level. These smaller scale changes in sea level control reef internal facies distribution differently in various depositional slope positions. Generally, the depositional cycles suggest that the reef grainier facies were only deposited at certain times during reef growth. The grainer facies is then followed by the deposition of the muddier facies which represents flooding surfaces. The structural cross section is used to explain the reef growth stages and facies variability through time. The structural cross section is oriented north-south along the depositional slope (Figures. 4.4 - 4.9) it, however, cut on the east-west direction through CIII and BRM reefs parallel to inferred paleo-wind direction by Gill (1973) and Rine et al. (2017), (Figure 4.5)
Stage 1: Bioherm Initiation

The *crinoidal mudstone* facies (also known as bioherm mud mound) is interpreted to be deposited below storm wave base during the overall sea level (SL) rise (Gill, 1973; Huh, 1973; Rine, 2015). The bioherm directly overlies the “Gray Niagara” Formation and underlies the *coral stromatoporoid boundstone* (within the organic reef stage) in the deeper reefs (CIII). The bioherm mound also underlies the *skeletal grainstone* of the organic reef stage in the shallower reefs (BRM) (Figure 4.8). Rine et al. (2017) interpreted the “Gray Niagara” as a relatively calm water deposit that was deposited below the storm-wave base (SWB, ~ 60 feet or 18 m based on Rine et al. 2017). Based on the observation that the bioherm consists of relatively deeper-water fauna (dominantly crinoids and bryozoans), in addition to relatively greater mud content, the bioherm was likely initiated in this same calm water environment. The initiation of the bioherm mark an ecological shift to different mud mound-building organisms, which agrees with Wood (1999) and Rine (2015). In the reef interior position, the uppermost (7 ft) interval of the bioherm is composed of thin, massively bedded crystalline dolomite. The crystalline dolomite could reflect either a relative sea-level fall, resulting in a small unconformity, or a small relative sea-level rise and the Formation of a submarine hardground (Rine, 2015).
Figure 4.4. Stratigraphic cross section shows Stage 1 bioherm initiation below storm wave, in a deeper water environment. Refer to figure 4.5 for cross section orientation.
Figure 4.5. Field map shows the reefs of study (in the green boxes) and the direction of the evaluated X section across the two reefs.

Stage 2A: Early Organic Reef Growth

The abundance of wave-resistant, framework building organisms indicates that the organic reef was formed above FWB for the majority of deposition. Following the bioherm intuition is a relative sea level fall and subaerial exposure. The subaerial exposure is suggested here based on the deposition of the crystalline dolomite and age data from Carbone isotopes age dating from Rine et al. in progress. As relative sea-level raised again, due to a combination of eustatic rise and basin-centered subsidence, the rapid growth rate of the reef core facies allowed it to grow above FWB. The early organic reef stage starts with *skeletal grainstone in BRM* reef and the *coral boundstone*
in CIII reef. The *skeletal grainstone and coral boundstone* are interpreted to be contemporaneous in deposition and represent the early time of the 2nd stage after the bioherm mud mound stage.

As sea-level continued to rise, BRM reef grew above FWB but below intertidal. The high energy environment at this reef position (upslope) favors the accumulation of the *skeletal grainstone* facies in the early organic reef stage (Figure 4.6). The depositional environment in the upslope reef during this time is interpreted to be between fairweather wave base and intertidal (FWB-intertidal, less than 9 m or 30 feet of water depth). Contemporaneously, CIII reef continued growing concurrently with the relative sea-level rise to reach FWB in the downslope position. The depositional environment in the downslope reefs, therefore, favored deposition of the coral *stromatoporoid boundstone* facies in the early organic reef stage.

A relative sea level rise combined with rapid reef growth led to form a carbonate bank represented in the reef interior position of both BRM and CIII reefs. Grainier facies in the reef margin and the slope positions are interpreted to have been transported from the reef interior contemporaneously with the deposition of the active carbonate bank (reef interior). This interpretation is based on the abundance of the skeletal fragments and the skeletal fragments in the margin and the slope positions.

