RESERVOIR CHARACTERIZATION AND GEOMECHANICAL EVALUATION
OF THE GREENHORN FORMATION IN THE NORTHERN
DENVER BASIN, COLORADO

By
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ABSTRACT

Success of unconventional reservoirs in the Denver Basin has led to increased interest in the petroleum potential of the Greenhorn Formation. The Denver Basin produces hydrocarbons primarily from Cretaceous-aged strata. An increase in hydraulic-fracture technology has shifted focus from conventional reservoirs, such as the “J” sandstone, to unconventional accumulations throughout the basin. Evidence indicates that hydrocarbons exist in the underexplored formations of the Benton Group, specifically within the Greenhorn Formation. While the individual formations within the Benton Group are historically recognized as a source rocks lacking in conventional appeal, the Cenomanian-Turonian Greenhorn Formation exhibits notable unconventional reservoir characteristics and should be further explored.

The Greenhorn Formation is comprised of three members: the Bridge Creek Limestone, the Hartland Shale, and the Lincoln Limestone. The Bridge Creek Limestone and the Lincoln Limestone act as reservoir intervals, while the Hartland Shale is a source, with total organic carbon (TOC) values of 2-4%, predominantly as Type II marine kerogen. Geochemical analyses of the organic-rich shales and marls within the source units indicate that hydrocarbons have been generated within the study area. Previous research on the Greenhorn Formation characterizes the source-rock reservoir properties and includes geochemical characterization and source-rock analysis. The Greenhorn Formation is mature and organic rich in Wattenberg Field and in the Northern Denver Basin, which includes Silo, Hereford, Fairway, and Redtail fields. The Greenhorn is of similar lithology and porosity to the overlying Niobrara Formation, which is the primary unconventional target within the Denver Basin. The Greenhorn contains source and reservoir intervals, Type I shows, high TOC values, elevated levels of thermal maturity, and internal fractures; all of which are indications that hydrocarbons may exist within this interval.

An extensive reservoir characterization has been completed in order to understand the reservoir and completion quality of the members within the Greenhorn Formation. This multidimensional study of borehole and core data, combined with a microscope study of mechanical behavior, utilizes basin-wide correlations, reservoir characterization, and rock mechanical analysis to understand the heterogeneity of the Greenhorn Formation. The study covers multiple scales to quantify the petroleum potential of the Greenhorn Formation, and strengthen the
understanding of the unit as an unconventional reservoir. Chalk intervals within the Bridge Creek Limestone and the Lincoln Limestone members exhibit comparable porosity to the Niobrara Formation, and contain microfractures for hydrocarbon storage and migration. Petrophysical, XRF elemental, and geomechanical data suggest that the Bridge Creek Member is similar to hydrocarbon-producing chalk beds in the Niobrara, and should be considered a possible unconventional target.

The Greenhorn Formation represents a complex mixed siliciclastic-carbonate depositional setting with seven main facies that represent a transition from chalk to marl to mudstone. The Bridge Creek Member represents a biogenic pelagic-dominated system, whereas the Hartland and the Lincoln represent a detrital dominated depositional system with significant clastic hypopycnal influence and tempestite deposition. Depositional fabric, sedimentary structures, dominant allochems, bentonite and limestone frequency, clay characterization, bulk mineralogy, elemental properties, organic content, and porosity and permeability influence the geomechanical response of each interval. Each of these characteristics has implications for geomechanical behavior and ultimately affect the reservoir and completion quality of the study interval. Based on these analyses, the Greenhorn Formation can be broken into 4 distinct geomechanical zones with differing mechanical behavior that can be quantified based on reservoir and completion quality. While the Bridge Creek Member has the highest completion quality and is most comparable to the Niobrara, the combined analyses from this study indicate that the Lincoln Member has the highest overall potential as an unconventional reservoir throughout the study area when reservoir, source, and completion quality are assessed.
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CHAPTER 1

INTRODUCTION

Cretaceous strata in the Denver Basin are known to successfully produce hydrocarbons. The Wattenberg Field has been a reliable and economic hydrocarbon producing field in the western Denver Basin since its discovery in 1970. An increase in hydraulic-fracture technology has shifted focus from conventional reservoirs to unconventional accumulations within the Niobrara Formation and Codell Sandstone. Additional evidence indicates that hydrocarbons may exist within currently underexplored formations of the Benton Group, specifically within the Graneros-Greenhorn petroleum system. The organic-rich Greenhorn Formation may contain significant unconventional resource potential that has been previously overlooked.

While the formations within the Benton Group have been historically recognized as source rocks lacking in conventional appeal, the Cenomanian-Turonian Greenhorn Formation exhibits notable unconventional reservoir characteristics and should be explored further. The Greenhorn Formation is mature and organic-rich, but exhibits low-resistivity responses and unfavorable lithologies for vertical production. Type I continuous phase oil shows in the Graneros and Greenhorn confirm the presence of hydrocarbon accumulations with limited production in the Fort Morgan area (Nolte, 2009, Schowalter and Hess, 1982). Horizontal drilling and hydraulic multi-stage fracturing completion techniques allow the previously overlooked hydrocarbon accumulations in the Greenhorn Formation to be exploited. Because of its lithology, porosity, high thermal maturity, high TOC, and close proximity to source rock intervals, the Greenhorn Formation exhibits notable reservoir quality and should be further explored as an unconventional target.

1.1 Objectives and Purpose

The purpose of this study is to continue the work of Kaiser (2013) on the Graneros-Greenhorn petroleum system. His thesis focused on source rock quality whereas this study focuses on reservoir and completion quality. This study aims to contribute to the overall understanding and growing interest in the Greenhorn Formation through a multidimensional study of borehole and core data, as well as petrographic study of mechanical behavior. This study will: (1) utilize
descriptions of 6 cores to make accurate facies descriptions of the Hartland, Bridge Creek, and Lincoln members of the Greenhorn Formation across the Denver Basin; (2) define facies through petrographic analysis of thin sections; (3) describe samples using images produced from a Field Emission Scanning Electron Microscope (FE-SEM); (4) understand micro-porosity of the unit through mercury injection and capillary pressure; (5) use petrophysical interpretations to correlate the Hartland, Bridge Creek, and Lincoln members of the Greenhorn Formation across the Northern Denver Basin; and (6) complete a geomechanical interpretation from a petrophysical standpoint by utilizing Young’s modulus, Poisson’s ratio, bulk modulus, and brittleness indices. Ultimately, these objectives will help evaluate the reservoir quality of the interval and strengthen understanding of its petroleum potential as an unconventional reservoir.

1.2 Motivation and Significance

The Greenhorn Formation is of interest because it is biostratigraphically and thus, time-equivalent to the Eagle Ford in South Texas. The Eagle Ford has been extremely successful in recent years with production rates of 1.7 MMBOPD in early 2015 (Denne, 2016). In addition, the Greenhorn is a similar but separate petroleum system to the Niobrara and is within close proximity to the overlying unit. The Denver Basin is expected to produce 4.1-4.6 billion barrels of crude oil and other liquids in the next few decades, mostly out of the Niobrara and the Codell (Niobrara News, 2014). Based on these factors, interest in exploration of the organic-rich Greenhorn Formation has increased in recent years. As stated previously, horizontal drilling and hydraulic multi-stage fracturing allow previously overlooked hydrocarbon accumulations in the Greenhorn Formation to be exploited as an unconventional resource.

Little has been done to characterize the Greenhorn Formation as a reservoir for hydrocarbons. Kaiser (2013) completed extensive research on the source quality of the Graneros-Greenhorn petroleum system. He analyzed, sampled, and described rocks from the Encana Aristocrat Angus 12-8. XRF and SRA data are available for this core. In addition, Nakamura (2015) analyzed Greenhorn Formation samples from the Noble Aristocrat PC H11-07 core. He acquired X-ray Fluorescence (XRF), X-ray Diffraction (XRD), Inductively Coupled Plasma Mass-Spectrometry (ICP-MS), Leco Total Organic Carbon (TOC) and thin sections for the Greenhorn section of this core. Log data is also available for this core but has not been analyzed for the
Greenhorn Formation. An extensive geomechanical evaluation, SEM, depositional model and correlative work are lacking for the Greenhorn Formation add motivation for this project.

The Niobrara Formation is subdivided into four main chalk benches (A, B, C, and Fort Hays) that are successful unconventional hydrocarbon producers in the Denver Basin. Petrophysical, XRF elemental, and geomechanical data suggest that the chalk beds within the Bridge Creek member of the Greenhorn Formation are similar in their log responses to the chalk beds in the Niobrara. This information provides further motivation to not only characterize the Greenhorn Formation as a reservoir, but also to compare its characteristics with those of the Niobrara in order to determine a viable unconventional target.

1.3 Study Area

The Denver-Julesberg Basin lies within Colorado, Wyoming, and Nebraska (Fig. 1.1). This study refers to the Denver-Julesberg Basin as the Denver Basin. Petroleum production is historically successful from Cretaceous strata throughout the Denver Basin. Since its first discovery in 1867 at Florence Field, the Denver Basin has produced over 1 billion barrels of oil and nearly 3.7 trillion cubic feet of gas (Higley et al., 2007). Paleozoic through Cretaceous reservoirs produce oil and gas in over 1,500 fields within the Denver Basin (Higley et al., 2007). The Dakota Formation, Muddy “J” Sandstone, the Codell Sandstone, and the Niobrara Formation have been past and current industry targets for years and have proven to be very successful. The first horizontal wells were drilled in the Niobrara in the early 1990s in Silo Field. More recent unconventional production from the Niobrara began in 2005 when Encana Corporation drilled a horizontal well in Wattenberg Field. The Niobrara Formation was the first unconventional chalk reservoir discovered in the Denver Basin. Since then, operators in the Denver Basin have focused on horizontal completion techniques instead of conventional vertical designs.

Wattenberg Field is the largest hydrocarbon producing field in the Denver Basin and is located just north of Denver, Colorado (Fig. 1.1). Numerous productive intervals exist in Wattenberg Field and have been exploited since the field’s discovery in 1970 (Kaiser, 2013). The primary target in Wattenberg Field was the Muddy “J” Sandstone, but production has expanded to include additional productive zones of both conventional and unconventional origin. While most
Figure 1.1. Denver Basin outline on structure map of the top of the Niobrara showing asymmetric character. Study area outlined in Orange Box. Wattenberg Field shown in Red. Silo, Fairway, Hereford, East Pony and Red Tail fields shown in Green.
of the horizontal wells have been drilled in the Codell and the Niobrara, a small number of wells have been drilled in the Greenhorn. However, of over 34,000 wells that have been drilled in the Greater Wattenberg Area, only approximately 40 wells include the Greenhorn Formation, and even less report favorable hydrocarbon production from this interval (Kaiser, 2013). Chesapeake Energy drilled a horizontal test well (State 16-3-61) in the Lincoln Limestone member of the Greenhorn Formation in 2012, but only produced 994 barrels of oil and 100 MCF of gas in three months (Kaiser, 2013). Since then, a handful of companies have chosen to complete the Lincoln Limestone, but completion information remains confidential.

The northern Denver Basin contains Silo, Hereford, East Pony, and Redtail Fields. In late 2009, EOG Resources re-introduced Niobrara production in this region of the Denver Basin with the discovery of the Jake well in Hereford Field (Anderson et al., 2015). Since this discovery, more than 4400 horizontal wells have been drilled in the Denver Basin Niobrara play (Anderson et al., 2015). In this region, however, the Greenhorn Formation is relatively underexplored. Few companies have drilled and cored the Greenhorn Formation, and even fewer have reported favorable production. However, type I shows indicate the presence of hydrocarbons throughout the interval and a handful of Greenhorn completions have produced hydrocarbons from this area.

1.4 Research Methods

Various methods were used to analyze and interpret the depositional setting, reservoir quality, geomechanics, and heterogeneity of the Greenhorn Formation. Facies within the Greenhorn Formation were analyzed at multiple scales: bed, bedset and member scale (meters), bedset scale (several centimeters to several meters), lamination scale (several millimeters), and microscale (less than 1 millimeter) (Hart, 2013). Outcrop description represents the unit at bed, bedset and member scale. Core analysis aids in the understanding of facies in both bedset and lamination scales. Petrographic thin section analysis enhances understanding of the lamination scale facies. Images from Field Emission Scanning Electron Microscope (FE-SEM) analysis describe the facies at a microscopic level. Use of these methods will further enhance the understanding of the facies within the Greenhorn Formation at different scales of heterogeneity.
1.4.1 Outcrop

Because of the easily erodible nature of mudrocks, few intact outcrops of the Greenhorn Formation exist in the Denver Basin. Most of the outcrop analysis for this study and other studies of the Greenhorn has been completed at the Rock Canyon Anticline near Pueblo, Colorado, although other Greenhorn outcrops exist along the Front Range. Outcrop descriptions serve the purpose to better understanding the physical character of the Greenhorn Formation.

1.4.2 Core Descriptions

Although the Greenhorn Formation is underexplored in the Denver Basin, several companies have taken cores through the interval. Six Greenhorn cores were used for this study (Fig. 1.2). These cores are listed in Table 1.1a. Depths and data available for these cores are listed in Table 1.1b.

