PETROLEUM GEOLOGY OF THE B CHALK BENCHES OF THE NIOBRARA FORMATION; WATTENBERG, SILO, AND EAST PONY FIELDS,
NORTHERN DENVER BASIN, CO/WY

By
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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geology).

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ABSTRACT

The Denver Basin has been explored and exploited for its immense petroleum potential for over 120 years. It is historically known for its conventional drilling success in the Permian Lyons Sandstone, Upper Cretaceous “D” and Lower Cretaceous Muddy “J” sandstones. With recent advancements in drilling and completions technology, exploration in the Denver Basin has transitioned to be focused on the unconventional Cretaceous stratigraphy present in the basin. The Niobrara is currently being explored and produced extensively within Wattenberg Field located just north-northeast of the Denver, CO. At the same time, exploration has extended outside of the Wattenberg Field proper and many locations are now being targeted for future exploration and production with the potential of having higher liquids to gas ratios, as well as, better permeability and porosity. Both Silo Field, located directly north of Wattenberg, and the East Pony and Redtail fields located northeast of Wattenberg Field, lie within some of these promising hydrocarbon-rich regions. These fields are currently being explored, with the B chalk Member of the Niobrara is the best horizontal target in the area, with porosity values that reach as high as 13-16%, and contains greater than 70% of the hydrocarbon as liquids. This study provides an in-depth look at the B1 and B2 chalk and marl benches of the Smoky Hill Member of the Niobrara including, 1) detailed core description and identification of six main facies, their vertical and lateral heterogeneities, and their depositional models, 2) reservoir characterization using petrographic thin sections, FESEM imaging, XRD bulk minerology, Source Rock Analysis, and porosity data, and, 3) petrophysical well log analysis and subsurface mapping.
Detailed core descriptions, petrographic thin section interpretation, and analysis of FESEM images of the B1 and B2 chalk and marl benches identified six main facies. These facies vary in location, thickness, structural features and major calcareous and terrigenous constituents. These facies vary from pure chalks to massive fossiliferous marly chalks, to pure marls. Location, thickness, and patterns in which these facies occur have an effect on overall effectiveness of the chalk benches as reservoirs.

XRD bulk mineralogy analysis, geochemical interpretations, and porosity values taken from the B1 and B2 chalk and marl benches help differentiate the two chalk beds. Integration of results from this study show that the B2 chalk is the dominant target in the study area. Results show the B2 chalk is: 1) dominated by Facies 1, 2, and 6, which have the greatest qualitative preserved porosity, 2) contains carbonate contents as high as 96% with only 3% siliciclastic input, increasing chances of greater amounts of preserved porosity, 3) it is comprised of the greatest amount of preserved nanno-fossils (containing high amounts of porosity), 4) it is organic rich with TOC values ranging from 1.5-4.5 wt. %, 5) it has very good to excellent free hydrocarbons present in the formation, and is in the mature oil window with Type II oil prone kerogen, 6) calculated porosity for the B2 chalk ranges from 5-12.5%, and 7) the B2 chalk occurs as the most widespread unit, and has the most homogenous stratigraphic thickness throughout the study area. The B1 chalk should be considered a secondary target where appropriate, as it has very similar qualities to the B2 chalk, but has slightly lower grade reservoir characteristics. Given the lack of detailed reservoir characterization of the B benches of the Niobrara, and the increasing interest in pursuing the B chalk benches throughout the
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Table 5.2: Expected expelled products from kerogen type and associated parameters. Taken from Krueger, 2013; Modified from Peters and Cassa, 1994.  

Table 5.3: Maturity stages as defined by maturation and generation parameters, Ro, Tmax, and PI. Taken from Krueger, 2013; modified from Peters and Cassa, 1994.
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CHAPTER 1

INTRODUCTION

Horizontal drilling and advanced hydraulic fracturing technology is driving unconventional oil and gas resource plays into the forefront of the energy industry. At a time when the world was feeling like hydrocarbon deposits were quickly being depleted, unconventional drilling has brought back to life the idea that the United States can be an energy exporting country. Exploration and production for unconventional oil and gas deposits have unleashed unprecedented drilling in many states across the United States. In some cases, exploration is targeting historically producing basins, with the intention of drilling oil and gas bearing formations that were previously thought to be uneconomic: one such example of this is the Denver Basin.

The Denver Basin, an asymmetric Laramide structural basin, covers nearly 70,000 square miles in eastern Colorado, southwestern Wyoming, western Nebraska and northwest Kansas (Figure 1). It has been explored and exploited for its immense petroleum potential for over 120 years. The Denver Basin is historically known for its conventional drilling success in the Permian Lyons Sandstone, Upper Cretaceous “D” and Lower Cretaceous Muddy “J” sandstones. With recent advancements in drilling and completions technology, exploration in the Denver Basin has transitioned to be focused on the unconventional Cretaceous source-reservoir intervals. Today, the Denver Basin is better known for the unconventional petroleum deposits within the Niobrara Formation and the Codell Sandstone. (Figure 1.2). It is estimated that there is approximately 2 billion barrels of oil recoverable from the Niobrara (EIA.com 10-1-15).
Figure 1.1: Map displaying the location of the Denver Basin and the top of the Niobrara structure (subsea), as well as the bounding mountain ranges. Fields are shown in green (oil) and red (gas). The dotted green line depicts the edge of the production window for the deep Niobrara production.
Figure 1.2: Cretaceous stratigraphy of the Denver Basin. The far left column depicts the formations that produce hydrocarbons.
The Niobrara Formation was deposited in the Cretaceous Western Interior Seaway, between the late Cretaceous stages of the early Coniacian and early Campanian, and includes two formal members: the basal Ft. Hays Limestone and the overlying Smoky Hill. The Smoky Hill Member is made up of alternating chalk and marl sequences and is broken into three main sections: the A chalk and marl, the B chalk and marl and the C chalk and marl (Figure 1.2). The main reservoir targets are the A, B, and C chalk benches, with the corresponding marls acting as the organic-rich sources.

The Niobrara is currently being explored and produced extensively within Wattenberg Field located just north-northeast of Denver, CO. At the same time, exploration has extended outside of the Wattenberg Field proper and many locations are now being targeted for future exploration and production with the potential of having higher liquids to gas ratios, as well as better permeability and porosity. Both Silo Field, located directly north of Wattenberg, and the East Pony and Redtail fields located northeast of Wattenberg Field, lie within some of these promising hydrocarbon-rich regions (Figure 1.3). These fields are currently being developed, and the B chalk Member of the Niobrara is the best horizontal target in the area, with porosity values that reach as high as 13-16%, and contains greater than 70% of the hydrocarbon as liquids (Noble Energy inc. 2014). Development of Silo Field was as the forefront of establishing Niobrara production outside of Wattenberg Field as early as the late 1980’s, and was also one of the first fields to establish horizontal production out of the B chalk interval.

Successful drilling of the B chalk across northern Colorado is variable, and there are many locations where the Niobrara has not been capable of economic production.
There is a need to better understand the distribution of the Niobrara across the northern Denver Basin, but more importantly, there is a need for a better understanding of how the B chalk of the Niobrara is distributed across the region and how the reservoir quality varies.

This study is focused on answering some of the questions as to how the B chalk of the Niobrara changes throughout the northern Denver Basin and how these reservoir characteristics are affecting the overall success of oil and gas exploration in this region.

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Figure 1.3: Map displaying the Denver Basin and the top of the Niobrara structure. Inset depicts the study area, including the major fields in red (gas) and green (oil) with the names of the fields included.
1.1 Purpose of Study

The Denver Basin has been explored and exploited for its immense petroleum potential for over 120 years. Today it is known for the unconventional reservoirs within the Niobrara Formation and the Codell Sandstone.

The B chalk of the Smoky Hill Member of the Niobrara is currently the best target interval for oil exploration within the north and northeastern parts of the Denver Basin. The motivation for doing an in-depth study of the petroleum potential of the B Chalk within this area of interest is to give insight into the reservoir within each location proposed in this study, as well as an interpretation as to how the B chalk changes across some of the most promising new fields within the basin.

An in-depth examination at the heterogeneity of the B Chalk through the study of the core, mineralogy, petrology, maturity, porosity, total organic carbon values, as well as tying these analyses to associated petrophysical log responses, will give insight as to how the B chalk varies, and its potential as a successful target in each proposed study area.

This is an exciting time to expand research on the Niobrara Formation as there is high industry activity pursuing new fields and expanding old fields within the study area in search of increasing production within the B chalk bench. This study will assist companies to more accurately refine the overall B chalk bench into preferred target zones, and allow them to make more accurate land acquisitions based on a better understanding of the distribution. The following reservoir characterization will give
companies the information needed to be more accurate with exploration and development programs.

1.2 Location of Study Area

The study area is the northern Denver Basin area expanding from the northern section of Wattenberg Field located just northwest of Denver, northward to Silo Field, located on the southeastern edge of Wyoming. This area of interest also extends east to include Noble Energy Inc.’s East Pony Field and Whiting Petroleum Corporation’s Red Tail field (Figure 1.3).

The Denver Basin is an asymmetrical Laramide structural basin, with the axis of the basin running parallel to the Front Range of Colorado and the Laramie Range of Wyoming (Clayton and Swetland, 1980). It has a steeply dipping western limb and a gently dipping eastern limb (Figure 1.4). The deepest part of the basin is present between Denver Colorado, and Cheyenne Wyoming, underlying well known fields such as Wattenberg Field and Silo Field, both of which are part of this study.

Wattenberg Field is located in the deepest and most thermally mature part of the basin, northeast of Denver in Weld County. It is located along trend of the Colorado Mineral Belt, which is a known heat source for many of the mineral and hydrocarbon accumulations across Colorado (Figure 1.5a). To the north and northwest, thermal maturity decreases, and the Niobrara transitions from dominantly gas productive in Wattenberg, to oil productive as you leave the hottest part of the basin. Geothermal gradients studied by Thul (2012) show that there is high heat flow present in Wattenberg, and moderate to high heat along the extension of the Colorado Mineral
Belt. Silo Field, located to the North also has high heat flow due to a separate heat anomaly.

Silo Field is located in the northern part of the Denver Basin in the southeast corner of Wyoming, in Laramie County. East Pony and Red Tail fields are located northeast of Wattenberg Field. East Pony and Red Tail fields are located on the northeastern extension of the Colorado Mineral Belt, which provides heat flow to mature the Niobrara petroleum system even as it extends out towards the eastern edge of the basin and becomes shallower (Figure 1.1).

Figure 1.4: Cross Section of the Denver Basin showing the steeply dipping western limb and the shallowly dipping eastern flank of the Denver Basin. Stratigraphy present in the basin is depicted in the different colors and key. (Sonnenberg, 2015)
Figure 1.5a, 1.5b: 1.5a) Image displaying temperature values across the middle of the Denver Basin. The warmer colors represent higher heat flow. High heat flow exists under Wattenberg field, but also extend out to the north east and is hot under the areas of Redtail and East Pony fields. 5b) Geothermal gradient map covering the Denver basin. Image shows high heat in Wattenberg and moderate to high heat along the extension of the Colorado Mineral Belt as well as in Silo Field area to the north (Thul 2012).
1.3 Data and Methods

The purpose of this study is to provide an in-depth interpretation and analysis of the B chalk bench of the Smoky Hill Member of the Niobrara Formation. This study is intended to aid in the ongoing exploration of the B chalk reservoir in the north and northeastern parts of the Denver Basin, in Colorado and Wyoming. The proposed project will cover the northern and northeastern parts of the Denver Basin across northern Colorado and southwestern Wyoming, comparing the B chalk throughout multiple field locations. This project will: 1) use conventional core and petrophysical log correlations to develop a depositional framework for the B chalk interval identify 2) utilize completed source-rock analyses, total organic carbon values, and porosity and permeability values to better characterize the B chalk reservoir within and across the proposed study areas, 3) interpret petrographic thin sections of the B chalk reservoir using the epi-fluorescence microscope, 4) interpret Field Emission Scanning Electron Microscope (FESEM) images, 5) use petrophysical parameters to determine and interpret key reservoir properties and their distributions across the study area.

1.3.1 Core and Core Data

The data set available for this study includes five cores and associated core data; as well as a sixth core data set that has no associated core. (Table 1.1).

1.3.2 Thin Section and FESEM

Ten Samples were taken from the Weld 11-28 core located in Grover Field. Sample locations were chosen to reflect an even distribution of the core, with at least one
sample from each facies discussed in chapter 3. A yellow box was drawn on the core identifying the sample location. Triple O Slabbing cut a one inch by two inch section of the butt of the core in the corresponding location to the yellow box. These samples were then broken into two pieces, one to be made into a thin section and one to be made into an FESEM sample.

Table 1.1: Core used in this study for core interpretation or data set interpretation. Table includes well name, API #, township, range and section, cored interval used in the study, and if there is an associated data set.

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<th>API Number</th>
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<th>RNG</th>
<th>SEC</th>
<th>Core Interval (in feet only)</th>
<th>Core</th>
<th>Data set</th>
<th>Thin section / FESEM</th>
<th>Porosity Data</th>
<th>XRD Data</th>
<th>Geochemical data</th>
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<td>6710-6790</td>
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</tr>
</tbody>
</table>
1.3.3 Well Logs

The well logs used in this study include gamma ray, spontaneous potential (SP), resistivity, and neutron porosity and bulk density curves. The gamma ray curve responds to the presence, or lack thereof, of radioactive isotopes such as thorium, uranium, and potassium. These elements are commonly present in clays, micas, feldspars, and organic matter. Interpretation of gamma ray curves aid in lithologic correlations as a higher gamma ray reading indicates shale, or in the case of carbonates, a marl, whereas a lower gamma ray reading generally represents a cleaner sand, or chalk. Resistivity curves measure the conductivity of fluid within the rock, making them useful for identifying hydrocarbon saturated rocks. Resistivity is also useful for lithologic correlation. The spontaneous potential (SP) curve was used for lithologic correlation when gamma ray curves were not available. The neutron and density curves were used when wells were missing a resistivity curve.

1.4 Previous Work

The Late Cretaceous Niobrara Formation is present throughout the basins of the Rocky Mountains (Dean and Arthur, 1998). The Niobrara Formation was deposited in the Western Interior Seaway, an epicontinental sea that stretched from the Arctic Ocean in the north to nascent Gulf of Mexico in the south, and from the mountains of the Sevier Orogeny in the west to the more gentle lowland topography to the east (Figure 1.5) (Weimer, 1984). The Western Interior Seaway was a result of high eustatic sea level during the Late Cretaceous, coupled with foreland basin subsidence associated with the Sevier Orogenic belt to the west.
The cyclicity of the chalk and marl sequences of the Niobrara have been studied extensively to better understand the controls driving the lithologic variations present throughout the Denver Basin. Many studies have helped provide a better understanding of the distribution of the organic-rich rocks and interbedded chalks (Kauffman, 1977; Arthur & Dean, 1991; Dean & Arthur, 1998; Longman et al. 1998; Landon et al., 2001; Locklair & Sageman, 2007, Stout, 2012; Nakamura, 2015; and O’Niel, 2015). The marl-rich zones of the Niobrara contain high TOC values, ranging from 1-8% and are dominated by oil prone type II kerogen (Landon et al., 2001).

Longman and others (1998) developed a depositional model for the Niobrara which show that 1) siliciclastic sediment input increases to west, 2) calcium carbonate (CaCO₃) fraction increases to the south, and 3) TOC abundance increases to the east where there is less terrigenous material diluting it. They proposed multiple mechanisms for explaining these major controlling factors on the deposition (Figure 1.6).

Dean and Arthur (1998) used X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD) results from rock samples to provide more detailed information on the relationship between elemental fractions, which allowed for a better understanding of the chemical environment in which the rocks were deposited.

This study will integrate previous work with the analyses and interpretation of this study to present a more detailed understanding of the distribution and reservoir properties of the B chalk petroleum target.
Figure 1.6: Image displaying the Cretaceous Western Interior Seaway and depositional patterns seen by Longman et al. in the 1998 study.