Grainier facies in the slope and the margin positions are interpreted to have only deposited during the time of growth when reef buildup is above FWB (sea level fall), the high wave energy when relative sea level fall, resulted in the accumulation of the transported skeletal fragments in all sides surrounding the CIII and BRM buildups, due to a relatively higher energy currents and the abundance of the storms. The type of facies in the reef slope and margin positions in addition to the location of the facies relative to the reef interior, however, does not support a single wind direction proposed by Gill (1977) and Rine et al. (2017).
The early organic reef growth stage additionally includes the deposition of the *Skeletal wackestone* facies. The *skeletal wackestone* facies in the reef system can be formed in two different ways, this interpretation is based on the type of faunal assemblages and facies thickness:

The high resolution facies descriptions (centimeter by centimeter) that were performed in this study led to define thin layers of *skeletal wackestone* facies (<3 ft), which are interbedded with the coral boundstone of the organic reef (interior position) throughout the entire time of the reef growth. The interbedded skeletal wackestone characterized by the abundance of different types of skeletal fragments, the thin layers of the *skeletal wackestone* (associated with the skeletal fragments) could be formed at any time during reef deposition and might represent an organic reef shed). On the other hand, thicker layers (20-30 ft) of the *skeletal wackestone* facies were defined overlying the reef grainy facies. The thick packages of *skeletal wackestone* were correlated laterally in all reef positions. The thick packages of the *skeletal wackestone* facies, (which are relatively muddy facies) capped the underlying grainier facies in all reef positions which was interpreted due to an overall relative sea level rise and a slower rate of reef growth (Figure 4.6). This facies was interpreted to have formed between the storm wave base and Fairweather wave base (SWB-FWB). The interpretation of the thick *skeletal wackestone* facies is based on the abundance of the deeper water faunal assemblages and high mud content. The deposition of the thick *skeletal wackestone* in all reef positions represents a flooding event which marked a time equivalent surface in all reef positions.

The *skeletal wackestone* observed in CIII reef within the early organic reef stage is interpreted as contemporaneous to a sequence of facies in the BRM reef. This sequence starts with the first unit of the skeletal *wackestone* from the bottom, transitions up section to coral boundstone, and then transitions to another *skeletal wackestone* facies (Figure 4.6). The correlation is based on
the exposure surfaces which bounded the depositional sequence of the early organic reef stage in CIII and BRM reefs. (Figures 4.6 & 4.9).

Generally, more vertical facies change can be seen in the BRM (upslope reef) compared to CIII (downslope reef) for the same reef position (reef interior for example). This observation supports the general understanding that the BRM reef was located closer to the shoreline at the time of reef deposition. Because they are closer to sea level, upslope reefs are more likely to experience facies responses compared to more basinward reefs. This is assuming that both reefs have grown at the same time (Rine et al., in preparation). The end of the early organic reef stage is marked by the facies shift from skeletal wackestone to coral stromatoporoid boundstone in both the deeper (CIII) and the shallower (BRM) reefs which marked another time of high reef growth above FWB.
Figure 4.6. Stratigraphic cross section shows Stage 2-A, the early organic reef stage, the early organic reef material deposition. Refer to figure 4.5 for cross section orientation.
Stage 2B: Late Organic Reef Growth

The late organic reef stage is marked by a facies shift from *skeletal wackestone* of the early stage up section to the *coral stromatoporoid boundstone* of the late organic reef stage. A transition from the early to the late stage is also evidenced by the presence of the exposure surface between the two facies (Figure 4.6 & 4.7). Following the end of the early organic reef growth and the deposition of the *skeletal wackestone* facies with deeper water organisms is evidence of possible exposure surfaces. Following the exposure surface is a gradual shift of reef facies that is associated with shallower water, wave resistance organisms (mostly tabulate corals and stromatoporoid). The deposition of the reef grainer facies following the exposure surface is indicative of a slow relative sea-level rise, resuming the reef growth after the subaerial exposure event concurrent with period of the growth of the coral stromatoporoid, reef builders (due to the suitable high energy environment) which allowed the reef buildup to grow above FWB.

