MIXED SILICICLASTIC-CARBONATE SYSTEM OF THE MIDDLE MEMBER OF THE 
BAKKEN FORMATION, WILLISTON BASIN, NORTH DAKOTA

by

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ABSTRACT

The Middle Member of the Bakken Formation (MM-BF) is a mixed siliciclastic-carbonate unit deposited in the shallow, epeiric shelf setting of the Williston Basin during the Famennian-Tournaisian Transgression. The MM-BF in North Dakota consists of six distinct units (MB-A to F) but primarily can be divided into: (1) lower variably calcareous dolomitic siltstone, (2) middle calcareous grainstone-sandstone, (3) and upper argillaceous dolomitic siltstone.

Stratigraphic analysis of subsurface core reveals that the lower siltstone unit (MB-A, B, & C) was deposited in a tide-dominated, wave-influenced environment as part of a highstand to falling stage systems tract. The middle MM-BF sandstone (MB-D) is a lowstand systems tract (LST) deposited in tide-dominated, wave-influenced environments. The upper MM-BF siltstone (MB-E & F) contains tide-dominated environment in a transgressive systems tract. Cycle analysis of alternating siliciclastic-carbonate intervals reveals that the interplay of tides, storms, and seasonal changes in oceanic surface current played an important role in the mixing of carbonate and siliciclastic constituents within the MM-BF.

The calcareous sandstone-grainstone of MB-D presents unique opportunity to investigate mechanisms of sediment delivery and siliciclastic-carbonate mixing in an epeiric shelf/low-angle ramp setting. The grain size, mineralogy, and zircon trends indicate a siliciclastic delivery system that originated from a northern ephemeral drainage system. Reworked carbonate grains were sourced from intra-basinal paleo-highs and subjected to significant storm and wave reworking.

The discontinuous nature of MB-D is due to both depositional and erosional thinning. Thickness variations of this facies are similar to modern oolitic environments where shoal and bars are cut and incised by tidal channels. The base of the MB-D is a 3rd order sequence boundary (Ss5) and the top of the unit is a transgressive surface of erosion event (Ss6). Variations in thickness are related to these two services. With the presence of erosional thinning, MB-D may not represent a complete depositional environment and is a depositional or accommodational remnant. MB-D thick trends in the north-northwestern part of the study area are preserved offshore bars that
developed on topographic or bathymetric highs. In the northeast- and central part of the study area, MB-D thicker sections are bats that filled bathymetric lows or are incised channels.

This study also presented a comprehensive initial look at the basic reservoir properties of the MM-BF in North Dakota. Porosity-permeability-grain density cross plots along with UV fluorescence reveal that early burial calcite cement prevented dolomitization, and this cement has detrimental effects on the reservoir properties of MM-BF.

Core mechanical analysis was conducted using a micro-rebound hammer, Proceq Bambino, to acquire the Leeb hardness value of the rock. Hardness refers to the measure of resistance to a permanent deformation and can lead to the evaluation of fine-scaled heterogeneity and anisotropy of the rock. The micro-Schmidt hammer data show small-scale heterogeneities within the MM-BF at the bed to lamina-scale.
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CHAPTER 1: INTRODUCTION

The Fammenian-Tournaisian Bakken Formation of the Williston Basin has garnered renewed exploration activity with recent technological developments. Advances in horizontal drilling and completion methods have unlocked the potential of these tight reservoirs. Current interests are focused on the Middle Member of the Bakken Formation (MM-BF), which is a primary target for oil and gas operations in the Williston Basin.

The MM-BF is a heterogeneous reservoir that contains mixed siliciclastic-carbonate lithologies. Evaluating productive zones can be complicated due to this heterogeneity, as variations in lithology, secondary porosity, and permeability development are related to enhanced production in select areas. Recent estimates suggest the MM-BF contains 3.65 billion barrels of technically recoverable oil (Gaswirth et al., 2013); therefore proper reservoir characterization is critical.

Despite studies that have been done on the Bakken, numerous questions remain about the depositional environment and stratigraphic evolution of the MM-BF in North Dakota. There is considerable debate on a prominent sandstone-grainstone interval, the Middle Bakken D (Sonnenberg et al., 2011), that varies in thickness and carbonate-clastic content. This unit is a conventional reservoir in SE Saskatchewan (Kohlruss & Nickel, 2011) and exhibits the highest depositional energy and lowest base-level during Bakken time. Understanding the origin and extent of this unit may aid in the overall interpretation of depositional environments, provenance and sequence stratigraphy for the Bakken Formation in North Dakota.

This study examines Middle Bakken D in North Dakota focusing on the origin of coarser-grained sediments and the mixing of siliciclastic-carbonate constituents. In addition to stratigraphic analysis, documentation of reservoir quality and mechanical properties of the MM-BF were performed to better characterize heterogeneities within this complex reservoir system.
1.1 Objectives and Purpose

The objectives of this study are to (a) document the environmental conditions in which the MM-BF was deposited, (b) to document facies changes across the North Dakota part of the Williston Basin, and to provide a large dataset compiled from several sources to serve for further MM-BF research. Specifically, this study addresses:

1) Depositional environments of MM-BF unit D, its geometry, continuity and contact relationship to underlying and overlying units;

2) Provenance and cyclicity of clastic and carbonate sediments;

3) Reservoir quality and mechanical properties;

This thesis will help address stratigraphic architecture of the Bakken Formation in North Dakota by documentation and interpretation of sedimentary facies, provenance, sequence stratigraphy, and reservoir properties. An interpretation of the study area is aided by a significant number of new cores that were taken during the last 10 years. Identifying the origin of Unit D will help increase understanding of the depositional controls and paleo-environments of the MM-BF by focusing on the source and mixing of siliciclastic and carbonate constituents. Lastly, reservoir quality and mechanical properties of the MM-BF are addressed to aid companies in selecting potential production targets.

1.2 Study Area

The study area is located in western North Dakota within the southeastern part of the Williston Basin (Figure 1-1). The primary focus were all or portions of Burke, Mountrail, Renville, Ward, McLean, Mercer, Dunn, Stark, Billings, Golden Valley, McKenzie, William, and Divide counties. To help show distinct changes across the basin, a few wells were included from surrounding counties.
1.3 Database and Methods

This study utilized 1) core measurements, 2) well-logs, 3) petrographic thin sections, 4) elemental-mineralogical data and 5) rock-mechanics data to analyze the MM-BF.

Figure 1-1: Inset map showing distribution of the Bakken Formation and its age equivalents in the Williston Basin (from Smith and Bustin, 2000). The focus of study is in the southeastern part of the paleo-basin (highlighted in purple).

1.3.1 Core Analysis

The data used in this study is from a database of fifty drill cores that were all visually examined (Figure 1-2). Of these cores, ten were described at a scale of six inch to one foot. Lamina analysis and rock-mechanics testing was done in addition to high resolution description (Table 1-1). Drill cores also document sedimentary facies and surfaces. Sedimentary facies were defined by lithology, texture, sedimentary structures, biogenic features, and early diagenetic associations. Abundant, common, and rare are used to describe relative facies proportions. Ichnological elements are named for the
species name or for the burrowing habit of the organism. Bioturbation index (BI) of Taylor and Goldring (1993) was used to quantify biological disturbance in the rock. Measurements were compiled into spreadsheets and core descriptions were digitized with Adobe Illustrator and Golden Software Strater.

Figure 1-2: Locations of cores used in this study with key shown on Table 1-1.

Gent’s methodology (2011) was used describe carbonate-clastic cycles in Unit D of the MM-BF. Laminae from photographs (North Dakota Industrial Commission) were measured with ImageJ, a freeware developed by the National Institute of Health. Lamination thickness and laminae event numbers were then compiled into spreadsheets and input into the Fast Fourier Transform algorithm in MATLAB (Figure
Routine core analysis data such as porosity, permeability, fluid saturation, and grain density are available from well reports in the NDIC database, and these data were compiled into spreadsheets.

### 1.3.2 Well Log Analysis and Subsurface Mapping

Gamma ray (GR), bulk density (RHOB), neutron-density porosity (NPHI-DPHI), photoelectric effect (PEF), and resistivity logs were used to identify core-described facies on well-logs. Subdivisions of lithostratigraphic units and electrofacies in the Bakken Formation by Simenson (2010) served as the foundation for subsurface correlations. The areal extent of sedimentary facies and the stratigraphic evolution of the middle member were illustrated through the creation of regional cross-sections and isopach maps. Isopach maps and structure maps were created by digital (IHS Petra) and hand contouring.

### 1.3.3 Petrographic Analysis

Thin-sections were examined from a variety of facies to obtain a precise grain size range and analyze diagenetic features. In addition, visual estimates of mineralogy and porosity were conducted and matched to core analysis and X-Ray diffraction (XRD) data to further characterize the provenance and reservoir quality of the middle member. Most petrographic thin sections were from the USGS Core Research Center and NDGS Wilson M. Laird Core Library. Additional thin sections were made at Weatherford Labs in Golden, Colorado. Most thin sections were impregnated with blue-dyed epoxy, and half-stained with alizarin red and potassium ferricyanide dye for carbonate differentiation.

### 1.4.4 Elemental and Mineralogic Analysis

X-Ray Diffraction allows the identification of minerals based on the unique spacing of the mineral structure of each individual mineral. XRD data were utilized to understand the effect of mineralogy on reservoir quality and mechanical properties of the middle member. Reported as semi-quantitative results, the data were compiled from a variety of cores in the study area. To better approximate sedimentary influx and early diagenetic influence, high resolution elemental data were also analyzed. Most of the
elemental data were obtained using the handheld energy dispersive x-ray fluorescence (ED-XRF) tool.

1.3.5 Rock Mechanics Analysis

Data obtained from triaxial tests were used to characterize the mechanical properties of various MM-BF lithofacies. Due to the destructive nature of these triaxial testing, rock-mechanics data are sparse. To supplement the traditional rock-mechanics data, non-destructive testing with the Proceq Bambino rebound hammer was performed (Figure 1-4). The methodology applied to measuring the Leeb hardness values while using the micro-rebound hammer follows a similar approach taken by Ritz and others (2014). Measurements near the center of core samples are more reliable than measurements taken near the edge of the core. Triaxial testing results were compared to Bambino measurements. Leeb hardness values (HLD) were then converted to unconfined compressive strength (UCS) values by cross plotting available data with derived data. A more detailed account on the Bambino data gathering can be found in Murray (2015) and Rolfs (2015).
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CHAPTER 2: GEOLOGIC SETTING

The following chapter outlines the geologic evolution of the study area by first examining the structural framework and timing of events related to the genesis of the Williston Basin, and secondly by describing the stratigraphic elements pertaining to this study.

2.1 Structural & Tectonics

The Williston Basin is an oval-shaped intracratonic basin that extends over parts of North Dakota, South Dakota, and Montana of the United States and Canadian provinces of Saskatchewan and Manitoba (Figure 2-1). The Williston Basin formed during Late Cambrian time (~500 ma). At the basin center, there are over 16,000 ft of Phanerozoic sediments (Gerhard et al., 1990).

2.1.1 Basin Subsidence

There are two hypotheses as to what initiated subsidence of the Williston Basin: 1) a thermal subsidence model by Fowler and Nisbet (1985), and 2) a Proterozoic left-lateral wrench fault system model by Gerhard and others (1990). In the Precambrian (~2.0-1.8 Ga), convergence of the Churchill Hinterland and the Superior Province formed the Trans-Hudson Orogenic belt. Fowler and Nisbet (1985) proposed the cooling and thermal contraction of a mafic body that was emplaced during the Trans-Hudson Orogeny as the primary cause of subsidence.

The North American plate then rifted apart and created a series of major basement faults in the late Precambrian (~1000 Ma). The model proposed by Gerhard and others (1990) argues that the shearing of these deep-seated lineaments is the main cause of subsidence. Shearing also controlled the development of major structural components within the Williston Basin, such as the Nesson Anticline. Plate collision during the Antler and Ancestral Rockies orogenies in the Late Paleozoic (~300 ma) reactivated the lineaments. Further deformation during the Laramide orogeny in the latest Cretaceous (~60 ma) and early Tertiary formed most of the tectonic features in the basin (Figure 2-3).
Figure 2-1: Map depicting the areal extent of the intracratonic Williston Basin. The basin covers parts of ND, MT, SD, Saskatchewan and Manitoba. Also shown on the map are the Precambrian basement blocks and suture zone (Wyoming, Superior, and Trans-Hudson) and major lineaments (Brockton-Froid and Colorado-Wyoming) that influence basin sedimentation and structural boundaries (from Cobb, 2013; after Gerhard et al., 1990).
2.1.2 Major Structural Features

Flexural subsidence and ancient wrench-fault systems are the dominant structural controls in the Williston Basin (Sloss, 1963; Gerhard et al., 1990). To the north and northwest, the lower Paleozoic Meadow Lake Escarpment and the late Devonian Sweetgrass Arch bound the basin (Figure 2-2). To the southwest, The Williston Basin is separated from the Powder River Basin by the Miles City Arch and Tertiary Black Hills Uplift. The Silurian Transcontinental Arch and the Sioux Arch define the southeastern and eastern boundaries of the Williston Basin (Gerhard et al., 1990; LeFever, 1992).

Figure 2-2: Regional paleostructure and paleogeography during the Paleozoic and Mesozoic (modified by Gent, 2011; from Peterson and MacCary, 1987)

The most prominent features in the North Dakota and Montana portions of the basin are the Nesson and Cedar Creek anticlines (Figure 2-3). Smaller but significant
structural features within the US part of the Williston Basin include the Billings Nose, Little Knife Anticline, Antelope Structure, and Poplar Dome Anticline. Early petroleum exploration focused on these large structural features, and all of the features are still producing (LeFever et al., 1987).

Figure 2-3: Prominent structural features within the Williston Basin. The left lateral wrench fault system may have created the Brockton-Froid fault zone. Nesson, Cedar Creek, and Little Knife anticlines are all structures associated with significant oil production (from Gerhard et al., 1990)

2.1.3 Nesson Anticline

A north-south trending structure, the Nesson anticline has two significant faults with one along the western edge of the anticline and another along the Antelope 'arm' of
the anticline. The movement along the Nesson anticline was initiated during the Precambrian. The greatest movement however, took place during the Devonian and early Mississippian (LeFever et al., 1987). The structure was formed by several hundred ft of Precambrian basement displacement. A second pulse of vertical movement along the anticline occurred during the Ancestral Rocky Mountain orogeny. A reversal in direction along the Nesson Fault occurred during the middle Permian due to a change in the stress regime. Gerhard and others (1990) attributed the asymmetric geometry of the anticline and deep dip along the west flank to the fault reversal.

2.2 Stratigraphy

The Bakken Total Petroleum System (TPS) includes Three Forks, Bakken and Lodgepole Formations (Figure 2-4). In the Late Devonian, the Williston Basin was open to the Antler Foreland Basin, Devonian Seaway, and Elk Point Basin (Figure 2-5). The Three Forks Formation was deposited during the Lower Kaskaskia (Gerhard et al., 1990; Sloss, 1963). An unconformity separates the Lower and Upper Kaskaskia sequence. Movement along the Transcontinental Arch and the uplift of the Sweetgrass Arch separated the Williston Basin from the Antler Foreland Basin and the Devonian Seaway. This event created a shift in sedimentation in the Williston Basin. The Bakken Formation was deposited in the Williston Basin during a regressive-transgressive cycle in the Late Devonian to Early Mississippian time. Deposition was in a shallow, epeiric sea. The Bakken and overlying Lodgepole are part of the Upper Kaskaskia sequence.

2.2.1 The Underlying Three Forks Formation

The Three Forks Formation conformably overlies the Birdbear and is unconformably overlain by the Bakken Formation. In Canada, it is known as the Torquay Formation of the Qu’Appelle Group. It is Late Devonian in age and consists of mudstones, silty to sandy dolostones, and anhydrites. The Three Forks can be divided into three different members (Figure 2-6). From oldest to youngest they are: lower (LTF), middle (MTF), and upper (UTF).

The LTF was deposited in a low-energy, supratidal (sabkha) environments (Newnam, 2015). The MTF is recognized as storm sediments deposited in a lower
supratidal to upper intertidal environments (Gantyno, 2010; Theloy, 2013). The UTF comprises a variety of depositional environments ranging from shallow, low-energy marine to tidal flat environments. The Three Forks represents an overall deepening within the transgressive Lower Kaskaskia sequence. The unconformity at the top of the Three Forks is associated with a major sea level fall during the Devonian-Mississippian transition.

The Three Forks is considered an unconventional reservoir and thought to be primarily charged by the overlying Lower Bakken Shale and, at the base, by the underlying Duperow and Birdbear (Bazzell, 2014). The upper and parts of the middle Three Forks comprise the lowermost portion of the Bakken Petroleum system. In the Williston Basin, the Three Forks reaches a maximum thickness of 270 ft near the basin center and thins toward the basin margins (Bottjer et al., 2011).