Modified from Roberts and Kirschbaum (1995) and Longman et al. (1998)
CHAPTER 2
GEOLOGIC FRAMEWORK

This chapter will introduce the regional structure of the Denver Basin; the stratigraphy, sequence stratigraphy, and sedimentology of the Niobrara Formation, and an overview of the production history of each major field in the study area.

2.1 Regional Structural Setting

The Niobrara Formation was deposited in the Wester Interior Basin- an asymmetric foreland basin which formed as a response to the Sevier orogenic activity occurring in the Middle to Late Cretaceous (Dean & Arthur, 1998). This Western Interior Basin extended from the edge of the Sevier Orogeny in the west out to the present-day Kansas, Nebraska, and North Dakota in the east. The Laramide Orogeny, which occurred in the Late Cretaceous to Early Eocene, partitioned the Western Interior Basin into many smaller intermontane basins that are present today.

The Denver Basin is one of the many intermontane synclinal basins created during the Laramide Orogeny. The Denver Basin is bounded on the west in Colorado by the Front Range of the Rocky Mountains and the Wet Mountain Uplift, and in Wyoming by the Laramie Range and the Hartville Uplift. It is bounded in the north by the southern flank of the Black Hills in Nebraska, and in the east by the Chadron Arch of west-central Nebraska and the Las Animas Arch in east central Colorado and northwestern Kansas. The basin is bounded in the south by the Apishapa Arch in southwestern Colorado. The Laramide Orogeny, which led to the uplift of the Rocky Mountains, is responsible for the formation of the Denver Basin. After the deposition of the Tertiary sediments originating from the Front Range, the entire Denver basin was tilted towards the east.
This tilting lead to the structural configuration in which the Denver basin is found today (Figure 1.4). The Denver Basin is an asymmetric basin with a gently dipping eastern flank, dipping 0.5° to the west, and steeply dipping western flanks that dip 10+° to the east (Sonnenberg, 2011).

2.2 Sequence Stratigraphy of the Upper Cretaceous

High eustatic sea levels coupled with foreland basin tectonics in the Late Cretaceous, resulted in a north-south oriented epicontinental seaway: the Western Cretaceous Interior Seaway (WCIS) (Figure 2.1). The WCIS extended from the Boreal Sea in the north to the nascent Gulf of Mexico in the south (Weimer, 1984). Series of third-order transgressions and regressions of the seaway characterize the Upper Cretaceous stratigraphy present in the Denver Basin. The Niobrara Cyclothem as well as the Niobrara stratigraphy will be discussed below.

Diverse strata including marine and continental facies are extensive throughout the basin and give insight to the fluctuations in depositional environments in the seaway at differing times. Sedimentation in the basin was controlled by a number of influences including; tectonic growth of the basin, eustatic sea level changes, climate changes, and water-mass dynamics in epicontinental seas (Kauffman, 1993).
Figure 2.1: Image of the Western Cretaceous Interior Seaway extending from the Boreal Sea in the North to the Nascent Gulf of Mexico in the south. Present day state outlines of the United States are shown in gray and the study area for this study is represented by the red box. (Blakey 2016)
The underlying Greenhorn Formation represents a highstand sequence with high carbonate content. The Codell Sandstone Member of the Carlile was deposited during a regression where siliciclastic material was deposited throughout the eastern portions of the seaway (Weimer, 1960; Weimer, 1984; Meissner et al., 1984) (Figure 2.2).

The Niobrara Formation, which was deposited in the Coniacian (89.5-83 Ma) lies unconformably above the Codell Sandstone, and consists of the basal Fort Hays Limestone, a chalk of greater than 95% carbonate, and the overlying Smoky Hill Member, an alternating chalk and marl sequence (Figure 1.2).

The Fort Hays Limestone represents a rapid transgression and period of highstand deposition (Kauffman et al., 1985). The Fort Hays Limestone is characterized by highly bioturbated micritic limestones and mudstones. These limestone-mudstone couplets are thought to be representative of climatic cycles known as Milankovitch Cycles. These Milankovitch Cycles are prominent in the Smoky Hill Member and will be discussed in detail later in the section.

The overlying Smoky Hill Member is broken into seven stratigraphic units based predominantly on lithology, which in ascending order are: the D interval, the C marl, the C chalk, the B marl, the B chalk, the A marl, and the A chalk (Figure 1.2). The alternating nature of the Smoky Hill Member is due to shorter fourth-order transgressive-regressive cycles that occurred during the third-order Niobrara Cyclothem (Figure 2.2).

The chalks, comprised of: calcite-rich peloids, pelagic foraminifera, coccoliths, and Inocermaid and oyster shells, were likely deposited during highstands, where biotic productivity was high (Lockridge & Scholle, 1978). High levels of bioturbation and minor
amounts of preserved TOC suggest the highstand depositional environment had low siliciclastic input and higher oxygen levels in the water column (Longman et al., 1998).

The marls are laminated and darker in color, and are comprised of greater amounts of siliciclastic materials such as clays, and fewer amounts of carbonate foraminifera, coccolith platelets, and Inoceramid shells. This suggests that the deposition of the Smoky Hill marls occurred during periods of higher order regressions or relative sea level drops, with increased terrigenous siliciclastic input into the basin diluting carbonate production (Longman et al., 1998) (figure 8). The lack of bioturbation, as well as the preservation of greater amounts of TOC suggest that suboxic to dysoxic conditions were prevalent during the time of marl deposition (Kauffman et al., 1985).

The chalks and marls of the Upper Niobrara are overlain by the Sharron Springs Member of the Pierre Shale. Deposition of the Pierre Shale occurred during a significant regression of the WCIS (Figure 2.2). The transition upward from the Niobrara is characteristic of a change from calcareous shales to a siliciclastic shales of the Pierre Shale. The overlying shales of Pierre act as a seal for hydrocarbons present in the Niobrara Formation.

2.2.1 Stratigraphy of the Smoky Hill Member of the Niobrara

As discussed above, conventional nomenclature of the stratigraphy of the Smoky Hill Member consists of the D interval, C marl, C chalk, B marl, B chalk, A marl, and A chalk in ascending order (Figure 1.2). Many companies and researchers exploring and producing in the Denver basin have identified a smaller unnamed chalk and marl sequence present between the A marl and the B chalk. Companies have come up with
individual names for this stratigraphic include the “baby B” the “upper B” the “B1” etc, but there is not a uniformly used term. For the purpose of this study, the chalk bench of this unit will be identified as the B1 chalk and the marl bench will be referred to as the B1 marl. The commonly known and correlated B bench of the Smoky Hill Member will be referred to as the B2 chalk and the B2 marl (Figure 2.3). Figure 2.3 shows a digital log with the tops of each member identified using this nomenclature.

Figure 2.2: Stratigraphic Chart of the Niobrara Formation, underlying Carlile Formation, and overlying Pierre Shale coupled with a sea level curve depicting the transgressions and regressions responsible for the alternating nature of distribution of the Niobrara Formation. (Kauffman, 1998)
2.3 Minor Cyclicity and Milankovitch Cycles in the Niobrara

The short fourth-order transgressions and regressions discussed above are responsible for the major cyclicity seen between the chalks and the marls of the Smoky Hill Member of the Niobrara. Smaller scale cyclicity, characterized by chalk and marl bedding couplets ranging in thickness from 10 inches to over 3 feet, and are present in both the chalk and the marl benches of the Smoky Hill Member (Barlow and Kaufman, 1985).
This cyclicity is interpreted to represent Milankovitch Cycles, or climactic changes that occur as a result of the Earth’s rotation around the sun. Variations in the Earth’s eccentricity, axial tilt, and procession, affect the distance in which the Earth rotates around the sun, and affects the seasonality of solar radiation reaching the Earth’s surface (Barlow and Kaufman, 1985). These cycles of increased and decreased solar radiation cause alternating wet and dry climatic periods on Earth (Barlow and Kaufman, 1985). Figure 2.4 shows the effect these wet and dry cycles have on: carbonate lithofacies, preservation of organic carbon, abundance of stable isotopes, diversity of species present, and abundance of specimens. During wet time periods, deposition of terrigenous siliciclastic materials into the basin increases, leading to the shale-rich marl bedding present in the couplets. The marls have: increased preserved organic carbon, but decreased stable isotopes, diversity and abundance of species. During the dryer time periods, siliciclastic input into the basin slows, allowing for carbonate production to be the dominant depositional sediment. The chalks deposited in the dryer climates have: increased diversity and abundance of species and specimens, increased bioturbation, and decreased preserved organic carbon. Figure 2.5 shows the effects of climate cycles on intrabasinal carbonate deposition.

The cyclicity interpreted in the Niobrara and underlying Greenhorn is thought to be reflective of the 21 Ka (processional) and 42 Ka (obliquity) orbital periods of the Milankovitch Cycles.
Figure 2.4: Image displaying the effects of Milankovitch climate cycles on the rock record of a chalk and marl carbonate system. Wet phases lead to marl deposition. The marls have higher preserved organic carbon, but decreased stable isotopes, diversity of species and abundance of specimens. Dry phases lead to chalk deposition. The Chalks have increased stable isotopes, biodiversity and abundance of specimens, but decreased organic carbon due to high levels of bioturbation.
Figure 2.5: Image displaying the effects of climate cycles on intrabasinal Carbonates, and extrabasinal siliciclastics. Wet and cooler phases lead to an increase in limestone shale (or marl) deposition, and dry and warmer phases lead to more chalk deposition.

2.4 Hydrocarbon Production and Field Overview

The study area for this thesis covers the northern Denver Basin; which includes: Wattenberg, Silo, Hereford, East Pony, Redtail and Grover Fields. To better understand the current petroleum exploration and production occurring in the study area, an overview of the main Niobrara activity in each field will be presented below.
2.4.1 **Wattenberg Field:**

Wattenberg Field is located in Weld County, northeast of Denver, Colorado (Figure 2.6). Wattenberg Field was discovered in 1970, and produced out of the Lower Cretaceous J-Sandstone. Niobrara production in the field began in 1981, and horizontal Niobrara drilling was initiated in 2005. The Niobrara Formation is overpressured in Wattenberg Field and is drilled at depths of 6,200 to 8,200 feet. Wattenberg field is located on a hot spot with temperature gradients ranging for 16-18 degrees Fahrenheit/ 1,000 feet near the edges of the field, and 28-29 degrees Fahrenheit/ 1,000 feet closer to the center of the field (Sonnenberg, 2015) (Figure 2.6).

Niobrara production in the field has increased markedly in the last 8 years; recent completions have seen initial production of 100 to 700 barrels of oil per day with a gas to oil ratio of 500 to 10,000 cubic feet per barrel. Estimated ultimate recoveries per well have reached as high as 300,000 barrels of oil equivalent or more (Sonnenberg, 2015). Today the Wattenberg Field is ranked as the fourth-largest oil field and ninth largest gas field in the United States (EIA, 2015).

2.4.2 **East Pony Field:**

East Pony Field is located in Weld County, CO, northeast of Wattenberg Field (Figure 2.7). East Pony Field is actively drilled in both the Niobrara and the Codell/Fort Hays, with most of the horizontals being drilled in the B Chalk bench of the Niobrara. Well volumes being produced from the Niobrara Formation in the field are averaging 80% or more oil and about 5% gas. Noble, one of the largest operators of East Pony Field, estimates a potential of 1 MMBOE EUR from their 9,000 foot laterals, and are
hoping to develop the field with high density drilling patterns that allow for up to 16 wells per section.

Figure 2.6: Structure map of top of Niobrara. Wattenberg Field is highlighted by the red dashed line and the Greater Wattenberg Area is identified by the blue box. Vitrinite reflectance values for the J Sandstone are shown in black illustrating the Wattenberg geothermal anomaly.
2.4.3 Redtail Field:

Redtail Field is located in Weld County CO, northeast of Wattenberg Field, and north of East Pony Field (Figure14). The majority of Redtail Field acreage is held by Whiting Petroleum Corporation who owns approximately 147,472 gross acres in the field, and average 80% working interest. Whiting is drilling a mixture of 960 and 630-acre spacing units, and have close to 5,782 potential drilling locations in the Niobrara “A”, “B”, “C” and Codell/ Fort Hays. Whiting’s Redtail production averaged 16,575 BOE/d in the 3rd quarter of 2015, which was up from 10,155 BOE/s in the 4th quarter of 2014. According to Whiting’s January 4th, 2016 presentation, total original oil in place (OOIP) for the Niobrara “A”, “B”, “C”, Codell, and Ft. Hays is 93 MMBOE/960 acre...
spacing, with the Niobrara B zone contributing 47 MMBOE/960 acre spacing (Whiting Petroleum Corporation’s 2014 Annual Report).

Figure 2.8: Map showing the location of the Redtail Field and its proximity to the Greater Wattenberg Area. Colored well spots show pre-2013 Codell and Niobrara production in gray, 2013-2015 Niobrara Production in Red, and the 2013-2015 Codell production in Yellow. Facts about Redtail Field are shown are the right side of the image.
2.4.4 Hereford Field:

Hereford Field is located in northern Weld County just south of the Wyoming border, and the majority of the acreage in the field is leased by EOG Resources. The 2009 discovery by EOG, of the Jake 2-01H horizontal well, (located in Hereford field and drilled in the B chalk bench) kicked off the reopening of the Denver Basin Niobrara play (Figure 2.9). As of July 2015, EOG has drilled 71 productive Niobrara horizontal wells within Hereford field, and over 4,400 horizontal wells have been drilled in the entire Denver basin, all targeting the Niobrara (Anderson et al., 2015). Hereford Field peaked in production in 2011 with 1,923,175 barrels of oil, 2,241,113 thousand cubic feet of gas, and 623,913 barrels of water, (COGCC, 2016).

Figure 2.9: Map showing the location of Hereford Field outlined in purple, and the Jake 2-01H discovery well.
2.4.5 Grover Field

Grover Field is located adjacent to Hereford Field in Weld County in northern Colorado (Figure 2.9). Grover Field covers approximately one township. The field production peaked in 2010 with 413,593 barrels of oil, 881,230 thousand cubic feet of gas, and 917,793 barrels of water.

2.4.6 Silo Field:

Silo Field is located in the northern Denver Basin, in the southeastern corner of Wyoming (Figure 2.10). Niobrara production in the field comes from depths ranging from approximately 7,600 feet to 8,500 feet. Cumulative production from 40 vertical and 68 horizontal wells at Silo fields has exceeded 10.4 million barrels of oil and 8.9 billion cubic feet of gas (Sonnenberg, 2015). Due to the success in the field, many companies are holding leases and drilling in the area. Expansion of the extents of the field as well as better optimization and superior completion success suggest increased future production.
Figure 2.10: Inset map shows location and size of Silo Field relative to Wattenberg Field. Image shows structure map of the Niobrara in Silo Field.
CHAPTER 3
FACIES DESCRIPTION AND INTERPRETATION

Five conventional cores taken from the Niobrara Formation were described in detail in terms of their lithology, sedimentary structures, biogenic structures, and fossil content at a 0.1 inch scale. As discussed previously, the Niobrara stratigraphy is divided into seven stratigraphic units, ascending from the D intervals up to the A chalk. Detailed interpretations and descriptions were made for the B1 chalk, B1 marl, B2 chalk and, when available, the B2 marl. This study divided the interval of interest (the B chalk and marl benches) into six main facies. These facies were classified based on the definition that a facies is: “a category of rock that is distinguishable by a number of characteristics that reflect the environment of deposition, composition, structures, or fossil content, and can be distinguished as different from the bodies of rock above, below, and laterally adjacent” (Walker, 1992).