Similar to the facies of the slope and the margin position in the early organic reef stage, the grainier facies are associated with the margin and the slope positions during the late organic reef stage and are interpreted as a facies deposited only in high energy environments when reef grows above FWB. This facies is interpreted as comprising transported material from the active carbonate bank (reef interior position) to the slope and the margin positions in both BRM and CIII reefs.
Figure 4.7. Stratigraphic cross section shows Stage 2-B, the late organic reef stage, the late organic reef material deposition. Refer to figure 4.5 for cross section orientation.
The abundance of the reef grainy and muddy facies in the reef slope and margin positions in the form of cyclic muddy-grainy vertical facies distributions supports the interpretation that the grainy facies in these positions were transported during the time of relative sea level fall due to relatively higher energy of water currents when reef buildup is above FWWB. The grainy transported facies on the slope and margin reef positions is then followed by *skeletal wackestone* facies (reef muddy facies) that could either be transported from the reef interior (carbonate bank) or alternatively, the *skeletal wackestone* in the slope and margins possibly deposited because of the relative sea level rise event. However, a detailed mapping the slope and margin facies in the CIII and BRM reefs indicated that the distribution of the transported facies surrounding the reef is not consistent with a specific direction, which does not support the control of one paleo-wind direction during the time deposition. The late organic reef stage end with the deposition of the *skeletal wackestone* in all reef positions which could possibly be the result of the relative sea level rise.

Stage 3: Stromatolite Boundstone Cap

The deposition of the *stromatolite boundstone* suggests a phase change from the underlying transgressive stage to the regressive stage, during the time of relative sea-level fall (Figure 4.8).
Figure 4.8. Stratigraphic cross section shows Stage 3, the deposition of the *stromatolite boundstone* after relative sea level dropped and reef growth was terminated. Refer to figure 4.5 for cross section orientation.
The *stromatolite boundstone* facies is interpreted to have been deposited due to the slow of relative sea level rise concurrent to the rapid reef growth which resulted in the deposition of the intertidal facies of the *stromatolite boundstone* (Rine, 2015). Deposition in the intertidal environment is reflected in the higher abundance of laterally-linked hemispheroidal forms of stromatolites. This is interpreted to reflect higher energy conditions (Rine, 2015) which favor the growth of the hemispheroidal forms of stromatolites (World, 2008; Rine, 2015). Following this stage is the lowstand phase and the deposition of the lower Salina A-1 Anhydrite and the termination of the reef growth (Rine, 2015).

Different numbers of vertical facies change in the upslope and the downslope reefs (for the same reef position) further support the control of the sea level fluctuation on the reef facies distribution (Figure 4.9). Different type of facies in the CIII and BRM reefs, as well as the number of the vertical facies changes in BRM relative to CIII reef, suggests that BRM is likely deposited in a shallower water depth relative to CIII reef. This argument is further supported by the thickness of the *crinoidal mudstone* facies as described below:

The *crinoidal mudstone* facies includes crinoid and bryozoan, which are not wave-resistant organisms (Wood, 1999) Therefore, these facies are interpreted as a facies reflecting deposition in relatively lower energy conditions (it can possibly be due to the deposition of this facies below storm wave base if only water depth is controlling the deposition), which allowed the Formation of a reef bioherm mud mound that underlies the organic reef growth.
Figure 4.9. Stages of the Silurian reef growth. Stage 1: bioherm initiation; Stage 2-A, early organic reef stage which is overlying the bioherm and bounded by exposure surfaces from top/bottom; Stage 2-B represents the interval between the second exposure from the top and the *stromatolite boundstone* facies; Stage 3 is the deposition of the *stromatolite boundstone*. BRM demonstrated a slightly different type of facies and a greater number of vertical facies change in the early organic reef stage. Comparison of shallower and deeper reef characteristics also presented in this figure.
The biohermal mound is interpreted to have grown upward into shallower-water, higher-energy conditions, as evidenced by a gradual increase of corals and stromatoporoid towards the upper half of the bioherm. Assuming that the hypothesis that all Silurian reefs in the Michigan Basin grew during the same time (Rine et al., 2018 in preparation) is valid, then the thickness of the bioherm should represent the relative water depth for any reef. This could explain why reefs that have grown downslope have thicker bioherms. The bioherm growth was keeping up with sea level therefore, the bioherm thickness is less in the upslope reef. This statement is true assuming that the reef deposition is on a gently dipping ramp/slope with a continuously deepening basinward. However, the Silurian reef literature (Gill (1977; Rine et al. 2017) provided a big range of CIII and BRM Bioherm thickness. Rine et al. (2017) reported 140 ft as a maximum bioherm thickness in CIII reef, this value is close to the thickness of the bioherm observed from CIII reef this study (160 ft). Gill (1977), on the other hand, documented a maximum thickness of BRM bioherm (245 ft) which is very different than what we documented here (150 ft). The same log signature (GR 18 API peaks) and rock criteria that were used by Rine et al. (2017) to define the bioherm thickness in CIII, were also used here to define bioherm thickness in CIII and BRM. The thickness of the Bioherm that was defined in this study from CIII is also close to the thickness value that was documented by Qualman (2009). The difference in the CIII Bioherm thickness between Rine et al. (2017) and this study (5-10 ft difference) probably depends on how both studies pick the top of the bioherm, which isn't trivial. The bioherm thickness discrepancies are from the BRM bioherm thickness value that Gill (1977) reported (95 ft difference if compared to this study) this difference is probably because Gill (1977) used different criterion (top and bottom datums) to define bioherm.
CHAPTER V
CONCLUSIONS