**Table 1.1a.** Core list and locations.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Well Name</th>
<th>Location</th>
<th>Field</th>
<th>County</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 SM Energy</td>
<td>Patriot 1-19H</td>
<td>Sec. 19-T14N-R64W</td>
<td>Silo</td>
<td>Laramie</td>
<td>WY</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sec.33-T14N-R65W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 EOG Resources</td>
<td>Big Sandy 132-33M</td>
<td>R65W Sec.11-T3N-R65W</td>
<td>Fairway</td>
<td>Laramie</td>
<td>WY</td>
</tr>
<tr>
<td>3 Noble</td>
<td>Aristocrat PC H11-07</td>
<td>Sec.11-T3N-R65W</td>
<td>Wattenberg</td>
<td>Weld</td>
<td>CO</td>
</tr>
<tr>
<td>4 Encana</td>
<td>Aristocrat Angus 12-8</td>
<td>Sec.8-T3N-R65W</td>
<td>Wattenberg</td>
<td>Weld</td>
<td>CO</td>
</tr>
<tr>
<td>5 USGS</td>
<td>1 Portland</td>
<td>Sec.20-T19S-R68W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AMOCO</td>
<td>1 Rebecca K Bounds</td>
<td>Sec.17-T18S-R42W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Core descriptions help with understanding the formation at bedset to sub-lamination scale. Detailed core descriptions were conducted on four cores available for this study. Depths of study are provided in Table 1.1b. The USGS cores were used to describe the facies and lithologies that make up members of the Greenhorn Formation and to understand the variations between the members across the basin. Both of these cores have been widely studied and facies have been
Table 1.1b. Available data and depths for provided cores.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Well Name</th>
<th>Min Depth</th>
<th>Max Depth</th>
<th>Thickness (ft)</th>
<th>Interval</th>
<th>Available data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 SM Energy</td>
<td>Patriot 1-19H</td>
<td>8580</td>
<td>8667</td>
<td>87</td>
<td>Lincoln</td>
<td>Vertical logging suite data (FMI, ECS, CMR, Sonic, triple combo, etc.), XRD, SRA, Leco TOC and GRI, digital core photos, thin sections and thin section photos</td>
</tr>
<tr>
<td>2 EOG Resources</td>
<td>Big Sandy 132-33M</td>
<td>8869</td>
<td>8987</td>
<td>118</td>
<td>Lincoln</td>
<td>A full suite of petrophysical logs, MICP data</td>
</tr>
<tr>
<td>3 Noble</td>
<td>Aristocrat PC H11-07</td>
<td>7162</td>
<td>7369</td>
<td>207</td>
<td>Greenhorn</td>
<td>XRF samples in 1 foot intervals, XRD, ICP-MS, and OC data have been analyzed for this core and extensive log data are available. Samples from Noble Aristocrat PC H11-07 were used for SEM, thin section, and MICP analysis</td>
</tr>
<tr>
<td>4 Encana</td>
<td>Aristocrat Angus 12-8</td>
<td>7397</td>
<td>7634</td>
<td>237</td>
<td>Greenhorn</td>
<td>XRF samples at 6-inch intervals are available. Lithologic core descriptions and source rock analysis (SRA) have been completed on this core (Kaiser, 2013)</td>
</tr>
<tr>
<td>5 USGS</td>
<td>1 Portland</td>
<td>448</td>
<td>568</td>
<td>120</td>
<td>Greenhorn</td>
<td>Petrophysical and geochemical data are available on the USGS website. <a href="http://geology.cr.usgs.gov/crc/">http://geology.cr.usgs.gov/crc/</a></td>
</tr>
<tr>
<td>6 AMOCO Production</td>
<td>1 Rebecca K Bounds</td>
<td>920</td>
<td>1045</td>
<td>125</td>
<td>Greenhorn</td>
<td>Petrophysical and geochemical data are available on the USGS website. <a href="http://geology.cr.usgs.gov/crc/">http://geology.cr.usgs.gov/crc/</a></td>
</tr>
</tbody>
</table>
Figure 1.2. Denver Basin map from figure 1.1 overlain by core locations. Cores within the study area were used for sampling and analyses in this study. Cores outside the study area were used to understand variations in Greenhorn stratigraphy across the basin.
previously determined. Kaiser (2013) completed an extensive description of the Greenhorn Formation in the Encana Aristocrat-Angus 12-8. Additional descriptions of Noble Aristocrat PC H11-07, and SM Patriot 1-19H were completed for this study. The Noble Aristocrat PC H11-07 is missing the top 30 feet of the Bridge Creek Member, but contains most of the Greenhorn Formation. The SM Patriot 1-19H contains the base of the Hartland Member and the full Lincoln Member of the Greenhorn. The Big Sandy 132-33M core also includes the base of the Hartland and the full Lincoln interval. Descriptions from these cores enhanced understanding of facies in Greenhorn Formation.

1.4.3 Thin Sections

Petrographical analysis of thin sections from SM Patriot 1-19H, Noble Aristocrat PC H11-07, USGS 1 Portland, and Amoco Production Rebecca K. Bounds cores contributed to understanding the heterogeneity within the Greenhorn Formation at lamination scale. Variations such as grain size, mineralogy, and porosity can be seen at this scale. Thin sections were used to further describe the sedimentary facies that exist within the Greenhorn Formation at lamination scale. Twenty-two samples were taken from the Noble Aristocrat PC H11-07 core and sent to Weatherford for ultra-thin (20 microns) thin section preparation (Table 1.2). Ultra-thin samples are beneficial to shale analysis where the samples are fissile mudrock. Thin sections were stained with blue epifluorescent dye to show porosity and alizarin red dye to differentiate carbonates. At least two samples from each facies were analyzed in thin section. Additional Greenhorn samples from the Noble Aristocrat core were available. Six additional thin sections and photos were provided by SM Energy on the SM Patriot 1-19H core. Thin sections from 23 locations on the Rebecca K Bounds core and 19 thin sections from the USGS 1 Portland core enhanced the understanding of the Lincoln and the Hartland members of the Greenhorn Formation. Analysis of thin sections from the USGS cores enhanced understanding in lamination scale heterogeneity in the Hartland and Lincoln members of the Greenhorn Formation. Bridge Creek thin sections were not available from the USGS cores, so thin section analysis for this member relied solely on the samples taken from the Aristocrat PC H11-07 core. Samples were compared to previously acquired XRD data to characterize the clay components that make up the unit.
**Table 1.2.** Sample list from Noble Aristocrat PC H11-07

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Depth</th>
<th>FESEM</th>
<th>Mercury</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bridge Creek</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA_BC_S1</td>
<td>7163.8</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NA_BC_S2</td>
<td>7164.0</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NA_BC_S3</td>
<td>7164.5</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NA_BC_S4</td>
<td>7169.0</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NA_BC_S5</td>
<td>7177.5</td>
<td></td>
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</tr>
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<td>NA_BC_S6</td>
<td>7178.5</td>
<td>yes</td>
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<tr>
<td>NA_BC_S7</td>
<td>7190.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA_BC_S8</td>
<td>7197.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA_BC_S9</td>
<td>7208.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hartland</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA_H_S10</td>
<td>7223.5</td>
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<td>Yes</td>
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<tr>
<td>NA_H_S11</td>
<td>7237.5</td>
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<td>NA_H_S12</td>
<td>7249.5</td>
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<td>Yes</td>
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<tr>
<td>NA_H_S13</td>
<td>7276.5</td>
<td></td>
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<td><strong>Lincoln</strong></td>
<td></td>
<td></td>
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<tr>
<td>NA_L_S14</td>
<td>7282.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA_L_S15</td>
<td>7286.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA_L_S16</td>
<td>7297.0</td>
<td>Yes</td>
<td>Yes</td>
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<td>NA_L_S17</td>
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<td>NA_L_S19</td>
<td>7322.5</td>
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<td>NA_L_S20</td>
<td>7334.0</td>
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<td></td>
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<tr>
<td>NA_L_S21</td>
<td>7344.5</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NA_L_S22</td>
<td>7364.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**1.4.4 FE-SEM**

Images acquired from the FE-SEM were used to evaluate a sample’s complex surface topography and composition at microscopic scales using a generated electron beam (Welton, 2003). Specimens can be magnified up to 100,000x with the use of this tool. The SEM samples were cut into a small cube approximately 5 by 10 by 10 mm. The surface that is face-up in the machine to be examined must be a fresh, broken surface perpendicular to bedding (looking into laminations) with minimal contamination. The samples were then coated with gold to allow for charging of the electrons in the sample when inserted into the machine. Each sample was analyzed on the FE-SEM machine at a working distance of around 8 mm which allows magnification at microscopic scales. Eight of the 22 Aristocrat PC H11-07 core samples were analyzed for FE-SEM: 4 from the Bridge Creek, 2 from the Hartland, and 2 from the Lincoln (Table 1.2). FE-SEM
provides insight to evaluating microscale heterogeneity between facies within the three members of the Greenhorn Formation. Each sample is descriptive of the main facies seen within each member.

1.4.5 X-ray Diffraction (XRD) Mineralogical

X-Ray diffraction measures the quantities of various minerals found in a sample. This allows for bulk mineralogy classification and clay characterization of each member of the Greenhorn Formation. Nakamura (2015) analyzed 10 Greenhorn samples with XRD from the Noble Aristocrat PC H11-07. These data had not been analyzed for the Greenhorn Formation and were available for use during this study. This allowed for further description of the Greenhorn formation on the basis of mineralogical character. Geomechanical and porosity interpretations rely heavily on the outputs from XRD mineralogical data.

1.4.6 X-Ray Fluorescence (XRF) Elemental

Elemental abundances are measured through X-ray fluorescence. High energy x-rays from a handheld XRF analyzer excite individual atoms characteristic to a specific element. This allows for the elemental concentrations to be semi-quantitatively determined. Like the XRD data used in this study, XRF data from 10 samples from the Greenhorn Formation in the Noble Aristocrat PC H11-07 well had previously been collected by Nakamura (2015) but not yet extensively analyzed. This study utilizes previously acquired XRF data to further characterize the Greenhorn Formation from an elemental standpoint.

1.4.7 Petrophysics

Correlative work has not been completed on the Greenhorn Formation in the Denver Basin and stratigraphic correlation using available well log data is needed. The Greenhorn Formation is distinguishable by its low gamma ray and resistivity response. Wireline logs are nearly always run in wells and generally available from public and commercial databases, making them an essential tool in oil and gas exploration. Using this information to generally interpret the Greenhorn Formation throughout the Denver Basin will provide a better understanding of the interval in the subsurface. IHS Petra was used to complete cross-sections showing changes in the Greenhorn Formation across the basin.
1.4.8 Mercury Injection and Capillary Pressure (MICP)

Capillary pressure measures the force necessary to draw a liquid through a thin tube, or capillary. Mercury injection capillary pressure (MICP) measures the capillary pressure of mercury drawn through a series of pores to determine porosity, permeability, pore throat radii, and water saturation, assuming the reservoir bears hydrocarbons (Olson and Grigg, 2008). MICP is very useful in tight rock reservoirs (Olson and Grigg, 2008). A sample is placed in the instrument chamber, which is subsequently evacuated and flooded with mercury. Porosity and pore throat size is measured by the pressure needed to force mercury through the pore throats. This tool is useful for determining shale porosity values between 1 and 10% (Olson and Grigg, 2008). MICP analysis was completed on 10 samples from the Greenhorn Formation in the Noble Aristocrat PC H11-07 well.

1.4.9 Geomechanics

Petrophysical openhole logs from the Noble Aristocrat PC H11-07, SM Patriot 1-19H, and EOG Big Sandy 132-33M cores also contained dipole sonic, composed of compressional and shear sonic logs, which were used in combination with neutron density, gamma ray, resistivity, and other openhole logs to calculate the moduli that determine rock mechanical properties. Calculated moduli include Young’s modulus (YM), Poisson’s Ratio (PR), Unconfined Compressive Strength (UCS), and Bulk Modulus (BR). These moduli help determine brittleness of the rock (YM/PR), cluster analysis, and comparisons with XRD, TOC, XRF, and MICP that further enhance the understanding of relationships between rock mechanical components and geochemistry. For example, brittleness can be plotted against total organic content to see if organic matter influences rock mechanics. Rock mechanical properties are essential to predicting a rock’s response to hydraulic fracture.
CHAPTER 2
GEOLOGIC OVERVIEW

This study utilizes background information about the Greenhorn Formation during its time of deposition to further understand the geologic setting, sequence stratigraphic framework and regional stratigraphy. Previous studies have quantified the source rock qualities of the Greenhorn Formation in order to understand its potential as a source rock reservoir (Kaiser, 2013). This information is useful when evaluating the petroleum potential of the Greenhorn Formation.

2.1 Geologic Setting

The Denver Basin developed in the Early Cretaceous (Martin, 1965). Prior to Laramide development of the Denver Basin, the Sevier Orogeny created the Western Interior Basin. The Western Interior Cretaceous Seaway (WICS) formed when marine waters transgressed from the northern Boreal Sea and the southern Tethys Ocean began flooding North America in Barremian-Aptian time, ultimately joining the oceans during the Cenomanian (Nakamura, 2013). Sediments were reworked as seas entered from the northwest and advanced towards the south. Cretaceous strata in the Denver Basin represent a marine transgression followed by regression and thin towards the southeast.