3.1 Methods for Analysis

Each core was described with a modified core description sheet (Figure 3.1). This allowed for the normal grain size interpretation curve to be altered to reflect observed color and visible characteristics and their connection to carbonate content using the four main Niobrara lithologies described by ElGhonimy (2015) which include: chalk, marly chalk, chalky marl, and marl. The definitions created by ElGhonimy can be seen in table 2. Core photos and correlations to gamma ray logs aided in the
identification of these six facies. Descriptions were made in one foot intervals, with smaller features annotated within the one foot interval. These six facies can be seen in similar patterns throughout all five cores and are described below.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Texture</th>
<th>Fossils</th>
<th>Sedimentary Structures</th>
<th>Grain Size</th>
<th>Biota</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>80</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

API Well Name: [Diagram with various annotations and measurements]
Figure 3.1: Image of the core description sheet used to describe all cores in this study, with one page taken from core. Note: lithology bar uses a shale to chalk scale.

Table 3.1: A summary of lithology recognized based on grey color scale of the rock paired with available XRD and TOC data. Generally the lighter colored intervals are chalkier and the darker colored intervals are marlier. Modified from ElGhonimy (2015).

<table>
<thead>
<tr>
<th>Lithologies</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalk</td>
<td>Composed of mainly carbonates and less than 5 wt. % clays. It is generally light grey in color and has a speckled appearance due to the abundance of Foraminifera, pellets, and shell fragments. It has less organic content than other facies.</td>
</tr>
<tr>
<td>Marly Chalk</td>
<td>This lithology is also carbonate-rich but contains more clays with up to 15 wt. % clay content. They are generally planar laminated or bioturbated.</td>
</tr>
<tr>
<td>Chalky Marl</td>
<td>Clay content can be up to 20 wt. % with carbonate content less than 60 wt. %. Chalky marls within the Niobrara core can also be planar laminated or bioturbated. Chalky marl and marly chalk lithologies are difficult to discern without a grey scale chart and XRD data.</td>
</tr>
<tr>
<td>Marl</td>
<td>Enriched in clays with clay content reaching up to 30 wt. %. It has a black appearance and has the highest organic content.</td>
</tr>
<tr>
<td>Bentonite</td>
<td>Ash beds that are generally pyritized and their color ranges from white to greenish-white. Their thickness is generally less than a few inches.</td>
</tr>
</tbody>
</table>

3.2 Facies

The B chalk benches can be subdivided into six main macroscopic facies based on hand-sample examination. These facies will be used to better understand the minute depositional changes that led to the cyclical deposition of the Niobrara, as well as act as a basis for in-depth understanding of the B chalk facies throughout the study area.

Table 3.2 is a summary of all facies identifying numerous descriptions for each facies as well as the legend used for core descriptions later in the chapter.
Table 3.2: Summary of all facies characteristics, including legend used in core
descriptions, name of facies, macro, micro and FESEM descriptions as well as
proposed depositional model. A number of these descriptions come from chapter 4 and
will be referenced at a later point.

<table>
<thead>
<tr>
<th>Facies #</th>
<th>Description Legend</th>
<th>Name</th>
<th>Description Macro</th>
<th>Description Micro</th>
<th>Description FESEM</th>
<th>Depositional Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Massive fossiliferous marly chalk to chalk</td>
<td>Massive, fossiliferous marly chalk to chalk</td>
<td>Massive, fossiliferous marly chalk to chalk specified</td>
<td>Cylindrical pellet packstone</td>
<td>Recrystallized foraminifera with preserved wall pores</td>
<td>Temporally deposited</td>
</tr>
<tr>
<td>2</td>
<td>Bioturbated to laminated marly chalk to chalk/</td>
<td>Planar laminated chalk with marl interbeds</td>
<td>Planar laminated chalk with marl interbeds and laminations specified</td>
<td>Highly pelleted and foraminifera-rich</td>
<td>Intact Coccolithophores, platelets and spines</td>
<td>Pelagic carbonate deposition with enough oxygen in the water column for bioturbation</td>
</tr>
<tr>
<td>3</td>
<td>Laminated chalk</td>
<td>Laminated chalk</td>
<td>Laminated chalk specified</td>
<td>Highly pelleted and foraminifera-rich</td>
<td>Intact Coccolithophores, platelets and spines</td>
<td>Pelagic carbonate deposition with enough oxygen in the water column for bioturbation</td>
</tr>
<tr>
<td>4</td>
<td>Chalky marl</td>
<td>Dark gray chalky marl</td>
<td>Dark gray chalky marl</td>
<td>Identification of sub-facies 4a and 4b</td>
<td>Sub-facies appear the same</td>
<td>Transitionally facies</td>
</tr>
<tr>
<td>5</td>
<td>Marl</td>
<td>Structureless marl</td>
<td>Structureless marl</td>
<td>NA</td>
<td>Broken and degraded coccolith fragments</td>
<td>Regional sea level regressions with increased terrigenous siliciclastic input</td>
</tr>
<tr>
<td>6</td>
<td>Chalk</td>
<td>Massive clean chalk</td>
<td>Massive clean chalk</td>
<td>Foram-pellet packstone</td>
<td>Bioturbated</td>
<td>Deposited eustatically</td>
</tr>
</tbody>
</table>

* During maximum transgression

* Or during a warm dry Mlianovitch cycle
3.2.1 Facies 1
Facies 1 is a marly chalk-to-chalk generally located near the bottom of the B2 chalk interval. Facies 1 is characterized as massive to bioturbated, with some rare laminations, highly fossiliferous, and highly speckled in nature due to pellets and/or foraminifera present in these zones. The macro fossils present tend to be both intact and broken Inoceramids and oyster shell fragments. In many instances these shells do not seem in situ, suggesting evidence of transport. They are randomly distributed throughout the areas where this facies is present.

3.2.2 Facies 2
Facies 2 is a marly chalk-to-chalk that is characterized by interbedded sections of bioturbation, with planar laminations and some wavy or ripple laminations, which are most visible in small 1-3 inch successions showing preserved clay laminations. Facies 2 is present in both the B1 and B2 chalk and can less commonly be seen interbedded in the B marl sections. Facies 2 maintains the speckled appearance observed in facies 1, but the abundance of the white speckles decreases in sub facies 2 higher in section. When facies 2 is present in the B1 chalk, the foraminifera appear to be smaller which results in a marlier looking appearance. Many small bentonites, or volcanic ash beds, are commonly present in facies 2.

3.2.3 Facies 3
Facies 3 is a planar laminated chalk with marl interbeds. Rarely a number of beds appear wavy, but the overall texture is planar. Facies 3 maintains the speckled
appearance due to the presence of foraminifera and copepod pellets, but mimics the upward decrease in size of foraminifera as observed in facies 2. Facies 3 is present in the B2 chalk, and is a dominant facies as you transition into the overlying B1 marl immediately below the overlying B1 chalk. Facies 3 contains fully developed stylolites and developing stylolites that tend to occur along preserved clay laminations and marl inter-beds. In general, facies 3 lacks large fossils such as Inoceramids and oyster shells. However, rare shell hash layers are preserved and are commonly confined to 1 inch thick intervals of fossiliferous chalky marls.

3.2.4. Facies 4

Facies 4 is a dark grey, marly chalk to chalky marl. Although this facies occurs within interbedded marly sections in the B1 and B2 chalk benches, it is most prevalent at the top and bottom of the chalk benches, at the transition zones in which the main chalk facies grade into marls. Facies 4 is characterized as planar laminated, dark gray marl, with significant amounts of interbedded chalk beds in the marl. Facies 4 has the rarel shell, pyrite nodule, and bentonite visible in core, but these observed characteristics are volumetrically minor in the facies.

3.2.5 Facies 5

Facies 5 is a structureless marl although some laminations are visible in minor chalk laminations. Overall, facies 5 is a dark gray marl facies lacking in bioturbation, speckles, or sedimentary structures; however, some shells, pyritized shells, or pyrite nodules are present. Although these things may not be visible in core, a macroscopic
view will give more detail. Facies 5 is almost always present as a broken section in core due to its apparent increased brittleness. Although there are intermittent marl lenses present in the B1 and B2 chalk benches, overall facies 5 is the major component of the B1 and B2 marl intervals.

3.2.6 Facies 6

Facies 6 is the purest chalk facies present in the observed cores and is also the rarest. Facies 6 is a massive nearly pure chalk with few minor clay drapes. Facies 6 is very speckled in nature due to its increased foraminifera and pellet content and has the infrequent ½ inch shell hash layer. Facies 6 is seen in 1-2 foot thick intervals in both the B1 and B2 chucks.

3.3 Location of Cores

The five cores used in this study are spread throughout the study area and span a vast geographic area (Figure 3.8). The Child VO 30-09 core is located along the western edge of Silo Field in Wyoming. The Lazy D-ZN 03-09 core is located on the southwestern edge of Silo Field near the Colorado border. The Sundance Breeden 2-17 core is located along the southern edge of Silo Field in Wyoming. The Weld 11-8 Core is located in Grover Field 1.5 miles south of the Colorado-Wyoming border. The Gill Land core is located in the north-eastern part of Wattenberg Field.
Figure 3.2: Core photo of facies 1 (highly fossiliferous marly-chalk to chalk), taken from the Child VO 30-09 core.
Figure 3.3: Core photo of facies 2 (bioturbated chalk), taken from the Gill Land core.
Figure 3.4: Core photo of facies 3 (laminated chalk), taken from the Child VO 3-9 core.
Figure 3.5: Core photo of facies 4 (chalky marl), taken from the Child VO 3-9 core.
Figure 3.6: Core photo of facies 5 (marl), taken from the Child VO 3-9 core.
Figure 3.7: Core photo of facies 6, taken from the Child VO 3-9 core.
Figure 3.8: Map showing the study area outlined by the black polygon, and the location of each core used in the study identified by the yellow stars.
3.4 Core Descriptions

Core descriptions were digitized using Strater 4 software provided by Golden Software. This program utilized all of the same parameters used in the original descriptions, but allowed for the image to be displayed alongside petrophysical well logs to better identify the facies throughout the basin, as well as depict the locations of vertical fractures and major shell layers. Each of the five cores that were described will be displayed and discussed below.

3.4.1 Lazy D-ZN 03-09

This core goes through the Codell up through the entire Niobrara, but was described from the bottom of the B2 chalk up to the top of the B1 chalk. This interval is 130 feet thick and was taken from 8,810 to 8,680 feet measured depth (MD).

The B2 chalk is comprised of a mixture of facies 1, 2, 3, and 4. Facies 1 is present only in the lower portion of the B2 chalk bench of this core and is characterized by the large amount of fossils present. Within the lower fossiliferous section there are small one to three foot sections of facies 2. Part way up the B2 chalk there is a seven foot section of marly facies 4. The presence of this facies is interpreted to represent either a climactic change to a wetter climate or a time period of sea level regression.

The B1 marl sits directly above the B2 chalk and is comprised of mostly facies 5. There are small one to four foot intervals of facies 3 present in the marl. A progression up section results in a gradual transition from the marl into the B1 chalk, this transitional zone is comprised entirely of facies 3 and 4. The B1 chalk is comprised of mainly facies 2 and 3. There are also sections of facies 5 present in one to two foot intervals in the B1
chalk. This may be representative of a period of transitional deposition as the A marl is initially deposited on top of the B1 chalk.

Overall, the transition and thickness of facies is representative of the stratigraphy in much of the northernmost section of the study area. In this area there are many gamma ray logs that depict the 'jagged' nature seen in the gamma ray log for the Lazy D-ZN 03-09 well. This is likely representative of the highly diverse nature of facies distribution seen in this core.

3.4.2 Child VO 30-09

The Child VO 30-09 core, located in Silo Field, is the northernmost core in this study. A 110 foot section of this core that spans the B2 chalk, the B1 marl, and the B1 chalk of the Smoky Hill was described. This core is approximately three and a half townships north of the Lazy D-ZN core. The gamma ray log appears similar to the Lazy D-ZN core in that it is 'jagged' in nature. The core, itself, has some similarities to the Lazy D-ZN core, but differs in that it has more predictable facies patterns.

The B2 chalk bench of the Child VO core is comprised of mainly facies 1, 2, and 6. Facies 1 is the highly fossiliferous zone visible in all 5 cores within this study. Facies 2 is the bioturbated chalk facies that is often seen in the B2 chalk bench. Near the top of the B2 chalk, there is a six foot section of facies 4 followed by a three foot section of facies 3. This is interpreted to be a transition into the overlying B1 marl.

At a depth of 8,574 feet MD, a 15 foot section of facies 5 is encountered. This is identified as the B1 marl. Overlying the B1 marl, an additional 20 foot transitional zone of facies 3 and 4 is observed. At a depth of 8,540 MD, the B1 chalk bench, which in this
core, is characterized mostly by facies 2. This seems unusual as this is the only core in the study area where the B1 chalk is dominated by bioturbation. Initial deposition of the overlying A marl is observed at 8,512 MD.

3.4.3 Gill Land Associates

The Gill Land Associates core is located along the northernmost side of Wattenberg Field and is described below (Figure 3.11). Roughly 80 feet of the uppermost section of the B2 marl, the B2 chalk, and the lower B1 marl was observed in the core ranging from 6,790 to 6,710 feet MD. The uppermost section of the B2 marl is characterized by seven feet of facies 4, the chalky marl-to-marl facies. This may be representative of a transition period as deposition changed from dominantly marl deposition to chalk deposition.

The B2 chalk observed in this core is representative of the B2 chalk seen throughout Wattenberg Field. The lower portion of the B2 chalk bench is characterized by a seven foot section of facies 1. This is the fossiliferous section identified in all of the cores described in this study. Moving up in section, there is a transition out of the highly fossiliferous facies 1 into a mixture of facies 2, 3, and 6. There is approximately 30 feet of chalk present in this section with only minor interbedded marl and clay drapes. There is three feet of facies 6. Facies 6 is representative of the cleanest chalks observed in the cores used for this study. It is interpreted that this facies occurs in the middle of the B2 chalk bench as this section of the stratigraphy is representative of the highest sea level highstand seen in the deposition of the Niobrara Formation. At the depth of 6,744 feet MD there is an abrupt change from chalk deposition directly into roughly 8 feet of
the dark marls of facies 5. This sudden change is also visible in the gamma ray log (Figure 3.11). Above this there is another pulse of chalk facies 3 and 4, and two feet of facies 2. This upper bench of facies 3, 4, and a small amount of facies 2 may represent a time period of fluctuating chalk and marl deposition. Above this section, the lower portion of the B1 marl is dominated by facies 5 marls.

3.4.4 Weld 11-28

The Weld 11-28 core is located in Grover Field just south of the Colorado and Wyoming border. Roughly 56 feet of this core was described, spanning the top of the B2 marl, the B2 chalk, the B1 marl, and the bottom of the B1 chalk.

The top of the B2 marl is characterized by mainly facies 4, with one foot of facies 1 and one foot of facies 2 present.

The B2 chalk bench of the Weld 11-28 core is dominated by facies 1 with roughly four feet of interbedded facies 2. The majority of the B2 chalk in this core is characterized by being highly fossiliferous.

At the depth of 6,841 feet, facies 4 appears as the system transitions into B1 marl deposition. This marl section is abnormally chalky compared to the other cores used in this study and only contains three feet of facies 5. The remainder of the section is a mixture of facies 3 and 4 with one foot of facies 1. At a depth of 6,825 feet, there is a one foot section of facies 6, which is representative of the initial deposition of the B1 chalk. The B1 chalk in this core is characterized by mainly facies 3 and 4, with the occasional section of facies 1 or 2. Overall, this is a far marlier representation of the B1 chalk than the B1 chalk observed in the other cores.
3.4.5 **Sundance Breeden 2-17**

The Sundance core is located on the southern edge of Silo Field. There are no logs available for this core, so the gamma ray log from the closest adjacent well, the Breeden 8-16 well, is shown below (Figure 3.13). Roughly 76 feet of core spanning 7,704 to 7,628 feet MD was described. Three feet of facies 5 was observed with one foot of facies 4 above it. This likely represents the top of the B2 marl. Abruptly overlying this, beginning at the depth of 7,696 feet MD, a 12 foot section of facies 1 and 6 with a thin marl inter-bed occurs near the bottom. This again, represents the highly fossiliferous section present near the bottom of the B2 chalk observed in each core. From 7,685 to 7,651, there is a 34 foot section of the B2 chalk comprised of facies 2 and 3. At roughly 7,651 feet MD, observations show the B1 marl consisting of 17 feet of facies 4 and 5 with three feet of facies 3.