In order to most effectively convey the conclusions, the fundamental research questions are reexamined. The first question is: Can sequence stratigraphic models constrain and predict the high-resolution lateral and vertical facies distribution of the Niagara reefs in the Michigan Basin? More vertical facies change can be seen in the shallower reefs (BRM) compared to the deeper downslope reefs (CIII). This observation supports the general understanding that the BRM reef was located closer to the shoreline at the time of reef deposition. Because they are closer to sea level, upslope reefs are more likely to experience facies responses compared to more basinward reefs. The reef grainier facies (coral boundstone, skeletal grainstone, and coral rudstone) are only produced during relative sea level fall events in all reef positions. Following the relative sea level, fall events are the relative sea level rise that causes the deposition of the muddier facies (Skeletal wackestone). The skeletal wackestone facies capped the reef grainier facies in all reef positions. Based on vertical facies changes in both reefs, high-frequency depositional cycles were interpreted in the deeper and the shallower Silurian reef within the organic reef stage (stage 2). Based on the reef vertical facies change, flooding and exposure surfaces, the organic reef stage was divided into two stages, the early and late organic reef stages. The different organic reef stages are discriminated by exposure surfaces, these stages are correlative between different reefs along the depositional slope.
The sequence stratigraphic model suggested four high-frequency depositional cycles in the reef interior position of the deeper reefs. These high-frequency cycles can be correlated to the high-frequency cycles of the interior position of the shallower reefs (BRM). Less depositional cycles can be obtained in other reef positions (reef slope and margin positions), this is interpreted due to the high turbulent current that can in some cases transport sediments from the active carbonate bank (reef interior) to the reef margin and slope positions during relative sea level fall.

The 2nd question is: What is the general geometry of the reef and how are sediments spatially distributed within the reef complex? Silurian reefs overall geometry indicates an asymmetry towards different directions. More specifically, the deeper reef (CIII) is asymmetric with a steeper slope on the east, whereas the shallower reef (BRM) is asymmetric with a steeper slope on the west. We concluded that the reef overall geometry was not the result of a single dominant paleo-wind direction. The variable reef overall geometry, in addition to the internal facies distributions both permit two possible dominant paleo-wind directions in different time periods of the reef growth. Furthermore, high-resolution facies distribution doesn’t show any consistency with any of the proposed paleo-wind directions (Gill 1973; Wold 2008; Rine et al. 2017). The abundance of a similar facies (the skeletal grainstone and the skeletal wackestone) on both E-W sides in addition to the south sides of BRM and CIII reefs provided further evidence that facies distributions were not controlled by paleo-wind direction Additionally, Based on the higher resolution facies distributions reported in this study, the lithoclast-coral rudstone was observed in the reef interior position interfingered with the coral boundstone in addition to the abundance of the coral rudstone in the eastern, western and the southern margin/slope positions. This observation is inconsistent with the arguments by Ingles (1963), Gill (1973), Wold (2008) and
Rine et al. (2017) which used the abundance of the *coral rudstone* in the slope position as evidence of paleo-wind directions.