During the late Cenomanian to Early Turonian, a combination of foreland-basin subsidence and tectono-eustatic highstand resulted in maximum flooding of the Western Interior Basin (Kauffman, 1984) (Fig. 2.1). Abundant siliciclastic input from the uplifted fold and thrust belt of the Sevier Orogeny to the west influenced sedimentation processes within the Denver Basin (Sageman et al., 1998) (Fig. 2.1). The Greenhorn represents a major transgression-regression cycle of the Cretaceous (Kauffman, 1984). The Greenhorn Sea reached maximum extent and depth in middle Turonian time, and extended approximately 2,000 km from present day Utah to Kansas. Water depths are highly debated. Oscillations between mud-rich and carbonate-rich facies formed limestone/marlstone couplets which also represent fluctuations in bioactivity that reflect changes in bottom-water oxygen content (Sageman et al., 1998). Oceanographic models for circulation in the WICS during Late Cenomanian to Early Turonian time combine periods of stratified and mixed water columns to explain the benthic and redox cycles (Sageman et al., 1998).
Figure 2.1. Paleogeography and distribution of lithofacies for the Western Interior Basin during Late Cenomanian time. (Modified from Blakey, 2014).
2.1.1 Sequence Stratigraphic Framework

The Western Interior Basin in North America has undergone dynamic interactions between tectonic, oceanographic, climatic, sedimentologic, and biologic factors during its evolution beneath an ancient epicontinental sea (Kauffman, 1993). Integration of biostratigraphy, chronostratigraphy, and geochronology based on high-resolution isotopic ages from volcanic ash and bentonite beds that record approximately 38 million years of Albian-Maastrichian time allows for rocks in the basin to be dated and correlated within a detailed stratigraphic framework (Kauffman, 1993). Global tectonic events shaped the western part of North America during the Cretaceous. Sedimentation in and around the basin was controlled by tectonic growth of the basin, eustatic sea level changes, climate changes, and watermass dynamics in epicontinental seas (Kauffman, 1993). Fluctuations in these conditions are reflected in the Cretaceous sedimentary record as biotic mass extinctions, isotope variability, episodic, widespread, organic-carbon enrichment cycles and Milankovitch-scale bedding rhythmicity (Kauffman, 1993).

Third-order eustatic fluctuations defined by large-scale cyclothsms averaging 10 My in duration consisting of marginal marine to deep water pelagic facies characterize the Western Interior Cretaceous Seaway (WICS) (Kauffman, 1985). Five third-order marine cyclothsms represent the development of environments and sedimentation throughout the Western Interior Basin (Kauffman, 1977). Each cyclothem is named for deposits that represent peak transgression and eustatic highstand. The Greenhorn Cyclothem (late Albian-middle Turonian) marks the greatest Cretaceous eustatic highstand and is the most extensive transgressive-regressive cycle in the Western Interior Basin (Kauffman, 1990). Global eustatic rise and fall resulted in symmetrical sequences of transgressive and regressive cycles of marine and marginal marine facies (Kauffman, 1985). The Greenhorn Cyclothem began with deposition of the Graneros and includes the Greenhorn, Carlile and Codell formations in the Denver Basin (Kauffman, 1985) (Fig. 2.2). The Lincoln Limestone and Hartland Shale members of the Greenhorn Formation represent various fourth-order stillstand and transgressive cycles.
<table>
<thead>
<tr>
<th>STAGE</th>
<th>GROUP</th>
<th>FORMATION</th>
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<th>REGIONAL EVENTS</th>
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<td>LYTLE</td>
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</tbody>
</table>

**Figure 2.2.** Sequence Stratigraphic framework of the Greenhorn cyclothem shown with Cretaceous Stratigraphy in the Denver Basin. One major transgression-regression can be seen. Oceanic Anoxic Event II (OAE II) is shown (From Zelt, 1985).

The Bridge Creek Member encompasses both the Oceanic Anoxic Event II (OAE II) just above the Hartland Shale Member contact and the Cenomanian-Turonian boundary, which corresponds to a mass-extinction event at the termination of OAE II (Keller and Pardo, 2004; Sageman et al., 2006) (Fig. 2.2). This event corresponds to a global episode of intense organic carbon burial over a period of about one million years that coincides with a maximum sea-level highstand. Upwelling from deeper oceanic water masses during this volcanic-tectonic event increased fertility and productivity in surface waters. In addition, high rates of freshwater runoff combined with deepening seas in the WICS created periodic stratification of the water column. The Bridge Creek Limestone represents deposition thought to be consistent with Milankovitch Cycles with periodicities of 20,000 to 100,000 years (Sageman, 1998). Cyclicity between chalk and marl intervals within the Greenhorn Formation directly relates to reservoir properties of each unit, which ultimately plays a role in determining reservoir quality of each member.
2.1.2 Structural Setting

The Western Interior Cretaceous Basin is one of the largest complex foreland basins in the world (Weimer, 1984). The Laramide Orogeny (~70 Ma-40 Ma) partitioned the pre-existing Western Interior Foreland Basin into individual Rocky Mountain intermontane basins (Weimer, 1996). Laramide tectonic activity peaked in the Eocene and initiated reactivation of the surrounding uplifts (Martin, 1965). The current Denver Basin spans 60,000 mi² in Colorado, Nebraska, and Wyoming (Martin, 1965). It is asymmetric, with gently dipping east flanks that dip ½° to the west and steeply dipping west flanks that dip 10+° to the east (Sonnenberg, 2009) (Fig. 2.3). The Basin is deepest near Denver, with over 13,000 feet of sediment.

![Figure 2.3. Cross section of the Denver Basin from west to east showing asymmetric character along basin axis. Oil window is shown in red (Sonnenberg, 2015).](image)

2.1.3 Regional Stratigraphy

Upper Cretaceous stratigraphy in the Denver Basin consists of the Benton Group (Graneros, Greenhorn and Carlile Formations), the Niobrara Formation, Pierre Formation and Fox Hills (Fig. 2.2, Fig. 2.4). Seas transgressed across a north-dipping alluvial flood plain in the Albian and early Cenomanian and deposited the Dakota Group. The Benton Group lies above the Dakota.
The formations in the Benton Group are predominately made up of organic-rich mudstones and shales with interbedded carbonate chalk reservoir units. The siliceous Mowry Shale exists in the northern Denver Basin, but thins and pinches out towards the south. The high organic black and bentonitic Graneros shale is Cenomanian in age and was deposited offshore as the WICS continued to transgress. The X-Bentonite represents the contact between the Graneros and the overlying Greenhorn Formation, and is an extensive marker from Alberta, Canada to North Texas that is easily recognizable in core, outcrop, and on logs (Kauffman, 1977).

The Greenhorn Formation is middle Cenomanian to early Turonian in age (95-92 Ma). It comprises the center portion of the Benton Group (Fig. 2.2, Fig. 2.4). Units of the Greenhorn are laterally continuous because they were deposited on a relatively low-gradient seafloor in the deepest part of the WICS (Hattin, 1975). The regionally extensive Greenhorn Formation can be correlated throughout the Central US into Canada, but has several different time-equivalent names: Eagle Ford Formation, Marias River Formation, Second White Specks Formation, and upper Belle Fourche member of the Frontier Formation (Hattin, 1975). The Greenhorn Formation consists of three members, the Lincoln, Hartland, and Bridge Creek, which consist of finely laminated organic-rich calcareous shales, marls, and chalk (Kaiser, 2013) (Fig 2.4, Fig. 2.5). The Hartland Shale is assumed to be strictly a source interval while the Bridge Creek and Lincoln members are thought to be self-sourced reservoir intervals (Kaiser, 2013). Total organic content (TOC) concentrations are relatively high (>2 wt. %) in the Greenhorn Formation, except in several carbonate-rich chalk and marl intervals of the Bridge Creek and Lincoln Limestone members.

The Lincoln Limestone is the basal member of the Greenhorn Formation and conformably overlies the X-Bentonite and Graneros Shale. The top of the Lincoln is harder to locate, but can sometimes be correlated based on a slight decrease in gamma ray response (Fig. 2.5). This member is relatively homogeneous in isopach thickness, ranging 70 to 90 feet throughout Wattenberg (Kaiser, 2013). The Lincoln Limestone member exhibits sufficient thickness for producing hydrocarbons throughout the Wattenberg area (Kaiser, 2013). Finely laminated, organic-rich, calcareous shales and marls with interbedded carbonate rich chalk beds comprise the Lincoln Limestone (Kaiser, 2013). Three distinct facies exist within the Lincoln (Kauffman, 1977). The first is a clean, light grey calcarenite with little quartz and clay, representing offshore, deepwater
Figure 2.4. Type log for Late Cretaceous units in the Greater Wattenberg Area. Gamma-ray response is shown in Track 1 using a color bar to represent varying lithologies. Sandstones and limestones have relatively low gamma-ray readings (yellow and blue colors); whereas the shales have higher gamma-ray readings (gray to black colors). Track 2 is induction-log resistivity (red shading is where resistivity is greater than 15ohm-m); Track 3 is neutron and density porosity.
active currents (Kauffman, 1977). The second is a dark, calcareous clay shale and chalky clay shale representing offshore conditions in quiescent water (Kauffman, 1977). The third facies composes the upper Lincoln and Hartland Shale and consists of olive to medium grey chalky shales and shaly chucks that are evenly bedded. Variable bioturbation with fecal pellets and some limestone concretions imply offshore quiet water conditions near the edge of clay transport (Kauffman, 1977). Localities in the deeper part of the Denver Basin have favorable low gamma ray and high resistivity log responses for hydrocarbon production, but deep resistivity is suppressed by the abundance of conductive clays in the Lincoln Limestone (Kaiser, 2013).

The Hartland Shale Member consists mainly of laminated to micro-burrowed, organic-rich marl and calcareous shale. It is composed of the same facies as the upper Lincoln, described above, but is relatively homogeneous compared to the interbedded nature of the other Greenhorn units (Kauffman, 1977; Kaiser, 2013) (Fig. 2.5). The Hartland Shale was deposited in a relatively stable,
benthic environment with gradual sedimentation (Pratt, 1984). This member shows TOC values of 2 to 4 wt. %, predominately Type II marine kerogen, and is a probable source bed for the Bridge Creek and Lincoln Limestone members (Pratt, 1984) (Fig. 2.5). The Hartland Shale Member exhibits similar TOC trends to the Graneros Formation. TOC values are lowest near the basin axis because of increased thermal maturity due to burial that causes degradation of kerogen into hydrocarbons, indicating petroleum accumulations (Kaiser, 2013). The Hartland Shale shows the greatest variance in thickness throughout Wattenberg, from less than 40 feet thick in outcrops along the Front Range to over 90 feet in Morgan County, CO (Kaiser, 2013).

The Bridge Creek Limestone contains bioturbated, thickly-bedded, relatively pure pelagic and chalky limestone facies with resistant blocky weathering (Fig. 2.5). This member was deposited at maximum tectono-eustatic sea level rise and maximum regional extent of the Greenhorn Sea (Kauffman, 1977). These beds were deposited in offshore, gentle currents and quiet water anoxic sedimentation (Kauffman, 1977; Eicher, 1985). The Bridge Creek Member reaches over 70 ft thick in outcrop and contains fractured “rhythmically interbedded, fine-grained chalks with laminar organic-rich calcareous shales and marls” (Kaiser, 2013). Chalk intervals within the Bridge Creek Limestone are bioturbated with little sedimentary structures and are considered reservoir units. TOC values are less than 1 wt. % (Kaiser, 2013). The calcareous shale and marlstone facies are considered source rocks (TOC 4-5 wt. %). Chalks were deposited during transgressive phases with less clay whereas calcareous shale and marlstone facies were deposited during progradational phases with increased clay sedimentation (Elder et al., 1994). The contact with the overlying Carlile shale is gradational and is sometimes determined by the uppermost prominent limestone.

The Carlile Formation overlies the Greenhorn and contains the Fairport Chalk, Blue Hill Shale, and Codell Sandstone members. The Niobrara Formation overlies the Benton Group and consists of the A, B, and C Chalks and Marls and the Fort Hays Limestone.
Figure 2.6. Van Krevelin plot of hydrogen indices vs. oxygen indices for organic matter in Greenhorn Formation from PU-79-Pueblo core. Kerogen types I, II, and III are from Espitalie et al (1977).
2.1.4 Chalks and Marls

Chalks are very fine-grained carbonate sediment or rock composed primarily of calcareous nannofossils and/or microfossils (Scholle, 2015). Chalks are only found in Jurassic and younger strata and are dominant throughout the Cretaceous. Most chalks are composed of biogenic nannoplankton, mainly coccolithophores. Coccoliths range in size from 1-20 μm and nannofossil chalks have average grain size of <1 to 4 μm. Coccolithophores are unicellular photosynthetic organisms that live in the photic zone of ocean waters. Chalks are deposited through pelagic sedimentation in deep water basins. Grain size distribution depends on the breakdown of skeletal material and is polymodal. Chalks have a high chemical stability because they are typically comprised of low-Mg calcite. They are generally white to light grey in color. While chalk is known to be very soft, chalks can actually be found in various stages of lithification, from a soupy “ooze” with primary porosity up to 60-70% to a hardened limestone with very low porosity and permeability. Because of their soupy nature upon deposition, soft-sediment deformation is common within chalks. Original mineralogy, sedimentation and resedimentation, grain size and shape, diagenesis, and cementation are all factors controlling the porosity of chalks.

Deepwater carbonates vary on their associated chalk contents. Clastic content within a carbonate rock can have major implications on depositional environment. Thus, the chalk content of each facies of the members of the Greenhorn Formation can reveal a lot about the depositional history. Marl or chalky marls are fine-grained chalky limestones with 30-70% terrigenous clay or silt (Scholle, 2015). A carbonate rock with over 70% clay is considered a calcareous mudstone or shale. Furthermore, dominant allochems within each facies provide further insight to water depths and energies during deposition. This information was taken into account when describing facies seen in each core.

Chalk diagenesis begins shortly after deposition. Compaction and dewatering occur in the early stages of burial and initial high porosities of 60-70% are rapidly reduced. Porosity is also reduced through the precipitation of authigenic calcite replacement in coccoliths. Thus, porosity reduction in chalks is faster than in nearly all other carbonate rocks (Fig. 2.7).
Figure 2.7. Average porosity loss with depth for chalks, limestones, and dolomites. Porosity reduction in chalk occurs more rapidly in chalks than in any other carbonate rock. Chalks also generally have the highest primary porosities of all carbonate rocks (Scholle, 2015).