Only the bottom 5 feet of the B1 chalk was available in this core. This section is comprised of one foot of facies 2 capped by four feet of facies 3.

The following five images show the digitized core descriptions completed in this study, each shown separately. Figure 3.19, located at the end of the chapter depicts all five core descriptions shown in a cross section. Figure 3.19 helps display how the stacking patterns in these cores vary, as well as how the patterns change across the study area.
Figure 25: Digitized core description of the Lazy D-ZN 03-09 core.
Figure 3.10: Digitized core description of the Child VO 30-09 core.
Figure 3.11: Digitized core description of the Gill Land Associates core.
Figure 3.12: Digitized core description of the Weld 11-28 core.
Figure 3.13: Digitized core description of the Sundance Breeden 2-17 core, and a gamma ray log from the Sundance Breeden 8-16 well.
3.5 X-Ray Diffraction (XRD)

Bulk mineralogy analysis through x-ray diffraction (XRD) was provided by Cirque Resources for the Lazy D-ZN 03-09 and the Child VO 30-09 cores, from Noble Energy Inc. for the Weld 11-28 core, and was acquired publicly from the USGS for the Gill Land Assoc. core. No XRD data was available for the Sundance core. XRD analysis semi-quantitatively measures the predefined x-ray diffraction angles of various minerals found within each sample, and provides the percentage of each major mineralogical constituent (Moore and Reynolds, 1997).

3.5.1 XRD Patterns

XRD data from the four cores listed above are consistent with the facies descriptions presented in the previous section (Table 3.2). XRD data was not collected in each facies described above, so general conclusions for each B1 and B2 chalk and marl benches will be drawn for all four data sets.

Mineralogical make-up of each sample varies based on the location in the core. Samples taken from marlier facies have increased siliciclastic percentages, pyrite percentages and total clays percentages. This is consistent with the depositional model that marls were deposited during regressions or cool and wet Milankovitch cycles when terrigenous siliciclastic input into the basin increased, thus diluting the deposition of carbonate material. Samples taken from more carbonate rich zones, such as the middle of the B1 or B2 chalk benches show extremely high carbonate content, as high as 96 wt.% in the Weld 11-28 core (Figure 3.17, Table 3.6). These results are consistent with the depositional model for chalks. Chalk deposition occurred during transgressions or warm and dry Milankovitch cycles, where very little terrigenous material was deposited.
into the basin, and deposition was dominated by pelagic production. XRD charts and corresponding tables are shown below for the four available cores.

Figure 3.14: Mineralogical composition in weight % of 14 samples taken from the Lazy D-ZN 03-09 core. High carbonate percentages present in chalks, and increased siliciclastics, pyrite and clay present in Marls.

Table 3.3: Table displaying weight % values used in figure 30

<table>
<thead>
<tr>
<th>Depth</th>
<th>Silioclastic wt %</th>
<th>Carbonate wt %</th>
<th>Pyrite wt %</th>
<th>Total Clay wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>8702.00</td>
<td>6</td>
<td>73</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
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</tr>
<tr>
<td>8760.50</td>
<td>4</td>
<td>91</td>
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<td>4</td>
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<td>8772.00</td>
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<td>8808.00</td>
<td>13</td>
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<td>8820.00</td>
<td>20</td>
<td>49</td>
<td>3</td>
<td>26</td>
</tr>
</tbody>
</table>
Figure 3.15: Mineralogical composition in weight % of 13 samples taken from the Child VO 30-09 core. High carbonate percentages present in chalks, and increased siliciclastics, pyrite and clay present in Marls. More varied than figure 30.

Table 3.4: Table displaying weight % values used in figure 31.
Figure 3.16: Mineralogical composition in weight % of 12 samples taken from the Gill Land Assoc. core. High carbonate percentages present in chalks, and increased siliciclastics, pyrite and clay present in Marls.

Table 3.5: Table displaying weight % values used in figure 32.
Figure 3.17: Mineralogical composition in weight % of 8 samples taken from the Weld 11-28 core. High carbonate percentages present in chalks, and increased siliciclastics, pyrite and clay present in Marls.

Table 3.6: Table displaying weight % values used in figure 33.
3.6 Depositional Model Analysis

Interpretations of the five cores used in this study show patterns that exist in all or most of the cores. In the section to follow observations will be presented, and hypotheses of the depositional environment and processes that shape the individual facies will be suggested.

3.6.1 Facies 1: Massive to Fossiliferous Marly Chalk to Chalk

Facies 1 is present at the base of the B2 chalk bench in every core observed. Facies 1 ranges in thickness from 5 to 14 feet. Descriptions of this section in each core show that facies 1 is dominated by Inoceramid and oyster shells, many of which are broken and do not seem to be in growth positions.

Growth position for Inoceramids is suggested to be erect by Kauffman and others (2007). However, all Inoceramid shells present in the B Chalk benches of the Smoky Hill Member are horizontal. One hypothesis presented by Kauffman and others (2007) is that the Inoceramids actually grew in the recumbent position for three reasons: 1) no preserved fossils are found erect, 2) there was a lack of suitable substratum to which the large shells could have been attached, and 3) oysters attached to the Inoceramid shells present growth patterns that suggest they grew on top of recumbent Inoceramids. Another theory described by Peter Scholle in his December 2015 presentation at The Colorado School of Mines suggests that there were debris flows and tempestites that occurred in the WCIS during the time of Niobrara deposition.

Observations made in this study will be described below, and related hypotheses will be presented:

Observations:
1) not all shells present in Facies 1 appear to be in-situ
2) many of the oyster shells (associated with the *Inoceramus*) appear oriented in all directions
3) some Inoceramids are fragmented (as if they broke while being suspended in semi-lithified or soupy substrates)
4) some Inoceramid shells are complete and do not appear to be broken
5) some shells are preserved with both sides of the valves intact and connected
6) shells can be present in core with only one valve
7) some shells are preserved with oysters attached while others have no oysters attached
8) Some zones have broken Inoceramid shells with suspended and randomly oriented oyster shells above and below the Inoceramid shell

The observations of facies 1 seen in core do not suggest that these shells have been preserved in their growth environment. The random orientation of the shells and the jumbled nature of the overall constituents of the facies suggests that this facies could be representative of a debris flow. However, this facies seems to be very regionally correlative. The widespread nature and regional distribution of this facies suggests that instead of a debris flow, this facies may represent a tempestite deposit. A tempestite, as defined by the Glossary of Geology (1979), “is a storm deposit, showing evidence of violent disturbance of pre-existing sediments followed by their rapid deposition.” The random orientation of the Inoceramid and oyster shells may be a result of this rapid distribution. It is suggested by Kauffman and others (2007) that Inoceramids are benthic bivalves that have adapted to survive not only in low-oxygen
environments but are capable of living in harsh hydrogen sulfide and methane-enriched environments. Miller (1968) discussed the environmental requirements for Inoceramids to grow to the large sizes in which they are found in the Niobrara and concluded that they must have lived in areas of very slow sedimentation and gentle bottom currents.

Facies 1 however is characteristic of relatively fast rates of sedimentation and also exhibits increased amounts of bioturbation. This suggests that not only are the fossils found in this facies not in their growth positions and environments, but that they were deposited at times of high energy and fast sedimentation rates.

3.6.2 Facies 2; Laminated to Bioturbated Marly Chalk to Chalk

Facies 2 is major component of the B2 chalk observed in every core described. Facies 2 is also present in the B1 chalk, but does not make up the majority of the composition.

Facies 2 is a bioturbated marly chalk to chalk with occasionally preserved planar laminations and wavy- to rippled-laminations. Observations of this facies suggest that the depositional environment was conducive to pelagic carbonate production and pelagic, or the settling of carbonate material that is produced in the upper water column. During deposition, oxygen at the sediment-water interface was significantly high enough to allow for burrowing and bioturbation of the sediments. Carbonate sedimentation rates are slow relative to regressive siliciclastic deposition in the WCIB. Slow sedimentation rates also allow time for significant alteration of sediments due to burrowing in facies 2. The interbedded nature of the planar to wavy or rippled bedding present in facies 2
are likely caused by pulsating influxes of terrigenous sediment into the basin due to cooler temperatures related to Milankovitch Cycles as well as relative sea level drops. Relating this facies to the concept of Milankovitch Cycles presented earlier in the study suggests that of facies 2 was deposited during a higher frequency of climate cycles, there were many smaller climate cycles occurring. Warm cycles are represented by the carbonate-rich and bioturbated sections. In pelagic systems, carbonate production is dependent on two main factors: the supply of nutrients, which are related to currents and upwelling, and competition between carbonate producing plankton and silica producers. Both of these factors are controlled by climate (Fischer et al., 1985). The planar to wavy bedded sections could be a result of intermittent wet climates which resulted in the increased siliciclastic input into the basin. Fischer and others (1985) discuss responsiveness of detrital sediment to sea level fluctuations and heavy rain and freshwater discharge, again both of which are controlled by climate changes. This siliciclastic input would be deposited relatively fast, not allowing for significant bioturbation. This increased deposition of siliciclastic material may have also altered the water column chemistry, poisoning the food chain for copepods, and also leading to the decrease of burrowing creatures, and the preservation of original bedding and organic matter.

3.6.3 Facies 3: Laminated Chalk

Facies 3 is characterized by planar laminated bedding and is present throughout each core. Although facies 3 is found in both the B1 and B2 chalks, it is most commonly present as a transitional facies between the chalks and marls. Figure 3.4 shows a
section of core that displays the variably alternating nature of the chalks and marls in
this facies. Planar lamination can be the result of low energy deposition, which leads to
the preservation of laminations. The preserved bedding seen in facies 3 suggests that
during deposition, the water column was oxygen-depleted, inhibiting the presence of
burrowing organisms.

Observations of this facies as well as its location in the cores, suggests that this
facies is truly deposited as a transition from chalk to marl or vice versa. In transitional
zones where chalk deposition is changing to marl deposition, sections tend to be lighter
in color and have higher carbonate content, with smaller, less common sections of marl
deposition. Transitioning from a marl to a chalk, these sections tend to be darker in
color and dominated by marly material, with some periods of preserved chalk deposition
(Figure 3.18).

Figure 3.18: image displaying two segments of facies 3. The segment on the left is
taken from a chalk to marl transition zone, and the segment on the right is taken from a
marl to chalk transition zone.
3.6.4 Facies 4: Chalky Marl

Facies 4 is a chalky marl to marl that is present in all of the cores. Although it is present in the middle of either the B1 or the B2 chalk benches, it is most commonly distributed close to facies 3 as a transitional facies. Facies 4 is often present right below or above facies 5 marl positions. Observations suggest that due to the location and composition of facies 4, the environment of deposition was likely either: 1) a time period of increased siliciclastic input due to sea level regression, or 2) a time period of a colder, wetter climate, that lead to increased terrigenous siliciclastic input into the seaway. While these are also the depositional environments for dominant marl deposition, it is likely that facies 4 deposition occurs at either the beginning or the end of one of the major regional events that influence siliciclastic input.

3.6.5 Facies 5: Marl

Facies 5, a true marl, is characterized as a massive dark marlstone lacking in sedimentary structures or carbonate constituents. During deposition, sea level fell, leading to large amounts of siliciclastic sediments being deposited into the basin. This, coupled with a potentially cooler climate would have created a siliciclastics dominated depositional setting. Carbonate production does not cease during this time, but rather the relative rates of sedimentation of marls greatly outweigh the sedimentation rates of the carbonate materials. This results in the large sections of rapidly deposited clay-rich marls with diluted amounts of carbonate constituents.
3.6.6 Facies 6: Chalk

Facies 6 present in three of the five cores: the VO Child 30-09, the Lazy D-ZN 03-09, and the Gill Land Assoc. cores. In the Gill Land and VO Child cores, facies 6 is present within the B2 chalk bench. Facies 6 is also exists in the B1 bench of the Lazy D-ZN core, which seems anomalous. Facies 6 is the purest chalk of all of the facies. The lack of siliciclastic clays present in facies 6 suggests that this facies was:1) deposited during the maximum transgression of the seaway, where little to no terrigenous material was deposited into the basin, or 2) deposited during a short Milankovitch cycle of a dry, warm climate which was conducive to carbonate production and restrictive to terrigenous input.

3.7 Correlation of Facies Successions and Overall Conclusions:

Although the core descriptions show similar patterns to the gamma ray logs provided in each image above, correlation on the facies level showed that the gamma ray and resistivity logs did not display enough fine-scaled variation to directly correlate changes in facies to the available logs. This posed a major complication in attempt to correlate facies changes across the study area, as the cores are a significant distance apart. To accurately correlate facies changes across the region, correlation of facies using only logs would be required. In conclusion, the minute changes in facies are not regionally correlative, and therefore a discussion of regional changes in facies throughout the basin follows in a later chapter.
3.8 Discussion:

Observations:

1) Location and thickness of the six facies vary drastically between each core
2) Overall patterns are similar, yet not the same, and not correlative
3) Cores in the north have greater facies diversity and variation throughout as compared to the cores located in the southeast region of the study area
4) Cores in the southeast display more pure chalk benches with fewer siliciclastic inter-beds

Until recently, the most commonly accepted depositional model for the Niobrara Formation and similar fine-grained mudrock intervals around the world, is a low-energy seaway that deposited pelagic or hemipelagic sediments. The dominant depositional process was thought to be suspension fallout, or the density settling of particles present within the water column (Prothero and Schwab, 2004; Potter et al., 2005). This gravity-driven sedimentation process would result in a regionally correlative laminated appearance. However, observations from this study show that not only are there sections of bioturbation, shell lags, and wavy or convoluted bedding, but the observed facies are not easily correlative, as might be expected with a simple pelagic system.

New research by Schieber and Southard (2009) and Schieber and others (2010) recognizes that instead of gravity-driven deposition, currents may be the primary transport mechanism for mud-size particles in pelagic systems. The presence and absence of the observed facies in core, as well as variations in thickness may likely be tied to currents and current winnowing. O’Neal (2015) used correlations of bentonite beds in very closely spaced cores, in the Smoky Hill Member to depict how seafloor
currents are capable of winnowing sediments, removing and reworking them. This study also suggests the presence of pre-existing bathymetry along the seafloor. Pre-existing bathymetry would lead to stratigraphically thicker zones in the paleo-lows, where accommodation space at the time of deposition was greater relative to paleo-highs. Current winnowing would also preferentially remove sediments from the paleo-highs and redistribute them in paleo-lows.

Figure 3.19 displays cross section A-B extending from the Child VO 30-09 core in Silo Field to the Gill Land Assoc. core in the northeast of Wattenberg Field. This cross section displays the complex facies variation across the five cores in the study area. Figure 3.19 also shows a thinning of the B1 marl and the B2 chalk moving into Wattenberg Field. The thinning of these major benches may be due to the paleo-bathometry present during time of deposition. To properly analyze accommodation space, and the potential for paleo-bathometric influences on depositional thickness and variation in facies, mapping of the A chalk through the Fort Hays will be presented in Chapter 6.
Figure 3.19: Cross section of digitized core descriptions hung on the top of the B2 chalk. Shows the pinching out of the B1 marl and the slight thinning of the B2 chalk.
Chapter 4 provides Field Emission Scanning Electron Microscope (FESEM), and petrographic microscope analyses on one FESEM sample, and corresponding thin section from each of the facies discussed in Chapter 3. Due to data constraints, all of the samples were taken from the Weld 11-28 core from Grover Field.