The 3rd question is: *What are the main geological controls on Niagaran pinnacle reef facies distribution?* CIII and BRM indicated facies stacking patterns in all reef positions are indicative of the sea level fluctuation control on Silurian reefs deposition. The reef grainier facies (*coral boundstone, skeletal grainstone, and coral rudstone*) are always followed by the deposition of the muddier facies (*Skeletal wackestone*). The *skeletal wackestone* facies has then capped another reef grainier facies in all reef positions. The vertical facies stacking patterns are in some cases discriminated by exposure surfaces which are indicative of sea level fluctuation control on reef facies deposition. The greater number of vertical facies changes in the shallower reefs compared to the deeper reefs is additionally indicted the water depth control on the reef facies deposition.
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Purkis, S. J. and Harris, P. M. Cavalcante, G.,2017, Depositional Facies Patterns Across the Modern Great Bahama Bank: Guidelines for Sequence Stratigraphic Correlations in Ancient Systems. 36th Annual GCSSEPM Foundation Perkins-Rosen Research Conference December 2017, Houston, TX


APPENDIX A
Additional Facies Core Photographs and Facies Stratigraphic Position
CIII interior well section-Well # 27778

Facies name: stromatolite boundstone/cap

Dunham Texture: Boundstone
Color: dark-light brown
Grain Size: Grainy facies
Faunal Composition: stromatolites
Por/perm: 12-18 % phi; 5-106 mD Q
CIII interior well section-Well # 27778

Facies name: skeletal wackestone

Dunham Texture: Wackestone
Color: light brown
Grain Size: muddy facies
Faunal Composition: reef rugose corals (Roc), crinoids (Cr), brachiopods (Br),

Por/perm: 8-12 % phi; 7-100 mD Q
CIII interior well section-Well # 27778

Facies name: coral stromatoporoid boundstone

Dunham Texture: Boundstone
Color: dark brown
Grain Size: Grainy facies
Faunal Composition: stromatoporoid/tabulate corals
Por/perm: 12-18 % phi; 200-500mD Q
Facies name: skeletal wackestone

Dunham Texture: Wackestone
Color: light brown
Grain Size: muddy facies
Faunal Composition: reef rugose corals (Roc), crinoids (Cr), brachiopods (Br),

Por/perm: 8-12 % phi ; 7-100 mD Q
CIII interior well section-Well # 27778

Facies name: coral stromatoporoid boundstone

Dunham Texture: Boundstone
Color: dark brown
Grain Size: Grainy facies
Faunal Composition: stromatoporoid/tabulate corals
Por/perm: 16-22 % phi; 200-500mD Q
Facies name: coral rudstone

Dunham Texture: Wackestone
Color: light brown
Grain Size: muddy facies
Faunal Composition: tabulate corals (fragments)
Por/perm: 14-20 % phi; 180-400mD Q
Facies name: coral stromatoporoid boundstone

Dunham Texture: Boundstone
Color: dark brown
Grain Size: Grainy facies
Faunal Composition: stromatoporoid/tabulate corals
Por/perm: 12-18 % phi; 200-500 mD Q
CIII interior well section-Well # 27778

Facies name: crinoid mudstone contact

Dunham Texture: Mudstone
Color: dark gray
Grain Size: muddy facies
Faunal Composition: Crinoids
Por/perm: 7-20 % phi ; 0.1-250mD Q
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BRM interior well section-stromatolite boundstone/cap core
Well # 25269

[Graph and image of core sample]
### BRM interior well section-coral/stromatoporoid boundstone

#### Well # 25269

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#### PN # 25269

- Depth (ft): 2300
- Image of samples at different depths.
BRM interior well section-skeletal wackestone
Well # 25269

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**BRM interior well section-skeletal grainstone**

**Well # 25269**
APPENDIX B
Additional Core Profiles
BRM reef slope VFA
 PN #23671

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MD: Meters Deep
GR: Gamma Ray Absorption
NEUT: Neutron
BRM reef rudstone slope VFA

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A-1 Carbonate

stromatolite boundstone

coral rudstone

Skeletal wackestone

crinoid mudstone
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APPENDIX C
Facies Stacking Patterns with Brown Niagaran Thickness.