Chalks are geologically significant because they are key producers in both conventional and unconventional reservoirs. The Niobrara Formation is a chalk reservoir in the Denver basin that has produced large amounts of hydrocarbons in recent years. Porosity must be somewhat preserved in order to allow for hydrocarbon accumulation. Diagenesis and compaction is the main control on porosity preservation. Overpressure and hydrocarbon migration also play a role in limiting diagenetic effects. Porosity preservation depends on the timing of overpressure relative to burial depth, the timing of hydrocarbon entry relative to burial, and burial history. Hydrocarbons can also slow or stop diagenesis, so the timing of hydrocarbon charge is critical. Understanding the diagenetic history of chalks during burial can be crucial to evaluating a chalk play as an unconventional reservoir.
2.2 Greenhorn Petroleum Potential

Laterally extensive source and reservoir beds in close proximity to each other make oil and gas exploration in the Benton Group appealing. The Greenhorn-Graneros petroleum system contains reservoir units between thermally mature and organic rich source rocks (Fig. 2.8). The overlying Carlile Shale and underlying Graneros Formation provides a seal for the system. Within the study area, the Greenhorn Formation has been buried to depths that exceed 7,000 ft, which allow sufficient burial for hydrocarbon generation (Fig. 2.9). Both the Graneros and the Greenhorn Formations contain mature, organic-rich source rocks interbedded with potential reservoir units (Kaiser, 2013). Source rocks are overpressured to help charge unconventional reservoirs within the Greenhorn Petroleum system (Kaiser, 2013). Elevated levels of thermal maturity indicate that source rocks have reached the thermal maturation windows for hydrocarbon generation. The members of the Greenhorn Formation have sufficient thicknesses to produce hydrocarbons. Type I shows in the Graneros and Greenhorn Formations confirm the presence of hydrocarbons. These qualities suggest that the Greenhorn has petroleum potential and should be researched further as an unconventional reservoir.

![Diagram of Greenhorn-Graneros petroleum system](image)

Modified from Kaiser, 2012

**Figure 2.8.** Greenhorn-Graneros petroleum system. This system contains viable source rocks, reservoirs, and seals, as well as sufficient overburden from burial, to allow for hydrocarbon generation and storage.
Figure 2.9. Plot of geochemical analysis from samples collected from the Aristocrat Angus 12-8 core. The graph shows increase Tmax, or thermal maturation with depth and that all source rocks within the study interval has surpassed the oil-generation phase (Kaiser, 2013).
2.2.1 Source Rock Potential

This section summarizes the source rock potential analyses completed by Kaiser (2013). Geochemical analysis of oil samples taken by Clayton and Swetland (1980) concludes that Cretaceous oils from the Benton Group are chemically similar to each other and are likely the source for the J, D, Terry and Hygiene sandstones (Clayton and Swetland, 1980). While the effective source beds of the Benton Group are limited to the basin axis area, they exhibit excellent source bed capabilities (Clayton and Swetland, 1980). Geochemical analysis shows that predicted or log-derived TOC values reflect measured TOC values of samples taken from source rock intervals in the Greenhorn Formation (Kaiser, 2013). Source rock analysis (SRA) shows elevated levels of thermal maturation in the Greenhorn and Graneros Formations (Kaiser, 2013). All source rock samples within the Greenhorn Formation taken from the Encana Aristocrat Angus 12-8 indicate that source rocks have entered the wet- and dry-gas windows (Kaiser, 2013).

Because of the elevated levels of thermal maturation in Wattenberg Field, data points from traditional source rock analysis methods are shifted down and indicate that source rocks have poor potential to produce hydrocarbons (Kaiser, 2013) (Fig. 2.10). This data shift results from the fact that hydrocarbons have already been generated within Wattenberg Field. TOC plots as excellent, while $S_2$ values are suppressed due to elevated thermal maturation (Fig. 2.10). The data points plot in descending stratigraphic order, and deeper samples are more mature despite low $S_2$ values from the maturation effect. Source rock analysis using source rock analyzer pyrolysis on cuttings from the Greenhorn Formation indicates that the Hartland Shale Member is the best source rock in the Greenhorn Formation (Kaiser, 2013). However, because the Bridge Creek and the Lincoln are interbedded with organic-poor chalks, their source rock quality values are also likely to be suppressed in cuttings data. Thermal maturity, burial history, and TOC data from source rock analysis and log calculations are indicators that the Greenhorn Formation has undergone sufficient burial to the depths and temperatures necessary to generate hydrocarbons, but a comprehensive burial history model has not been completed.
Figure 2.10. Plot of geochemical data from samples collected from the Aristocrat Angus 12-8 core. Source rocks of the study interval plot as poor quality based on low S2 values caused by elevated thermal maturation. When the level of thermal maturity is taken into effect, these source rocks would plot as good to excellent (Kaiser, 2013).
2.2.2 Reservoir Potential

The Benton Group is historically recognized as a source rock. Despite being previously overlooked as a conventional reservoir, the Greenhorn Formation exhibits some notable reservoir characteristics. Isopach thickness, resistivity, and fracturing patterns contribute to the reservoir quality of the Greenhorn Formation. The Lincoln Member is considered to be the best reservoir horizon in Wattenberg (Kaiser, 2013). The Bridge Creek Limestone Member is also a reservoir unit, but has been overlooked as a potential target in much of the Denver Basin.

The Lincoln Limestone Member exhibits significantly lower resistivity values in Wattenberg than the Bridge Creek and the Niobrara, causing it to have been overlooked as a reservoir under traditional standards (Kaiser, 2013). Values increase with depth, causing several anomalies along the basin axis associated with oil-saturated fracture swarms with high thermal maturities (Kaiser, 2013). Kaiser (2013) suggests that low resistivity values in the Lincoln are the result of the thinly bedded nature of the interval and should not be overlooked. Hydrocarbon saturated intervals rarely appear on logs when they are interbedded with thin layers of conductive clay-rich marls (Kaiser, 2013). Based on his study, Kaiser (2013) determined that the western portion of the Greater Wattenberg Area is oil saturated, despite its low resistivity values.

Thickly bedded chalk intervals within the Lincoln Limestone Member of the Greenhorn Formation represent the first of two reservoir units (Kaiser, 2013). Although clay content in the Lincoln is relatively high, these zones contain slight porosity that can store hydrocarbons (Kaiser, 2013). Heavily fractured zones at the base of the Lincoln Limestone allow hydrocarbons to migrate between the Lincoln Limestone and the Graneros Shale (Kaiser, 2013). The presence of shear fractures in the Lincoln and upper Graneros could explain the shows in these intervals. Type I shows indicate the presence of hydrocarbons, which are likely stored in the tight matrix of interbedded chalk and marl facies (Kaiser, 2013). Because of its natural fractures and close proximity to thermally-mature, organic-rich source rocks, the Lincoln has previously been considered to be the better of the two Greenhorn reservoir units and could be successful as a horizontal target (Kaiser, 2013).
The chalk units of the Bridge Creek Limestone Member create a second reservoir unit for the Greenhorn Formation (Kaiser, 2013). Cyclic couplets of thin, limey chalk followed by bedded chalk ending with organic-rich marl make up very fine-grained, massive, carbonate-rich reservoir beds (Kaiser, 2013). The Bridge Creek Limestone contains fewer fractures than the Lincoln Limestone, despite it being the most brittle unit in the Greenhorn Formation (Kaiser, 2013). However, the Bridge Creek Member of the Greenhorn exhibits similar characteristics to the chalks in the Niobrara on the basis of petrophysical, XRF Elemental and geomechanical data. The Niobrara chalk beds are productive intervals in the Denver Basin. Further analysis of XRF elemental, petrophysical and geomechanical properties of these units will strengthen the understanding of the reservoir characteristics of the Bridge Creek Member of the Greenhorn Formation.
CHAPTER 3

FACIES ANALYSIS

Detailed core, petrographic, and FE-SEM analyses were conducted on the SM Patriot 1-19H, Noble Aristocrat PC H11-07, Encana Aristocrat-Angus 12-8, USGS 1 Portland, and Amoco Production Rebecca K. Bounds cores. Each analysis method corresponds to a particular scale of heterogeneity (member, bedset, lamination, and microscale). Use of these methods will further enhance understanding of the facies within the Greenhorn Formation at different scales of heterogeneity.

Descriptions of the SM Patriot 1-19H, Noble Aristocrat PC H11-07, Encana Aristocrat-Angus 12-8, USGS 1 Portland and Amoco Production Rebecca K. Bounds cores were used to evaluate the facies of each of the three Greenhorn Members at bedset and lamination scales (Fig. 3.1). Twelve facies, including eight main facies and seven sub-facies, have been identified in the Greenhorn Formation throughout the different analyses (Table 3.1). Descriptions of the USGS 1 Portland, Amoco Production Rebecca K. Bounds, and Encana Aristocrat-Angus 12-8 cores confirm the facies of the members of the Greenhorn Formation that have already been published. These facies include two distinct chalk and marl facies in the Bridge Creek Member, one homogeneous mudstone facies in the Hartland Member, and two interbedded chalk and mudstone facies in the Lincoln Limestone. Furthermore, these core descriptions confirm the presence of three separate Greenhorn Members, divided on the basis of physical appearance. Certain facies appear to be unique to each member of the Greenhorn Formation in the Noble Aristocrat PC H11-07.

Facies within each of the Greenhorn members exhibit variations in sedimentary structures, depositional energy, clastic content, major allochems and trace fossils, biodiversity and abundance, bioturbation, and fracture content. Extreme variations among facies were not common and therefore the main distinguishing factors between each facies is the ratio of carbonate to clay content, sedimentary structures, and associated dominant allochems. Intervals that are predominantly fine-grained carbonate sediment or rock, composed principally of calcareous nannofossils and/or microfossils are considered chalks (Scholle, 1977). Marls are intervals that have elevated clay content. Because of the cyclic nature of the Greenhorn Formation, changes from
Figure 3.1. Transect of cores used in core description from the SM Energy Patriot 1-19H well in Silo Field in the north to Noble Aristocrat H11-07 in Wattenberg to USGS 1 Portland in the south. The Greenhorn Formation thickens significantly from north to south and this change is represented by the change in facies seen in core.
<table>
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<th>* Sub-Facies name</th>
<th>Dunham name</th>
<th>Description</th>
<th>Rel. Depo.</th>
<th>Energy</th>
<th>Major allochems</th>
<th>Bio diversity</th>
<th>Abundance</th>
<th>Trace fossils</th>
<th>Bioturb. %</th>
<th>TOC %</th>
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<td>High?</td>
<td>Foraminifera, Coccoliths</td>
<td>Low</td>
<td>High?</td>
<td>Planktonic Forams, Fecal pellets</td>
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<td>&lt;5%</td>
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<td>Bioturb. Fossil-dom Marly Chalk</td>
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<td>High</td>
<td>High</td>
<td>Foraminifera, Oysters, Coccoliths</td>
<td>High</td>
<td>High</td>
<td>Planktonic Forams</td>
<td>High</td>
<td>Low</td>
<td></td>
<td>BCS2: recrystallized coccoliths, clay laminations, not as recrystallized as BCS1, more forams, more clay, compacted chalk, smaller coccoliths</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Bridge Creek</td>
<td>Chalky Marly</td>
<td>3</td>
<td>Laminated Fossil rich marl</td>
<td>Foraminifera-rich wackestone; Forams concentrated in laminae, parallel lam, ripples</td>
<td>Moderate</td>
<td>High</td>
<td>Foraminifera, Oysters, Coccoliths</td>
<td>Moderate</td>
<td>High</td>
<td>Planktonic Forams, Fecal pellets</td>
<td>Low</td>
<td>Low</td>
<td>Mod</td>
<td>BCS3: same stuff but More clay, smaller coccoliths, more fragments less intact</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Bridge Creek</td>
<td>Marly</td>
<td>4</td>
<td>Laminated foraminforic marl</td>
<td>Foraminifera-rich mudstone; Forams concentrated in Laminae, parallel lam, ripples</td>
<td>Low</td>
<td>High</td>
<td>Foraminifera, Oysters, Coccoliths</td>
<td>Low</td>
<td>Low</td>
<td>Planktonic Forams, Fecal pellets</td>
<td>High</td>
<td>Low</td>
<td>4-5%</td>
<td>BCS4: Crushed coccoliths, clay flakes, not as recrystallized, pyrite</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Bridge Creek</td>
<td>Mudstone</td>
<td>5</td>
<td>Homogeneous Mudstone</td>
<td>Starved foraminifera white specks less visible except when concentrated on laminae, graded beds (turbidites), fractured</td>
<td>Low</td>
<td>Low</td>
<td>Foraminifera</td>
<td>Low</td>
<td>Low</td>
<td>Inoceramus, Foraminifera, Coccoliths</td>
<td>Low</td>
<td>Low</td>
<td>4-5%</td>
<td>M513: Clay partings, wavy looking stuff, not as much calcite/montmorillonite, more clay, Crushed coccoliths L512: (Mudstone) Coccoliths-Forams. Pyrite frambooids. Forams, but not the same kind as hartland?, more clay (crushed, not flakes). Calciospheres, crushed</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Bridge Creek</td>
<td>Mudstone</td>
<td>5a</td>
<td>Homogeneous Mudstone</td>
<td>Starved foraminifera white specks less visible except when concentrated on laminae, graded beds (turbidites), fractured</td>
<td>Low</td>
<td>Low</td>
<td>Foraminifera</td>
<td>Low</td>
<td>Low</td>
<td>Inoceramus, Foraminifera, Coccoliths</td>
<td>Low</td>
<td>Low</td>
<td></td>
<td>M512: More clay, quartz and pyrite. Clay, coccoliths, forams, pocked grains, pyrite frambooids, coccolith fragments, less clay than lincoln? Forams in laminations</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>All</td>
<td>Mudstone</td>
<td>5b</td>
<td>Laminated Mudstone</td>
<td>Foraminifera concentrated in laminae, parallel lam, ripples, turbidites</td>
<td>Low</td>
<td>Low</td>
<td>Foraminifera, Coccoliths</td>
<td>Low</td>
<td>Low</td>
<td>Planktonic Forams, Fecal pellets</td>
<td>Low</td>
<td>Low</td>
<td></td>
<td>L516 and L517: Foram packstone (chalk) Rougher surface than other samples, crushed chalk, crushed forams, coccoliths? (crushed), interparticle porosity in forams, calcite matrix, recrystallization</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>All</td>
<td>Mudstone</td>
<td>5c</td>
<td>Fossil-rich Laminated Mudstone</td>
<td>Foraminifera in laminae, parallel lam, ripples, curved laminations</td>
<td>Moderate</td>
<td>High</td>
<td>Foraminifera, Coccoliths</td>
<td>Moderate</td>
<td>High</td>
<td>Planktonic Forams, Fecal pellets</td>
<td>Low</td>
<td>Low</td>
<td></td>
<td>L512: More clay, quartz and pyrite. Clay, coccoliths, forams, pocked grains, pyrite frambooids, coccolith fragments, less clay than lincoln? Forams in laminations</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Hartland</td>
<td>Laminated Calcareous Mudstone with Foram Packstone/Grainstone interbeds</td>
<td>6</td>
<td>Laminated Calcareous Mudstone with Foram Packstone/Grainstone interbeds</td>
<td>Foraminifera concentrated in laminae, tightly packed, microbrowsing, ripples, parallel laminations, forams, tight, calcite matrix, recrystallization</td>
<td>Low</td>
<td>Varies</td>
<td>Foraminifera</td>
<td>varies</td>
<td>Low</td>
<td>Planktonic Forams</td>
<td>Varies</td>
<td>Low</td>
<td></td>
<td>L516 and L517: Foram packstone (chalk) Rougher surface than other samples, crushed chalk, crushed forams, coccoliths? (crushed), interparticle porosity in forams, calcite matrix, recrystallization</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Lincoln</td>
<td>Laminated Calcareous Mudstone with Foram Packstone/Grainstone interbeds</td>
<td>7</td>
<td>Laminated Calcareous Mudstone with Foram Packstone/Grainstone interbeds</td>
<td>Foraminifera concentrated in laminae, tightly packed, microbrowsing, ripples, parallel laminations, forams, tight, calcite matrix, recrystallization</td>
<td>Low</td>
<td>High</td>
<td>Foraminifera</td>
<td>High</td>
<td>Low</td>
<td>Planktonic Forams, Fecal pellets</td>
<td>High</td>
<td>Mod</td>
<td></td>
<td>L516 and L517: Foram packstone (chalk) Rougher surface than other samples, crushed chalk, crushed forams, coccoliths? (crushed), interparticle porosity in forams, calcite matrix, recrystallization</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Lincoln</td>
<td>Foram Packstone to Grainstone</td>
<td>8</td>
<td>Foram-packstone to Grainstone</td>
<td>Foraminifera concentrated in laminae, tightly packed, microbrowsing, ripples, parallel laminations, forams, tight, calcite matrix, recrystallization</td>
<td>Low</td>
<td>High</td>
<td>Foraminifera</td>
<td>High</td>
<td>Low</td>
<td>Planktonic Forams, Fecal pellets</td>
<td>High</td>
<td>Mod</td>
<td></td>
<td>L516 and L517: Foram packstone (chalk) Rougher surface than other samples, crushed chalk, crushed forams, coccoliths? (crushed), interparticle porosity in forams, calcite matrix, recrystallization</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>All</td>
<td>Bentonite</td>
<td>9</td>
<td>Bentontite layers 1/2&quot; to 6&quot; thick interspersed with various facies</td>
<td>Bentontite layers 1/2&quot; to 6&quot; thick interspersed with various facies</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>
chalk to marl occur over small intervals and are easy to distinguish based on color. In that regard, a grayscale has been created to recognize chalks and marls in the Niobrara Formation (ElGhonimy, 2015). This grayscale has been modified to apply to members of the Greenhorn Formation. This grayscale method is an easy way to distinguish facies on the basis of physical appearance at bedset and lamination scale. For example, Figure 3.2 shows the full Rebecca K Bounds core. The limestone/marlstone couplets within the Bridge Creek Formation are easily comparable relative to the rocks of the Hartland shale, which are more homogeneous.