### 2.2.2 The Bakken Formation

The Late Devonian-Early Mississippian Bakken Formation is called the Sappington Member of the Three Forks Formation in western Montana and the Exshaw Formation in Alberta (Sandberg & McQueen, 1970; Sandberg et al., 1983). In the Williston Basin, the Bakken Formation is subdivided into four formal members: Pronghorn, Lower Bakken Shale (LBS), Middle Member and Upper Bakken Shale (UBS) (LeFever et al., 2011).

#### 2.2.2.1 Pronghorn Member

The Pronghorn is the basal member of the Bakken Formation and it lies above the regional unconformity separating the Three Forks and the Bakken formations. Lithofacies includes sandstone, siltstone, skeletal lime wackestone and packstone, and shale that are part of an overall deepening (Figure 2-7). The Pronghorn is thickest in North Dakota in the south central portion of the basin. Thick trends are oriented northwest-southwest and parallel the Cedar Creek Anticline (Johnson, 2013).

#### 2.2.2.2 Bakken Shales

The Upper (UBS) and Lower Bakken (LBS) shales are black organic-rich, siliceous, and pyritic (Cobb, 2013). The UBS is thinner, more organic rich, and covers a larger areal
extent than the LBS (Figure 2-8). The Bakken shales were deposited in a relatively shallow, marine setting during sea level rise (Smith and Bustin, 1996; LeFever et al., 1991). A stratified water column created an anaerobic setting which preserved organic-rich (Figure 2-9).

Figure 2-4: Stratigraphic column of the Williston Basin with geologic age, major Sloss sequences and regional unconformities (modified by Cobb, 2013; Kowalski, 2010; after Gerhard et al., 1990).
Figure 2-5: Paleogeographic reconstruction of (A) the Lower Kaskaskia sequence in the Late Devonian (360 Ma) showing the connection between Williston Basin and Elk Point Basin (W-E); and (B) Upper Kaskaskia sequence in the Early Mississippian (325 Ma) showing the shifting of the Williston Basin (WB) and the uplift of the Sweetgrass Arch that separates the Williston Basin from Alberta Basin (AB) (modified from Blakey, 2005).
Figure 2-6: (A) Subdivision of the Three Forks Formation according to various authors (modified by Bazzell, 2014; from Bottjer et al., 2011). (B) Lithofacies and depositional model for the Three Forks Formation depicting a shallow epeiric platform or ramp under arid climate conditions (from Franklin and Sonnenberg, 2012).
Figure 2-7: Lithofacies of the Pronghorn Member. The facies succession is part of an overall sea level rise (from Johnson, 2013).
Figure 2-8: (A) Sub-crop limits of the Bakken shales and the middle member. (B) Sub-crop extents show the onlapping character along what is interpreted to be the depositional or erosional limit of the three different members. (C) Vertical distribution of organic matter within the Bakken shales. Average TOC values for the lower and upper shale are 11.5% and 12.1% respectively (modified by Gent, 2011; from Webster, 1984).
Figure 2-8: Continued
Figure 2-9: This schematic depicts the shallow marine depositional environments of the Lower and Upper Bakken shales. Anaerobic environments were created by a stratified water column (modified by Sonnenberg, 2011; from Smith and Bustin, 1996).

Figure 2-10: Isopach of the MM-BF showing an isopach thick east and north of the Nesson Anticline (modified by Gent, 2011; from Webster, 1984).
Figure 2-11: Lithofacies and depositional model for the Lower Lodgepole depicting a low-energy carbonate ramp (from Mackie, 2013).

Table 2-1: Table showing the exploration history of the Bakken play (from Gent, 2011)

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<td>1950s to 1960s</td>
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<td>1973</td>
<td>Oil Embargo – Surge in North America exploration</td>
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<td>Late 1970s</td>
<td>Vertical wells targeting upper Bakken shale on Billings Nose structure</td>
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<td>1982</td>
<td>Oil price collapse</td>
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<td>1980s</td>
<td>Decrease in exploration activity</td>
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<td>1987</td>
<td>Devonian pinnacle reef discoveries in Saskatchewan</td>
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<td>1987</td>
<td>First Bakken horizontal well discovery - Meridian Oil MOI No. 33-11</td>
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<td>Elm Coulee discovery – Richland County MT</td>
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<td>2005</td>
<td>Parshall field discovery by EOG Resources and Michael Johnson</td>
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Figure 2-12: Graphs showing (A) horizontal wells by formation and (B) cumulative horizontal production of oil and gas in the Williston Basin, North Dakota (data from NDIC, 2015). Note that the MM-BF has the most horizontal completions and production.
2.2.2.3 Middle Member of the Bakken Formation (MM-BF)

The MM-BF lithology is highly variable throughout the basin and exhibits mixed siliciclastic-carbonate character. The Middle Bakken is divided into stratigraphic units based on lithology, sedimentary structures, and biota. Brachiopods, bryozoans, conodonts, gastropods, and ostracods are rare to moderately common at the base and top of the middle member. Bioturbation and the faunal assemblage suggest open to oxygen-stressed environments. Common diagenetic features within the MM-BF include pyrite replacement of bioclastic material, pyrite nodules, calcite cement, and dolomitization. The Middle Bakken is massively-bedded, bioturbated to planar laminated, and trough cross-stratified. The MM-BF depocenter is located east of the Nesson Anticline where the member reaches a maximum thickness of approximately 90 ft (Figure 2-10).

2.2.3 The Overlying Lodgepole Formation

Within the Williston Basin, the Mississippian-aged Lodgepole Formation conformably overlies the Bakken Formation. The Lodgepole Formation is part of the Madison Group and reaches a maximum thickness of 900 ft in eastern McKenzie County (Heck, 1979; Webster, 1984). The lower portion of Lodgepole is considered to be the uppermost units of the Bakken TPS (Bottjer et al., 2011). The Scallion is the basal member of the Lodgepole and is described as an argillaceous, cherty and micritic limestone with a high degree of bioturbation (Figure 2-11). The Scallion also contains an organic-rich pyritic shale bed commonly termed the “False Bakken”. The impermeable limestones of the Lodgepole act as a regional seal for the Bakken TPS. There is production from the lower Lodgepole in Stark County from Waulsortian-type mounds (Theloy, 2013; Bazzell, 2014).

2.3 Petroleum System and History

Oil was first produced from the Bakken in North Dakota in 1951 when Amerada Hess drilled on the Nesson anticline (LeFever et al., 1991). As technology advances allowed for horizontal drilling, Meridian Resources drilled the first horizontal well into fractured Upper Bakken Shale in 1987 (EERC, 2013). It was not until 2000 that the first horizontal well was drilled into the MM-BF by Lyco Energy in Elm Coulee (Table 2-1). A
recent USGS geological study has estimated the Bakken and Three Forks Formation to have a mean recoverable oil resource of 3.65 and 3.73 billion barrels respectively (Gaswirth et al., 2013).

The Bakken Petroleum System is considered to be a continuous unconventional tight oil accumulation based on pervasive hydrocarbon saturation over a very large geographic area and the lack of well-defined down dip oil-water contact. The system is abnormally pressured in many locations and hydrocarbon accumulation is enhanced by stress induced fracturing and partings (Sonnenberg, 2010). Production from low porosity and permeability reservoirs is associated with low recovery rates and low water production. The reservoir units of the Bakken petroleum system include the upper Three Forks and the MM-BF. As the play evolves more productive intervals are being identified and targeted including the upper and middle Three Forks and the Pronghorn Member. However, the MM-BF is still the most sought after target in the Williston Basin and will be the main focus of this thesis (Figure 2-12).
CHAPTER 3: MIDDLE MEMBER OF THE BAKKEN FORMATION (MM-BF)

This chapter contains a summary of relevant work on the Middle Member of the Bakken Formation (MM-BF).

3.1 Age Relationships and Biostratigraphy

Hayes (1985) and Karma (1991) assigned a Famennian age to the Lower Bakken Shale and a Kinderhookian age to the Upper Bakken Shale based on conodont biostratigraphy. The Late Devonian–Early Carboniferous boundary is within the MM-BF (Figure 3-1).

3.2 Depositional Environment and Sequence Stratigraphy

The MM-BF records a complex depositional history, involving several sea-level changes and a wide range of depositional reconstructions by various authors. Interpretations range from progradational wave-dominated to transgressive tidally-influenced depositional environments.

Christopher (1961) subdivided the MM-BF into two units which include a calcareous siltstone and a heterolithic unit containing a combination of mudstone, siltstone, and very fine- to fine-grained sandstone. In Christopher’s model, the MM-BF is comprised of allochthonous sediments that were deposited in shallow marine, transgressive environment.

LeFever and others (1991) identified seven lithofacies within the MM-BF based on core studies from 12 North Dakota wells. LeFever and others (1991) described the basal and upper most middle member as massive to laminated, fossiliferous, with abundant bioturbation and pyrite. The middle lithofacies is interbedded massive, cross-stratified, and laminated, fine to medium-grained sandstones and mudstones with soft sediment deformation, ooids, and bioclasts. LeFever also noted a parallel laminated bed which she named the Central Basin Facies which underlies the oolitic sandstone lithofacies (LeFever, 1995).

Smith and Bustin (1996) proposed a wave-dominated shoreface model to explain the facies assemblage of the MM-BF (Figure 3-2). The middle member initially
progrades across a shallow-marine shelf as part of a regression. A transgression then led to the backstepping of these shoreface deposits and deposition of the upper shale. Smith and Bustin (1996) placed a sequence boundary between the lower and middle member of the Bakken Formation. Smith and Bustin (1996) also observed an average upward increase in grain size, upward thickening in sandstone beds, and an upward decrease in bioturbation within the MM-BF.

Figure 3-1: Geologic age of the Bakken Formation in North Dakota and Central Montana based on conodont biostratigraphy. Note that the Late Devonian-Early Mississippian boundary is placed within the middle member. The deposition of the middle member is thought to span approximately 10 million years (modified by Sonnenberg, 2015; from Sandberg et al., 1988; Hartel et al., 2012).
In west-central Saskatchewan, workers utilize a tide-dominated depositional model. These studies recognized a northeast-southwest trend to Bakken oil pools in west-central Saskatchewan (Figure 3-3). Kasper (1995) interpreted the middle member to be deposited in an open marine or estuarine setting. An interpretation by Toews (2005) involves a subtidal setting where sand ridges are deposited perpendicular to a paleo-shoreline. These sandstone bodies are linear and have asymmetric ridge and swale morphology. Toews (2005) also identified four transgressive-regressive cycles within the middle member, each capped by a flooding surface.

Canter and others (2008) focused on the MM-BF in Mountrail County, North Dakota. Using cores located in the Sanish and Parshall fields, they described five facies with additional subfacies. The overall depositional interpretation of Canter and others (2008) are similar to previous studies, but differ significantly on the origin of the parallel laminated sandy siltstone. Canter and others (2008) interpreted the sandy siltstone as distal storm deposits and prodelta hyperpycnal gravity flow deposits.

Eggenhoff and others (2011) identified eleven MM-BF facies and recognized six parasequences in the basin center and three to four parasequences in the basin margin. Eggenhoff and others (2011) interpreted the MM-BF as a lowstand systems tract with a transgressive surface at the top.

Hlava and others (2012) identified eleven facies and subdivided the MM-BF into a lower package, a middle package, and an upper package. Hlava and others (2012) placed a sequence boundary at the base of the MM-BF. The lower and middle packages are interpreted as lowstands separated by a second sequence boundary. The upper package was then deposited as a transgressive systems tract and eventually overlain by the Upper Bakken Shale.

Angulo and Buatois (2012) interpret the lower part of the MM-BF to be deposited in an open-marine, offshore to lower shoreface setting as part of a highstand systems tract. The upper section of the MM-BF was deposited in a marginal-marine embayment as part of an early transgressive systems tract (Figure 3-4).

The Colorado School of Mines (CSM) Bakken Consortium subdivides MM-BF into six units: (A) fine grained skeletal lime wackestone, (B) bioturbated argillaceous
siltstone, (C) laminated sandstone to siltstone, (D) calcareous cross stratified sandstone to oolitic and bioclastic grainstone, (E) laminated to bedded dolomitic siltstone, and (F) massive fossiliferous wackestone (Sonnenberg, 2011). Unit A, B, and C are upward coarsening highstand deposits.

Figure 3-2: The wave dominated shoreface model as presented by Smith and Bustin (1996). The mudstones and siltstones of MM-BF were deposited in offshore to lower shoreface settings. Sandstones represented middle to upper shoreface settings (modified by Smith and Bustin, 1996; from Walker and Plint, 1992).

Gent (2011) recognized an erosive contact between Middle Bakken C and Middle pocket D which she designated a sequence boundary. She interpreted Unit D to be a laterally discontinuous lowstand deposit. Within this lowstand, shoals rich in ooids, bioclasts, and carbonate muds were deposited by longshore currents. Gent (2011) analyzed the parallel laminae of unit C and identified semi-diurnal to mixed tidal cycles. Gent (2011) also proposed this model for the parallel laminated fabric of units D and E. Gent (2011) also recognized a possible erosive contact between unit D and E. The overlying MM-BF units (E and F) represent a progressive deepening. Unit E is interpreted to be deposited in an intertidal setting while unit F is deposited in a subtidal setting. Both units are transgressive deposits.
Unit D is calcareous sandstone in the northern part of the study area while in other parts of the basin it is limestone with minor clastic constituents (Theloy, 2013).

The various subdivisions, depositional models and sequence stratigraphic framework of the MM-BF are summarized below (Table 3-1; Table 3-2).

Figure 3-3: Map showing producing Bakken oil pools in west-central Saskatchewan. Note the overall northeast-southwest linear trend of the wells (from Chabanole, 2015).
3.3 Reservoir Properties & Rock Mechanics

Recent Colorado School of Mines consortium studies in North Dakota have focused on the MM-BF in the Parshall-Sanish area in Mountrail County where there is prolific oil production due to high formation pressures (Simenson, 2010; Gent, 2011) (Figure 3-5). Documentation of Middle Bakken reservoir properties on a regional scale has not been well documented (Theloy, 2013).

Grau and others (2011) recognized the importance of early dolomitization in enhancing both reservoir quality and storage capacity for the MM-BF. They also proposed that the shoal deposits (CSM unit D) may play an important role in preventing early dolomitization. Theloy (2013) observed that high production rates are encountered where the Middle Bakken is very rich in dolomite and siliciclastics with minimal calcite cement. Pervasive calcite cementation can effectively occlude fluid flow migration pathways and negatively affect dolomitization and ultimately hydrocarbon production. In the southern carbonate-rich part of the basin (St. Demetrius and Mondak areas), the abundance of calcite and the paucity of dolomite adversely affect reservoir quality and production (Figure 3-5).

Theloy (2013) analyzed a static and dynamic rock property dataset to determine if variations in rock-mechanical character of different MM-BF lithologies would have an
impact on both natural and induced fracture behavior of the rock. No conclusive relationships were observed with regard to facies, texture, presence or absence of natural fractures, or mineralogical composition. Differences in the rock-mechanical character of the MM-BF are subtle and that there are no zones within the MM-BF that would act as fracture baffles or intervals particularly prone to fracturing. Theloy (2013) recommended that a larger static rock property dataset is needed to strengthen this hypothesis.

The acquisition of static rock properties within the MM-BF using the Proceq Bambino, a non-destructive testing method, will be discussed further in chapter 6 along with a summary of MM-BF reservoir properties.
Figure 3-5: Map showing estimated ultimate recovery values (in million barrels) for MM-BF wells in the Williston Basin. Note high EUR values in Sanish-Parshall and low EUR values in Mondak and St. Demetrius (from Theloy, 2013).
Table 3-1: Table summarizing the subdivisions and lithofacies descriptions of MM-BF by various authors. Unit D is highlighted with a yellow box and is the main focus of this study (modified from Gent, 2011).