4.1 Methods

Permission was given to take ten samples from the Weld 11-28 core. Sample locations were chosen to reflect a fair distribution of the core, with at least one sample from each facies discussed in chapter 3. A yellow box was drawn on the core identifying the sample location. Triple O Slabbing cut a one inch by two inch section of the butt of the core in the corresponding location to the yellow box. These samples were then broken into two pieces, one to be made into a thin section and one to be made into an FESEM sample.

4.1.1 Sampling for FESEM

Each piece saved for FESEM sampling was broken using a rock hammer so that there was a freshly broken surface of the sample displaying all of the bedding planes. This sample was then cut down to .3 inches by .3 inches using a rock saw. Each sample was then washed to remove any dust or fingerprints from the broken surface.
Samples were left to dry for over 24 hours. Once dry, samples were placed in a gold
coater and coated for three minutes. Samples were removed from the coating machine
and stored covered so that they did not accumulate dust.

4.1.2 Sampling for Thin Section

Each sample saved for petrographic thin sections was sent to Weatherford
Laboratories in Golden, Colorado to be made into ultra-thin thin sections stained with
blue epoxy. Ten samples were obtained.

4.2 Petrographic Facies Analyses

Petrographic interpretation of samples taken from the Weld 11-28 core provide
enhanced facies descriptions for each facies at the lamination scale in thin section
analysis, and microscale in FESEM analysis.

4.2.1 Facies 1: Massive to Fossiliferous Marly Chalk to Chalk

Thin section analysis for facies 1 was completed on two samples taken at depths
of 6,848.65 feet (Figure 4.1) and 6,861.5 feet (Figures 37 and 38). At the depth of
6,848.65 feet MD, facies 1 is comprised of calcareous-rich pellets, and calcite
recrystallized foraminifera (figure 36 A, B). At the depth of 8,861.5 feet MD, facies 1 is a
recrystallized grainstone comprised of foraminifera and oyster and *Inoceramus*
fragments (figure 37 A,B, 38 A,B,). The matrix appears darker, suggesting an increase in clay
content, however pellets are still visible between nanofossils. Figure 4.3 A shows the
presence of organic material between the Foraminifera. Forams present in Facies 1 appear to be uniserial *globigerinid* planktic Foraminifers (figure 38 A).

Figure 4.1: Thin section images of facies 1 taken at a depth of 6,848.65 feet MD. A) depicts the highly pelleted nature of facies 1, calcite recrystallized foraminifera, and oyster shell fragments, as well as a micrite filled fracture. B) depicts calcareous pellets, calcite spar recrystallized uniserial globigerinid planktic foraminifera. Appears to be a pelleted wackestone.

Figure 4.2: Thin section images of facies 1 taken at a depth of 6,861.5 feet MD. A) Recrystallized packstone comprised of foraminifera and oyster and *Inoceramus* shell fragments. B) Foraminifera packstone with dark micrite matrix, copepod pellets visible between foram and shell fossils.
Figure 4.3: Thin Section images of facies 1 taken at a depth of 6,861.5 feet MD. A) Foram packstone with uniserial *globigerinid* planktic Foraminifers recrystallized with calcite spar. Organic matter present between fossils, copepod pellets visible. B) Broken *Inoceramus* surrounded by foraminifera.

FESEM imaging of Facies 1 allowed for microscale interpretations of facies 1 constituents. FESEM analysis confirmed the presence of large foraminifera (Figure 4.4). Figure 4.4 shows the presence of *Globigerinelloid* foraminifera with numerous wall pores. On a scale of 10µm, Facies 1 matrix is comprised of calcareous coccolith platelets, spines and fragments (Figure 4.5). Intact coccolith platelets and spines suggest that a low amount of bioturbation occurred in facies 1 in this location as preservation of original fossils are common. Figure 4.6 shows a fully intact coccolithosphore surrounded by a mixture of coccolith fragments, platelets, and spines, as well as clay flakes. Figure 4.7 confirms that the inside of the foraminifera present in facies 1 are recrystallized with calcite. FESEM imaging of facies 1 also highlighted fossiliferous material. Figure 4.8 shows a fully calcite recrystallized *Inoceramus* fragment surrounded by coccolith platelets and fragments. Pyrite is present along the top of the *Inoceramus* shell fragment. Pyrite
framboids are spherical aggregates of euhedral microcrystals, and are present in marly regions of the B facies.

Figure 4.4: A) *Globigerinelloid* foraminifera with numerous wall pores. B) Coccolith platelets, and the intact coccolithosphore surrounding the foraminifera show difference in size between the two nanno-fossil types. Euhedral calcite shows secondary crystallization and cementation.

Figure 4.5: Coccolith platelets, spines and fragments show the composition of the matrix. Image depicts pore space present when coccolith fragments are preserved.
Figure 4.6: Large intact coccolithosphore surrounded by coccolith platelets, spines, fragments and flakey clay.

Figure 4.7: Calcite recrystallized foraminifera. Outer wall of fossil shows foram wall pores, while cross section of the interior displays calcite crystal growth.
4.2.2 Facies 2: Laminated to Bioturbated Marly Chalk to Chalk

Thin section analysis was done on one sample from facies two at a depth of 6,841.7 feet MD. Interpretation of facies 2 in thin section confirms that there was significant bioturbation during and after deposition. Lack of preserved pellets and overall mixing of the matrix suggests the presence of burrowing organisms. Calcite and pyrite recrystallized foraminifera are preserved and visible in thin section. Figure 4.9 shows both the recrystallized foraminifera and the lack of preserved pellets. Figure 4.10 clearly shows the foraminifera present in facies 2 are recrystallized with both calcite and pyrite. Figure 4.10 A identifies areas containing preserved organic material, as well as the bioturbated matrix.
Figure 4.9: Thin section images of facies 2 taken from a depth of 6,841.7 feet MD. Some preserved pellets visible. Recrystallized foraminifera present. Overall matrix more bioturbated. Pellet and foraminifera wackestone.

Figure 4.10: A and B) Pellets not preserved due to bioturbation, but major foraminifera remain intact with calcite and pyrite recrystallization. Pellet and foraminifera wackestone.

FESEM analysis done on a sample taken from the same depth of 6,841.7 feet MD further confirms the depositional model laid out in chapter 3. As compared to FESEM images taken from facies 1, significantly fewer coccoliths remain intact in facies 2. Figure 4.11 A and B clearly show the overall texture of facies 2 is dominated by broken fragments of coccoliths, and euhedral and anhedral calcite and calcite cement. Annotations for figure
46 A and B identify some of the fragmented coccolith platelets and spines that can be seen in facies 2.

Figure 4.11: FESEM Images taken from the same depth of 6,841.7 feet MD. Some coccolith fragments and spines visible. Areas of euhedral calcite growth. Matrix comprised mainly of coccolith fragments.

4.2.3 Facies 3: Laminated Chalk

Thin section analysis was done on one sample of facies 3 taken from a depth of 6838.65 feet MD. Figure 4.12 A) displays figure 3 as a highly pelleted and foraminifera rich-facies. The laminated features seen in core were not visible in thin section analysis. Figure 4.12 B) show the calcite and pyrite recrystallized foraminifera that were seen in facies 2. Figure 4.12 B) also displays a rim around the edge of a large foraminifera, which is labeled calcite rind. FESEM imaging confirms this identification.
Figure 4.12: A) highly pelleted and foraminifera-rich facies 3. Some oyster shell fragments present. B) Pyrite and calcite recrystallized foraminifera, calcite rind present on largest of foraminifera.

FESEM analysis was completed on a sample taken at the same depth of 6,838.65 feet MD. FESEM analysis identified images taken of both the clay-rich and calcite-rich alternating laminations present in facies 3. Figure 4.13 A and B are images taken from a calcite-rich laminae of facies 3. Mostly intact coccolithosphores are seen in both images, surrounded by coccolith fragments and spines, and some euhedral and micritic calcite growths. Little to no calcite growth is visible directly on the coccolith platelets of the coccolithosphores. Figure 4.14 A and B depict images of the more clay-rich laminae present in facies 3. Figure 4.14 A shows the overall make-up of this sample contains more clays than can be seen in the calcite-rich samples of facies 3, or samples taken from facies 1 or 2. Figure 4.14 B shows the pyrite frambooids present in this sample. The presence of these frambooids is a reflection of the anoxic to dysoxic environment in which the more siliciclastic laminae of facies 3 were deposited. Figure 4.15 A and B show images of foraminifera ranging from 15-25 µm in diameter. FESEM imaging distinctly shows the calcite rind mentioned above. This rind appears to be comprised of tightly fused anhedral micrite. Figure 4.16 show what this rind looks like when the foraminifera
chamber has been removed. Inside of the calcite rind, euhedral dog-tooth calcite crystals formed where foraminifera wall pores allowed growth into the foraminifera from the outside.

Figure 4.13 A) Partly degraded coccolithosphere with some calcite overgrowth, surrounded by broken coccolith fragments, euhedral calcite, pyrite and flaky clays. B) Intact coccolithosphere with minimal calcite growth, surrounded by mostly broken coccolith fragments and spines, some micritic calcite and larger euhedral calcite rhombs.

Figure 4.14 A) Image of a clay-rich segment of facies 3 dominated by clay, broken coccolith fragments, pyrite framboids, and calcite overgrowths. B) Image of pyrite framboids covered with clay coating, surrounded by coccolith and calcite fragments.
Figure 4.15 A) Recrystallized foraminifera with preserved intraparticle porosity, covered by a calcite rind. Foraminifera surrounded by coccolith platelets fragments and spines, and some euhedral calcite growth. B) Recrystallized foraminifera with calcite rind and preserved intraparticle porosity, large euhedral calcite growth, likely in place of a separate foraminifera chamber.

Figure 4.16: imprint of recrystallized foraminifera. Calcite rind, with euhedral dogtooth calcite growth where foraminifera wall pores allowed growth into the allochem. Pyrite and abnormal euhedral growth also visible inside of the calcite rind.
4.2.4 Facies 4: Chalky Marl

Thin Section analysis was completed on two samples from different depths. Figure 4.17 A and B show thin section images taken from a depth of 6,814.1 feet MD, and C and D are taken from a depth of 6,863.23 feet MD. Although these two depths looked the same in core and are both identified as facies 4, thin section analyses identify these as sub-facies of facies 4: sub-facies 4a. and sub-facies 4b. The sample taken from the depth of 6,814.1 feet MD (sub-facies 4a.) appears to have many stylolites present as a result of pressure dissolution, whereas the sample taken from a depth of 6,863.23 feet MD (sub-facies 4b.) does not have any stylolites. The two samples also vary drastically in abundance of foraminifera and preserved copepod pellets. The matrix in the sample taken from 6,863.23 feet appears significantly darker, however this may be a result of thin section preparation.

Figure 4.17 A) Thin section image of highly stylolitic sub-facies 4a. with many coccolith-rich pellets, and few foraminifera. B) Visible pellets and stylolites little to no foraminifera.
C) Foraminifera wackestone sub-facies 4b. with a darker micritic matrix. D) Recrystallized foraminifera with significant calcite rinds, dark matrix, fish bone in the lower left corner.

FESEM imaging of the same samples shown above do not show a drastic variation in overall texture of the samples. Figure 4.18 A shows micro-constituents of sub-facies 4a. Figure 4.18 B shows micro-constituents of sub-facies 4b. Both images display extremely similar abundance of carbonate material as well as presence of siliciclastic input and secondary calcite growth, suggesting that there is not a drastic different in the matrix of the two sub-facies. FESEM analyses also identify large foraminifera present in sub-facies 4b (Figure 4.19 A and B). FESEM imaging of sub-facies 4b confirms that this sub-facies is a foraminifera wackestone (Figure 4.19 A). Figure 4.19 B displays large foraminifera with diameters as great as 80 µm. These Foraminifera resemble *Hastigerinoides subdigitata* as identified by Frerichs and Gaskill 1988. Figure 4.19 B also shows calcite rinds present along the outside of the foraminifera.

Figure 4.18 A) Image of sub-facies 4a comprised of coccolith platelets, spines and fragments, with some euhedral calcite and calcite cement. B) Image of sub-facies 4b comprised of coccolith platelets, spines and fragments, some clay visible with some calcite cement and overgrowth.
Figure 4.19 A and B: Zoomed out images of sub-facies 4b depict large foraminifera ranging from 30 to 90 µm in diameter. Foraminifera resemble *Hastigerinoides subdigitata* as identified by Frerichs and Gaskill 1988.

4.2.5 Facies 5: Marl

No thin section analysis exists for facies 5 as the corresponding thin section was broken. FESEM imaging was completed on facies 5 on a sample taken from a depth of 6,813 feet MD. Figure 4.20 A shows an image of facies 5 that shows the clay dominated nature of the facies 5 marls. Some euherdal calcite growth is visible as well as some broken and degraded coccolith fragments. Figure 4.20 B shows a more carbonate rich section of facies 5 dominated by coccolith fragments and coccolith spines. There is significantly more euherdal calcite growth present in this carbonate-rich section than in other facies.
Figure 4.20 A) clays dominated facies 5 with some euhedral calcite and eroded coccolith fragments visible. B) coccolith fragments and spines still present, significant euhedral calcite overgrowths.

4.2.6 Facies 6: Chalk

Thin section analysis was done on one sample taken from a depth of 6,823.7 feet MD. Analysis of facies 6 confirms that this is a highly pelleted and foraminifera-rich facies. Figure 4.21 A depicts the numerous pellets visible in facies 6 as well as the abundance of large foraminifera. Figure 4.21 B shows calcite recrystallized foraminifera with calcite rinds. Foraminifera present in the upper left of figure 56 B shows a clear cross section of a full foram, completely recrystallized with a fill rind. This particular view of the foraminifera suggest this may be of the *Heterohelix* species of foraminifera that has been identified in the Niobrara by Frerichs and Gaskill (1988). Lack of pyritic recrystallization of the foraminifera present in facies 6 may be suggestive of higher oxygen in the water column at the time of deposition and burial of facies 6. Thin section analysis does not suggest high bioturbation.
Figure 4.21 A) highly pelleted and foraminifera-rich facies, represents foraminifera-pellet packstone. B) recrystallized foraminifera with almost solely calcite, large intact cross section of a full foraminifera with calcite rind present.

FESEM analysis was completed on the corresponding sample from the same depth of 6,823.7 feet MD. FESEM analyses show that this facies seems highly bioturbated even though it did not appear so in thin section analysis. Figure 4.22 A and B both depict coccolith-rich matrices with little to no calcite overgrowth. Coccolith fragments are very crunched, but a significant amount of porosity remains. The bioturbation seen here may be a result of what is called cryptic bioturbation. Cryptic bioturbation would be significantly smaller scale bioturbation that is not at a scale great enough to alter the form of pellets or depositional fabric.

Figure 4.23 shows a large foraminifera approximately 60 μm in diameter resembling *Globigerinelloides volutus* as identified by Frerichs and Gaskill 1988. The interior of the foraminifera is recrystallized with calcite, with the wall pores preserved. A large (15 μm) calcite rind surrounds the foraminifera with coccolith fragments attached to the exterior.
Figure 4.22 A) coccolith-rich matrix comprised of mostly fragmented coccolith platelets and spines, little to no calcite growth or cement. B) highly bioturbated chalk facies 6 with fragmented coccolith platelets and spines, minimal euhedral calcite growth.

Figure 4.23: Foraminifera approximately 60 µm in diameter resembling *Globigerinelloides volutus* as identified by Frerichs and Gaskill 1988. Interior recrystallization with calcite, wall pores preserved, large (15 µm) calcite ride with coccolith fragments attached to the exterior.
4.3 Micro-Porosity

Porosity is a valuable attribute to help identify pore space capacity within a sample. Poor types will be qualitatively analyzed for each facies using FESEM images to identify what types of pore space exist in each of the facies (Figure 4.24). Loucks (2012) classified pore types by interparticle, intraparticle and organic matter pores. Interparticle pores are present in the B chalks between coccolith fragments, recrystallized calcite crystals, and clay platelets. Interparticle porosity is greatly reduced by compaction, and the abundance of interparticle porosity would vary within each facies for different cores based on burial depth. Intraparticle pores exist within individual constituents of the rock. The largest contributor to intraparticle porosity is the space within coccolith platelets and spines and foraminifera.