Figure 3.2. Photograph of the full Rebecca K Bounds core. Limestone and Marlstone couplets are seen as color variations throughout the core.
Petrographic thin sections of the SM Patriot 1-19H, Noble Aristocrat PC H11-07, USGS 1 Portland and Amoco Production Rebecca K. Bounds enhanced facies descriptions at lamination scale. The Patriot and Aristocrat cores provided thin section samples of each facies present throughout the entire core, while the Portland and Rebecca Bounds cores only had thin sections from the facies in the Hartland and Lincoln Members. Thus, the Aristocrat core was the only core with samples of the Bridge Creek chalk and marl facies. Samples of facies that differ on the basis of fossil content are identifiable in thin section analysis. Samples of facies that differ on the basis of sedimentary structures were less discernable in thin section, and have been grouped under their corresponding main facies. Thin sections exhibit similar facies to what is seen in core. FE-SEM imagery of samples from the Noble Aristocrat PC H11-07H core enhanced the facies descriptions at microscales. Heterogeneity of the Greenhorn sub-facies cannot be seen at microscopic scales in FE-SEM. Thus, sub-facies can be described collectively under the main dominant facies.

3.1 Facies Descriptions

3.1.1 Facies 1: Bioturbated Coccolith-rich Chalk (Grainstone)

Chalk is a carbonate rock composed mainly of calcareous nannofossils such as foraminifera or coccoliths. This facies contains less than 5 wt. % clays or clastics, over 95% calcium carbonate, and low organic content. The chalk facies is a light grey to beige or white, coccolith-rich, bioturbated chalk or nannofossil limestone (Fig. 3.3a). Chalk beds, approximately 6-12 inches thick, are highly bioturbated and contain *Planolites* and *Thalassinoides* burrows (Fig. 3.3b).

Facies 1 appears as a recrystallized grainstone in thin section (Fig. 3.3c). Globigerinid multi-chambered, uniserial and biserial planktonic foraminifera, calcspheres, inoceramids, and oysters are common throughout the sample in random orientations (Fig. 3.3c-d). Foraminifera have been completely recrystallized (Fig. 3.3c). A large detrital echinoderm plate with honeycomb micro-texture and syntaxial overgrowth cement shows unit extinction under crossed polars (Fig. 3.3d). Porosity is low under epifluorescent lighting.

FE-SEM confirmed the presence of compacted coccolith-rich chalk that has been completely recrystallized (Fig. 3.3e). Coccoliths are the dominant allochem and have a high abundance in this facies. Complete calcite recrystallization of the matrix and dominant allochems
can be seen in this sample. Whole and broken coccolith spines and plates are abundant throughout the sample (Fig. 3.3f). The abundance of coccolith fragments, as opposed to intact coccolithophores, can be attributed to the bioturbated nature of the coccolith-rich chalk. Two different types of planktonic foraminifera are present within the bioturbated chalk facies (Fig. 3.4). Small foraminifera on the order of 10µm exhibit intraparticle porosity (Fig. 3.4a). Larger foraminifera on the order of 50µm have been completely recrystallized or replaced with equant calcite cement, and prismatic calcite burial cement has precipitated along grain boundaries (Fig. 3.4b). Foraminifera are also present with internally precipitated (i.e., diagenetic) euhedral sparry calcite rhombs on the order of 20µm (Fig. 3.4c).

3.1.2 Facies 2: Marly chalk

Marly chalk is a carbonate-rich lithology containing higher clay content than found in chalks (up to 15 wt. % clay or clastic content, 85-95% calcium carbonate). Marls are generally ripple laminated and may be bioturbated. Two sub-facies are present within the Marly Chalk facies that can be determined in core on the basis of fossil content. Because this is bedset-scale heterogeneity on the basis of fossil content, these sub-facies cannot be determined in thin section or FE-SEM.

2a. Bioturbated Fossiliferous Marly Chalk: Facies 2a is a light grey, bioturbated, fossiliferous marly chalk. Small inoceramid fragments in random orientations along ripple laminated beds characterize this unit in core (Fig. 3.5a).

2b. Laminated Fossiliferous Marly Chalk: Facies 2b is a grey laminated fossiliferous marly chalk (Fig. 3.5b). This facies is similar to facies 2a but is laminated instead of bioturbated. This facies contains large inoceramid fragments, chalk interbeds, ripples, drapes, and scour and fill features with carbonate lenses. These marly chalk facies represent the first introduction of marl into the chalk-dominated facies, and typically exists as a condensed facies representing a transition between facies 1 and 3. This facies is rarely seen as an interval thicker than a few inches in core.
Figure 3.3. Facies 1 (Chalk) in the Noble Aristocrat H11-07 core. (a) Core photograph of light grey to white bioturbated chalk or nannofossil limestone from depth 7163 ft. (b) Core photograph of large *Planolites* and *Thalassinoides* burrows in the bioturbated chalk facies from depth 7183 ft. (c) Facies 1 (chalk grainstone) thin section photomicrograph from the Noble Aristocrat H11-07 core. Recrystallized multi-chambered Globigerinid foraminifera in sparry calcite matrix. (d) Thin section photomicrograph of recrystallized uniserial and biserial planktonic foraminifera. A large detrital echinoderm plate with honeycomb micro-texture and syntaxial overgrowth cement shows unit extinction under crossed polars. (e) FE-SEM micrograph of compacted coccolith chalk matrix that has been recrystallized. (f) FE-SEM micrograph of an abundance of coccolith fragments. This is the result of the bioturbated nature of this chalk facies.
Figure 3.4. FE-SEM micrographs of foraminifera present in Facies 1 (chalk). (a) Small foraminifera on the order of 10µm exhibit intraparticle porosity. (b) Larger foraminifera on the order of 50µm have been completely recrystallized or replaced with equant calcite cement, and prismatic calcite burial cement has precipitated along grain boundaries. (c) Foraminifera with euhedral sparry calcite rhombs on the order of 50µm.
In thin section, the fossiliferous marly chalks appear as skeletal wackestone to packstone (Fig 3.5c). This facies contains predominantly carbonate material and a high abundance of globigerinid foraminifera, and intact and disaggregated inoceramid and oyster fragments in random orientations (Fig. 3.5d). Unlike the chalk facies, this facies contains a higher abundance of micrite mud in its matrix. Some clastic and organic material is present in the matrix.

FE-SEM imagery shows that coccolith fragments, spines, and plates are dominant components of this sample (Fig. 3.5e). This facies still showed recrystallized coccoliths and coccolith fragments. An increase in the abundance of clay flakes is seen in this facies (Fig. 3.5f). This sample still showed recrystallized calcite, but was not as recrystallized as the chalk sample. Recrystallized foraminifera are present with recrystallized calcite, and euhedral sparry calcite rhombs are present in the same specimen (Fig. 3.6).

### 3.1.3 Facies 3: Chalky marl

The third facies consists of a grey foraminifera-rich chalky marl (Fig. 3.7a). This facies contains foraminifera concentrated in laminae, and microburrowing, also known as cryptic bioturbation, along laminae. The major allochems in this facies are predominantly planktonic forams, coccoliths, and fecal pellets. Biodiversity is relatively low, while abundance of these allochems remains high. Bioturbation is moderate compared to other facies. Clay/clastic content up to 20 wt. %, with carbonate content is less than 70 wt. %. Chalky marls are ripple laminated or bioturbated. Chalky marl and marly chalk lithologies are difficult to discern without a grey scale chart and XRD data.

The chalky marl facies is hard to distinguish from the marly chalk facies in thin section but appears as a skeletal wackestone with more apparent laminations (Fig. 3.7b). The main difference is the lack of large inoceramid fragments. Globigerinid foraminifera clusters are still present. Additionally, the interaction between carbonate and clastic material can be seen within laminae as cross-bedding (Fig. 3.7c). Compaction of clastic material around a large carbonate grain can be seen (Fig. 3.7d). Quartz silt grains exhibit unit extinction under crossed polars and indicate that clastic content is increasing.
Figure 3.5. Facies 2 (marly chalk) in the Noble Aristocrat H11-07 core. (a) Core photograph of facies 2a: bioturbated fossil-rich marly chalk from depth 7162.4 ft (b) Core photograph of facies 2b: Laminated fossil-rich marly chalk from depth 7163 ft (c) Facies 2 (Fossil-rich marly chalk) thin section photomicrograph showing skeletal wackestone to packstone with inoceramids, oysters, foraminifera, and other skeletal fragments in a micrite mud matrix. (d) Thin section photomicrograph showing disaggregated inoceramid shells and large oyster fragments. Oysters, calcispheres, foraminifera, and pelecypod fragments are present surrounding large grains. Recrystallized pelecypod wall structure preserved. (e) FE-SEM micrographs showing an intact coccolith with clay drapes. (f) FE-SEM micrograph showing calcite and clay with pyrite frambooid molds.
Figure 3.6. FE-SEM micrographs of foraminifera present in Facies 2 (marly chalk). (a) Recrystallized foraminifera in calcite and clay matrix. (b) Recrystallized foraminifera with unique diagenetic character. Recrystallized prismatic sparry rind with both euhedral and rhombic intraparticle calcite cements.
Figure 3.7. Facies 3 (chalky marl) in the Noble Aristocrat H11-07. (a) Core photograph showing foraminifera concentrated in laminae, starved ripples and micro-burrowing. (b) Thin section micrographs from showing skeletal wackestone in micrite mud matrix. (c) Cross-bedding showing laminated chalky marl facies against fossil-rich marly chalk. (d) Mechanical compaction and alignment of clays around an inoceramid fragment. (e) FE-SEM micrographs of Facies 3 (chalky marl). This facies shows a higher abundance of clay than the facies 1 and 2.
FE-SEM imagery reveals the same dominant allochems as the previous chalk and marly chalk facies, but contains a higher abundance of clay (Fig. 3.7e). Coccolith fragments are still present but are less intact or are harder to find because of increased clay content. Recrystallization is lower than in previous samples and is likely the result of increased clay content.