<table>
<thead>
<tr>
<th>MIDDLE BAKKEN LITHOFACIES</th>
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</thead>
<tbody>
<tr>
<td>Nickel &amp; Kohlruess, 2009</td>
</tr>
<tr>
<td>L5-Siltstone, graygreen,</td>
</tr>
<tr>
<td>massive mottled dolomitic,</td>
</tr>
<tr>
<td>Nerites ichnofacies</td>
</tr>
<tr>
<td>C-Siltstone, laminated</td>
</tr>
<tr>
<td>argillaceous, &amp; vfg sandstone, bioturbated, soft sediment deformation. Phycosiphon, Planolites &amp; Teichnichnus</td>
</tr>
<tr>
<td>L4-Interbedded dark-gray</td>
</tr>
<tr>
<td>shale and buff, silty sandstone, coarsens upward, moderately bioturbated (Cruziana ichnofacies)</td>
</tr>
<tr>
<td>B-Sandstone, fg, sharp basal contact, from base upwards, massive to cross bedded to laminated. Rare Planolites.</td>
</tr>
<tr>
<td>A-Siltstone, gray-green, argillaceous, abundant bioturbation, Nerites &amp; Phycosiphon</td>
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<tr>
<td>L2-Interbedded dark-gray shale and buff, silty sandstone, moderate to intense bioturbation (Cruziana ichnofacies), fossiliferous</td>
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<tr>
<td>L1-Siltstone, gray-green massice, bioturbated (Nerites ichnofacies), fossiliferous.</td>
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<tr>
<td>LeFever &amp; Nordeng, 2008</td>
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<tr>
<td>A0-Patterned pyritic dolostones</td>
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<tr>
<td>F1-Pyritic dolostones</td>
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<tr>
<td>L4-Interbedded dark-gray shale and buff, silty sandstone, coarsens upward, moderately bioturbated (Cruziana ichnofacies)</td>
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<tr>
<td>A1-Calcitic, whole fossil, dolo-to lime wackestones: fossil-rich beds.</td>
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<tr>
<td>A2-Thin-bedded dolo-mud/wackestone, more dolomitic.</td>
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<td>A3-Thin organic-rich mudstone, gamma ray marker</td>
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<td>C-Siltstone, laminated</td>
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<td>L2-Interbedded dark-gray shale and buff, silty sandstone, moderate to intense bioturbation (Cruziana ichnofacies), fossiliferous</td>
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<tr>
<td>D-Bioturbated, argillaceous, calc. poorly sorted, vfg, sandstone/siltstone with helminthopsi/sclarituba.</td>
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<tr>
<td>E-Intraclastic-skeletal lime wackestone, 1-4ft thick.</td>
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<tr>
<td>A-Siltstone, gray-green massice, bioturbated (Nerites ichnofacies), fossiliferous.</td>
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<tr>
<td>LeFever &amp; Nordeng, 2008</td>
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<tr>
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<td>E-Intraclastic-skeletal lime wackestone, 1-4ft thick.</td>
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Table 3-2: Table showing sequence stratigraphic framework for the Bakken Formation according to various authors. Sequence boundaries are highlighted in red. HST, LST, and TST stand for highstand, lowstand, and transgressive systems tract respectively (Theloy, 2013).

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<td>MB-A</td>
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<td>LBS</td>
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CHAPTER 4: STRATIGRAPHIC ANALYSIS OF THE MM-BF

This chapter will discuss the stratigraphy of the Bakken Formation, specifically the middle member. Stratigraphic data and correlations are presented using both new and historical subsurface information to better understand the depositional framework and processes for the MM-BF in North Dakota.

4.1 Introduction and Type Log

The MM-BF has a complex nomenclature. Most recent studies use a combination of descriptive terms with either a numbering system (LeFever & Nordeng, 2008; Egenhoff et al., 2011; Angulo & Buatois, 2012) or a lettering system (Nickel & Kohlruss, 2009; Canter & Sonnenfeld, 2009; CSM, 2010). The Colorado School of Mines stratigraphic framework put forth by Simenson (2010) divides the MM-BF into six units designated A through F (from base to top). Subsequent Colorado School of Mines (CSM) consortium studies expanded Simenson’s (2010) framework to different areas in North Dakota (Figure 4-1).

This study will incorporate the CSM Bakken consortium stratigraphic framework over a larger areal extent than. The following observations and interpretations of stratigraphic units and boundaries are presented stratigraphically: Three Forks Formation, Pronghorn Member, Lower Bakken Shale, MM-BF, Upper Bakken Shale, and the lowermost Lodgepole Member.

A type log for the Williston Basin in North Dakota is presented in Figure 4-3. As the MM-BF thins toward the basin margins, the different sub-units become more difficult to identify on the logs and are only discernable in core.

To understand the connection between the distribution of trace fossils and the physical sedimentary processes present in the depositional system, a method of semi-quantifying the degree of bioturbation established by Taylor and Goldring (1993) was used (Table 4-1). The sequence stratigraphic framework of the MM-BF presented in this study is largely based on the interpretations of the CSM Bakken Consortium (Sonnenberg, 2015) which uses the Depositional Sequence IV terminology (Figure 4-2) presented by Hunt and Tucker (1992).
4.2 Three Forks

For more detailed information on the Three Forks Formation, readers are encouraged to see Gantyno (2010) and Franklin-Dykes (2014) among others. The upper Three Forks (UTF) exhibits a “clean” gamma ray response in logs and is separated from the middle Three Forks (MTF) by a shale marker. Some of the lithofacies from the UTF and MTF that were briefly examined in this study include: a) interbedded to interlaminated silty to sandy dolostone with green mudstone and massive to chaotic bedded dolostone (Figure 4-4).

Figure 4-1: Map showing the areal extent of previous works from the CSM Bakken Consortium. This study combines the core observations and stratigraphic interpretations made by previous authors from different counties in North Dakota. Cores from Divide and Dunn counties were added to the dataset to further improve the MM-BF stratigraphic framework.
Gantyno (2010) observed that the deposition of the Upper Three Forks laminated facies was strongly tidal in character. The chaotic to brecciated facies are interpreted to be either solution breccia or reworked storm deposits. Overall the lithofacies assemblage was deposited on a low angle carbonate ramp or epeiric platform. The UTF and uppermost MTF are a highstand system tract (HST).

Table 4-1: Classification scheme for analyzing the degree of bioturbation present in core. BI (bioturbation index) refers to the sharpness of the primary sedimentary fabric, burrow abundance, and amount of burrow overlap (modified after Taylor, and Goldring, 1993).

<table>
<thead>
<tr>
<th>BI</th>
<th>Percent Bioturbated</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>No bioturbation</td>
</tr>
<tr>
<td>1</td>
<td>1-4</td>
<td>Sparse bioturbation, bedding distinct, few discrete traces and/or escape structures</td>
</tr>
<tr>
<td>2</td>
<td>5-30</td>
<td>Low bioturbation, bedding distinct, low trace density, escape structures common</td>
</tr>
<tr>
<td>3</td>
<td>31-60</td>
<td>Moderate bioturbation, bedding boundaries sharp, traces discrete, overlap rare</td>
</tr>
<tr>
<td>4</td>
<td>61-90</td>
<td>High bioturbation, bedding boundaries indistinct, high trace density with overlap</td>
</tr>
<tr>
<td>5</td>
<td>91-99</td>
<td>Intense bioturbation, bedding completely disturbed (just visible), limited reworking, later burrows discrete</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>Complete bioturbation, sediment reworking due to repeated overprinting</td>
</tr>
</tbody>
</table>

4.2.1 Significant Surface 1 (Ss1): Three Forks – Bakken Boundary

A major unconformity is present at the top of the Three Forks Formation. This unconformity is a sequence boundary (SB) that corresponds to a eustatic drop in sea level that happened close to the Devonian-Mississippian boundary (Theloy, 2013; Haq and Schutter, 2008). The hiatus at the unconformity is unknown but is widely accepted to be significant (> 3 Ma). The Three Forks is overlain by the Pronghorn Member (PH) or lower Bakken shale (LBS) within the study area (Figure 4-4). A lag of rip-up clasts and abundant pyrite is usually found at this surface (Theloy, 2013).
The structure map based on this surface showed gentle dip toward the basin center and minimal structural features. This is typical of a low angle ramp or epeiric platform setting. However, Cobb (2013) argued that small-scale structural features can often be masked by regional dip. Cobb (2013) suggested the use of residual structure maps which allows for small-scale features to be observed by essentially subtracting the regional dip. This study utilized 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd} order residual structure maps, which are created by subtracting a 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd} order trend surface (average regional dip) from the original top of the Three Forks structure map (Figure 4-5).

The resulting residual maps depict highs and lows relative to the average trend surface and are often used to indicate paleotopography (Evenick et al., 2008). According to Davies (2012), Bakken paleotopography is best represented by the 3\textsuperscript{rd} order residual map. The 3\textsuperscript{rd} order residual map of Ss1 shows the presence of paleo-highs on the north, east, and southwest part of the study area. Paleo-lows are present in the central part of the basin separated by what seems to be the “active” Nesson Anticline. Previous works from CSM such as Vickery (2010), Gent (2011), and Theloy (2013) have made similar observations largely based on core interpretations and thickness trends of the Bakken Formation. Cobb (2013) interpreted the paleo-lows present during Bakken time to be mainly the result of underlying Prairie salt-dissolution and collapse.

4.3 Pronghorn Member of the Bakken Formation

For more detailed information on the Pronghorn Member, readers are referred to the works of Berwick (2008) and Johnson (2013) among others.

The Pronghorn is the basal member of the Bakken Formation and unconformably overlies the Three Forks. Some of the lithofacies observed in this study include a) heavily bioturbated fine-grained sandstone and b) skeletal wackestone to packstone (Figure 4-4). The bioturbated sandstone mainly contains \textit{Skolithos} and \textit{Cruziana} ichnofacies traces and was probably deposited in subtidal environments. The limestone beds contain abundant crinoids and disarticulated brachiopods.
Deposition was along a shallow offshore ramp. Pronghorn lithofacies assemblages of Johnson (2013) also include burrowed, dolomitic, and silty mudstone and shale, siltstone, and sandstone laminations that were deposited in storm-dominated deeper ramp environments.

Pronghorn limestones can be identified by clean gamma ray (GR) of about 50 API. Sand-rich and argillaceous facies have higher GR (>140 API). The Pronghorn reaches its maximum thickness of 54 ft in southwest-central North Dakota where it was deposited in topographic lows created by erosion, or non-deposition of the underlying Three Forks. Prairie Salt dissolution may have controlled this sub basin (Theloy, 2013).

Figure 4-2: Nomenclature of systems tracts, and timing of sequence boundaries for the various sequence stratigraphic approaches. The CSM Bakken consortium sequence stratigraphic framework presented in this chapter follows the Depositional Sequence IV nomenclature (Catuneanu et al., 2011).
4.3.1 Significant Surface 2 (Ss2): Pronghorn – Lower Bakken Shale Boundary

A sharp contact is present at the boundary between the Pronghorn and the overlying lower Bakken shale (LBS). This surface commonly has a lag of sandy phosphate granules, abundant pyrite replacement, and limestone clasts (Figure 4-6). The contact between the Pronghorn and LBS is interpreted as a transgressive surface of erosion. This surface marked the onset of the transgressive systems tract (TST).

4.4 Lower Bakken Shale

For more detailed information on the LBS, readers are referred to works of Jin (2013) and Kocman (2014).

The primary lithology of the LBS is massive to fissile-bedded organic-rich mudstone. Color observed in core ranges from dark gray to brownish-black to black. The shales are hard, brittle, and exhibit a waxy luster due to the high silica and organic content. Silt-sized quartz, radiolaria, and sponge spicules are major contributors to silica content (Theloy, 2013). Clays are another major component of the LBS (illite and less common smectite).

Hayes (1985) noted the presence of fossils in the LBS such as tasmanites spores, conodonts, fish scales and bones, inarticulate brachiopods, ostracods, choncostracans, and woody plant fragments. Other features of the LBS observed in this study include fine pyrite lenses and laminations, sand-filled injectites, and horizontal and vertical calcite-filled fractures (Figure 4-6). The presence of frambooidal pyrite, lack of bioturbation, and preservation of organic matter suggests anoxic deposition. The horizontal and sub-vertical calcite-filled fractures are interpreted to be product of hydrocarbon expulsion and influenced by the existing stress regime. The sand-filled injectites are likely to be product of seismic shock or fluidized flow during the deposition of the LBS and overlying strata. The sand is thought to be sourced from the underlying Pronghorn Member.

The lower Bakken shale represents a transgressive systems tract and records rising sea level conditions. The depositional environment of the LBS is interpreted to be a basinal ramp setting with low energy and anoxic conditions. The LBS can be recognized
in logs by its high gamma ray and resistivity values. Jin (2013) recognized maximum flooding surface (MFS) within the LBS corresponding with the highest gamma ray count and total organic carbon (TOC). The depocenter of the LBS is just east of the Nesson Anticline where the unit reaches a thickness of 55 ft (Jin and Sonnenberg, 2012).

4.4.1 Significant Surface 3 (Ss3): Lower Bakken Shale – Middle Member of the Bakken Formation (MM-BF) Unit A/B Boundary

The basal unit of the MM-BF (Unit A) overlies the LBS with a sharp and erosional contact (Figure 4-7). Below this surface, indistinct burrowing of Chondrites and Thalasinoides at the top of LBS with a bioturbation index (BI) of 1 was observed. Abundant brachiopods and crinoids along with Helminthopsis burrows (BI = 5-6) associated with Unit A are present above Ss3. Pyrite, greenish glauconitic peloids and bioclasts, phosphatic nodules, pseudomorphs of anhydrite, and small vertical burrows have also been observed at the boundary.

This surface represents a base level fall and a turnover from anoxic to oxygenated conditions. Ss3 is interpreted to be a downlap surface of the highstand systems tract (HST) above the transgressive Lower Bakken Shale (Sonnenberg, 2015).

4.5 MM-BF Unit A (MB-A): Crinoid-Brachiopod Wackestone/Calcareous Siltstone

The primary lithology of MB-A consists of skeletal lime wackestone to argillaceous siltstone. This unit is typically very fine-grained, dense, and contains brachiopods and crinoids. Green glauconitic peloids, bryozoans, and gastropods have also been observed. The concentration of bioclasts is highest at the base and decreases towards the top. Intense burrowing is associated with this unit and trace fossils are predominantly Helminthopsis with some Scalarituba (BI = 5-6).

The texture and ichnofacies assemblage of MB-A indicates a depositional environment of an offshore ramp setting below storm wave base. The low diversity and small size of fossils and the trace assemblage indicates a stressed marine environment with low siliciclastic input. Overall, MB-A represents a base level fall with condensed sedimentation in a highstand systems tract.
Figure 4-3: Left: Type log for the central part (Mountrail County) of the Williston Basin, North Dakota. The Whiting Oil and Gas Corporation Braaflat 11-11H. Right: Quantitative mineralogy from Braaflat 11-11H showing the different lithologies within the MM-BF. Both well logs and mineralogical data show similar vertical stacking trend throughout the basin with some units thinning or absent near the basin margins (modified by Sonnenberg, 2015; from Kowalski, 2010).
Figure 4-4: Three Forks lithofacies: (A) Interlaminated dolosiltstone and green mudstone from the RS Nelson 1423H-1 at 9,300 ft; (B) Brecciated to chaotic bedded dolostone from the RS Nelson 1423H-1 at 9,323 ft. Pronghorn lithofacies: (C) Burrowed sandy siltstone from the USA 42-24 at 10,862.3 ft; (D) Argillaceous limestone from the Grassy Butte 12-31 at 11316 ft. Sequence boundary (Ss1) in red dashed line separating Three Forks with (E) LBS (from the Nordstog 14-23 at 8,712 ft) and (F) Pronghorn Member (from the Mertes 1-32 at 7230 ft) (photo courtesy of NDIC).
Figure 4-5: (A) Structure map of top Three Forks sequence boundary (Ss1). (B) 1st order residual map. (C) 2nd order residual map. (D) 3rd order residual map. Note the changing elevation on the color scale bar, with each lower order regression showing progressively smaller scale and subtler topographic features. All the depths shown are Sub Sea True Vertical Depth (SSTVD).
Figure 4-6: Transgressive surface of erosion (Ss2) in red arrows separating Pronghorn with LBS is characterized by: (A) sandy pyritic and phosphatic lag (from the Rogne 11-34H at 10,721 ft) and (B) limestone intraclasts (from the Grassy Butte 12-31 at 11,309 ft). Some of the sedimentary and diagenetic features present in the LBS are: (C) coarser more silica rich beds (from the Nordstog 14-23 at 8,710 ft), (D) chevron-shaped pyrite nodules (from the Nelson Farms 1-24H at 9,666.7 ft), (E) horizontal and sub-vertical calcite filled fractures (from the Fertile 1-12H at 9,420 ft), and (F) sand-filled injectites (from the Mertes at 7,212.5 ft) (photo courtesy of NDIC).
Figure 4-7: The contact between LBS and MB-A is interpreted as a downlap surface (red arrows). This surface represents base level fall and a turnover from anoxic to oxygenated conditions. Ss3 include features such as: (A) pyrite replacement (from the Loucks 44-30 at 7,698 ft); (B) crinoid columns and brachiopod fragments (from the Carus Fee 21-19 at 11,342 ft); (C) greenish glauconitic pellets (from the Fertile 1-12H at 9,400.2 ft) (photo courtesy of NDIC).

The transition into dolomitic and calcareous siltstones of the overlying MM-BF Unit B is very gradual and typically marked by a decrease in the fossil abundance and increase in bioturbation. The boundary between the two units is indistinct. MB-A can be recognized in logs due to its clean gamma ray deflection from the underlying LBS.

4.6 MM-BF Unit B (MB-B): Bioturbated Calcareous Siltstone/Sandy Siltstone

Lithologically, MB-B is a light-gray to tan colored, massively-bedded, argillaceous, variably calcareous, dolomitic siltstone (Figure 4-8). The average grain size for this unit ranges from medium to coarse silt and grades upward into upper very fine-grained sand. Brachiopod and crinoid fragments are sparse to absent throughout the unit. MB-B is dominated by the occurrence of Scalarituba and Helminthopsis
burrows (BI = 4-5). Other subordinate trace fossils include *Asterosoma* and *Planolites*. The high degree of bioturbation obscures most original sedimentary structures.