Mineralogical composition of the chalk has a large effect on overall inter-and intraparticle porosity. Clays, organic matter and pellets are more ductile constituents of the rock, and are able to distort as a result of compaction. This leaded to a closing of interparticle pore space and the plugging of open pore throats (Loucks, 2012). Less ductile grains such as quartz, feldspars, coccoliths, calcite growths and foraminifera are not easily affected by compaction. However, when compaction is great enough these grains can break. When they do break they often create new interparticle pore space around them, increasing overall interparticle pore space.

Dissolution can create secondary intraparticle porosity. ElGhonimy (2015) measured dissolution porosity in Niobrara chalk samples and found that they are generally less than 100nm in size.

Petrographic analyses completed on the Weld 11-28 core show an abundance of pellets, coccoliths and foraminifera, all of which play a major role in the overall porosity of
the B1 and B2 chalk facies. The pore space available in these grains play an effective role in overall storage capacity of the rock. Fecal pellets in particular are often comprised of euhedral calcite micrites and broken coccolith fragments. The more calcite-rich the fecal pellets are, the less effected they will be by compaction, thus allowing the fecal pellets to maintain more porosity than the surrounding matrix.

Figure 4.24 shows one image from each of the six facies. Facies 1 and 3 have a significant amount of preserved intraparticle porosity found within coccolith platelets, coccolithosphores, and coccolith spines (also known as Rhabdoliths). There is also abundant interparticle porosity as a number of the coccolith grains have been broken, but not calcite cemented. Facies 2 maintains some intraparticle porosity, but due to increased bioturbation, many coccolith constituents are fragmented. The majority of facies 2 porosity is due to interparticle porosity between fragmented grains. Facies 4 maintains some inter and intraparticle porosity, but the matrix present in facies 4 is dominated in siliciclastic input (clays) as well as calcite cement, and therefore is tighter. Facies five does contain some intact allochems, but the majority of the sample is recrystallized, decreasing the overall porosity. Facies 6 is characterized by an abundance of preserved and fragmented coccoliths and foraminifera, preserving a significant amount of both inter and intra particle porosity.

Facies 1 and 6 qualitatively appear to have the most preserved pore space of the facies present. A more detailed pore size and abundance study would include ion-milled FESEM samples to allow for point counting and measuring of individual pores in each sample.
Figure 4.24: Inter- and intra-particle porosity identified in each of the facies, as well as euhedral calcite where it is abundant.
CHAPTER 5
GEOCHEMICAL ANALYSIS

Geochemical characterization is essential for source-rock evaluation. Organic richness, potential for hydrocarbon generation, thermal maturity and original kerogen quality and type are vital when understanding unconventional resource plays such as the Niobrara. Unconventional resource plays are also controlled by porosity.

5.1 Methods

Rock-Eval pyrolysis was used on samples taken from four cores to assess the organic matter quality and potential of the B chalk and marl benches of the Smoky Hill. Rock-Eval pyrolysis is a process that steadily heats a sample to temperatures at high as 550°C. During this process evolved hydrocarbons are monitored as a function of temperature and recorded as S1, S2, S3, and sometimes S4. Free hydrocarbons present in the sample are volatized at a moderate temperature, these hydrocarbons are measured and recorded as S1. S2 measures the hydrocarbons that are produced under greater heat by the breakdown of kerogen, and represents future potential for hydrocarbon production. S3 measures the amount of carbon dioxide present in the sample. These results coupled with TOC data can give a variety of information such as the type of organic matter in the rock, levels of hydrocarbon maturity, and quality of the rock as a hydrocarbon producer. A number of parameters can be derived from equations using S1, S2, S3, and TOC, such as oxygen index (OI), hydrogen index (HI), production index (PI), and normalized oil content (S1/TOC) (Figure 5.1).
Figure 5.1: Image display equations for the oxygen index (OI), the hydrogen index (HI), Production index (PI), and normalized oil content (S1/TOC).

Tables 8, 9, and 10, are from Peters (1986) and Peters and Cassa (1994), they are useful in assessing the quality, as well as the petroleum potential of a sample using Rock-Eval results and TOC data. A number of parameters can be derived from equations using S1, S2, S3, and TOC.

These tables will be used when assessing the petroleum potential of the B chalk and marl benches of the Smoky Hill. Analyzed samples taken from the Child VO 30-09, Lazy D-ZN 03-09, Timbro PC 16-17, and the Gill Land Associates cores will be discussed below.

Table 5.1: Source rock petroleum potential using TOC, S1, and S2 parameters. Taken from Krueger, 2013; modified from Peters 1986; and Peters and Cassa, 1994.

<table>
<thead>
<tr>
<th>Quality</th>
<th>TOC (wt. %)</th>
<th>S1 (mg HC/g rock)</th>
<th>S2 (mg HC/g rock)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>0-0.5</td>
<td>0-0.5</td>
<td>0-2.5</td>
</tr>
<tr>
<td>Fair</td>
<td>0.5-1.0</td>
<td>0.5-1.0</td>
<td>2.5-5.0</td>
</tr>
<tr>
<td>Good</td>
<td>1.0-2.0</td>
<td>1.0-2.0</td>
<td>5.0-10.0</td>
</tr>
<tr>
<td>Very Good</td>
<td>2.0-4.0</td>
<td>2.0-4.0</td>
<td>10.0-20.0</td>
</tr>
<tr>
<td>Excellent</td>
<td>&gt;4.0</td>
<td>&gt;4.0</td>
<td>&gt;20.0</td>
</tr>
</tbody>
</table>

Table 5.2: Expected expelled products from kerogen type and associated parameters. Taken from Krueger, 2013; Modified from Peters and Cassa, 1994.

<table>
<thead>
<tr>
<th>Kerogen Type</th>
<th>HI (mg HC/g rock)</th>
<th>S2/S3</th>
<th>Atomic H/C</th>
<th>Main Expelled Product at Peak Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>&gt;600</td>
<td>&gt;15</td>
<td>&gt;1.5</td>
<td>Oil</td>
</tr>
<tr>
<td>II</td>
<td>300-600</td>
<td>10-15</td>
<td>1.2-1.5</td>
<td>Oil</td>
</tr>
<tr>
<td>II/III</td>
<td>200-300</td>
<td>5-10</td>
<td>1.0-1.2</td>
<td>Mixed Oil and Gas</td>
</tr>
<tr>
<td>III</td>
<td>50-200</td>
<td>1-5</td>
<td>0.7-1.0</td>
<td>Gas</td>
</tr>
<tr>
<td>IV</td>
<td>&lt;50</td>
<td>&lt;1</td>
<td>&lt;0.7</td>
<td>None</td>
</tr>
</tbody>
</table>
Table 5.3: Maturity stages as defined by maturation and generation parameters, $R_o$, $T_{max}$, and $P_l$. Taken from Krueger, 2013; modified from Peters and Cassa, 1994

<table>
<thead>
<tr>
<th>Stage of Thermal Maturity for Oil</th>
<th>Maturation</th>
<th>Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_o$ (%)</td>
<td>$T_{max}$ ($^\circ$C)</td>
</tr>
<tr>
<td>Immature</td>
<td>0.2-0.6</td>
<td>&lt;435</td>
</tr>
<tr>
<td>Mature-Early</td>
<td>0.6-0.65</td>
<td>435-445</td>
</tr>
<tr>
<td>Mature-Peak</td>
<td>0.65-0.9</td>
<td>445-450</td>
</tr>
<tr>
<td>Mature-Late</td>
<td>0.9-1.35</td>
<td>450-470</td>
</tr>
<tr>
<td>Postmature</td>
<td>&gt;1.35</td>
<td>&gt;470</td>
</tr>
</tbody>
</table>

5.2 Child VO 30-09

The Child VO 30-09 core is located in Silo Field. Fourteen pyrolysis data points corresponding to the section of core described in this study are analyzed below utilizing the criteria outlined in Tables 8, 9, and 10.

5.2.1 Total Organic Carbon (TOC)

Total organic carbon (TOC) is a measurement of the amount of organic carbon within the sample rock, and is measured in weight percent (wt. %). TOC gives a depiction of how organic-rich a stratigraphic unit might be. As thermal maturation increases, TOC values will decrease due to the loss of organic carbon during the generation of hydrocarbons. Figure 5.2 shows a plot of TOC against depth. Five data points from the B1 chalk range from very good to excellent. Four data points from the B1 marl are shown in orange and plot with three values in the very good range and one in the excellent range. Six data points from the B2 chalk are shown in red with four plotting in the very good range and two plotting in the good range.

Variations in TOC may be due to a number of factors. Preservation of TOC is often a product of the depositional environment. In the Niobrara, marls tend to have higher TOC values. This is a result of increased sedimentation rates occurring during regressions and increased siliciclastic input into the basin, coupled with the potential of
anoxic to dysoxic water column conditions leading to decreased bioturbation. However, Figure 5.2 shows that with depth, TOC values are plotting in a decreasing trend, regardless of lithology. This may be representative of maturity of the rock, as increasing depth leads to increased maturity. However, it is unlikely that maturity is the main cause of the variation in TOC values as the data spans only 100 feet, not enough for a significant maturity effect on TOC values. Based on the core description for the Child VO 30-09 core in Chapter 3, the B1 chalk bench in this location is comprised of alternating Facies 5 marl benches and Facies 2 bioturbated marly chalk to chalk. The high marl content in the B1 chalk may be making the data points plot in a similar fashion to the B1 marl when it would be expected to show a pattern more like the B2 chalk in Figure 5.2.

Variations within the different B benches is indicative of variability in facies. The five data points for the B1 chalk alternate between values as low as 2.5 to as high as greater than 4. This is due to lithology variation in the B1 chalk. Chapters 3 and 4 discuss the high variation of facies succession throughout the B1 and B2 benches. Facies that are more marl-rich, or lack in bioturbation should have greater amounts of preserved TOC, therefore the vast variation in the TOC values within each B1 and B2 chalk and marl bench must be due to facies variation throughout the section.

Figure 3.10 in Chapter 3 shows the core description for this well. The B1 chalk has interbedded bioturbated zones and marls. Likely the TOC values plotting in the excellent range were taken from marl-rich samples, while the TOC values plotting in the very good range come from more bioturbated facies. The B2 chalk on the other hand is comprised of bioturbated to massive chalks and marly chalks. The B2 chalk therefore
has likely undergone more extensive burrowing, reducing TOC preservation. Additionally there are fewer marl interbeds in the B2 chalk, likely decreasing over TOC values throughout the section.

TOC variation in the B1 chalk and marl and the B2 chalk suggest that the B1 chalk and marl benches have greater source rock potential, and the B2 chalk bench is a better reservoir due to the presence of greater amounts of Facies 1, 2, and 3 (which have fewer observed clays, calcite overgrowths, and higher observed porosity).

Figure 5.2: TOC versus depth in the Child VO 30-09 core. The B1 chalk plots very good to excellent, the B1 marl plots very good with one excellent data point, and the B2 chalk plots good to very good. The highest TOC values are recorded in the B1 chalk.
5.2.2 S1

S1, or the amount of free hydrocarbons in the sample, is a direct representation of the free oil and gas that is emitted from the rock without generating additional hydrocarbons through increased maturation through pyrolysis. S1 represents how many milligrams of free hydrocarbons exist per gram of rock. This can be a risky indicator of hydrocarbon potential, as hydrocarbons such as volatile gas can escape the sample during pre-test preparation. Figure 5.3 shows S1 plotted versus depth for the Child VO 30-09 core. Values taken from the same depths as TOC, show the B1 chalk plotting in the good to very good range, the B1 marl plotting in the very good range, and the B2 chalk shows a general decrease from very good at the top of the unit to poor-fair near the bottom of the unit.

The higher S1 values present in the B1 chalk and marl as compared to the B2 chalk may be a result of higher TOC values in these units, coupled with a lack of migration into the more porous B2 chalk. If migration was a major factor, it could be suggested that these better source rocks would be charging the more porous B2 chalk, however, this is not observed in Figure 5.3 where the B2 chalk has the lowest values. S1 values for each of the plotted zones suggests a good to very good presence of extractable hydrocarbons. The higher S1 values seen the B1 marl are a result of the marl rich facies present in this unit. The higher percentages of marl suggest greater amounts of TOC. This increase in TOC is likely to increase S1 values.
Figure 5.3: S1 (mg/g) versus depth. B1 chalk plots in the good to very good range, the B1 marl plots in the very good range, while the B2 chalk plots in the very good to poor/fair range, decreasing with depth.
5.2.3 Kerogen Type and Maturity

Samples taken from the same depths as TOC and S1 are shown below in Figure 5.4. Figure 5.4 is a plot of Tmax (°C) versus hydrogen index (HI). Hydrogen index can be used as a maturation and kerogen type indicator and is calculated by the formula: S2/TOC*100. Table 5.2 shows that HI values ranging from 300-600 indicate Type II oil prone kerogen, usually marine in origin. Figure 5.4 shows that all of the data taken from the B1 chalk, B1 marl, and B2 chalk of the Child VO 30-09 well all plot within the bounds of Type II kerogen.

Table 5.3 shows that Tmax values ranging from 435-470 °C suggest that the samples are mature. The data for the Child VO 30-09 well range from 440-455 °C, and therefore plot within the mature-peak oil window (Figure 5.4).

5.2.4 Summary of Child VO 30-09 Geochemistry

The Child VO 30-09 core is located on the northwestern edge of Silo Field, which sits along the axis of the basin. TOC values for this core are good to excellent, with the highest values occurring in the more marly facies in both the B1 chalk and B1 marl. S1 values, which can be a risky indicator, show that there are greater amounts of free hydrocarbons in the B1 chalk and B1 marl than the B2 chalk. Figure 5.4 shows that the core sits within the oil productive window, and could be targeted in the B1 or B2 chalk benches and successfully produce hydrocarbons.
Figure 5.4: Tmax (°C) versus hydrogen index (HI, mgHC/g TOC) of the B1 chalk and marl and B2 chalk benches of the Child VO 30-09 core. Data from all three benches has similar Tmax values plotting in the mature oil window, and HI values ranging from 283 to 487, indicating type II, oil prone kerogen of marine origin.
5.3 Lazy D-ZN 03-09

The Lazy D-ZN 03-09 core is located just inside the Colorado border, just south-southwest of Silo field. Fourteen pyrolysis data points corresponding to the section of core described in this study are analyzed below utilizing the criteria outlined in Tables 8, 9, and 10.

5.3.1 Total Organic Carbon TOC

TOC values for the Lazy D-ZN 03-09 are shown in Figure 5.5. Four data points from the B1 chalk plot along the edge of the good to very good range, two data points from the B1 marl plot in the very good range, and eight data points from the B2 chalk plot in a wide spread from good to excellent.

Aside from the lowermost two data points for the B2 chalk, all of the data plots as expected; the B1 chalk and the majority of the B2 chalk plot on the edge of the good to very good range, and the B1 marl, which generally has higher TOC values, plots on the higher end of the very good window. The lowermost two data points of the B2 chalk plot on the edge of excellent. Likely this a response to depositional mixing of the B2 chalk with the underlying B2 marl. This mixing could increase the amount of preserved TOC present in the lowermost section of the B2 chalk.