3.1.4 Facies 4: Marl

Facies 4 exhibits elevated clastic content, reaching up to 30 wt. %. It is dark grey to black in appearance, and is planar- or ripple- laminated with occasional foraminifera in laminae. The marl facies also appears as a skeletal wackestone, but contains a higher abundance of organic matter and clastic material such as silt. Two sub-facies are identifiable in core and in thin section:

4a. Laminated foraminifera-rich marl: Facies 4a consists of dark grey laminated foraminifera-rich marl (Fig. 3.8a). This facies contains foraminifera concentrated in laminae, parallel laminations, carbonate lenses, and ripples. Major allochems consist of planktonic foraminifera, coccoliths, inoceramid fragments, and fecal pellets. Biodiversity is moderate, faunal abundance is high, but bioturbation is low in this unit. This facies contains 4-5 wt. % TOC and is one of two marl facies that make up the source bed facies that Kaiser (2013) described. The laminated marl facies is identifiable in thin section where inoceramids, foraminifera, and other fossil fragments are oriented along parallel laminations (Fig. 3.8b). Clay, organic matter, and other clastic material are present along laminations (Fig. 3.8c). Some laminations have been dolomitized (Fig. 3.8d-e).

4b. Bioturbated Marl The second marl facies is similar to facies 4a but is characterized by its lack of allochem biodiversity and abundance, and also by lenticular beds and microburrowing along laminae (Fig. 3.9). Foraminifera are still the dominant allochem but exist in a much lower abundance than in the other facies. Unlike the laminated marl, allochems are randomly dispersed throughout the matrix in thin section (Fig. 3.9b). Burrows are present and appear as color differences in thin section (Fig. 3.9c-e). This facies contains recrystallized and mud-filled foraminifera, oysters, echinoderms and inoceramid fragments in thin section (Fig. 3.9d-e). Parallel laminations are less apparent.
Figure 3.8. Facies 4a (Laminated marl) in the Noble Aristocrat H11-07 core. (a) Core photograph showing forams concentrated in laminae, ripples, and carbonate lenses. (b) Thin section photomicrograph showing laminations of inoceramid fragments, foraminifera, silt, and organic matter. (c) Recrystallized foraminifera amongst organic matter, silt and clay laminations. (d) Recrystallized and dolomitized skeletal grainstone laminations amongst mud matrix. (e) Rhombic dolomite in recrystallized skeletal grainstone lamination. Dolomite does not stain red with Alizarin Red S dye.
Figure 3.9. Facies 4b (Bioturbated marl) (a) Core photograph from depth 7168 ft. The main difference between facies 4a and facies 4b is the apparent abundance of foraminifera within ripple-laminated and lenticular beds. (b) Thin section photomicrograph showing skeletal wackestone with mud matrix. Recrystallized multi-chambered foraminifera are present throughout. (c) Interaction between carbonate and clastic material (mudstone) shown as color differences. (d) Mud-filled foraminifera and echinoderm fragment amongst other skeletal grains. (e) Skeletal grains between laminations. Contact between different colored facies. Marl facies is lighter colored, mudstone facies is darker colored and has higher volumes of organic matter and clay.
According to FE-SEM observations, this facies contains crushed coccoliths and has more clay than in the previous facies (Fig. 3.10a). Pyrite frambooids are common within clay-dominated portions of the sample (Fig. 3.10b). This facies is significantly less recrystallized than the previous samples, whereas clay content has significantly increased. Thus, recrystallization decreases with increased clay content as the Bridge Creek facies shift from chalk to marl.

3.1.5. Facies 5: Pelleted Calcareous Mudstone

Calcareous mudstone contains clay content greater than 30 wt. %, but still maintains some carbonate content. This facies is dark grey to black in appearance, and is planar- or ripple-laminated. This facies is relatively homogeneous compared to the interbedded nature of the other Greenhorn units. Mudstone makes up the Hartland Member in all cores, but it is also present in other members. TOC values are between 2 to 4 wt. %. The main difference between mudstone sub-facies exists on the basis of fossil content. These facies appear in thin section as skeletal mudstones with low faunal abundance. Pellets are abundant in all subfacies.

5a. Homogeneous Mudstone: Facies 5a is a dark grey to black homogeneous mudstone with low allochem content and sedimentary structures (Fig. 3.11a-b). The mudstone appears homogeneous in core, but shows a laminated micrite matrix with organic matter, silt, clay, compacted fecal pellets, and foraminifera along laminae in thin section (Fig. 3.11c-d). Collapsed kaolinite-filled globigerinid foraminifera and ellipsoid fecal pellets with long axes parallel to bedding indicate burial compaction (Fig. 3.11d).

5b. Foraminifera-rich Laminated Mudstone: Facies 5b is a dark grey to black laminated calcareous mudstone (Fig. 3.12a-b). This facies exhibits starved ripples, laminations, foraminifera concentrated in laminae, and graded beds in turbidites. Clastic content is higher than in the other facies, giving it the mudstone name. Planktonic forams, coccoliths, and fecal pellets are present in this facies. Bioturbation is relatively low. In thin section, the laminated mudstone facies consists of an organic-rich mudstone with pellets and foraminifera concentrated in laminae (Fig 3.12c-d).
Figure 3.10. FE-SEM photomicrographs of Facies 4 (marl). (a) Clay flakes and coccoliths. (b) Pyrite framboid with platy clays.
Figure 3.11. Calcareous mudstone facies 5a (Homogeneous mudstone). (a) Core photograph of dark grey homogeneous mudstone. (b) Core photograph of black homogeneous mudstone. (c) Thin section micrographs from the SM Patriot 1-19H core showing large carbonate skeletal grains are absent. (d) Organic matter, mud, and clay along laminations.
Figure 3.12. Calcareous mudstone facies 5b (Foraminifera-rich laminated mudstone). (a) Core photograph from Noble Aristocrat H11-07 showing white foraminifera specks along laminae. (b) Foraminifera-rich laminated mudstone in Rebecca K Bounds core. (c) Thin section micrograph showing forams, organic matter and compacted pellets concentrated in laminae from Noble Aristocrat H11-07 at depth 7249 ft. (d) Forams, organic matter and pellets concentrated in laminae from Rebecca K Bounds at depth 1000.5 ft. Pellets are significantly less compacted than in previous micrograph, but overall appearance is the same.
5c. *Fossiliferous Laminated Mudstone*: Facies 5c is exactly the same as 5b except with a higher biodiversity and abundance of inoceramids, bivalves, and oyster fragments (Fig. 3.13a-b). In this facies, inoceramid fragments can be seen in concave down positions, indicating low-energy bottom currents (Fig. 3.14). Facies 5c is the same as 5b in thin section, but has a higher concentration of foraminifera, inoceramids, fish bones, and other skeletal fragments (Fig. 3.13c-d).

**Figure 3.13.** Calcareous mudstone facies 5c (Fossil-rich laminated mudstone). (a) Core photograph from Noble Aristocrat H11-07 showing graded beds, ripples, and a higher fossil abundance present than in other mudstone facies. (b) Core photograph from Encana Aristocrat-Angus 12-8 showing inoceramid fragments in concave down positions. (c) Thin section micrographs showing inoceramid with foraminifera concentrated in laminae. (d) Skeletal fragment indicating compaction in mudstone.
Heterogeneity of the mudstone sub-facies is not observable at microscopic scales in FE-SEM because facies differentiations are based mainly on large fossil content or sedimentary structures as opposed to microscopic characteristics. Because of this, the mudstone facies can be described as a single dominant facies in FE-SEM. All samples show similar characteristics: more clay flakes than calcite, quartz, pyrite frambooids, foraminifera, and a large abundance of coccoliths and coccolith fragments (Fig. 3.15). Samples display a higher percentage of clay flakes than is seen in the chalk, indicating clastic influx (Fig. 3.15). This is inferred to be clay concentration along laminae. Pyrite frambooids are present amongst clay flakes (Fig. 3.15d). Recrystallized foraminifera are present in this facies and exhibit euhedral sparry calcite rhombs and bladed calcite growing on the surface of pyrite frambooids within equant calcite (Fig. 3.16). This is a unique diagenetic feature that must be explored further. A higher abundance of coccoliths than foraminifera is characteristic of this unit, but coccoliths are concentrated in certain locations as opposed to throughout the facies as seen in the chalks (Fig. 3.17). These coccoliths are inferred to be along laminae as seen in core.
Figure 3.15. FE-SEM photomicrographs of Facies 5 (mudstone). (a) Authigenic clay flakes. (b) Mixed-layer illite smectite clay flakes. (c) Coccolith within clay. (d) Pyrite framboids within clay laminations.
Figure 3.16. FE-SEM photomicrographs of Facies 5 showing foraminifera diagenesis. (a) Recrystallized foraminifera exhibit euhedral sparry calcite rhombs and bladed calcite on pyrite framboids spheres within equant calcite. (b) Zoomed in micrograph showing difference between pyrite framboids and bladed calcite spheres in equant calcite cement.

Figure 3.17. FE-SEM micrographs of Facies 5 (mudstone). (a) Abundance of concentrated coccoliths. (b) Wheel-like appearance of abundant coccoliths.
3.1.6  Facies 6: Interbedded Mudstone and Grainstone

The sixth facies is a calcareous laminated mudstone with foraminifera-packstone to grainstone interbeds (Fig. 3.18). This is essentially a transition between facies 5 and facies 7. Foraminifera concentration has increased in laminations. This facies contains an elevated clastic content in the mudstone intervals with interbeds of facies L1 that are 1-10 mm thick. Microburrowing is seen within this facies (Fig. 3.18a-b). Graded beds with foraminifera concentrated in laminae are characteristic of this facies (Fig. 3.18a-e). Ripples, drapes, swaly laminations, and cross-bedding are also present in this facies (Fig. 3.18c-e). Ripples in this facies are not starved of carbonate material and thus represent a higher sediment supply of carbonate grains. Planktonic foraminifera, coccoliths, and fecal pellets are the major allochems, and bioturbation is variable.

Thin sections show laminated bands of mudstone and foraminifera-rich grainstone that are 3-6 mm thick. Foraminifera occur in high concentrations in this facies (Fig. 3.19a). Foraminifera are fully and partially recrystallized (Fig. 3.19b). The contact between grainstone and mudstone facies is apparent in thin section (Fig. 3.19c-d). Some foraminifera have been dolomitized (Fig. 3.19e). Large, multi-chambered, kaolinite-filled foraminifera indicates diagenesis (Fig. 3.19e-f). This transition facies was not analyzed in FE-SEM simply because it consists of interbeds of facies 5 and 7 and therefore differences in this facies will not be distinguishable on a microscale.

3.1.7  Facies 7: Foraminifera-rich Grainstone

Facies 7 is a light grey, laminated foraminifera-rich packstone to grainstone or chalk (Fig. 3.20a). This facies exhibits tightly packed forams concentrated in its laminae, as well as microburrowing, ripples, and parallel laminations (Fig. 3.20a-c). Clastic content is low. Scours are common at the base of this facies, indicating higher energy than the previously described facies (Fig. 3.20b). Planktonic foraminifera are the dominant allochem in this facies. Biodiversity is low, but abundance of foraminifera is high. Bioturbation is moderate but is predominantly microburrowing along laminae and therefore laminae are still intact (Fig. 3.20c). Graded beds are characteristic of this facies (Fig. 3.20c).
Figure 3.18. Facies 6 (Interbedded mudstone and grainstone). Laminated mudstone with foraminifera-rich packstone/grainstone interbeds. Interaction between Facies 5 and Facies 7 (a) Microburrowing in packstone interbeds. (b) Scours, ripples and foraminifera concentrated in laminae. (c) Scoured surface and cross bedding with stacked ripples and abundant mud drapes. (d) Stacked ripples and cross bedding. (e) Graded beds. (f) Ripples in interbedded foraminifera packstone layer that has been pyritized.
Figure 3.19. Facies 6 (interbedded mudstone and grainstone) thin section photomicrographs from the Noble Aristocrat H11-07 core from various depths. (a) Concentrated foraminifera. (b) Fully and partially recrystallized globigerinid foraminifera. (c) Contact between high concentrations of foraminifera and mudstone facies. (d) Cross bedding between grainstone and mudstone facies. (e) Dolomitized foraminifera within interbedded grainstone. (f) Kaolinite-filled foraminifera near mudstone-grainstone contact.
The foraminifera-rich grainstone facies also appears as a skeletal grainstone in thin section (Fig. 3.20d). Thin sections show highly concentrated foraminifera concentrated into laminated bands, with some organic matter between grains (Fig. 3.20e). Foraminifera are all similar sizes and shapes. Broken inoceramid shells are present with organic matter staining (Fig. 3.20f). Skeletal grains are cemented in a drusy mosaic of equant sparry calcite matrix (Fig. 3.20f). Pyrite and mud exist between some of the grains. Silt is also present (Fig. 3.20g).

FE-SEM images of this facies show intact and recrystallized foraminifera in a recrystallized calcite matrix (Fig. 3.20h). Because of this, the sample was analyzed at multiple scales: around 50-200 µm for foraminifera observation (Fig. 3.21), and around 5-20 µm for coccoliths and recrystallization (Fig. 3.22). Concavo-convex contacts and calcite burial cements are present along grain boundaries (Fig. 3.21b). Round, recrystallized foraminifera exhibit effects of burial diagenesis (Fig. 3.21c). Recrystallization of prismatic spar along foraminifera grain boundaries is commonly present (Fig. 3.21d). These layers reflect the paragenesis of this facies, beginning with the initial internal recrystallization of the foraminifera, followed by the deposition of clay and coccoliths along the grain boundary (Fig 3.22a-d). Burial diagenesis resulted in compaction of clay, coccoliths, and foraminifera. Diagenesis also resulted in recrystallization of the foraminiferal rind and recrystallization of the matrix into equant sparry calcite cement.