Calcareous concretions and calcite-filled fractures have been observed especially in the western and central part of the study area (Figure 4-8). These calcite nodules are crudely layered and appear light gray in color. This is discernable from the tan dolomitic areas creating a patchy appearance. These calcareous concretions are a product of early diagenesis and may be associated with an increase in fine bioclasts within MB-B (Brennan, 2015, personal communication).

Overall the MB-B exhibits a coarsening upward trend, smaller diversity of larger-sized trace fossils, and larger calcareous nodules. Deposition was in upper offshore to inner ramp environments. MB-B represents a continuing base level fall in a HST.

MM-BF Unit B gamma ray value ranges from 80 to 140 API. Spikes in the density and sonic logs are responding to calcite-cemented zones. The thickness of this unit ranges between 3 and 35 ft (Simenson, 2010; Gent, 2011). The unit and is not present due to erosion or non-deposition in the southwest and northeast portions of the study area.

### 4.6.1 Significant Surface 4 (Ss4): MM-BF Unit B – Unit C Boundary

Where MM-BF Unit C is present, it overlaps Unit B with a relatively abrupt contact (Figure 4-9). This boundary is characterized by indistinct burrowing of *Scalarituba* and a slight increase in grain size. Other small tubular burrows and vertical burrows have also been observed. Ss4 is interpreted to be a facies boundary that records continued base level fall and a change in depositional facies within the HST.

### 4.7 MM-BF Unit C (MB-C): Laminated Calcareous Siltstone/Sandstone

The primary lithology of MB-C is an inter-laminated, variably calcareous, dolomitic, coarse siltstone to very fine grained sandstone. The unit can be subdivided into three subfacies based on the sedimentary structures and from bottom to top are: 1) parallel-laminated; 2) bi-directional wave ripple-laminated; 3) flaser-bedded to ripple-laminated. The parallel laminae exhibit cycles of alternating thick and thin layers that vary in thickness from 1 mm to 1.2 cm (Figure 4-9). The thicker layers are usually coarser-
grained and more dolomitic while thinner layers are finer-grained and more-argillaceous. Other features that are found with this laminated subfacies are calcareous nodules and algal boundstone texture. The calcite nodules are larger than in the underlying MB-B facies.

Figure 4-8: MB-B lithofacies variation: (A) argillaceous dolomitic siltstone with Helminthopsis and small Scalarituba burrows (from the Laredo 26-1 at 9,310.4 ft); (B) calcareous dolomitic sandy siltstone with less diverse but larger burrows. Note the dark muddy fills of Scalarituba burrows (from the Sanish 36-44 at 10,465 ft). Diagenetic features of MB-B: (C) patchy and nodular calcite cementation (from the Clifford Marmon #1 at 9,951 ft); (D) calcite filled fractures (from the Nordstog 14-23 at 8,868 ft) (photo courtesy of NDIC).

The wave-rippled siltstone to very fine-grained sandstone contains climbing ripples and ripples with flattened tops (Figure 4-10). Soft sediment deformation, fluid escape features, and calcite-filled fractures are present in this facies. Flaser-bedded and ripple-laminated sandstones commonly contain clay drapes. Planolites is the dominant trace fossil in MB-C (BI = 0-2).
Gent (2011) analyzed laminites cyclicity by using the Fast Fourier Transform (FFT) method and recognized the presence of semi-diurnal to mixed tidal pattern. Rare fossils, the presence of algal fabric, and the low diversity of burrows indicate a stressed marine environment subjected to tidal conditions and falling sea level. Overall, the MB-C is interpreted to represent a late HST to falling stage systems tract (FSST).

MB-C is recognized in the logs by its slightly cleaner gamma ray response than the underlying MB-B. Similar to the MB-B, density and sonic spikes are associated with calcite concretions. The thickness of this unit ranges between 2 to 17 ft. Its depocenter located within the central part of the study area.

4.7.1 Significant Surface 5 (Ss5): TF, PH, LBS, MB-B/C – MM-BF Unit D Boundary

The boundary between MM-BF Unit D and its underlying unit is characterized by a sharp, erosive contact (Figure 4-11). The oolitic grainstone-bioclastic sandstone of MB-D progressively truncates the MB-C, MB-B/A, LBS, Pronghorn, and Three Forks within the study area. The contact between the MB-D and the Pronghorn is found along the southwest margin of the basin. In the northeast margin, the MB-D down cuts to the top LBS and Three Forks. In some areas, sand injectites have been observed at this contact.

Ss5 is interpreted to be a 3rd order sequence boundary at the onset of a lowstand systems tract (LST), and the surface records a significant base level drop. This surface is regarded as an unconformity, but the hiatus cannot be determined due to poor conodont recovery.

4.8 MM-BF Unit D (MB-D): Calcareous Bioclastic Oolitic Sandstone/Grainstone

The primary lithology of MM-BF Unit D is light to dark gray, calcareous, oolitic, bioclastic, sandstone and grainstone. Texturally, MB-D ranges from very fine-grained to upper fine-grained sand and locally the carbonate constituents can reach the medium-grain size. Smaller grains are subangular to subrounded while the larger fraction is usually rounded to well rounded. Sandstones are generally well-sorted except for localized areas with poor sorting. Compositionally, the siliciclastic grains are
predominantly quartz and minor feldspars. The carbonate grains consist of coated grains and fossil and algal fragments.

Figure 4-9: (A) Ss4 (red arrows) separated the MB-B with the MB-C and is characterized by small vertical and tubular burrows (from the Titan E Gierke 20-1H at 11,301 ft); (B) Laminite with *Planolites* burrows at the base of coarser thicker lamina (from the Clifford Marmon #1 at 9,938 ft); (C) Tidal couplets in varve-like laminites (from the AS Wisness #2 at 10,254 ft); (D) Stromatolitic-like structure (blue dashed line) in algal boundstones (from the Grassy Butte 12-31 at 11,263 ft) (photo courtesy of NDIC).
Based on the sedimentary structures, MB-D can be subdivided into four subfacies: 1) cross-bedded; 2) laminated to massively-bedded; 3) bi-directional wave to climbing ripple-laminated; 4) finely-laminated to lag. The low angle cross-beds are either trough or planar to tangential in nature (Figure 4-12). The main composition of this surface is ooid, bioclast, and quartz sand grains. Darker-colored argillaceous laminae enhance cross-stratification.

The cross-bedded subfacies exhibits bar and/or channel geometry and is most prominent in the north and central part of the study area (Figure 4-24). The laminated to massively-bedded subfacies shows normal grading. The graded laminae can either show an abrupt transition into climbing ripples or a transition into massive grainstones. This subfacies is mainly comprised of ooids, bioclasts, and quartz sand grains. The bi-

Figure 4-10: (A) Flaser-bedded to rippled and burrowed argillaceous siltstone to v.f.g sandstone (from the Catherine Peck #2 at 10,768 ft); (B) Bi-directional-wave rippled argillaceous siltstone to v.f.g sandstone (from the Carus Fee 21-19 at 11,318 ft); (C) Soft sediment deformation with micro-faults (blue dashed line) and calcite-filled fractures (blue arrows) (from the Carus Fee 21-19 at 11,313.4 ft); (D) Differential compaction associated with early diagenetic calcareous concretions (blue dashed line) (from the Violet Olson 31-29H at 9,994 ft) (photo courtesy of NDIC).
directional wave to climbing-ripple laminated subfacies is sand with argillaceous drapes. Locally, the subfacies is flaser-bedded with *Planolites* burrows (BI = 1-2).

The finely-laminated subfacies is relatively coarser-grained than the other MB-D subfacies, and ooids and bioclasts are commonly preserved as lag deposits. This subfacies is prevalent in the central, northeast, and southwest portions of the study area. Other features that have been observed within MB-D include soft sediment deformation, calcite-filled fractures, and stromatolitic fabric. The four sub-facies either inter-finger or are vertically stacked. The presence of ooids, bioclasts, finely-laminated fabric, wave ripples, and lack of bioturbation indicate wave agitation and high energy conditions associated with marine and tidal currents. Tidal influence is suggested by the presence of graded lamina, climbing ripples, flaser-beds, and mud drapes.

The MB-D was deposited in inner-ramp shoal or channel environments with a significant intertidal influence. Taking into account the underlying sequence boundary, the MM-BF Unit D is a lowstand deposit that represents the lowest base level and most basinward shift in facies within the Bakken Formation.

MB-D is recognized in the logs by a strong deflection to the left in the gamma-ray reading showing the lowest values within the Bakken Formation (40-55 API). This clean gamma ray bench is not present where MB-D is very thin or absent. High resistivity and low porosity are the result of calcareous ooids, fossil fragments, and pervasive calcite cementation. The MB-D is very discontinuous but has a thickness that ranges from less than a foot to 20 ft.

4.8.1 Significant Surface 6 (Ss6): MM-BF Unit D – Unit E Boundary

The oolitic, bioclastic, calcareous sandstone and grainstone of MM-BF Unit D is overlain by argillaceous, dolomitic, flaser-bedded, and bioturbated sandy siltstone of MM-BF Unit E (Figure 4-13). The contact is sharp and locally erosional. Ss6 is interpreted as a transgressive surface of erosion that records a base level rise at the onset of a transgressive systems tract.
Figure 4-11: Ss5 (dashed red line/red arrow) is interpreted to be a sequence boundary and separates the MM-BF Unit D from underlying units. The boundary between: (A) MB-D and MB-C (from the Loucks 44-30 at 7657.3 ft); (B) MB-D and MB-B (from the Fertile 1-12H at 9382.1 ft); (C) MB-D and LBS (from the Pullen 1-33 at 7,713 ft); (D) MB-D and PH (from the Graham USA 1-15 at 10,374 ft); (E) MB-D and TF (from the A Trout 6H at 5,458 ft). (D) Sand injection structures (dashed blue line) associated with Ss5 (from the Fleckten 1-20 at 7,681 ft) (photo courtesy of NDIC).
Figure 4-12: Examples of the different sedimentary features found within MB-D: (A) cross-beds overlain by rippled laminations and flaser beds (from the Mertes 1-32 at 7189 ft); (B) finely-laminated to massive beds overlain by graded laminae (from the W Quale #1 at 10207.2 ft); (C) wave and climbing ripples overlain by massive beds (from the H Borstad #1 9658.3 ft); (D) fine laminae overlying pyritic oolitic lag (red arrow) from the southwest margin of the study area (from the MOI Elkhorn Ranch #13-21 10,731.5 ft) (photo courtesy of NDIC).
4.9 MM-BF Unit E (MB-E): Interbedded Dolomitic Very Fine-Grained Sandstone and Argillaceous Siltstone

MM-BF Unit E consists of very fine-grained sandstones interbedded with darker argillaceous siltstones. MB-E can be subdivided into a lower, middle, and upper units based on primary sedimentary structures and trace fossils.

4.9.1 Lower MB-E

The basal part of MB-E is flaser bedded and commonly rippled. Mud drapes, Planolites burrows (BI = 2-4), and mottled textures are common (Figure 4-14). The texture of lower MB-E ranges from very fine to lower fine-grained sandstone. Unlike the underlying MB-D, the lower part of MB-E is very dolomitic, pyritic, and contains rare ooids and bioclasts. Other features in the lower part of MB-E include micro-faulting and soft sediment deformation.

The lower part of MB-E was deposited in inner ramp subtidal shoal environments. The lack of diversity of trace fossils indicates a stressed environment. In core, the lower part of MB-E has a thickness ranging from less than a foot to 5 ft.

4.9.1.1 Significant Surface 7 (Ss7): Lower – Middle MB-E

The flaser-bedded sandstone from the lower part of the MB-E is overlain by a planar laminated unit. Ss7 is interpreted as a facies boundary associated with an overall base level rise.

4.9.2 Middle MB-E

The middle part of MM-BF Unit E is characterized by fine laminations that can be planar, wavy, or crinkly (Figure 4-15). The normally graded laminations exhibit thin-thick alternations (1 – 5 mm) similar to that of a tidal couplet. Laminations may transition into ripples (hydrodynamic change) or a stromatolitic fabric (salinity change). The texture ranges from silt to very fine-grained sand and lacks bioturbation (BI = 0-1). Soft sediment deformation (fluidized beds) is also observed in the middle part of MB-E. The middle part of MB-E was likely deposited in deeper ramp subtidal environments below storm wave base. The lack of bioturbation again reveals a stressed environment.
Figure 4-13: The boundary between MB-D and MB-E is marked by a transgressive surface of erosion (dashed green line). Ss6 separates the underlying laminated oolitic sandstone with the overlying flaser-bedded sandy siltstone with *Planolites* burrows. (A) From the Parshall 2-36H at 9,282 ft; (B) From the Fertile 1-12H at 9,382 ft; (C) From the Long 1-01H at 9,382 ft (photo courtesy of NDIC).

This unit is part of the transgressive systems tract and records an ongoing base level rise. In core, the middle part of MB-E has a thickness ranging from less than a foot to 7 ft.

4.9.2.1 Significant Surface 8 (Ss8): Middle – Upper MB-E

The finely laminated very fine-grained sandstone from the middle part of the MB-E is overlain by an argillaceous silty burrowed unit. The contact between the middle and upper part of MB-E is relatively abrupt but with indistinct burrowing. Ss8 is interpreted as a facies boundary that represents a change in the depositional environment associated with an overall base level rise.
Figure 4-14: Lower part of MB-E: (A) flaser-bedded to ripple-laminated dolomitic argillaceous v.f.g sandstone with Planolites burrows (from the Long 1-01H at 9150.3 ft); (B) Soft sediment deformation and microfaulting (dashed blue line) indicate substrate instability (from the Fleckten 1-20 at 7673.5 ft). (C) Ss7 (red arrow) is an abrupt surface that separates the laminites of middle MB-E from the flaser-bedded lower MB-E (from the McAlmond 1-05H at 8837.5 ft) (photo courtesy of NDIC).

4.9.3 Upper MB-E

The uppermost part of the MM-BF Unit E is burrowed argillaceous siltstones that are thinly interbedded with very fine-grained sand stringers (Figure 4-16). The main trace fossil assemblages include *Planolites* and small *Teichichnus* (BI = 3-4). Less common *Asterosoma* and *Skolithos* burrows are present. Sharp-based event beds are found at the boundary between MB-E and MB-F. These event beds are characterized by a sharp base with bioclasts that grades vertically into hummocky cross-stratification and shaly siltstone laminations. In this unit, Gent (2011) identified normal marine fossil fragments that include brachiopods, echinoids, and bryozoan fragments.

The uppermost part of MB-E was deposited in tidally-influenced, deeper ramp environments. The low diversity and small size of burrows indicates a stressed environment. The bioclastic and HCS event beds are interpreted to be storm beds and possibly storm-induced gravity deposits (tempestites). The upper part of MM-BF Unit E
is part of the transgressive systems tract and records ongoing base level rise. In core, the upper part of MB-E has thickness ranging from a less than a foot to 9 ft.

Figure 4-15: Middle part of MB-E: (A) normally graded sandy silt laminites exhibiting thin-thick alternation interpreted to be tidal couplets (from the Florence Ingerson #2 at 7,593.5 ft); (B) planar laminated grading up into more crinkly laminations and stromatolitic fabric (from the Young Bear 32-4 at 10,444 ft); (C) Micro-faulting suggesting unstable substrate (from the Fleckten 1-20 at 7673.5 ft). (D) Ss8 (red arrow) is an abrupt surface that separates the argillaceous burrowed siltstone of the upper MB-E from the middle MB-E (from the McAlmond 1-05H at 8837.5 ft) (photo courtesy of NDIC).

MB-E is recognized in the logs by a high gamma ray spike at the bottom followed by a serrated signature. Fast sonic, high density, and low porosity values show the presence of tight beds and laminae in MB-E. The total thickness of MB-E ranges from 6 ft to 11 ft (Kowalski, 2010; Gent, 2011).

4.9.4 Significant Surface 9 (Ss9): MM-BF Unit E – Unit F

The contact between the MB-E with the overlying Unit F is relatively abrupt but can also be gradational (Figure 4-16). The placement of Ss9 can be problematic and is usually picked in cores at the sharp base of an olive to buff colored bioclastic lag. This
surface is interpreted to be a facies boundary that records a change in depositional environments associated with an overall base level rise.

Figure 4-16: Upper part of MB-E: (A) bioturbated siltstone interbedded with v.f.g sand stringers. Dominant burrows include Planolites and Teichichnus (from the Negaard #1 at 7,389 ft).; Towards the boundary with MB-F sharp based event beds are observed containing (B) hummocky cross-stratification (from the Violet Olson 31-29H at 9975.4 ft) and (C) bioclastic packstone (from the Fertile 1-12H at 9372.5 ft). (D) Ss9 is a facies boundary that separates greenish to olive buff colored dolomitic siltstone of MB-F from the MB-E (from the Skarphol D #5 at 8,938 ft) (photo courtesy of NDIC).