Overall, the TOC data for the Lazy D-ZN 03-09 core is slightly lower than the TOC values for the Child VO 30-09 well seen above.
Figure 5.5: TOC versus depth in the Lazy D-ZN 03-09 core. The B1 chalk plots good to very good, the B1 marl plots on the high side of the very good window, and the B2 chalk plots with six data points on the edge of good to very good, with the lowermost two data points plotting in the excellent window. The highest TOC values are recorded in the B2 chalk, likely a result of mixing with the underlying B2 marl.
5.3.2 S1

S1 values for the Lazy D-ZN 03-09 well are plotted below in Figure 5.6. The B1 chalk plots from good all the way to excellent, the B1 marl plots with one data point in the very good window, and the other in the excellent window, and the B2 chalk plots in a random distribution ranging from excellent to the lower end of good. Both the B1 chalk and B1 marl plot in a predictive manner, with S1 values that are reasonable based on the TOC values and the location of the well relative to the main part of Silo field. The B2 chalk on the other hand plots in an unexpected manner, and with an unpredictable zig-zag pattern. The B2 chalk S1 data points that are plotting in the excellent range may be a result of migration of hydrocarbons into the B2 chalk reservoir. At similar depths, TOC values that plotted in the good range consistently plot anywhere from the upper end of excellent to the lower end of the good window, suggesting that the presence of hydrocarbons seen here as the S1 values, are representative of migrated hydrocarbons rather than hydrocarbons produced locally.

These results show that there are significant hydrocarbons present in both the B1 and B2 chalk reservoir benches. The B1 marl also appears to be a good source rock. These results also indicate the presence of fractures that allowed for hydrocarbons to migrate and pool in the B2 chalk reservoir.
Figure 5.6: S1 (mg/g) versus depth. B1 chalk plots in the good to excellent range, the B1 marl plots in the very good to excellent range, while the B2 chalk plots in a random distribution ranging from excellent to the lower end of good.
5.3.3 Kerogen Type and Maturity

Kerogen type and maturity levels for the Lazy D-ZN 03-09 well are shown below in Figure 5.7, Tmax °C versus hydrogen index (HI, mg HC/g TOC). All of the data points for this well have hydrogen index values ranging from 312 to 628. Table 5.2 displays that HI values ranging from approximately 300-600 are indicative of Type II oil prone kerogen, usually marine in origin. Figure 5.7 shows that all of the data for this well falls within that range.

Tmax values less than 435 represent immature source rocks. All of the values for the Lazy D-ZN 03-09 well plot between 430-436, right on the edge of immature to early stage maturity.

5.3.4 Summary of Lazy D-ZN 03-09 Geochemistry

The Lazy D-ZN03-09 well is located just south-southwest of Silo Field. TOC values for this well were overall slightly lower than those of the Child VO 30-09 well located in Silo Field proper. Based on the core description of the Lazy D-ZN 03-09 core shown in Figure 25, and Child VO 30-09 core shown in Figure 3.10, the Lazy D-ZN 03-09 well has fewer marl interbeds present in the chalk benches, and the B1 marl present in this core is thinner with more chalk than what is seen for the Child VO 30-09 core. The decrease in Facies 5 marls beds may be a direct correlation to the decrease in TOC, as marls tend to have higher preserved TOC content due to sedimentation rates and lack of burrowing in the anoxic to dysoxic conditions.

S1 Values for the Lazy D-ZN 03-09 core show that there are significant hydrocarbons present in this location. The wide range of S1 values may be a result of
migrated hydrocarbons into the B2 chalk bench. This migration may be due to the presence of fracturing.

Figure 5.7 shows that this well has Type II oil prone kerogen of marine origin, and has Tmax values that place this well on the edge of the immature to early maturity window. These results suggest that this well may still be in the producible region of Silo Field, however it is not as high grade of a location as Silo Field proper.

Figure 5.7: Tmax °C versus Hydrogen Index (HI, mg HC/g TOC) plot shows that the Lazy D-ZN 03-09 well has type II oil prone kerogen and has immature to early maturity stage hydrocarbons.
5.4 **Timbro PC 16-17**

The Timbro PC 16-17 well is located in Noble Energy Inc.’s East Pony Field. Noble Energy Inc. donated the data set, but the core was not available for viewing. Twelve samples from the B1 chalk, B1 marl, and B2 chalk benches of the Timbro PC 16-17 well underwent rock-Eval pyrolysis and the results will be shown and discussed below.

5.4.1 **Total Organic Carbon (TOC)**

Total organic carbon (TOC) Versus depth is shown in Figure 5.8 below. Three TOC data points from the B1 chalk plot in the very good to excellent window, two data points from the B1 marl plot in the very good range, and seven data points from the B2 chalk plot all the way across the very good range. TOC data across the 80 feet of section does not vary drastically. It would be expected that the B1 marl would have higher TOC values than the chalks, however the Gamma ray log for this well suggests that the B1 marl has a significant amount of chalk interbeds, which if bioturbated would decrease the amount of preserved TOC.

Overall, TOC in the Timbro PC 16-17 well is slightly higher than the values seen in both the Child VO 30-09 well and the Lazy D-ZN 03-09 well. If the corresponding core to this well was available for core description, the presence and amount of bioturbation could be explored as a factor in the amount of preserved TOC. Without the core description it is hard to identify the cause of the greater amounts of TOC present in this location.
Figure 5.8: TOC versus depth in the Timbro PC 16-17 well. The B1 chalk plots in the very good to excellent range, the B1 marl plots in the very good range, and the B2 chalk plots across the spectrum of the very good window. The highest TOC value is recorded in the B1 chalk bench.
5.4.2 S1

Twelve S1 values for the Timbro PC 16-17 core are shown below in Figure 5.9. The S1 values for the Timbro PC 16-17 well are extraordinarily high. Table 5.1 shows that any S1 values greater than 4.0 mg/g is considered excellent. The values taken from the Timbro PC 16-17 well range from 4.89 mg/g to 14.77 mg/g. Figure 5.9 shows how far above the boundary between very good to excellent these points sit. The data from the B1 chalk has the lowest S1 values suggesting the lowest amount of free hydrocarbons present in the samples. The B1 marl has slightly higher values reaching as high as 13, but the B2 chalk has by far the highest S1 values, indicating the presence of a significant amount of free hydrocarbons per gram of sample.

In comparison to the Child VO 30-09 and the Lazy D-ZN 03-09 wells, the Timbro PC 16-17 well has significantly greater amounts of free hydrocarbons present, yet not significantly different amounts of TOC.

The drastic variation in the S1 values between these wells may be due to the presence of fractures, and/or higher porosity and permeability present in this area.

The Timbro PC16-17 well is located on the shallower eastern limb of the study area. This well occurs at depths of 5685-5765 feet, as compared to the Lazy D-ZN 03-09 well which occurs 3,000 feet deeper at depths of 8684-8804 feet. This variation in depth would have a large effect on compaction and diagenesis. The Timbro PC 16-17 likely has undergone less compaction and diagenesis, allowing for greater migration of hydrocarbons into the reservoir units seen here.
Figure 5.9: S1 (mg/g) versus depth. The B1 chalk, B1 marl, and the B2 chalk all plot in the excellent window, suggesting significant amounts of free hydrocarbons present in this well (x axis scale was changed to accommodate higher values).
5.4.3 Kerogen Type and Maturity

Figure 5.10 shows Tmax values in degrees Celsius versus hydrogen index (HI, mg HC/g TOC). All of the data from the Timbro PC 16-17 well plots in the Type II oil prone window with kerogen of marine origin (Figure 5.10). The Tmax data from the Timbro PC 16-17 well varies from 431-441°C, and therefore plots mostly in the mature oil window, with three data points falling on the edge of immature. Based on the location of this core out to northeast of Wattenberg Field, it would be expected that the Tmax values for this well would be significantly lower than those seen in the Child VO 30-09, and Lazy D-ZN 03-09 wells, however they are not. This is a result of the Colorado Mineral Belt that was mentioned earlier, that extends northeast out of Wattenberg, and supplies heat flow to the wells in East Pony and neighboring Redtail Fields.

5.4.4 Summary of the Timbro PC 16-17 Geochemistry

The Timbro PC 16-17 well is located in East Pony Field. The data points shown in this section range in depth from 5685 to 5765 feet MD, while the Child VO 30-09 ranges from 8510-8610 feet MD, and Lazy D-ZN 03-09 ranges from 8684-8802 feet MD, placing the Timbro PC 16-17 well 3,000 feet shallower. TOC values do not vary drastically between these wells, although overall the Timbro PC 16-17 well has slightly higher TOC values. S1 values do vary drastically, which is likely a result of better porosity and permeability in the shallower East Pony field. Kerogen type is approximately the same in all three wells, and Tmax values are fairly similar. Tmax values remain high in East Pony Field due to the presence of the Colorado Mineral Belt.
Figure 5.10: Tmax °C versus Hydrogen Index (HI, mg HC/g TOC) plot shows that the Timbro PC 16-17 well has type II oil prone kerogen and early to peak mature hydrocarbons.
5.5 Gill Land Associates

The Gill Land Associates core is located along the northeast edge of Wattenberg Field. Nine samples, corresponding to the section of core described in Chapter 3, underwent rock-Eval pyrolysis. Results will be shown and discussed below.

5.5.1 Total Organic Carbon (TOC)

TOC values for the Gill Land Associates core are shown below in Figure 5.11. Two TOC data points from the B1 chalk plot in the very good range, two data points from the B1 marl also plot in the very good range, four data points from the B2 chalk plot along the edge of good to very good, with one in the good range and three in the very good range, and one data point from the B2 marl plots on the higher edge of the very good range. All of the TOC values for this well plot in a predictable manner, with the marls containing slightly higher TOC values than the chalks.

TOC values for the Gill Land Associates well plot lower than the Child VO 30-09 well, in a similar range to the Lazy D-ZN 03-09 well, and slightly below the Timbro PC 16-17 well. Location and exposure to higher heat flow may be a cause of the lower TOC values in this well; increased heat will lead to greater amounts of TOC converting to hydrocarbons, and thus decreasing the amount of preserved TOC. The core description for this well shown in Figure 3.11 shows that there is little to no bioturbation in the B1 chalk and B1 marl and slightly more bioturbation present in the B2 chalk. A high degree of organic matter consumption associated with high proportion of bioturbation could be a cause of lower TOC in this section.
Figure 5.11: TOC versus depth in the Gill Land Associates core. The B1 chalk plots in the very good range, the B1 marl plots in the very good range, the B2 chalk plots with one sample in the good range and three samples in the lower end of the very good range, and one point for the B2 marl plots on the high side of the very good range.
5.5.2 S1

The S1 values for the Gill Land Associates well plotted against depth are shown in Figure 5.12. The two data points from the B1 chalk appear in the very good to excellent range, while the B1 marl S1 values are lower and plot in the good to very good range. All of the B2 chalk S1 values plot within the very good range, and the B2 marl S1 values are lower, plotting in the good range. All of the S1 values for the Gill Land Associates core plot in a predictable manner with higher S1 values in the chalks and slightly lower values in the marls. These results are indicative of free hydrocarbons that have migrated from the higher TOC marls and accumulated in the more porous B bench chalks.

The S1 values seen in the Gill Land Associates core represent good but not exceptional amounts of free hydrocarbons in the target B benches. Although the Gill Land Associates S1 values are not as high as those seen in the Timbro PC 16-17 well, they are of good enough quality to consider the northeastern edge of Wattenberg Field within the bounds of a good target zone.

Both the burial depth of the Gill Land Assoc. core, as well as the well location occurring near the heat anomaly of Wattenberg field may affect the S1 values seen in Figure 5.12. As the hydrocarbons are heated and matured, the hydrocarbons are converting from oil to gas. Gas is more volatile, and therefore more gas may have escaped during testing, leading to the slightly lower values seen for this well.
Figure 5.12: S1 (mg/g) versus depth. The B1 chalk S1 values plot in the very good to excellent range, the B1 marl S1 values plot in the good to very good range, the B2 chalk S1 values all plot in the very good window, and the B2 S1 value plots in the good range.
5.5.3 Kerogen Type and Maturity

Figure 5.13 shows Tmax values in degrees Celsius versus hydrogen index (HI, mg HC/g TOC). The hydrogen index data points from the Gill Land Associates well range from 113 to 182 mg HC/g TOC. These results therefore plot in the Type III gas prone kerogen window. This is, however, not accurate. Due to the maturity of source rocks present in Wattenberg Field, the HI values are lower than they would be if they were in a less mature zone. This makes them plot lower on the map even though it is known that they are produced from a Type II kerogen from marine origin. This is actually a phenomenon that occurs regularly when plotting data from Wattenberg Field as compared to other areas in the Denver Basin. Figure 5.14 shows a number of different well data taken from many locations/fields within the Denver Basin; the results consistently show that wells in Wattenberg Field have pyrolysis results that plot in the Type III window, due to their maturity levels.

Tmax values for the Gill Land Associates core range from 434-457 °C, landing them in the mature oil to condensate window.

5.5.3 Summary of Gill Land Associates

TOC values for the Gill Land Associates well were slightly lower than the Child VO 30-09 core and the Timbro PC 16-17 well, and were similar to the TOC values in the Lazy D-ZN 03-09 well. The lower TOC values are likely a result of high maturity as this well is located on the edge of Wattenberg Field. S1 values for the Gill Land Associates core are similar to those of the Child VO 30-09, lower than those of the Lazy D-ZN 03-09 core, and significantly lower than those of the Timbro. Likely, there is less migration of hydrocarbons in this location due to reduced porosity, a result of deeper burial.
The Gill Land Associates core is more mature than all of the other wells, and therefore HI values appear low. Tmax values suggest mature oil to condensate window.

Figure 5.13: Tmax °C versus Hydrogen Index (HI, mg HC/g TOC) plot shows that the Gill Land Associates well has type III gas prone kerogen and mature hydrocarbons in the oil to condensate window. Low HI values are a result of maturity skewing the kerogen type, which is actually type II of marine origin.
5.6 Maturity throughout the Denver Basin

The maturity plots shown above shed light on a number of patterns that can be seen throughout the Denver Basin. Figure 5.14 shows maturity data from a number of wells from across the north-northeastern Denver Basin. The plot below is Tmax °C versus hydrogen index (mg HC/g TOC). Figure 5.14 shows that wells coming from the mature Wattenberg Field plot in the late mature to post-mature window. This increase in maturity makes the HI values lower, making it look as though the kerogen type is changing across the basin. The State 1-29 well from Silo Field plots on the edge of immature to mature in the oil window, similar to the Child VO 30-09 well displayed in figure 63. The Whomble 1-32, Powell 1-33 and Brophy 1 wells are all from eastern Denver Basin, they are so immature, the HI values plot Type I, Type II and nearly Type III kerogen windows. However, it is known that all of the Niobrara kerogen is type II of marine origin.

Figure 5.14 is summary of the variation of maturity throughout the basin varies, Thul (2012) shows how the maturation pathway for the Niobrara source rocks is defined by decreasing HI with increasing Tmax. This study also shows that for the Niobrara, hydrocarbon generation appears to initiate at Tmax values of 430°C and 435°C. All of the wells in this study have Tmax values that are equal to or greater than 430°C, except for the Lazy D-ZN 03-09 well.
Figure 5.14: Maturity plot of Tmax °C versus hydrogen index (HI) (mg HC/g TOC). Seven wells from across the Denver Basin, showing that wells from Wattenberg Field are so mature HI values appear extremely low. Wells from Silo appear vertical in the mature window, and the eastern Denver Basin wells plot in the immature window (modified from Sonnenberg, 2016, unpublished).
5.7 Porosity

Understanding variations in porosity is critical when trying to interpret geochemical source rock data. Amounts of available porosity in the rock play an important role in where hydrocarbons can form, migrate and accumulate.

5.7.1 Methods

Porosity and permeability values from the Child VO 30-09 core, the Lazy D-ZN 03-09 core, the Timbro PC 16-17 well, and the Gill Land Associates core are displayed and discussed in the following section.

5.7.2 B1 Chalk

Porosity data taken from the B1 chalk was only available in the Lazy D-ZN 03-09 core and the Gill Land Associates core. Average porosity for the B1 chalk in the Lazy D-ZN 03-09 core is 8.57%. The average porosity for the B1 chalk in the Gill Land Associates core is 5.43%.