3.1.8 Bentonite

Altered volcanic ash beds (bentonites) range in color from white to green (Fig. 3.23a-c). They are commonly pyritized (Fig. 3.23b). Thickness ranges from ½ to 6 inches thick, with the exception of the X-Bentonite at the base of the Lincoln Member, which is 6-10 inches depending on the core (Fig. 3.23c).

3.2 Fractures

Sub-vertical fractures exist within the Hartland and Lincoln members of the Noble Aristocrat PC H11-07 core and throughout the SM Patriot 1-19H core (Fig. 3.24). Sub vertical fractures have calcite cement, indicating that they occurred before the core was taken. Most fractures in the Patriot core exist within the laminated mudstone facies, which is slightly more brittle than the homogeneous mudstone facies due to its higher carbonate content. In contrast,
Figure 3.20. Facies 7 (Foraminifera-rich packstone to grainstone or chalk). (a) Core photograph showing laminated character of foraminifera-rich grainstone or chalk. Microburrowing and laminations present. (b) Scour at base of in Foraminifera-rich grainstone facies contact with calcareous mudstone. (c) Reverse grading, laminations, microburrowing and scours. (d) Thin section photomicrographs from the Noble Aristocrat H11-07 core showing that facies 7 appears as a foraminiferal grainstone in thin section. (e) Skeletal grainstone with some mud and organic matter along laminations. (f) Broken inoceramid shells with organic staining in a drusy mosaic of equant sparry cement. (g) Pyrite and mud exist between some of the grains. Silt is also present. (h) FE-SEM photomicrograph of Facies 7 showing abundant foraminifera in recrystallized calcite matrix at 200µm scale.
Figure 3.21. FE-SEM photomicrographs of Facies 7 (Foraminifera-rich grainstone). (a) Abundant foraminifera in recrystallized calcite matrix at 200µm scale. (b) Concavo-convex contacts and calcite burial cements are present along grain boundaries. (c) Intact recrystallized foraminifera exhibit effects of burial diagenesis. Precipitation of burial cements along grain boundaries. (d) Layers on recrystallized foraminifera. Initial internal recrystallization of the foraminifera occurred first, followed by the deposition and compaction of clay and coccoliths along the grain boundary. Burial allowed for the recrystallization of the foraminiferal rind and also resulted in the recrystallization of the matrix into equant sparry calcite cement.
Figure 3.22. FE-SEM photomicrographs of Facies 7 at 5-10µm scale. (a) Foraminifera showing location of coccoliths along grain boundaries. (b) Coccolith fragments along foraminifera grains. (c) Coccoliths and clay at 10µm. (d) Coccoliths and clay at 5µm.
Figure 3.23. Bentonites. (a) 6 inch bentonite bed in the SM Patriot 1-19H core from depth 8638 ft. (b) Pyritized bentonite bed from the SM Patriot 1-19H core. (c) X-Bentonite at the base of the Lincoln Member at depth 568 ft from the USGS 1 Portland core.
fractures in the Wattenberg cores exist in the mudstone facies near the base of the Lincoln, which is the most ductile facies in that area. This implies that the mudstone facies are more prone to fracturing, despite having a higher clay content. However, the Greenhorn Formation is about 1000 ft deeper in the Patriot core than in the Wattenberg cores. This implies that fractures are more closely related to burial than to clay content. This implication will be explored further in the geomechanical evaluation later.

**Figure 3.24.** Fractures throughout the Greenhorn from various cores. (a) Calcified fracture swarms at the base of the Lincoln at 7630 ft from the Encana Aristocrat Angus 12-8 core. (b) 9-inch fracture at 8593 ft from the SM Patriot 1-19H. (c) Small 1-inch fracture from 8617 ft in the SM Patriot 1-19H core. (d) Calcified 9-inch fracture from depth 8644.7 ft in the SM Patriot 1-19H core.
3.3 Facies Interpretation and Discussion

The lamination-scale heterogeneity between facies depends mainly on its foraminifera to micrite and mud ratio. Globigerinid planktonic foraminifers are abundant throughout the Greenhorn Formation (Fox, 1954; Denne, 2016, personal communication). More carbonate-rich facies exhibit higher concentrations of foraminifera, whereas mudstone facies have higher concentrations of silt and organic matter. In addition, facies with higher carbonate content contain larger forams than facies with low carbonate content. Forams are generally recrystallized but are sometimes filled with micrite in the mudstone facies. The matrix consists mainly of nanofossil debris in the chalk and grainstone facies. As the facies change from chalk to mudstone, the relationship between carbonate and clastic material can be seen as compactional features, cross bedding, and interbedded laminations. The relationship between low energy pelagic sedimentation and higher energy wave action is crucial to understanding the complex depositional setting of the Greenhorn Formation.

Each of the facies identified represents a unique depositional environment with a particular energy associated with deposition. Each facies has been subdivided based on internal structure, fossil content, and bioturbation (Table 3.1). However, not all facies are distinct to each member as initially postulated. Instead, some facies are present only in certain members, while other facies can be found throughout the entire Greenhorn Formation. The identified facies represent a transition from chalk to marl to mudstone from both chalk end members (Facies 1 and Facies 7) (Fig. 3.25). Chalk intervals are carbonate rich and lighter in color, while marl and mudstone intervals are darker and contain higher percentages of clay and organic material when compared with XRD, XRF, SRA, and TOC data. Carbonate content is highest in Facies 1 and Facies 7, and decreases towards the mudstone facies. The alternate of this is that siliciclastic content is increasing as the facies change from the chalk end members into mudstone.

Biodiversity remains the same throughout the facies, and while overall abundance of allochems remains relatively high due to the pelagic nature of carbonate deposition, the abundance of each dominant allochem changes. The chalk facies consists almost entirely of coccoliths and foraminifera microfossils that have been compacted and crushed during burial. The main factors affecting biodiversity and abundance is the influx of clay and other clastic material.
Figure 3.25. Depositional model of the Greenhorn Formation. (a) Changes in carbonate and clastic content, TOC, energy, and depth from facies 1 to facies 7. (b) Depositional model as it relates to changes in facies. Planktonic foraminifera, coccoliths, copepods, algae and fecal pellets settle to the basin floor through pelagic sedimentation. Hyper- and hypo-pycnial flows from onshore rivers bring an abundance of clastic sediment and clay into the oceanic basin. Volcanic ash is also brought in through this method as well as carried by wind, and either settles as pelagic rain or within the hyper- and hypo-pycnial flows. (Base image borrowed from Sonnenberg, 2015).
Although facies 1 and facies 7 are both chalk grainstones, they are very different in depositional environments and energy (Fig. 3.25). Depositional energy increases and depth decreases from Facies 1 to Facies 7. Commonly, geologists interpret the darkest facies to mean greatest water depth, and lightest facies to represent shallowest. However, pelagic chalks are deep-water carbonates and therefore represent an environment that is deeper than that of the darker colored marls and mudstones. While both facies are technically chalks or microfossil limestones, Facies 1 is predominantly comprised of coccoliths, while Facies 7 consists mainly of foraminifera. Planktonic foraminifera, coccoliths, copepods, algae and fecal pellets settle to the basin floor through pelagic sedimentation (Fig. 3.25). Facies 1 is representative of deep water, low-energy pelagic sedimentation and can be referred to as a pelagic grainstone. Facies from this end of the spectrum (Facies 1-5) are considered rainstones because they form through “pelagic rain” (Pahnke, 2014). Thalassinoides and Planolites burrows further indicate that the chalks were deposited in a relatively low-energy environment. The presence of starved ripples and lenticular bedding in the marl facies confirms that energy is high enough to create ripples and carbonate is diluted in the marl facies.

In contrast, Facies 7 represents an allochthonous chalk grainstone. This end of the spectrum, facies 5-7, is representative of allochthonous chalks, from allomudstone to allograinstone, which form from the mass movement of chalks on the sea floor (Pahnke, 2014). These facies contain scours, wave and current ripples, turbidites, debris flows, graded beds, and cross-bedding, which indicate a higher energy flow regime environment related to carbonate sediment gravity flows associated with storm processes and currents. During a large storm, sediments on the shallow seafloor are disturbed and churned by oscillating storm wave action (Fig 3.25). Meanwhile, onshore flooding causes an abundance of clastic sediment and clay to be brought into the oceanic basin through hyper- and hypo-pycnal flows (Fig. 3.25). This results in an intermixing of clastic and carbonate sediment, as seen within facies 6. The features seen between facies 5 and 7, specifically wave and current ripples, combined-flow ripples, and scours, represent density induced flow as the result of storm wave action. These storm deposits are called tempestites (Myrow and Southard, 1996). Volcanic ash is also brought in through this method as well as carried by wind, and either settles as pelagic rain or within the hyper- and hypo-pycnal flows, which explains the presence of bentonites.
There is a vertical component to the suggested depositional model that reflects the control of sea level fluctuations and climate. Periods of stratified and mixed water columns explain benthic and redox cycles recorded in the Bridge Creek Limestone (Sageman et al., 1998) (Fig. 3.26).

**Figure 3.26.** Depositional model of chalks and marls. Periods of stratified and mixed water columns explain benthic and redox cycles. In both scenarios, surface waters remain nutrient rich, and allow for photosynthetic organisms to flourish. (a) The influx of clastic material from progradational phases, with increased clay sedimentation during wetter climates, accounts for a stratified column resulting in deposition of laminated calcareous mudstones and marls. (b) Arid conditions allow for deposition of the chalky limestones during transgressive phases with less clay resulting in vigorous vertical circulation of the water column.
In both scenarios, surface waters remain nutrient-rich and allow for photosynthetic organisms to flourish. The influx of clastic material in the form of hypopycnal flows from progradational phases with increased clay sedimentation during wetter climates accounts for a stratified column resulting in deposition of laminated calcareous mudstones and marls (Fig. 3.26a). In contrast, arid conditions allow for deposition of the chalky limestones during transgressive phases, with less clay resulting in vigorous vertical circulation of the water column (Fig. 3.26b). These climatic cycles reflect lithologies seen in the Greenhorn Formation.

The thin sections and FE-SEM images show evidence of burial cementation and diagenesis. Diagenesis decreases into more clay-rich intervals. This is likely the result of lower permeability from increased clays which equates to less fluid flow to influence diagenesis (Scholle, 1977). Round foraminiferal grains show concavo-convex contacts which indicate mechanical compaction. Compacted foraminifera tests have been filled with kaolinite in the mudstone facies, which is another form of diagenesis. Inoceramid shells and oyster fragments exhibit brittle fractures. Equant sparry calcite burial cement is seen in both the thin sections and the FE-SEM. Calcite burial cements have precipitated along foraminifera grain boundaries. Facies that contain high concentrations of primary carbonate material have been recrystallized. Foraminifera have also been recrystallized. Syntaxial burial cement is present on echinoderm grains. Dissolution of the original internal structure of the foraminifers resulted in the internal collapse and recrystallization of the grains. The effects of burial compaction and cementation are critical components of evaluating the reservoir quality of the Greenhorn Formation, because these diagenetic processes typically result in a reduction of porosity and permeability. Interparticle porosity occurs in coccolith chalks but decreases with burial from 27-38% to lower than 5-17% (Pahnke, 2014). Ultimately, this inhibits reservoir quality but does not necessarily mean the reservoir is ineffective. Other factors can affect chalk porosity, such as the pressure history of the reservoir and the timing of hydrocarbon entry (Scholle, 1977). Burial history vs. timing of overpressuring and oil migration is critical in preserving chalk porosity. More research into this component of the Greenhorn Formation will be crucial for understanding the reservoir quality.
3.2.1 Lincoln Discussion

The facies observed in this study correspond to the facies observed by Kauffman (1977) and Kaiser (2013). Facies 7, a light grey foraminifera-rich packstone to grainstone or chalk, corresponds to Kauffman’s light grey foraminifera-rich packstone with little quartz and clay. This facies represents offshore active currents with increased oxygen levels that are shallow enough to be affected by storm waves. Facies 6 is a calcareous laminated mudstone with interbedded foraminifera-rich grainstone/chalk beds and corresponds to the dark-colored calcareous mudstone with calcarenite and bentonite interbeds from Kaiser’s study. This facies represents a transition from facies 5 to 7 in offshore quiet water conditions near the edge of clay transport. Facies 5 in the Lincoln Member is a dark grey to black laminated calcareous mudstone, which corresponds to the evenly bedded dark-grey, calcareous, homogeneous mudstone with low fossil content seen in previous studies. This facies represents offshore deposition in quiescent water conditions (Kauffman, 1977). While each facies contains varying levels of bioturbation, laminations are preserved through much of the Lincoln facies, indicating that depositional energy remains fairly low through fluctuating bottom water currents with an indication of dysoxia. Biodiversity remains low, and consists mainly of coccoliths and foraminifera, but abundance varies between facies. Variable bioturbation with fecal pellets and some limestone concretions imply offshore quiet water conditions near the edge of clay transport (Kauffman, 1977). The upper Lincoln represents a dynamic paleoceanographic system that fluctuates between relatively quiet, oxygen-deficient water and well-circulated, well-oxygenated benthic conditions (Kauffman, 1985). Sea level fluctuation is the main control. The overall clay content is relatively high in the Lincoln Member. Suppressed resistivity response can be attributed to the thinly interbedded nature of the clay-rich beds throughout the unit, despite the presence of hydrocarbons.