4.10 MM-BF Unit F (MB-F): Dolomitic Fossiliferous Wackestone/Siltstone

The primary lithology of MB-F is massively-bedded fossiliferous dolomitic siltstone. MB-F unit is buff-colored hummocky cross stratified (HCS) and bioclastic siltstone beds at the base that grade vertically into olive green mottled dolowackestones (Figure 4-17). There is a general lack of bioturbation, but small burrow traces of Chondrites and Skolithos are rarely present. Bioclastic fragments include brachiopods and crinoids that are commonly replaced by pyrite.
MB-F is interpreted to be deposited in an offshore ramp environment near storm wave base. The low diversity and frequency of trace and body fossils along with the abundance of pyrite indicates a stressed environment and possible onset of anoxic conditions. Overall, MB-F represents the transgressive systems tract and records an ongoing base level rise. MB-F can be recognized in the logs by its medium gamma ray value along with a higher density and sonic response that correspond to the tight nature of this unit. Thickness of MB-F ranges from 1 ft to 6 ft.

Figure 4-17: Sedimentary features found within MB-F: (A) hummocky cross stratified sandy siltstone with a burrowed top. Traces include Skolithos and Diplocraterion (from the Negaards #1 at 7,381.1 ft); (B) bioclastic lag consisting mostly of brachiopod fragments (from the Young Bear 32-4 at 10,439 ft); (C) burrow mottled texture with Chondrites traces (from the Florence Ingerson #2 at 7,580 ft) (photo courtesy of NDIC).

4.10.1 Significant Surface 10 (Ss10): MM-BF Unit F – Upper Bakken Shale

The contact between the MB-F and the upper Bakken shale is sharp (Figure 4-18). It is not obvious whether the contact is erosional. This boundary is characterized by larger-sized pyrite nodules and brachiopod lag deposits. Small, compacted, vertical burrows are rarely present. Overall Ss10 is a transgressive surface associated with an ongoing base level rise. The surface also records a change from oxygenated to less
oxygenated and/or anoxic conditions. A decrease in the rate of siliciclastic and carbonate input accompanies this change.

4.11 Upper Bakken Shale (UBS)

For more detailed information on the UBS, readers are referred to works of Jin (2013) and Kocman (2014). The lithology of the UBS is very similar to the LBS (Figure 4-18). However, the UBS has a slightly higher average TOC content and more common fossils than the LBS (Theloy, 2013). Some of the other UBS features observed in core include lime mudstone beds and calcite-filled fractures.

The upper Bakken shale was deposited in low-energy basinal ramp environments with minor siliciclastic and minimal carbonate input. Organic material and fine silt were preserved under anoxic conditions. Overall, UBS represents a transgressive systems tract where the rate of sea level rise is close to reaching its maximum. The maximum flooding surface is placed within the upper shale closer to the boundary with the overlying Lodgepole. This boundary coincides with the highest TOC values. The UBS can be recognized in logs by its very high gamma ray response. The upper Bakken shale is thinner (maximum thickness of 28 ft) but has a larger areal extent than LBS.

4.11.1 Significant Surface 11 (Ss11): Upper Bakken Shale – Lodgepole

The contact between the UBS and the overlying Lodgepole is relatively abrupt (Figure 4-18). Taking into account the placement of the MFS surface not below the boundary, Ss11 is interpreted to be a downlap surface and represents a base level fall at the onset of a highstand systems tract.

4.12 Lodgepole Formation and False Bakken

The Scallion Member of the Lodgepole Formation is stylolitic and nodular bedded crinoidal lime mudstone to lime wackestone (Figure 4-18). The Scallion contains brachiopods, ostracods, mollusk shells, and coral fragments. Other features observed include calcite-filled vugs and vertical fractures. Primary sedimentary structures were destroyed by intense bioturbation. There is a transitional contact with the overlying False Bakken (Stroud, 2010). The False Bakken Member of the Lodgepole is a
laminated calcareous mudstone unit that is recognizable in logs due to a high spike in the gamma ray reading. The False Bakken contains thin crinoid beds that differentiate it from the Lower and Upper Bakken shales. The Scallion and False Bakken were deposited at the toe of northward prograding clinoforms that downlapped onto the UBS (Sereda, 1990).

4.13 Overall Stratigraphic Trends of the MM-BF and Recap

Isopach maps of Sonnenberg (2015) were combined with the top Three Forks residual structure map to show the effect of paleotopography on the lateral thickness distribution of the different MM-BF units (Figure 4-19; Figure 4-20). Log calibrated core descriptions were used where some MM-BF units are hard to distinguish in well logs, examples of which are shown in Figure 4-21, Figure 4-22, and Figure 4-23. By using a combination of log and core derived thicknesses, a regional southwest to northeast cross-section was constructed that is roughly parallel to the Bakken paleo-shoreline (Figure 4-24). Table 4-2 and Figure 4-25 summarizes the lithofacies and surfaces of the MM-BF observed in this study along with its sequence stratigraphic interpretation.

After the major drop in sea level (2nd order sequence boundary) at the Three Forks – Bakken boundary, all four members of the Bakken (Pronghorn, LBS, MM-BF, and UBS) show a successively larger areal extent and onlapping relationships with the Three Forks at the basin margin, reflecting rising sea level conditions.

The Middle Member of the Bakken Formation is divided into six units: MB-A) skeletal lime wackestone, MB-B) bioturbated argillaceous siltstone, MB-C) calcareous laminated sandstone / siltstone, MB-D) calcareous sandstone / grainstone, MB-E) dolomitic laminated siltstone, and MB-F) massive fossiliferous wackestone. The lower part of the Middle Bakken (facies MB-A to MB-C) displays a coarsening-upward trend and is interpreted as a highstand deposit. MB-A and MB-B lacks sedimentary structures (massively bedded) but high bioturbation indexes have been linked to wave-dominated influenced processes (Gani et al., 2007). The low diversity and small size of the burrows is likely due to salinity stress. A lower order sequence boundary (3rd) is recognized at the base of the coarsest-grained Middle Bakken facies MB-D due to a significant base-level drop in an overall rising sea level trend. The sea level fluctuation within the MM-BF
is implied to be 4th or 5th order. Considering the erosional scour at the base of MB-D, it is possible that the pinchouts of underlying units (MB-A, B, C and LBS) represent an erosional limits rather than depositional limits. Based on the geometry, sedimentary structures, and lack of trace fossils, MB-D is interpreted as a lowstand deposit. The following MM-BF units (MB-E and MB-F) show a progressive deepening fining-upward trend and are interpreted as the initial deposits of the transgressive systems tract. The MB-E siltstone contains the strongest tidal signature based on the sedimentary structures and low abundance and diversity of trace fossils. Previous works on other ancient epeiric sea deposit supports the CSM sequence stratigraphic interpretation of the MM-BF. Steel and others (2011) worked on the Cretaceous Western Interior Seaway and found that tidal deposits are best preserved in a transgressive setting while the highstand systems tract are more associated with storm and wave dominated facies.

Overall, the Middle Member of the Bakken Formation is a complex mixed siliciclastic-carbonate system. Various authors have tried to determine which depositional environment model and sequence stratigraphic framework best fit the MM-BF. But few have focused on the source and mixing processes of the siliciclastic and carbonate components. The next chapter addresses the topic of siliciclastic-carbonate mixing in the MM-BF using insights from the sandstones and grainstones of Unit D.
Figure 4-18: (A) Contact between MB-F and UBS (Ss10) interpreted to be a transgressive surface (dashed green line). Note the presence of pyrites and oxidized Chondrites burrows (from the Jensen 12-44 at 9,170 ft). (B) Possible erosional nature of Ss10 cutting down into Pronghorn (from USA 33-23 at 10,604 ft). Features observed in the UBS include (C) coarser lime mud and silt beds (from the Titan E Gierke 20-1H at 10,997.3 ft) and (D) vertical calcite-filled fractures (from the Titan E Gierke 20-1H at 10,997 ft). (E) Ss11 (dashed blue line) separates the UBS from the overlying Lodgepole. This surface is interpreted to be a downlap surface (from the Loucks at 7,623). (F) Crinoidal limestone from the lodgepole exhibiting stylotitic and nodular texture (from the Parshall 2-36H at 9,251.2 ft) (photo courtesy of NDIC).
Figure 4-19: Isopach maps (C.I. 10 ft; modified from Sonnenberg, 2015) overlain on top Three Forks 3rd order residual contours. Left: Thickness distribution of the total MM-BF section. Right: Thickness distribution of the MM-BF HST/FSST (MB-A, B, C). Hotter colors show thick trends on the isopach and highs on the residual structure map. There seems to be a good relationship between the thickness distribution of the whole MM-BF section and the lower HST with what is inferred to be paleotopography at the time of Bakken deposition which may suggest active subsidence along the Nesson Anticline.
Figure 4-20: Isopach maps (C.I. 10 ft; modified from Sonnenberg, 2015) overlain on top Three Forks 3rd order residual contours. Left: Thickness distribution of the MM-BF LST section (MB-D). Right: Thickness distribution of the MM-BF TST (MB-E, F). Hotter colors show thick trends on the isopach and highs on the residual structure map. The thickest MB-D trend seems to be developed on top of or adjacent to paleo-highs. The TST shows more of a blanketing thickness distribution within the study area which may suggest a halt in subsidence along the eastern edge of the Nesson Anticline.
Figure 4-21: Core to log calibration for the Grassy Butte 12-13. This well is representative of the southern part of the study area.
Figure 4-22: Core to log calibration for the Texel 21-15. This well is representative of the central part of the study area.
Figure 4-23: Core to log calibration for the Loucks 44-30. This well is representative of the northern part of the study area.
Figure 4-24: Top: Aerial view of wells used in the regional SW to NE cross-section on top of the inferred paleotopography during Bakken time. Bottom: Stratigraphic cross-section showing the vertical and lateral distribution of the different MM-BF units flattened on the MFS close to the top of UBS. The pinch outs of the LBS and lower MM-BF siltstone (MB-A, B, C) are interpreted to be an erosional rather than depositional limit. Note that MB-D not only builds up topography (bar) but can also fill in topographic lows (channels). The topography created by MB-D seems to affect the thickness development of the overlying units.
Table 4-2: Various unit and facies observed in the core of MM-BF. Facies are presented in stratigraphic order.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Sedimentary Structures/Detailed Lithology</th>
<th>Thicknesses</th>
<th>Bed Characteristics</th>
<th>Bioturbation</th>
<th>Depositional Processes Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Dolomitic wackestone to vfg siltstone</td>
<td>HCS sand-silt event beds, graded bioclastic event beds (storm), decreasing upward.</td>
<td>1-5 ft</td>
<td>Tops are sharp and flat with local basal scour surface</td>
<td>Chondrite, Skolithos</td>
<td>Stressed offshore carbonate mud ramp</td>
</tr>
<tr>
<td>E</td>
<td>Dolomitic mudstone to vfg siltstone</td>
<td>HCS sand-silt event beds, bioclastic beds increasing upward. Extensively burrowed flaser-bedded</td>
<td>6-11 ft</td>
<td>Tops and bases are sharp and flat</td>
<td>Planolites, Teichichnus, Asterosoma, Skolithos</td>
<td>Deepening up distal lower shoreface/offshore shelf/ramp, with tidal influence.</td>
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<tr>
<td></td>
<td></td>
<td>Ryhtmic-laminated to rippled; texturally-graded laminae var. with soft sed. deformation</td>
<td></td>
<td></td>
<td></td>
<td>Tide dominated offshore ramp setting, below wave base, subtidal-intertidal</td>
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<td></td>
<td></td>
<td>Flaser-bedded silty vfg sandstone</td>
<td></td>
<td></td>
<td></td>
<td>Tidally influenced shoreface to sandy shoal inner ramp environment</td>
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<tr>
<td>D</td>
<td>Calcareous grainstone to fg sandstone</td>
<td>Fine-laminated, lag</td>
<td>inches-20 ft</td>
<td>Tops are sharp and flat with basal scour surface</td>
<td>None</td>
<td>Middle to upper shoreface, within wave base, in barrier bar or shoal within inner ramp setting. Ooids indicating very shallow, wave-agitated system with supersaturated normal marine to mesosaline seawater.</td>
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<td></td>
<td></td>
<td>Wave ripple-laminated to flaser bedded</td>
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<td>Graded-laminated to massively bedded</td>
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<td></td>
<td></td>
<td>Flaser-bedded</td>
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<td></td>
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<td>Cross-bedded</td>
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<tr>
<td></td>
<td>Var. Calcareous Dolomitic coarse siltstone to vfg sandstone</td>
<td>Flaser-bedded/rippled with clay drapes</td>
<td>2-14 ft</td>
<td>Tops and bases are sharp and flat</td>
<td>Planolites</td>
<td>Sand-dominant tidal shoal inner ramp</td>
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<tr>
<td>C</td>
<td>Bidirectional wave-rippled</td>
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<td></td>
<td>Wave dominated, tidally influenced</td>
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<tr>
<td></td>
<td>Laminated, commonly in two thick-to-thin laminites sets with algal boundstone; tidal 'couplets'</td>
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<td></td>
<td>Tide dominated, but below storm wave base, subtidal-intertidal</td>
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<td>[389x52]73</td>
<td>[72x529]Table 4-2: Continued</td>
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<td></td>
<td>[87x454]C Var. Calcareous Dolomitic siltstone to sandy siltstone</td>
<td>Well sorted cleaner beds interbedded with muddier siltstone</td>
<td>3-35 ft</td>
<td>No distinct bedding</td>
<td>Scalarituba, Helminthopsis</td>
<td>Shallowing up, stressed environment, offshore transition, to distal lower shoreface subtidal</td>
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<tr>
<td>B</td>
<td>Bioclastic lag, overall muddier, increasing crinoid content to base</td>
<td>Base is flat with small-scale scour</td>
<td></td>
<td></td>
<td>Scalarituba, Helminthopsis</td>
<td>Condensed sedimentation, stressed water condition, subtidal</td>
</tr>
<tr>
<td>A</td>
<td>[131x479]Bidirectional wave-rippled</td>
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<td></td>
<td>[117x479]Well sorted cleaner beds interbedded with muddier siltstone</td>
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<td></td>
<td>[116x442]Laminated, commonly in two thick-to-thin laminites sets with algal boundstone; tidal 'couplets'</td>
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<td></td>
<td>[575x507]Sand-dominant tidal shoal inner ramp</td>
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<td></td>
<td>[575x507]Planolites</td>
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<td></td>
<td>[575x507]Tide dominated, but below storm wave base, subtidal-intertidal</td>
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<td></td>
<td>[566x476]Wave dominated, tidally influenced</td>
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<td>[566x476]Tide dominated, but below storm wave base, subtidal-intertidal</td>
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<td></td>
<td>[566x476]Shallowing up, stressed environment, offshore transition, to distal lower shoreface subtidal</td>
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<tr>
<td></td>
<td>[566x476]Condensed sedimentation, stressed water condition, subtidal</td>
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Figure 4-25: The Colorado School of Mines sequence stratigraphic framework of the Bakken Formation with significant surfaces, systems tract, and relative sea level curve (modified from Sonnenberg, 2015).
CHAPTER 5: CALCAREOUS SANDSTONE AND GRAINSTONE INTERVALS OF MM-BF UNIT D

The Middle Member of the Bakken Formation exhibits a range of sedimentary textures and proportions of lithologies in a mixed sedimentary system within an epeiric shelf/low-angle ramp setting. Various depositional reconstructions and sequence stratigraphic interpretations have been presented by various workers (reviewed in Chapter 3) and the Colorado School of Mines Bakken Consortium (Chapter 4) to explain the overall stratigraphic evolution of the MM-BF. However, these previous studies lacked a clear explanation for the origin, distribution, and preservation of the calcareous sandstone-grainstone unit (MB-D) within the MM-BF. The discontinuous nature of MB-D, origin of coarse sands, abundant coated grains and bioclasts, sediment delivery, and carbonate-siliciclastic mixing mechanisms were barely addressed in the past.

Interpretation of the depositional environment for the sandstones and grainstones of MB-D ranges from progradational wave-dominated upper shoreface and ooid shoals (Smith and Bustin, 2000; Egenhoff et al., 2011) to transgressive, tidally-influenced shelf sand ridges and barrier bars in a brackish marine embayment (Toews, 2005; Angulo & Buatois, 2012). Poor understanding of ancient epeiric seas and the lack of modern analogues create problems in understanding MM-BF depositional environments.

Schlager (2005) argues that the lack of high slopes in epeiric seas makes it difficult or impossible to distinguish between sand shoals rimming a lagoon and sands of a tidal-bar belt that formed on the epeiric shelf in zones of amplified tides (Figure 5-1). Based on modern and ancient examples, Schlager (2005) also observed that epeiric seas have: 1) highly variable tides and restriction; 2) very low (less than 0.1° slope) and more irregular topographic gradients than on shelves of continental margin. As sea level changes, facies belts shift farther and more rapidly. Rates of progradation are higher because less accommodation space needs to be filled; 3) low sedimentation rates and on average thinner deposits because of stable continental interiors.