5.7.3 B2 Chalk

Porosity data for the B2 chalk was available in all four wells. The Child VO 30-09 well had an average of 8.3%, the Lazy D-ZN 03-09 well had an average of 7.61%, the Timbro PC 16-17 well had an average of 12.5% and the Gill Land Associates core had an average of 5.06% porosity. Figure 5.15 displays the variation in porosity across the four wells.
5.7.4 Summary and Discussion of Porosity

Porosity data taken from the four wells varies between locations in the study area. The Child VO 30-09 and the Lazy D-ZN 03-09 wells are both located in or near Silo Field. The B benches of the Niobrara occur at similar depths, between 8500 and 8800 feet md, and have similar average porosities (Figure 5.15). The Timbro PC 16-17 well is located in East Pony Field. The B benches in this well are seen at depths of 5685-5770 feet MD, nearly 3,000 feet shallower than the two other wells. The Gill Land Associated well is located on the edge of Wattenberg Field and the B benches occur at depths of 6710-6790 feet MD. However, the average porosity values for both the B1
and B2 chalk benches are the lowest of the all the averages. A number of things can influence porosity in chalks. These will be discussed below.

Porosity in chalks when they are deposited can be anywhere from 60-80% (Pollastro and Scholle 1986). The significant loss of porosity is a result of initial mechanical compaction, including dewatering, grain reorientation, and grain breakage. Figure 5.16 shows the relationship between density log porosity and depth for the Beecher Island zone chalk of the Niobrara Formation, present on the eastern flank of the Denver Basin.

Figure 5.16: Relationship between density log porosity for Beecher Island zone chalk of the Niobrara Formation, east flank of the Denver Basin. Approximate average permeability is noted at right for the Niobrara. Porosity-depth curve for European chalks is also plotted for comparison (modified from Pollastro and Scholle, 1986).
Secondary factor affecting porosity in chalks is chemical compaction. This is the process of dissolution of calcium carbonate at points of higher intergranular stress, and the re-precipitation of this material as cement (Pollastro and Scholle, 1986). Often the re-precipitation of this cement occurs between grains that have little to no differential stress, or within pore spaces.

Thermal maturity can also have an effect on porosity. As a chalk undergoes thermal maturation, kerogen, which is often present in organic matter, is converted into hydrocarbons. Organic matter has organic porosity present in it, and is often filled with these hydrocarbons. As thermal maturity continues to increase, all of the gas moving through the rock can actually lead to organic pore space collapse, reducing overall porosity.

The factors affecting porosity suggest that the deepest wells such as the Child VO 30-09 and Lazy D-ZN 03-09 wells would have the lowest porosity, however this is not the case. The Gill Land Associates core, which is only slightly deeper than the Timbro PC 16-17 well has the lowest porosity values. Likely a secondary porosity inhibitor, such as high thermal maturity or chemical compaction, is affecting porosity in the location of the Gill Land Associates core. FESEM imaging and comparison of the amount of calcite overgrowths may shed light on how much chemical compaction is affecting overall porosity.

When discussing porosity loss and preservation, it is important to consider a number of factors that can inhibit chalk porosity loss such as; clay-poor or clay-free chalk, high sedimentation rate (which minimizes marine cementation), debris flows and
redeposition of chalk material, burial with marine fluids, and minimal overall depth of burial (Pollastro and Scholle, 1968). Over pressuring and hydrocarbon entry into the chalk can also act as porosity loss inhibitors. Timing is critical for these to have an effect, if these occur after major burial, there will be little porosity left for them to protect, whereas if over pressuring or hydrocarbon entry occurs before extreme burial, more porosity can be preserved.

Likely overall minimal burial depth is the main factor in the high preserved porosity seen in the Timbro PC 16-17 well. However, a number of other influences may be contributing. Further inquiry may shed light on the most prominent factors affecting the variations in porosity seen above.
The well logs used in this study include gamma ray, spontaneous potential (SP), resistivity, and neutron porosity and bulk density curves. The gamma ray curve depicts the proportions, or lack thereof, of the radioactive elements such as thorium, uranium, and potassium. These elements are commonly present in clays, micas, feldspars, and organic matter. Interpretation of gamma ray curves aid in lithologic correlations as a higher gamma ray reading is indicative of shale, or in the case of carbonates, a marl, where as a lower gamma ray reading generally represents a cleaner sand, or carbonate chalk. Resistivity curves measure the conductivity of fluid within the rock, making them useful for identifying hydrocarbon saturated rocks. Resistivity is also useful for lithologic correlation. The spontaneous potential (SP) curve was used for lithologic correlation when gamma ray curves were not available. The neutron and density curves were used when wells were missing a resistivity curve. Close to 200 wells were used to create the following map.

6.1 Basin Structure

A structure map on the top of the Fort Hays Limestone Member of the Niobrara was created to examine the present day structure of the Denver Basin within the study area (Figure 6.1). The Denver Basin is an asymmetric basin with a steeply dipping western slope and a shallow dipping eastern slope. The axis of the basin runs north-south from Denver, Colorado to Cheyenne, Wyoming. Figure 6.1 shows that the Fort Hays is at its deepest close to 3,000 feet sub-surface along the axis of the basin, and occurs at shallower depths such as 1,000 near East Pony and Red Tail Fields.
Figure 6.1: Structure map on the top of the Fort Hays Limestone Member of the Niobrara. The Fort Hays occurs at its deepest along the axis of the basin, shallowing to the west and the east.
6.2 B2 marl Isopach

An Isopach of the B2 marl was calculated using the zone from the top of the B2 marl down to the top of the C chalk. Figure 6.2 shows the isopach map associated with this data. The B2 marl occurs at thicknesses greater than 45 feet along the middle of the study area, to the north, and to the east. The B2 marl thins to the west, northwest, and near Weld 11-28 and Sundance 2-17 wells. The B2 marl becomes complicated in the southern part of the study area where there is a significant amount of data, but also complex faulting.

Figure 6.2: Isopach map of the B2 marl, which thickens in the north, northeast, and along the center of the study area. The B2 marl thins to the west, northeast and south.
6.3 B2 Chalk Isopach

An isopach map of the B2 chalk was calculated from the top of the B2 chalk to the top of the B2 marl. Figure 6.3 shows the isopach thickness of the B2 chalk across the study area. The B2 chalk is thickest in the southwest, and maintains thicknesses greater than forty in a trend extending to the northeast. The B2 chalk thins to the northwest and southeast. Figure 6.3 shows the locations of the five cores used in this study. The cores all occur in areas with a thickness of 30 feet or greater.

Figure 6.3: Isopach map of the B2 chalk with the thickest region in the southwest. B2 chalk remains thick in a north east trend, thinning to the northwest and southeast.
6.4 B1 Marl Isopach

An Isopach of the B1 marl was computed from the top of the B1 marl to the top of the B2 chalk. Figure 6.4 shows the isopach variation of the B1 marl. The thickest area of the B1 marls occurs in a similar northeast trend as the B2 chalk, although it does not extend all the way to east side of the study area. The B1 marl thins in the northwest and northeast, and thickens slightly to the south. Variation in thickness of the B1 marl occur more widespread than the B2 chalk.

Figure 79: Isopach of the B1 marl which is thickest in a northeastern trend, thinning to the northwest and northeast.
6.5 B1 Chalk Isopach

An isopach was computed for the B1 chalk from the top of the B1 chalk to the top of the B1 marl. Figure 6.5 shows the Isopach variations for the B1 chalk seen in the study area. The B1 chalk is at its thickest along the southeast side of the study area with thicknesses as high as 40 feet. Figure 6.5 also shows a thickening trend that is similar to the B2 chalk and B2 marl, extending in the northeast trend, however the B1 chalk thick also extends up to the north of the study area. The B1 chalk thins just to the right of the present day axis of the basin, as well as to the west.

Figure 6.5: Isopach map of the B1 chalk which occurs at its thickest in the northeast trend across the study area and along the east. The B1 thins to the west, and along the edge of the present day axis of the basin.
6.6 Cross Sections

Figures 81, 82, and 83 are three stratigraphic cross sections through the study area. Figures 81 and 82 are hung on the top of the Fort Hays Limestone Member. Figure 6.8 is hung on the top of the B2 chalk so that it is easily comparable to the cross section shown in Figure 3.19. The B1 chalk is highlighted in green and the B2 chalk is highlighted in blue, to show variations in target units across the study area. Stratigraphic units are identified by color coded tops of each unit with labels on the left.

Figure 6.6 shows a cross section extending west to east. Both the B1 and B2 chalk stay fairly uniform across the section. The B1 and B2 marl however vary drastically in thickness across the study area.

Figure 6.7 is a north to south cross section through the study area. The B1 chalk thins to the south from approximately 30 feet thick in the Cole Jack A 8-16 Breeden, to 18 feet thick in the Gill Land Associates well. The B2 chalk also varies drastically in thickness, the B2 is approximately 50 feet thick in the Cole Jack A 8-16 Breeden well and is 25 feet thick in the True Oil LLC 41-22 Peterson Federal well. The B1 marl also thins to approximately 6 feet thick in the Cole Jack A 8-16 Breeden, and the Gill Land Associates wells.

Figure 6.8 is a cross section through the five cores used in this study. This cross section is hung on the top of the B2 chalk so that it can be compared to Figure 3.19; a cross section of the five digitized cores used in the study. Figure 83 shows the same patterns seen in Figure 3.19; 1) a thinning of the B2 chalk to the south in the Gill Land Assoc. well, 2) a thinning of the B1 marl to the south, 3) variations in the B2 chalk with the thickest section in the Lazy D-ZN 03-09 well, and 4) a drastic thinning of the B2 marl.
from the Child VO 30-09 well with 35 feet, to 12 feet in the Weld 11-28 well. Where the B2 bench thins in the Gill Land associates well, a thickening occurs in the A marl. This is likely due to accommodation space above the thinned B benches.

6.7 Conclusions

Both the maps and the cross sections seen in this chapter show thickness variations of each stratigraphic unit across the study area. This is likely a result of two main influences, 1) paleobathemetry along the sea floor during time of deposition, and 2) bottom water currents, and geostrophic bottom currents causing current winnowing. Paleobathemetry along the sea floor during the time of deposition of any given stratigraphic unit would lead to more accumulation in paleo-lows where accommodation space is greater, and less accumulation on paleo-highs. Accumulation on the paleo-highs is also subject to current winnowing, removing sediments from paleo-highs and redistributing them in the paleo-lows. If however, these paleo features were large scale features, it would be expected that similar patterns would be seen throughout all of the stratigraphic units, and stacking patterns would exist. Some patterns can be seen, such as the thickest zones in the B2 chalk, B1 marl, and B1 chalk all occur in similar areas along the western edge of the study area. However, these patterns do not suggest that deposition and accumulation is controlled solely by major paleo-bathymetric features. Likely the bathymetry along the sea floor during the time of deposition is constantly changing as a result of tectonics and strong currents.
Figure 6.6: West to east cross section through the study area. Stratigraphic units are shown by color coded tops of each unit with labels on the left. The B1 chalk is highlighted in green and the B2 chalk is highlighted in blue between wells to show target location variation.
Figure 6.7: North to south cross section through the study area. Stratigraphic units are shown by color coded tops of each unit with labels on the left. The B1 chalk is highlighted in green and the B2 chalk is highlighted in blue between wells to show target location variation.
Figure 83: Cross section through the five cores used in this study. Stratigraphic units are shown by color coded tops of each unit with labels on the left. The B1 chalk is highlighted in green and the B2 chalk is highlighted in blue between wells to show target location variation.
CHAPTER 7

DISCUSSION

Detailed core descriptions, petrographic thin section interpretation, and analysis of FESEM images of the B1 and B2 chalk and marl benches identified six main facies. These facies vary in location, thickness, structural features and major calcareous and terrigenous constituents. These facies vary from pure chalks to massive fossiliferous marly chalks, to pure marls. Location, thickness, and patterns in which these facies occur have an effect on overall effectiveness of the chalk benches as reservoirs. XRD bulk mineralogy analysis, geochemical interpretations, and porosity values taken from the B1 and B2 chalk and marl benches help differentiate the two chalk beds as major horizontal targets. Integration of results from this study show that the B2 chalk should remain a major horizontal target in the study area, and the B1 chalk should be considered a secondary target where appropriate.
CHAPTER 8

CONCLUSIONS

This study has found a number of conclusions that can be very useful when trying to understand the variations in the B chalk and marl benches of the Smoky Hill Member of the Niobrara. The following conclusions should be considered when aiming to high-grade exploration areas while targeting the B chalk benches within the study area.

1) Six main facies comprise the B chalk and marl benches of the Smoky Hill Member; they vary in stratigraphic location and thickness between each core. Overall stratigraphic patterns are similar in core, yet not the same and are not correlative. Cores in the northern parts of the study area have greater vertical facies variations as compared to the cores located in the southeast region of the study area. The variations in facies distributions may be attributed to bottom water current, current winnowing and paleobathemetry.

2) XRD bulk mineralogy analyses helped confirm the depositional model for the main B benches. Samples taken from marlier facies have increased siliciclastic percentages, pyrite percentages and total clays percentages., consistent with the depositional model that marls were deposited during regressions or cool and wet Milankovitch cycles when terrigenous siliciclastic input into the basin increased, thus diluting the deposition of carbonate material. Samples taken from more carbonate rich zones, such as the middle of the B1 or B2 chalk benches show extremely high carbonate content, consistent with the depositional model for chalks. Chalk deposition occurred during transgressions or warm and dry Milankovitch cycles,
where very little terrigenous material was deposited into the basin, and deposition was dominated by pelagic production.

3) Petrographic interpretations supported the depositional model for each facies as defined by core descriptions, and also identified micro scale variations in Facies 3 that are not visible in core, leading to the breakout of Facies 3 into Facies 3a and Facies 3b.

4) FESEM imaging confirmed the depositional model of each facies, as well as identified many of the major constituents present in each facies and how they vary between facies. FESEM imaging also allowed for qualitative micro-porosity interpretations that concluded the Facies 1 (Massive to Fossiliferous Marly Chalk to Chalk) and Facies 6 (Chalk) have the greatest amount of preserved pore space occurring between preserved coccolithosphores, platelets and fragments.

5) Geochemical analyses confirm that the variations in facies have a major effect on preserved TOC, as well as accumulated free hydrocarbons. A) Areas affected by increased bioturbation have decreased overall TOC, B) areas with increased marl interbeds have higher overall TOC due to a lack of bioturbation, coupled with fast sedimentation rates.

6) Maturity throughout the study area varies from mature-late stage to post-mature in Wattenberg Field, to mature-early stage in the Lazy D-ZN 03-009 well located on the edge of Silo Field. Tmax versus hydrogen index plots appear to show that wells throughout the basin have varying kerogen types and origins, however this is a result of high thermal maturity in and around Wattenberg Field. Patterns show that wells with high Tmax values plot with low HI values.
7) Porosity variations throughout the study area may be attributed to: 1) mechanical compaction: dewatering, grain reorientation, and grain breakage, 2) chemical compaction; dissolution of calcium carbonate and re-precipitation in pores, 3) thermal maturity: decreasing organic pore space, pore space collapse, 4) porosity loss inhibitors: high sedimentation rates, clay poor sediments, overpresuring and hydrocarbon entry.

8) Subsurface mapping showed variation in thickness of the different B chalk and marl benches, supporting the theory behind paleobathemetry, bottom water currents and current winnowing as major contributors to facies variations throughout the study area.
CHAPTER 9
SUGGESTED FUTURE WORK

1) Utilize facies identification scheme on more cores in the study area to better map variations between wells.

2) Create a detailed petrographic study using a number of different wells.

3) Perform geochemical analyses of each individual facies.

4) Acquire a more complete petrophysical log suite to allow for identification of electrofacies.
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