By taking into account the depositional complexity associated with epeiric shelf/low-angle ramp setting, this chapter provides a closer look into the origin, distribution, and preservation of coarser-grained mixed siliciclastic-carbonate interval of MM-BF Unit D.
Figure 5-1: Sand transport pathways on the modern siliciclastic dominated epeiric sea of the NW European shelf. Transport and distribution of sand bodies is largely controlled by tides and poorly correlated with distance from shore or from shelf break. Note that in some sediment-starved areas (bed-load parting) sand is carried off in opposite directions (Schlager, 2005).
5.1 Origin of Siliciclastic and Carbonate Constituents within MM-BF Unit D

The lithology of MB-D ranges from sandstone to limestone (grainstone) with varying amounts of clastic and carbonate grains. Clastic components are predominantly quartz grains with fewer feldspar constituents. Carbonate components are dominated by carbonate coated grains and bioclastic material. Overall the sandstone-grainstone textures exhibit moderate sorting with discrete well-sorted fine and coarser-grained intervals, but sorting is poorer where textures are mixed.

5.1.1 Siliciclastic Grains

Texturally, the quartz and feldspar grains are very fine- to coarse-grained sand. Smaller-sized grains are subangular to subrounded while larger-sized grains (medium sand or larger) can be rounded to well-rounded (Figure 5-2). Petrographic trends show a decrease in size and increase in rounding. This trend suggests increasing maturity of the clastic grains from north to south (Figure 5-3). Based on quantitative mineralogy data (XRD), Vickery (2010) noticed a decreasing amount of quartz and feldspar constituents from northeast to southwest and suggested that MB-D was probably sourced from the north-northeast (Figure 5-4). This interpretation is further supported by recent zircon and conodont work by Mohamed and Henderson (2015) in the Canadian part of the Williston Basin. They identified a northern Franklinian clastic wedge associated with the Ellesmerian orogeny of the eastern Canadian Shield, and also a southerly provenance for the MM-BF sands (Figure 5-5). Mohamed and Henderson (2015) further suggested that sediments were transported from the north and east over long distance by rivers and long-shore drift.

During the Late Devonian and Early Mississippian the Williston Basin was located close to the paleo-equator (Figure 5-6). The hinterland climate at the time of MM-BF deposition was inferred to be arid due to the lack of fluvial sediment and terrestrial carbonaceous material preservation. Jin (2013) used the Al/K elemental proxy to support the aridity of MM-BF climate. Aplin (1993) suggests that streams draining humid regions are relatively enriched in aluminum and depleted in sodium, potassium and calcium compared to streams in temperate or drier regions. A high Al/K ratio would indicate high precipitation and a low ratio would indicate low precipitation. Jin (2013)
concluded that the MB-D facies has the lowest level of Al/K, which suggests very arid conditions.

Taking the arid climate of the hinterland during MM-BF deposition into account, some of the finer silt-sized siliciclastic grains may have been delivered from the north and east by eolian processes while the coarser-grained less-rounded sands were mainly delivered by seasonal rivers. The sands were then transported south into the study area by longshore and oceanic currents as suggested by Mohamed and Henderson (2015). Model from the Triassic of the Western Canada Sedimentary Basin illustrates the interplay of these different processes (Figure 5-6).

5.1.2 Carbonate Grains

The MB-D is the most calcareous unit within the MM-BF due to the abundance of carbonate grains and carbonate cement. The carbonate grains are mostly composed of coated grains and various fossil and algal fragments. Generally, the carbonate grains are sub-rounded to well-rounded and have moderate to good sorting.
Figure 5-3: Petrographic trend of MM-BF Unit D siliciclastic constituents. From north to south, the size of siliciclastic grains decreases and rounding increases. This increase in maturity infers a source to the north-northeast of the study area (modified from Nandy et al., 2015).
Figure 5-4: Mineralogy trend compiled from X-Ray Diffraction data (XRD) of the MM-BF shows a decreasing amount of siliciclastic minerals and increasing amount of carbonate minerals from the northeast to the southwest which infers a clastic source from the north-northeast of the study area (Vickery, 2010).
Figure 5-5: (A) Map showing the core locations used by Tarig Mohamed, north of this thesis study area. (B) Core log depicting the stratigraphic intervals that were sampled for detrital zircon study. (C) Detrital zircon probability curves for the MM-BF samples. The Zircon ages are subdivided into four distinct age groups and provinces. These provinces are located north-northeast of the Canadian study area. Provenance interpretations agree with the CSM Bakken Consortium (Mohamed and Henderson, 2015).
5.1.2.1 Coated Grains

The coated grains found within MB-D are predominantly ooids. Ooids are spherical to elliptical with a diameter less than 1 mm. Nuclei of the ooids vary and
include peloids, abraded brachiopods, bryozoans, crinoids and quartz grains (Figure 5-7). The ooids commonly exhibit large radial fabric and a relatively large nucleus classified by Strasser (1986) as type 5 ooids. Type 5 ooids form in low-energy, restricted environments (Figure 5-8). However, ooids of the MB-D can be found both as fractured and re-cemented fragments that indicate wave reworking and transport from origin sites.

Halley (1977) suggests that the abundance (greater than 1 %) of fractured ooids along with radial fabrics can be significant indicators of abnormal salinity. Vickery (2010) stated that the ooids of MB-D show a greater than 1% fractured fraction. This supports formation in a restricted marine environment. Overall, most ooids (modern and ancient) are deposited in warm sea water supersaturated with respect to CaCO$_3$, at shallow depths of 1-5 m (max. 10-15 m) and periodically agitated by tidal and wave currents.
5.1.2.2 Skeletal Grains

Complete body fossils were not observed within MB-D. Instead, fossil brachiopod, bryozoan, crinoids, echinoid spines, and gastropods fragments are abundant (Figure 5-9). Rare appearance of phosphatic skeletal grains like fish scales, teeth, bone fragments and shell fragments has also been noted. The bioclastic materials commonly are nuclei for a lot of the ooids and coated grains found within the MB-D. The overall fossil assemblage is typical of normal marine to stressed ramp environments. Abrasion of bioclastic material indicates reworking and transport by wave and tidal currents.

Figure 5-8: Diagram showing the inferred mineralogy, water energy, and depositional environment of different ooid types from the Upper Jurassic and Lower Cretaceous. MB-D coated grains exhibit fabric similar to the type 5 ooids (Strasser, 1986).
There are no clear petrographic data that indicate the source of MB-D carbonate sediments (Figure 5-10). The only common features are abraded fossil fragments and fractured ooids. Both indicate that these sediments were transported from their sites of origin. Wright and Burchette (1998) argue that coarser carbonate sediment is typically produced in, or close, to the environment in which it was created. In contrast, siliciclastic sediment is closely linked to hinterland tectonism and/or climate. Wright and Burchette (1998) further suggest that carbonate sediment production rates are water-depth dependent and are highest in shallow water which makes carbonate systems sensitive even to small amounts of subsidence and uplift.

The paleo-structural highs were bathymetric highs in the study area is interpreted to be an intra-basinal source of coarse carbonate sediments within the MM-BF (Figure 5-11). Another possible source for the coarse carbonate sediment would be extra-basinal. These components were transported into the basin during the sea level fall and

Figure 5-9: Thin section images showing abraded bioclastic materials which include fragments of bryozoan (yellow arrow), brachiopod (orange arrow), crinoid (red arrow), echinoid spine (blue), and fish bone (green). (A) Deadwood Canyon 43-28H, Sec. 28, T 154N, R 92W, Mountrail County, ND; (B) Gunnison State 44-36H, Sec. 36, T 161 N, R 91W, Burke County, ND (photo courtesy of Dipanwita Nandy).
Figure 5-10: Petrographic trend of MM-BF Unit D carbonate constituents. The abraded bioclastic material and fractured and re-cemented ooids indicate wave and tidal current reworking and transport of these coarse carbonate sediments (modified from Nandy et al., 2015).
Figure 5-11: (A) Intra-basinal source of coarse carbonate sediment within MB-D. Paleo-highs are inferred from the 3rd order residual map on top Three Forks structure. (B) Paleogeographic reconstruction showing Bakken-equivalent formations that may provide extra-basinal source for coarse carbonate sediment. Highlighted in the blue square is the study area (Sandberg et al., 1988).
erosional scouring at the onset of MB-D (Hendricks, 2015, personal communication). More work is needed to compare the MB-D sediments with Bakken-equivalent or older formations outside the Williston Basin.

5.2 Cyclicity and Mixing of Carbonate and Siliciclastic Sediments

Carbonate-rich and siliciclastic-rich intervals are present throughout the middle member of the Bakken Formation; however there are different styles and cyclicities observed in different MM-BF sub-units. Carbonate-clastic cycles were recognized as elemental/mineralogical changes in XRF/XRD data and distinct laminations and beds in core and thin-sections (Figure 5-13). One of the basic concepts of sedimentology is that voluminous carbonate production does not occur under the constant influx of siliciclastic sediment. With the sources of carbonate and siliciclastic constituents of the MB-D addressed, it is necessary then to identify sedimentary processes that could lead to the formation of mixed sediments in an epeiric shelves/low angle ramp setting.

5.2.1 Cycle Analysis of MB-D

Periodicity of mixing plays an important role in the genesis of mixed sediments. Gent (2011) noted the presence of cycles above the MB-C where plane-parallel to low angle bedding alternates with more massive grainstone beds and suggested that an underlying tidal signature may be present within MB-D. To analyze the variation in thicknesses within parallel laminations of MB-D, the thicknesses of individual laminae

![Image](image.png)

Figure 5-12: Scaling and measurement of individual lamina thickness using the ImageJ software (Gent, 2011).
Figure 5-13: Carbonate-siliciclastic cycles within the MB-D at different scales of observation (modified from Nandy et al., 2015).
were measured using accurately scaled photographs through the ImageJ software so that pixels could be converted to millimeters (Figure 5-12). The lamination thickness data were compiled into an Excel spreadsheet along with a laminae event number and these were used to produce bar charts (Figure 5-14).

The thick-thin lamination alternations from the bar chart exhibit an underlying sinusoidal pattern which corresponds to tidal neap-spring cycles. Abnormally thick laminations or a set of alternating thick thin laminations without a sinusoidal shape indicate non-tidal influence and were associated with seasonal changes or meteorological events such as storm surges.

Cyclostratigraphic analysis can then be applied to interval thickness using a number of techniques. Gent (2011) in particular used the Fast Fourier Transform (FFT) algorithm for the parallel laminations of MB-C. The FFT algorithm utilizes the Discrete Fourier Transform (DFT) to detect any underlying sinusoidal signal within a noisy data set. DFT is a computational method used to determine if spectral peaks are present within the data and their frequency (Burden et al., 1981). The basic principle of frequency analysis is shown in Figure 5-15.

For this study, the FFT algorithm was run using the signal analysis feature within the software MATLAB with the thickness data spreadsheet as the input. The result of the FFT analysis is a periodogram that show signal energy at different frequencies (Figure 5-15). The y-axis shows the frequency units in number of cycles per unit time or tidal cycle length per lamination (Gent & Sonnenberg, 2014). Significant frequencies can be identified by searching for peaks above a noise cut-off. Once the significant frequencies are recognized, they can be converted back to periodicities in the depth domain by taking the inverse of the frequency. The peaks and periodicities were then compared to the known cycles and signatures from the work of Gent (2011) (Figure 5-16). The majority of the observed signal in periodicity analysis can be attributed to tidal cyclicity. Spectral peaks in the 2-3 laminations/cycle indicate semidiurnal (two tides/day) and mixed tidal (1-2 tides/day) system.

Spectral peaks in the 10 to 12 lamination per cycle and the 15 to 21 lamination per cycle represent neap-spring alternation and are related to the synodic month tidal
cycle. The presence of tidal signatures in both the FFT analysis and empirical analysis of bar charts corroborates the claim presented by Schlager (2007) that tides play an important role in the transport and distribution of sand bodies in epeiric shelf/low angle ramp settings.

Figure 5-14: Bar charts showing lamination thickness on the y-axis and lamination number on the x-axis for MB-C and MB-D in the Braaflat 11-11H well. Note that while there is an underlying sinusoidal shape to the lamination variations, MB-D has significantly more “noise” that is attributed to the more massive grainstone beds. The sinusoidal pattern is associated with tidal cyclicity and the more irregular thick-thin pattern may indicate seasonal or meteorological influence.
Figure 5-15: (A) Spectral decomposition. The signal is decomposed into a number of sine waves with different frequencies. Amplitudes are assigned to each frequency. A frequency plot is made by plotting frequency versus amplitude (Al-Ibrahim, 2014). (B) The resulting periodogram for the Braaflat 11-11H well. The Y-axis shows the amplitude/signal power and x-axis shows the frequency unit. Significant frequencies were labeled and converted into periods. The FFT algorithm was run using MATLAB.
Figure 5-16: Left: Map showing the location of cores used for cycle analysis of MB-D. Right: Table showing the spectral peak occurrences for the MB-D periodograms. The periodicities are in units of lamination/cycles. 2-3 laminations/ cycle indicate semi-diurnal to mixed tidal signature. Strong peaks from 4 to 7 correspond to storm or other non-meteorological event. The peaks in the 10 to 12 lamination per cycle and the 15 to 25 lamination per cycles are associated with synodic tidal signature or seasonal influences. For more information on the MM-BF tidal cycles, readers are referred to Gent (2011).

Cyclicities with periodicities not attributed to tidal cycles are also observed. One major signal is at 4 to 7 lamination/cycle interpreted to be a storm or other non-meteorological events. Spectral peaks at 25 laminations per cycle and more indicate seasonal variations in wind and surface currents. Wright and Burchette (1998) suggested the role of storms, longshore, and contour currents in shaping sediment bodies on ramp systems. Seasonal wind variations associated with the monsoon system are known to strongly affect the sea surface circulation in the modern epeiric setting of the South China Sea (SCS) and Sunda Shelf (Figure 5-17). The Williston Basin has a similar latitudinal position as the SCS during Bakken deposition and paleoclimate reconstructions by Golonka and others (1994) show seasonal variations in wind directions (Figure 5-18).

In the summer, warm surface water flows from the south to the north which mitigates siliciclastic influx from the north and leads to ideal conditions for basin wide carbonate deposition. In the winter, cold water inflow from the north to south allowed for
a more siliciclastic-dominated basin deposition. Figure 5-19 illustrates the interplay
between the tidal cycles and seasonal variations of wind and surface currents. This may
explain the alternating cycles of carbonate and siliciclastic intervals within the MB-D.

Figure 5-17: Sea surface circulation in the South China Sea (SCS). The water
circulation in the SCS particularly in shallow areas, where the wind has a major
contribution, is strongly influenced by the monsoon system (Chen et al., 1985).

5.2.2 Style of Mixing

Mount (1984) classified four different mixing processes on rimmed, siliciclastic-
influenced carbonate platforms (Figure 5-20). Mount (1984) noted that similar processes
occur on ramps or open shelves, although their magnitude and distribution will be varied
due to the lack of shallow rim on the outer shelf. Two of the mixing styles, punctuated
and facies mixing, have been observed within the MM-BF Unit D. Punctuated mixing,
which refers to the mixing of sediments by rare, high-intensity events, is associated with
the more massive beds rich in carbonate or siliciclastic constituents. Storm-generated
currents rapidly transport nearshore siliciclastic sediments into deeper water, carbonate-
dominated environments (Mount, 1984). On the other hand, major storms can also
Figure 5-18: Paleoclimate reconstruction of the Famennian (Late Devonian-363 m.y.a). Red contour lines indicate pressure contours while red arrows represent wind vectors. Black square indicates the location of the Williston Basin at the time. Note the seasonal change in wind directions resembling the modern epeiric SCS (modified from Golonka et al., 1994).

erode sediments of the reef or shoal complex and redeposit them landward in siliciclastic-dominated lagoon environments. In punctuated mixing, energetic hydraulic processes act to sort and abrade carbonate clasts.

The more inter-laminated intervals which correspond to tidal and seasonal cycles are associated with facies mixing. Facies mixing represents the gradational lateral
Figure 5-19: Schematic illustrating the interplay of tides and oceanic currents on a low angle ramp setting during the deposition of MB-D. Seasonal variation in wind direction may affect sea surface currents and give way to carbonate-dominated (above) or siliciclastic-dominated (below) deposition (modified from Nandy et al., 2015).
transition between carbonate and siliciclastic facies. Environments where facies mixing occur include flanks of carbonate shoal complexes that shelter siliciclastic lagoons and where tidal flats and nearshore siliciclastic belts interfinger with deeper subtidal carbonates (Mount, 1984). Modern examples of coeval carbonate siliciclastic mixing have been presented as analogs for the middle member of the Bakken Formation.

Figure 5-20: Processes of siliciclastic-carbonate mixing. Not depicted in the model is source mixing which is caused by uplift and erosion of carbonate source terranes and admixture of carbonate detritus with siliciclastic material (Mount, 1984).
Grau and Sterling (2011) suggested the modern Belize shelf while Nandy and others (2015) suggested the Great Barrier Reef (Figure 5-21). The Belize model represents a shallow shelf and shoreline setting where sediments from the Maya mountains are delivered by rivers and the sands are redistributed by long shore drift to the south. The presence of a barrier reef acts as protection to the more carbonate restricted area to the north. Grau and Sterling (2011) argued that during Bakken time, the Nesson anticline acted as the barrier that sheltered carbonates from siliciclastic deposition. The Great Barrier Reef model works in similar way, in which siliciclastic sediment is sourced from dry tropical rivers and reworked by shelf processes.

5.2.3 Alternative Interpretation

Studies on the Mississippian St. Genevieve Limestone of Indiana have revealed that marine grainstones are commonly found with eolian grainstones. Dodd and others (1993) have made a petrographic comparison between the grainstones of eolian and marine origin (Table 5-1). Interestingly enough, the characteristics of Ste. Genevieve eolian grainstones resemble those found within the oolitic, bioclastic, sandstone-grainstone laminae of MB-D (Figure 5-22).

Dodd and others (1993) further suggested both an autogenic and an allogenic model to explain the origin of carbonate eolianites (Figure 5-23: Schematic illustrating the two models of carbonate eolianite deposition: (A) Autogenic origin in which marine waves and currents build oolitic or skeletal shoals above sea level to form low islands. Winds blowing across these islands form dunes and eolian deposits; (B) Allogenic origin in which sea level falls, exposing broad areas of carbonate sediment. Winds blowing across these surfaces form dunes and eolian deposits (Dodd et al., 1993).

Carbone eolianites cannot be completely eliminated as a possible cause of carbonate-clastic mixing, but the lack of subaerial exposure surface (e.g. calcrete, rhizoliths, alveolar texture, fitted fabric, etc.) within the MB-D make them unlikely.

5.3 Distribution and Preservation of MM-BF Unit D Sands

The laterally discontinuous nature of MB-D has been documented by various authors at different scales (Figure 5-24). Possible analogs for deposition of the MM-BF
Unit D include the Bahamian oolitic sand shoals (Figure 5-25) and the Holocene oolitic deposits in Abu Dhabi, UAE (Figure 5-26).

The homoclinal ramp setting and arid conditions of the UAE oolites resemble the geomorphologic profile and paleogeography of the Williston Basin during Bakken deposition, compared to the more humid conditions and isolated platform setting Figure 5-21: Modern examples of facies mixing include the Belize shelf and Great Barrier Reef. Both of which have been proposed as analogs for the mixed deposition of MM-BF (Grau and Sterling, 2011; Nandy et al., 2015).
associated with the Bahamian oolites. But both modern settings show similar facies variability where oolitic sand ridges, barrier bars, and ebb deltas are being incised by tidal channels. This might explain the lateral discontinuity of MB-D encountered at the well and field scale.

5.3.1 Facies Variability within MM-BF Unit D

On the basin-wide scale, MB-D exhibits facies variability that is unique compared to modern oolitic sand environments. Based on core observations within the study area, four distinct facies were identified (Table 5-2):

5.3.1.1 Finely laminated and coarse-grained lag facies

Non-graded fine laminations with variable amounts of oolites and bioclasts are typically a foot thick or less and are present in the east and central part of the study area (Figure 5-27). On the basin margins or structurally high areas, this facies is present as a coarse lag or oolitic bed above the Ss5 sequence boundary. Previous works from the Colorado School of Mines Bakken Consortium would classify this facies as part of the MB-C or MB-E, or indicate the absence of MB-D in cores.

The fine laminations are likely a product of wave swash, tidal action in beach settings, or deposition along the margins of shoals and bars (Figure 5-28). This thin facies or lag deposit is possibly a preserved remnant of a thicker MB-D unit.

Table 5-1: Comparison of properties of eolian and marine grainstones in Ste. Genevieve Limestone (Dodd et al., 1993).

<table>
<thead>
<tr>
<th>Property</th>
<th>Eolian</th>
<th>Marine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detrital quartz</td>
<td>present</td>
<td>absent</td>
</tr>
<tr>
<td>Broken ooids</td>
<td>present</td>
<td>absent</td>
</tr>
<tr>
<td>Grain diversity</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Rounding and sphericity</td>
<td>tabular grains have high sphericity</td>
<td>tabular grains rounded, not spherical</td>
</tr>
<tr>
<td>Intraclasts</td>
<td>well-lithified</td>
<td>poorly lithified</td>
</tr>
<tr>
<td>Laminations</td>
<td>present</td>
<td>absent</td>
</tr>
<tr>
<td>Sorting</td>
<td>poor; may be good within laminae</td>
<td>generally good</td>
</tr>
<tr>
<td>Inverse grading</td>
<td>present</td>
<td>absent</td>
</tr>
<tr>
<td>Large grains</td>
<td>absent</td>
<td>present</td>
</tr>
<tr>
<td>Solution packing</td>
<td>extensive</td>
<td>minor</td>
</tr>
</tbody>
</table>
5.3.1.2 Cross-bedded facies

Low angle planar to trough cross-beds are present mainly in the north and northeast part of the study area. Cross bedding is migration of sand under uni- or multi-directional current with relatively high velocities. Thick cross-bedded, oolitic, and bioclastic sandstone and grainstone are localized barrier bars, shoals, or channels.

![Image of cross-bedded sandstone](image)

Figure 5-22: Examples of grainstones from the MB-D. Left is from the Gunnison State 44-36H, Sec. 36, T 161 N, R 91W, Burke County, ND while right is from the Liberty 2-11H, Sec. 11, T 151N, R91E, Mountrail County, ND. Dodd and others (1984) would argue an eolian origin for the grainstone on the left due to the presence of quartz silt (black arrow), abraded bioclast (blue arrow), and a tighter grain packing (photo courtesy of Dipanwita Nandy).

5.3.1.3 Normally graded lamina and massively-bedded facies

Oolitic and bioclastic grainstones and sandstones are present as normally graded lamina sets and thin beds. Normal or inverse grading is related to changing energy conditions during deposition or tidal variation. Vertically, this facies may abruptly transition into ripple laminated sands. Deposition was in inter-shoal settings.
5.3.1.4 Wave to climbing ripples and flaser-beds

Centimeter-size wave ripples are evidence of wave action, climbing ripple sets and flaser beds indicate periodical switching and opposed current directions in very shallow tidal environments. Finer argillaceous siltstone drapes were also found in this facies and further suggest tidal influence. In a vertical succession, this facies may transition into normally graded lamina or thin beds and together they represent inter-shoal setting in quiescent depressions.

Figure 5-23: Schematic illustrating the two models of carbonate eolianite deposition: (A) Autogenic origin in which marine waves and currents build oolitic or skeletal shoals above sea level to form low islands. Winds blowing across these islands form dunes and eolian deposits; (B) Allogenic origin in which sea level falls, exposing broad areas of carbonate sediment. Winds blowing across these surfaces form dunes and eolian deposits (Dodd et al., 1993).
Figure 5-24: Lateral distribution of MM-BF Unit D at different scales: (A) along a horizontal well (from the MHA 2-05-04H-148-91). MB-D (cyan blue color) had a variable thickness throughout the length of the lateral. MB-C was not present in this well (Kocman, 2014); (B) on a field/development scale (from the Parshall and Sanish Fields in Mountrail County, ND). Left: Isopach of facies D. Thickest section parallels the subcrop edge. A thick extends to the northeast and is interpreted as a tidal channel.
Within the study area, two semi-isolated trends of MB-D thicks occur in the northern and east-central part with an apparent NW-SE orientation (Figure 5-24). These thick trends are either barrier bars, shoals, or channels. The thick trends develop over, or on the flanks of, underlying structural highs (Figure 4-20). But in most of the study area, MB-D is thin (<1 ft). Towards the basin margins, MB-D is preserved as a lag or is absent by non-deposition or erosion. MB-D barrier bar and shoals record the shallowest depositional environments in the MM-BF inner ramp setting. In order to understand why MB-D sands are preserved as localized thick trends and are generally thin or absent everywhere, it is necessary to understand the surfaces that bound this unit.
Figure 5-25: Modern oolitic sand bodies of the Bahamas deposited in an isolated platform setting under humid conditions. Note the discontinuous nature of bars and ridges as they are cut by tidal channels (Rankey, 2010).
Figure 5-26: Modern oolitic sand bodies of the Arabian Gulf deposited in a homoclinal ramp setting under arid conditions. Lagoon, algal mat, and supratidal sabkha deposits were also observed within the Williston Basin during Three Forks-Bakken deposition. Note the discontinuous nature of oolitic shoals and barrier islands incised by tidal channels (Nandy et al, 2015).
Table 5-2: Various facies observed in core of the Middle Member of the Bakken Formation Unit D. Facies are presented in stratigraphic order (bottom to top).

<table>
<thead>
<tr>
<th>Facies</th>
<th>Composition</th>
<th>Sedimentary Structures</th>
<th>Dominant Process</th>
<th>Example</th>
</tr>
</thead>
</table>
| 1      | Variably oolitic and fine bioclastic sandstone to fine grainstone | Fine laminated with thicker oolitic event beds | • Wave swash  
• Erosion | ![Image](image1.png) |
| 2      | Oolitic, abraded bioclastic grainstone and sandstone | Graded laminae to thin beds | • Tides  
• Wave swash | ![Image](image2.png) |
| 3      | Oolitic, abraded bioclastic sandy dolomitic grainstone and very fine to fine grained sandstones | Low-angle planar to tangential and trough cross-bedded | • Tides | ![Image](image3.png) |
Table 5-2 Continued

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Rumination</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Less oolitic abraded bioclastic argillaceous dolomitic siltstone to very fine sandstone</td>
<td>Bidirectional wave ripple to climbing ripple, flaser fabrics • Tides • Waves</td>
</tr>
</tbody>
</table>
Figure 5-27: Facies distribution of MB-D from the study area. Contour map represents paleotopography at the time of deposition inferred from the 3rd order residual map on Top Three Forks Structure.
Figure 5-28: Schematic showing the interfingering or vertically stacked relationship between the different facies of MB-D.
5.3.2 Surfaces bounding MM-BF Unit D

The sequence stratigraphic interpretation of significant surfaces and systems tracts of the Bakken is presented in Figure 5-31. The lower boundary of the MM-BF unit D is a regional unconformity that extends across the study area. The surface (Ss5) progressively truncates down into underlying units (Figure 4-11) and has been interpreted by various authors as a sequence boundary. In this study however, a hierarchical distinction is made between the top Three Forks sequence boundary (Ss1) and the sequence boundary at the base of MM-BF Unit D (Ss5). Ss1 is a 2\textsuperscript{nd} order sequence boundary that records a eustatic drop in sea level at the Famennian-Tournaisian boundary. Ss5 is interpreted as a lower order (3\textsuperscript{rd}) sequence boundary that records a smaller-scale drop in sea level in an overall rising sea level trend (Figure 5-29).

With the recognition that the base of MB-D represents a 3\textsuperscript{rd} order sequence boundary, the oolitic and bioclastic sandstone-grainstone of this unit is part of a lowstand systems tract that records a basinward shift in facies.

The upper boundary of the MM-BF unit D (Ss6) is a sharp contact with the overlying MB-E siltstone (Figure 4-13). The overlying transgressive MB-E siltstone to very fine-grained sandstone is finer-grained than MB-D, lacks ooids or bioclastic

<table>
<thead>
<tr>
<th>Hierarchical order</th>
<th>Duration (My)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First order</td>
<td>50 +</td>
</tr>
<tr>
<td>Second order</td>
<td>3–50</td>
</tr>
<tr>
<td>Third order</td>
<td>0.5–3</td>
</tr>
<tr>
<td>Fourth order</td>
<td>0.08–0.5</td>
</tr>
<tr>
<td>Fifth order</td>
<td>0.03–0.08</td>
</tr>
<tr>
<td>Sixth order</td>
<td>0.01–0.03</td>
</tr>
</tbody>
</table>

Table 5-3: Hierarchy system based on the duration of stratigraphic cycles of Vail and others, 1991 (Catuneanu, 2006)
Figure 5-29: Superimposed patterns of shoreline shifts at different orders of cyclicity (Catuneanu, 2006)

material, and is characterized by sedimentary structures and biogenic features that indicate strong tidal influence. Ss6 itself is commonly planar to undulating with very fine draping laminations and abundant pyrite nodules. This surface (Ss6) is interpreted by various authors as a transgressive surface that represents a base level rise at the onset of a transgressive systems tract. Gent (2011) was the first to note the possible erosive nature of this transgressive surface, and in this study the upper boundary of MB-D is interpreted as a transgressive surface of erosion (TSE) (Figure 5-30). Transgressive erosion surfaces can be planar and may develop relief in a direction perpendicular to the shoreline. This is a function of changing rates of sea level or a function of wave energy and sediment supply, but the rate of change and magnitude of relief is generally
low (Martinsen, 2003). The TSE eroded and reworked the oolitic and bioclastic sandstone-grainstone and may explain MB-D thin and thick trends on a basin-wide scale.

5.3.2.1 Depositional Remnants

It is possible that only part of the original depositional system has been preserved. According to Martinsen (2003), the preservation of sedimentary strata below erosion surfaces can be highly variable laterally and commonly only small remnants of originally more extensive deposits remain. Preserved geometry of remnants can be quite different from the geometry of the original deposit and interpreting a preserved geometry as a depositional geometry can result in significant misunderstandings.

Martinsen (2003) further stated that transgressive as well as lowstand subaerial erosion surfaces are capable of regionally eroding entire depositional system successions in low-accommodation and shallow shelf settings. According to Valasek (1995), accommodation is relatively low and transgressive erosion can be significant during lowstand and early transgression, so overall preservation potential is low and small lateral variations in accommodation can significantly impact preservation. These processes explain the discontinuous nature of MB-D.

The preservation of MB-D thick sections overlying paleo-highs in the north-northwestern part of the study area is caused by shoaling and corresponds to predominantly cross-bedded sandstone (Figure 5-32). In the east-central part of the study area with locally increased subsidence, thick heterolithic units of MB-D are sag or channels.

5.3.2.2 Alternative Interpretation: Incised Channels

The weakest part of the previous interpretation would be the placement of a sequence boundary at the base of the MB-D. The erosional surface represents either a basinward shift in facies or a major drop in sea level (or both). Without assigning a sequence stratigraphic interpretation, MB-D thick trends in the basin can be interpreted based on stacking patterns instead.

Semi-isolated MB-D thick trends in the northern and northwestern portions of the study area (Figure 5-24) are predominantly cross-bedded facies. These thick beds are
Figure 5-30: Transgressive surface of erosion and its role in the reworking of low stand deposits and prograding shoals. Left: Formation and abandonment of a lowstand delta during a rise and fall of sea level from the Alberta Foreland Basin (Bhattacharya & Posamentier, 1994); Right: (A) shoreface profiles in the case of barrier overstep & (B) shoreface profile at various positions during a shoreface retreat interrupted by a porgradation episode (Cattaneo & Steel, 2003)
Figure 5-31: Sequence stratigraphic interpretation of systems tract and significant surfaces of the Bakken. Note that MB-D is a lowstand systems tract bounded by a 3rd order sequence boundary at the bottom and a transgressive surface of erosion at the top (modified from Figure 4-24 and Figure 4-25).
Figure 5-32: Two types of MB-D thick trends observed within the study area: (1) a predominantly cross-bedded sandstone thick overlying a paleo-high interpreted to be a bar buildup (red box) and (2) heterolithic sandstone thick overlying an area of locally increased subsidence interpreted to be channel or sag deposit (blue box). Paleotopography and accommodation is inferred from 3rd order residual map on top Three Forks Structure while illustration of different types of accommodation remnants is from Martinsen (2003).
on paleo-highs and exhibit coarsening upward cycles indicative of shoals and/or offshore bars. MB-D thick trends in the east-central part of the study area are cross-bedded and grade vertically into wave and current ripples (Figure 5-27). These beds exhibit a fining upward sequence and laterally confined geometries typical of channels.

The linear thick trends extend into Canada and fill topographic lows on the flanks of the Nesson Anticline. Some of these trends could be incised valleys (channel systems) originating in source areas to the north-northeast (Figure 5-6). Carbonate sediments produced on bathymetric highs of Nesson anticline were periodically deposited by tides, waves, and storms into these topographic lows producing alternating siliciclastic and carbonate beds and laminae.

More work needs to be done on comparing the scale of these channel systems in the Williston basin with other ancient channel systems such as the Fort Union Formation and “D” sandstone of the DJ Basin (Mike Hendricks, personal communication). If the linear trend does extend to Canada, it would make the Middle Bakken channel system hundreds of miles long and significantly larger than most known incised valley systems.

5.4 MM-BF Unit D Summary

The calcareous sandstone-grainstone of MB-D presents an opportunity to investigate mechanisms of sediment delivery and siliciclastic-carbonate mixing in an epeiric shelf/low-angle ramp setting. The integration of petrographic observations, mineralogical data, elemental data, and radiogenic isotopic data help to delineate several key features of MB-D Williston basin carbonate and siliciclastic sediment origins.

The grain size, mineralogy, and zircon trends indicate that siliciclastic delivery to the basin predominantly originated from an ephemeral drainage system generally from the north. Reworked carbonate grains were sourced from intra-basinal paleo-highs and demonstrate significant storm and wave influence. Cycle analysis of alternating siliciclastic-carbonate intervals reveals that the interplay of tides, storms, and seasonal

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changes in oceanic surface currents played an important role in the mixing of carbonate and siliciclastic constituents within the MM-BF.

The discontinuous nature of MB-D is due to both depositional thinning and erosional thinning. Depositional thinning due to facies variability is akin to modern oolitic environments where shoal and bars are cut and incised by tidal channels. Erosional thinning is common because the base of the MB-D is a 3rd order sequence boundary (Ss5) and in the top of the units is a transgressive surface of erosion (Ss6). MB-D is a low order LST system and initially prograded into the basin as shoals and barrier bars. The sands were subsequently reworked by storms and transgressions and capped by dolomitic sandstone and siltstone of MB-E.

With the presence of erosional thinning, MB-D is not a complete depositional record and is instead a depositional or accommodational remnant instead. MB-D thick trends in the north-northwest part of the study area are bar buildups over a paleo-highs while in the east-central part of the study area MB-D thick trends fills topographic lows (sag or channels).
CHAPTER 6: DIAGENESIS, RESERVOIR CHARACTERIZATION, ROCK MECHANICS OF THE MIDDLE MEMBER OF THE BAKKEN FORMATION (MM-BF)

This chapter will present and discuss the overall reservoir properties of the Middle Member of the Bakken Formation (MM-BF) with a particular focus on Unit D. It will primarily discuss the MM-BF in the North Dakota part of the Williston Basin. The properties included will be (1) porosity, (2) permeability, (3) density, (4) hydrocarbon saturations, and (6) rock mechanic data.

Data from sixteen cores from the Williston Basin are shown (Figure 6-1). Core data were publically available from the NDIC. Additional rock mechanic data were acquired from non-destructive testing of cores with the micro-schmidt hammer.

Figure 6-1: Map showing the locations of 16 key wells used for the study of MM-BF reservoir property.

List of Wells:
1. Rosenvold
2. Violet Olson
3. Charlotte
4. BN Flattop Butte
5. Graham USA
6. Federal 11-4
7. Federal 12-1
8. Debrecen
9. Henry Bad Gun
10. Parshall
11. Deadwood Canyon
12. Laredo
13. Nelson Farms
14. IM Shorty
15. Gunnison State
16. Nelson
6.1 Core Data Characteristics

The data were compiled and plotted graphically to evaluate reservoir quality of the various MM-BF lithofacies (Figure 6-2; Figure 6-3; Figure 6-4). Table 6-1 summarizes the petrophysical characteristics of the main reservoir units of the MM-BF in North Dakota.

Table 6-1: Table showing the petrophysical characteristics of the main reservoir units of the Bakken Formation in North Dakota based on core analysis.

<table>
<thead>
<tr>
<th>UNITS</th>
<th>POROSITY (%)</th>
<th>PERMEABILITY (mD)</th>
<th>SAMPLE SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Arithmetic Mean</td>
<td>Standard Deviation</td>
<td>Harmonic Mean</td>
</tr>
<tr>
<td>Lower Silt (MB-A, MB-B, &amp; MB-C)</td>
<td>5.6</td>
<td>2.0</td>
<td>0.0015</td>
</tr>
<tr>
<td>Middle Sand (MB-D)</td>
<td>6.2</td>
<td>3.8</td>
<td>0.0043</td>
</tr>
<tr>
<td>Upper Silt (MB-E &amp; MB-F)</td>
<td>6.6</td>
<td>2.4</td>
<td>0.0022</td>
</tr>
</tbody>
</table>

6.1.1 Porosity versus Permeability

There is not a clear trend of increasing permeability with increasing porosity for the lower siltstone of MM-BF. Poor reservoir quality in the MB-A, MB-B, and MB-C is attributed to the high frequency of nodular to massive calcite cement that may correspond to higher volumes of fine bioclastic material. The origin and distribution of these nodular calcite cements in the lower MM-BF siltstone is discussed in detail by Brennan (2016).

There is a general increase in permeability with increase in porosity for the middle sandstone of MM-BF. Reduction in the porosity and permeability of MB-D is attributed to higher volumes of bioclastic and oolitic material and the calcite cement that nucleates around it.

The upper siltstone of MM-BF shows a broad range of data with higher permeability values than the other units but there is no clear relationship between increasing permeability with increasing porosity. Higher porosity and permeability values
Figure 6-2: (A) Porosity and permeability chart from MB-A, MB-B, and MB-C; (B) Cross-plot between porosity and grain density. Density lines for quartz, calcite, and dolomite were established based on Doveton (1999).
Figure 6-3: (A) Porosity and permeability chart from MB-D; (B) Cross-plot between porosity and grain density. Density lines for quartz, calcite, and dolomite were established based on Doveton (1999).
Figure 6-4: (A) Porosity and permeability chart from MB-E & MB-F; (B) Cross-plot between porosity and grain density. Density lines for quartz, calcite, and dolomite were established based on Doveton (1999).
in the MB-E and MB-F are attributed to the coarser-grained ‘event’ beds and reduced volume of calcitic bioclast material. Overall, the MM-BF in North Dakota has a porosity average of 6% to 7% and a permeability average of 0.01% to 0.1 md

6.1.2 Porosity versus Grain Density

Plotting the porosity against the grain density is a useful method of determining the influence of mineralogy on reservoir quality. Note that the majority of the data lie between the calcite and dolomite density line. The cross-plots show a generalized trend of increasing porosity with increasing density which may suggest the importance of dolomitization in improving the reservoir quality.

6.1.3 Porosity versus Depth

Figure 6-5 shows data for MB-D from different counties within the study area. The cross-plot reveals a general trend of decreasing porosity with increasing depth for the sandstones of MM-BF. With increasing burial compaction, primary intergranular porosity is reduced by increasing amounts of dolomite, calcite, and quartz cement. Reservoir quality of MB-D seems to be controlled by the volume of calcareous bioclastic components within it.

6.1.4 Hydrocarbon Saturation

The UV fluorescence response of cores was used to capture the true nature of the hydrocarbons. According to Riecker (1962), blue to white fluorescence indicates light oil; dull orange fluorescence indicates heavy oil and black or no fluorescence denotes the absence of hydrocarbons and fluorescing minerals. Detailed, high resolution observations of core photos (Figure 6-6) reveal areas that fluoresce have features distinct from the areas that do not fluoresce under UV light. Non-fluorescence corresponds to intervals with abundant bioclastic components and calcite cement.

6.1.5 Discussion

This section discusses the differences in reservoir quality, hydrocarbon saturation, early diagenesis, and interpretations, where the MM-BF Unit D sandstone is prospective.
Table 6-2: Table showing differential UV fluorescence in the MM-BF. Non-fluorescence is associated with intervals of increased calcareous bioclastic material.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Non-Fluorescing</th>
<th>Fluorescing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Siltstone (MB-A, MB-B, MB-C)</td>
<td>Massive, Nodular, Patchy cements</td>
<td>Planar-laminations, Burrow-mottle texture</td>
</tr>
<tr>
<td>Middle Sandstone (MB-D)</td>
<td>Massive grainstone</td>
<td>Cross-bedded, ripple texture</td>
</tr>
<tr>
<td>Upper Siltstone (MB-E &amp; MB-F)</td>
<td>Faint (diffuse) planar laminations</td>
<td>HCS event beds, Burrow-mottle texture</td>
</tr>
</tbody>
</table>

6.1.5.1 Differences in reservoir properties and early calcite diagenesis

Grau and Sterling (2011) indicated that calcite cements prevented dolomitization and reduced porosity, permeability, and hydrocarbon saturation in the middle sandstones and lower siltstones of the MM-BF. The porosity-permeability-density cross plots seems to corroborate this interpretation. There is a complex diagenetic history associated with the compaction history of the Bakken. Diagenesis affects the type, size, distribution and volume of pores. Previous work from CSM Bakken Consortium suggested that the calcite cements precipitated during early burial (Figure 6-7). However, more petrographic work is required to determine the paragenesis of the Middle Bakken in North Dakota.

6.1.5.2 Where is the MB-D Prospective?

The sandstones and grainstones of MB-D are good to excellent quality reservoirs in the northern and northwestern part of the study area. In the Saskatchewan part of the Williston Basin, economic accumulations require a conventional trap. More work on hydrodynamics and oil migration pathways is required to show favorable regions where conventional traps may exist.

In the deeper (basinal) parts of the study area, MB-D along with other MM-BF units have very low porosity and permeability values. Oil saturations are expected to be high throughout the MM-BF as not all oil left the area after thermal maturation.
Figure 6-5: Left: Depth vs porosity data by counties for MB-D. The trend shows a general decrease in porosity with increasing depth; Right: Thin section photographs of the three data points from the left chart showing the effects of burial depth and volume of bioclastic component on porosity. (A) From the Charlotte 1-30H at 9288.5 ft; (B) From the Charlotte 1-30H at 9292.4 ft; (C) From the Debrecen 1-3H at 10762.55 ft.
Figure 6-6: Core photographs under UV (left) and normal light (right) showing the differential hydrocarbon saturation of the MM-BF. From the Rosenvold 1-30H, Divide County, ND (Courtesy of Continental Resources).
Overpressure is a key factor for production in these areas and more pressure studies would be beneficial. Aside from being an additional target, operators in the basin have been using MB-D to steer and land their horizontal wells due to its distinct low gamma ray response.

Figure 6-7: Paragenetic sequence of the MM-BF and the effect of diagenesis on reservoir quality, modified from Theloy (2013) and Alexandre (2011).

### 6.2 Rock Strength Characterization of the MM-BF

According to Fjaer and others (2009), there are many properties which can be used to determine the geomechanical behavior of rocks. Theloy (2013) has presented two of these properties, Youngs Modulus and Poisson’s Ratio, by using a dataset provided by the EERC (Figure 6-8). The differences in rock-mechanical character of the MM-BF were subtle and no conclusive relationships observed with regard to facies,
texture, presence or absence of natural fractures, or mineralogical composition. A larger static rock property dataset is needed to corroborate this hypothesis. ‘Static’ refers to a specific technique where a sample of rock material is tested directly by applying force and the resulting stress and strain recorded afterwards. Unfortunately this type of testing is expensive and destructive.

Figure 6-8: Rock mechanical dataset from EERC investigated in terms of a) formation adherence and facies, b) texture, c) presence or absence of natural fractures, and d) visual estimates of mineral content (from Theloy, 2013).

Another important geomechanical property is the compressive strength of a material. Compressive strength is measured by the capacity of a material to withstand axially directed compressive forces. The most common measurement to define the compressive strength of a material is uniaxial compressive strength or Unconfined Compressive Strength (UCS). A low-energy non-destructive rebound hammer (Bambino) was implemented to further characterize rock strength (UCS) in the MM-BF.
Leeb hardness values (HLD) were obtained from the rebound hammer and later converted to UCS values by cross plotting Bambino data with lab-derived data (Figure 6-9). The linear regression value is excellent \(R^2 = 0.9834\), but the lack of lab-derived data may lead to the overestimation of UCS values. A more robust relationship between HLD and UCS for the MM-BF was established by Rolf (2015) using a larger sample in the Elm Coulee area and was used to convert the HLD values into UCS instead.

**6.2.1 Micro-Schmidt Hammer Results**

The empirically-derived UCS values reveal that on average there is a subtle difference in rock strength values between the different units of MM-BF. This observation supports the hypothesis suggested by Theloy (2013); the MM-BF reservoir rock units do not seem to contain zones which would act as fracture baffles or intervals particularly prone to fracturing.

However, there is a large variance in the rock strength value within a single MM-BF unit attributed to small-scale heterogeneity on the bed- to lamina- scale. Figure 6-10 shows how differences in mineralogical composition affect the rock strength of MM-BF. UCS values, which can be a proxy for brittleness, increase as the percentage of carbonate material increases and clay material decreases. More work is required to investigate whether heterogeneities on the lamina- to bed-scale affects the overall process of hydraulic stimulation in the MM-BF.
Figure 6-9: Cross-plot of HLD vs UCS values acquired from the Nelson Farms 1-24H core and Larson 11-26. While both wells showing acceptable relationship values, the Larson 11-26 well was chosen for the conversion of HLD to UCS in order to avoid overestimation of rock strength.
Table 6-3: Units of MM-BF and empirically-derived UCS values from the micro-rebound hammer.

<table>
<thead>
<tr>
<th>Unit/Facies</th>
<th>UCS Value (PSI*10^3)</th>
<th>Mean</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB-F</td>
<td>17.5</td>
<td>7.22</td>
<td></td>
</tr>
<tr>
<td>MB-E</td>
<td>11.8</td>
<td>4.24</td>
<td></td>
</tr>
<tr>
<td>MB-D</td>
<td>12</td>
<td>7.43</td>
<td></td>
</tr>
<tr>
<td>MB-C</td>
<td>9.4</td>
<td>5.23</td>
<td></td>
</tr>
<tr>
<td>MB-B</td>
<td>14.2</td>
<td>4.29</td>
<td></td>
</tr>
<tr>
<td>MB-A</td>
<td>12.6</td>
<td>4.66</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6-10: Cross plot between mineralogy and UCS values showing decent relationship for both carbonate ($R^2=0.56$) and clay ($R^2=0.58$) minerals and weak relationship for detrital-clastic ($R^2=0.14$) minerals. Mineralogy values were taken from X-Ray diffraction data.
CHAPTER 7: CONCLUSIONS & FUTURE WORK

The main objectives of this study are: (1) interpret the depositional environments of MM-BF unit D, its geometry, continuity and contact relationship to underlying and overlying units, (2) investigate provenance and cyclicity of clastic and carbonate sediments, (3) and analyze reservoir quality and mechanical properties.

The conclusions from this study are as follows:

- The Middle Member of the Bakken Formation (MM-BF) is a mixed siliciclastic-carbonate unit deposited in a shallow epeiric shelf/low-angle ramp setting during a period of sea-level rise.
- MM-BF can be divided into six distinct units (MB-A, MB-B, MB-C, MB-D, MB-E, and MB-F) that represent lower order sea level fluctuation and change in depositional environments.
- The lower MM-BF dolomitic siltstone and silty dolomite (MB-A, B, & C) were deposited in a tide-dominated, wave-influenced environment as part of a highstand to falling stage systems tract.
- The middle MM-BF sandstone (MB-D) was deposited as part of a lowstand systems tract in tide-dominated, wave-influenced environments.
- The upper MM-BF siltstone (MB-E & F) was deposited in a tide-dominated environment as part of a transgressive systems tract.
- Siliciclastic grains of MB-D were delivered into the basin by an ephemeral drainage system from the north north-east.
- Carbonate grains of MB-D were sourced from intra-basinal paleo-highs and underwent significant wave and tidal reworking.
- The mixing of carbonate and siliciclastic constituents within MB-D took place due to the interplay of tides, storms, and seasonal changes in oceanic surface.
- The discontinuous nature of MB-D is due to both deposition and erosional changes in thickness.
- MB-D thick trends in the north-northwest part of the study area are bar buildups over paleo-highs while in the east-central part of the study area MB-D thick trends fill topographic lows.
Porosity-Permeability-Grain Density cross plots along with UV fluorescence reveal the presence of early burial calcite cement. This prevented dolomitization and has a detrimental effect on the reservoir properties.

Non-destructive testing using the micro-schmidt hammer provides a way to supplement the static mechanical properties dataset. The micro-schmidt hammer data show small-scale heterogeneities within the MM-BF at the bed to lamina-scale.

7.1 Recommendations

The recommendations for future work include:

- Expand the study area west into Montana and north into Canada to build in-depth sequence stratigraphy correlations that will further build upon the current CSM Bakken Consortium framework.
- Detailed conodont and biostratigraphic work on the different MM-BF units to better understand depositional rates.
- Zircon dating and more petrographic analysis in North Dakota and Montana part of the Williston Basin to determine the provenance for the MM-BF.
- Additional cycle analyses on the MM-BF upper silt (MB-E & F) to help better define depositional environments.
- Advance petrophysical models to calibrate for fluid saturations and mineralogy.
- In depth study of calcite diagenesis by way of XRD and SEM.
- Hydrodynamics study in the north-northwestern part of North Dakota to identify oil migration pathways and help find conventional accumulations.
- Extensive pressure mapping of the MM-BF to identify areas of overpressuring.
- Data from the micro-schmidt hammer should also be compared with sonic logs to observe the relationship between static and dynamic rock-mechanic properties.
- Engineering study to investigate the effect of bed to lamina scale heterogeneities within the MM-BF on hydraulic stimulation fracture growth.
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## APPENDIX A: SUPPLEMENTAL FILE

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<thead>
<tr>
<th>File</th>
<th>Description</th>
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</thead>
<tbody>
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<td>Contains all of the core description data used in this study</td>
</tr>
</tbody>
</table>