3.2.2 Hartland Discussion

The Hartland Shale consists of laminated foraminifera-rich mudstone with varying fossil content (facies 5). The main difference between cores is the color (Fig 3.11, 3.12). For instance, the mudstones in the Hartland Shale in the Rebecca K Bounds core is significantly lighter in color than in the Wattenberg cores. This can be attributed to the thermal maturation and burial depths of the Hartland source rocks. Depositional energy within the Hartland is relatively low with elevated
clastic content. Bioturbation is very low and biodiversity and abundance fluctuates between facies, but still remains relatively low. Thus, the Hartland Shale was deposited in a relatively stable, benthic environment with gradual sedimentation (Pratt, 1984). This member is representative of quiescent water deposition near the edge of clay transport and reflects an interplay between clastic deposition and pelagic sedimentation in an offshore deep-water environment. High levels of organic carbon and low levels of fossil diversity and abundance suggest an anoxic event (Kauffman, 1985). The oxygen deficiency in the Hartland shale is interpreted to be the result of eustatic sea-level rise as the WICS transgressed towards peak highstand.

3.2.1 Bridge Creek Discussion

Facies 1-4 have only been identified in the Bridge Creek Member of the Greenhorn Formation. The identified facies and sub-facies in the Bridge Creek Member represent a full transition from chalk to marl (Fig. 3.27). Relative depositional energy increases from chalk to marl. Gradational parasequences of shoaling-upward cycles with transgressive lags represent a transition from pelagic dominated skeletal grains near the base of the Bridge Creek chalks into terrigenous dominated calcareous marls and mudstones near the top (Fig. 3.27). The transition from pelagic to terrigenous sedimentation is consistent with the regression that began in the Bridge Creek and continued through the Turonian into the overlying Carlile Formation.

The Bridge Creek Member consists of alternations between mud-rich and carbonate-rich facies that make up limestone/marlstone couplets representing cyclical deposition during Cenomanian-Turonian time (Fig. 3.28). Alternations between mud-rich and carbonate-rich facies represent changes in bottom water oxygen content due changes in clastic dilution and water column stratification from Milankovitch cycles with periodicities of 20,000 to 100,000 years (Sageman et al., 1998). Milankovitch cycles are Earth orbital variations that reflect equinox precession (about 21 k.y.), axial obliquity (41 k.y.), and orbital eccentricity (100 k.y. and 413 k.y.). Cycles in the Bridge Creek correspond to Milankovitch cycles that appear to be 41 k.y. obliquity cycles (Sageman, 1998).
Figure 3.27. Generalized parasequence model of the Bridge Creek member of the Greenhorn Formation. The Bridge Creek represents a full transition from pelagic dominated chalks at the base to terrigenous dominated marls at the top. (Modified from Bohacs and Lazar, 2010, and Anderson and Lewis, 2014).
Figure 3.28. Bridge Creek cyclicity in core. Carbonate cycles in the Rebecca K Bounds core are distinguished by light and dark coloring. Lighter facies correspond to Facies 1 (Chalk) and darker facies correspond to Facies 4 (Marl). Cenomanian-Turonian (CT) Boundary and OAE II are shown.
CHAPTER 4

MINERALOGICAL, ELEMENTAL, AND PETROPHYSICAL ASSESSMENT

The descriptions in the previous chapter describe the physical heterogeneity of each facies that make up the members of Greenhorn Formation. XRD and XRF analyses further enhance the facies descriptions previously described on the basis of mineralogical and elemental concentrations.

4.1 XRD Mineralogy

Bulk mineralogy and clay characterization are crucial components to the reservoir characterization of the Greenhorn Formation. Mineral abundances and distribution throughout the members of the Greenhorn Formation were determined through XRD analysis and are summarized in Figure 4.1. The Greenhorn Formation is composed of siliciclastic material (quartz silt and clay) and carbonates (mostly calcite with some dolomite). Overall siliciclastic abundance increases from the Bridge Creek to the Lincoln, from less than 20 wt. % to over 30 wt. %. In contrast, carbonate material decreases between the Bridge Creek and the other members. For example, the Bridge Creek Member contains >50 wt. % carbonate, the Hartland is ranges from 30-45 wt. % and the Lincoln Member ranges from 20-30 wt. %. As expected, clay abundance exhibits a similar trend to the siliciclastics where the Bridge Creek has the lowest abundance of clay (<25 wt. %), while the Hartland and the Lincoln have higher percentages of clay material (30-40 wt. %). These trends are also observed when XRD data is plotted on a ternary diagram (Fig. 4.2). The Bridge Creek, Hartland, and Lincoln Members can easily be separated into distinct groups in this method of analysis. This is attributed to differences in facies and depositional environments described in the previous chapter. Using the classification scheme for organic mudstones based on bulk mineralogy from Gamero et al (2012). The data points from the Bridge Creek Member represent a mixed carbonate mudstone, while those from the Hartland and the Lincoln members fall within the mixed mudstone classification due to their elevated siliciclastic and clay contents. Furthermore, the data was borrowed from another study and do not reflect data points from the Bridge Creek chalk facies. Thus, it can be inferred that the chalk facies will reflect XRD data towards the carbonate end member (Fig. 4.2).
Figure 4.1. Bulk mineralogy plot measured in weight percent (wt. %) of 10 Greenhorn Samples from the Noble Aristocrat PC H11-07 core.

Figure 4.2. Ternary diagram of bulk mineralogy overlain on organic mudstone lithofacies classification based on Gamero et al., 2012.
Clay characterization has important implications for depositional environment interpretations, as well as geomechanical interpretations, discussed later in this study. Clays in the Bridge Creek Member have a total abundance of <25 wt.% and consist mainly of illite and mixed layer illite-smectite (Fig. 4.3). The Hartland Member contains 30-40 wt.% clay and is predominantly illite and mixed layer illite-smectite, but low percentages of chlorite (1-2 wt.%) are introduced. Like the Hartland, the Lincoln member is also composed of 30-40 wt.% clay, mainly illite and mixed layer illite-smectite, low percentages of chlorite (1 wt. %), as well as small proportions of kaolinite (1-2 wt.%).

**Figure 4.3.** Clay characterization plot measured in percent of total clays from XRD data of 10 Greenhorn Samples from the Noble Aristocrat PC H11-07 core.

Illite and mixed layer illite-smectite are both present in all three Greenhorn members. Illite is a dominant clay mineral in most argillaceous rocks with low shrinkage ability and can be either detrital resulting from the weathering of silicates or authigenic through the alteration of other clay minerals (USGS). Smectite is also associated with montmorillonite, which is found in bentonites. Energy-dispersive x-ray spectroscopy (EDS) creates a map of dominant elements and confirms the presence of mixed-layer illite-smectite in the Lincoln Member (Fig. 4.4). Smectite is commonly detrital in origin and has a high shrink-swell capacity. Mixed-layer illite-smectite results from the
hydrothermal alteration of these clay minerals during a transition from non-swelling to swelling clays. Laminations of mixed layer illite-smectite flakes exist parallel to bedding indicate detrital origin of the primary mineral (Fig. 4.5a-b). In this case, the presence of mixed-layer illite-smectite is likely the result of thermal alteration of detrital smectite into authigenic illite. The presence of mixed-layer illite smectite can also be related to burial history and indicates thermal maturation (Pollastro, 1993). This has implications for hydrocarbon saturation, porosity and completion quality that will be discussed later in this study.

Chlorite is absent in organic-poor facies in the Bridge Creek, but exists in the Harland and the Lincoln which have elevated clastic and organic contents. Authigenic chlorite is associated with burial diagenesis in organic-rich mudrocks with elevated vitrinite reflectance values (Hillier, 1993). Chapter 3 provides further evidence of burial diagenesis in the Greenhorn Formation. The presence of chlorite in the organic-rich mudstone facies is consistent with this observation (Fig. 4.5c). FE-SEM imagery also shows that chlorite clay also exists as small floccules (Fig. 4.5d). The lack of in-situ chlorite growths suggests either micro-bioturbation disturbing in situ sediments or detrital origin instead of authigenic (Fig. 4.5d).

Kaolinite forms from the chemical weathering of feldspars in wet climates (Ho et al., 1995). Because feldspar is not a dominant component of any of the members of the Greenhorn Formation, the kaolinite present in the Lincoln is either detrital or is a component of the bentonite content. If detrital in origin, kaolinite in the Lincoln has implications of climate during this time period. During periods of humidity, kaolinite precipitation tends to increase while illite and smectite concentrations decrease. This same trend is exhibited in the Greenhorn Formation, possibly indicating that the climate during Lincoln deposition was more humid than during Hartland or Bridge Creek deposition. However, diagenetic kaolinite fills foraminiferal tests in the Lincoln formation and is seen in thin section. Kaolinite is also a common component of altered volcanic ash or bentonite. This indicates that the kaolinite spike in the XRD data is the result of diagenesis and not deposition.
Figure 4.4. EDS map of a Lincoln grainstone sample showing the presence of Al- and Si-rich mixed-layer illite-smectite clay compared to the Mg- and Ca- rich sparry calcite matrix.
Figure 4.5. FE-SEM micrographs showing clay types in the Greenhorn Formation. (a) Laminations of mixed-layer illite and smectite. (b) Mixed layer illite-smectite flakes. (c) Authigenic chlorite on mixed-layer illite-smectite flakes. (d) Chlorite appears as flocs instead of in-situ crystals. This is either the result of bioturbation or this chlorite is detrital.
4.2 XRF Elemental Geochemistry

Mudrock facies can be further characterized using XRF elemental geochemistry. Organic richness, paleo-productivity, and provenance of detrital sediments can be determined through the use of this method. When plotted against facies core descriptions, variations in elemental concentrations provides further insight into heterogeneity at a molecular scale. Geochemical data used in this study was provided by Nakamura (2015). XRF data from the Greenhorn suggests that elemental signatures fall into five categories (ElGhominy, 2015):

1. **Detrital indicators**: Aluminum (Al), titanium (Ti), Potassium (K), and silicon (Si). These elements are associated with terrigenous minerals including clay minerals, feldspars, and quartz.

2. **Carbonate indicators**: Calcium (Ca) and strontium (Sr). These elements are associated with carbonate.

3. **Organic suite**: Chromium (Cr), zinc (Zn), vanadium (V), molybdenum (Mo), uranium (U) and nickel (Ni). These elements are associated with organic matter, redox conditions and is indicative of suboxic environments.

4. **Anoxic suite**: The elements in this category have some overlap with the organic suite. This group also includes vanadium (V), molybdenum (Mo), uranium (U) and nickel (Ni), as well as iron (Fe) and sulfur (S). The latter two elements are associated with pyrite. These elements are associated to anoxic conditions associated with redox reactions.

5. **Oxic suite**: Consists of manganese (Mn) which is associated to oxic to suboxic conditions.

The elements described above relate to the facies described in the previous chapter. Groups 1-2 show trends that correspond to changes in clastic and carbonate sediment supply as opposed to paleo-oceanic oxygen water conditions (Fig. 4.6). Concentrations of the elements that are associated with terrigenous minerals and clay increase in the marl and mudstone facies within each member (Fig. 4.6). In contrast, elements associated with carbonate production are elevated in the chalk facies of the Bridge Creek but decrease as the facies transition into mudstones in the Hartland
and the Lincoln. This is consistent with the trends described in the previous chapter that relate to availability of carbonate and clastic sediment supply as opposed to changes in paleo-oceanographic oxygen water conditions. The concentrations of detrital indicators are significantly higher in the mudstone facies of the Hartland and the Lincoln than in the carbonate-rich facies. Likewise, the carbonate indicators are highest in the carbonate-rich facies in the Bridge Creek and the Lincoln (Facies 1-4 and Facies 7). In addition, mixed systems can involve both biogenic and detrital Si. A positive trend between Si and Zr indicates detrital Si and a negative trend implies biogenic Si (ElGhonimy, 2015). A positive trend exists between these elements, indicating the presence of detrital Si from terrigenous origin (Fig. 4.7).

Figure 4.6. Elemental data for detrital (Al, Ti, K, and Si) and carbonate (Ca and Sr) indicators plotted against the Noble Aristocrat PC H11-07 core description and depth. Elemental concentrations are in parts per million (ppm).
Figure 4.7. Cross-plot of Si and Zr from XRF data showing a positive trend, indicating a detrital source of silica.

Groups 3-5 show trends that correspond to changes in depositional environment and oxygen supply (Fig. 4.8). Again, a clear grouping between the elements and members is present. Every element in the organic and anoxic suite shows elevated concentrations in the facies of the Hartland and the Lincoln members (Facies 5-7), which includes the foraminifera-rich grainstones as well as mudstone (Fig. 4.8). Elements in the anoxic suite precipitate under highly reducing conditions. The presence of these elements within the Hartland and Bridge Creek facies indicate that deposition is the result of reducing, dysoxic to anoxic water conditions. Anoxic conditions in a reducing marine environment will also provide the best conditions for preserving organic matter. This is consistent with the notion that the Hartland and the Lincoln members have the best source rock potential in the Greenhorn Formation, with TOC values up to 4.5 wt. %.

In contrast, the organic and anoxic elements exist in low quantities or are absent in the carbonate-rich chalk and marl facies of the Bridge Creek (Fig 4.8). The oxic indicator, Mn, shows the inverse to the organic and anoxic suite of elements and maintains significantly higher concentrations in the chalk and marl facies of the Bridge Creek than in laminated facies in the Hartland and Lincoln members. This demonstrates that periodically the chalks were deposited in oxic to suboxic conditions. The chalks within the Bridge Creek member are also heavily bioturbated. This is consistent with oxygenated marine conditions that allow for the precipitation of Mn. This also suggests that the small Mn spikes in the Lincoln are related to the microburrowing along laminae. Mn can also be detrital or diagenetic. The basal portion of the Bridge Creek
members shows a decrease in Mn, but an increase in anoxic indicators Fe and S. Fe and S are associated with pyrite and suggest redox conditions. This spike is associated with the Oceanic Anoxic Event II, described previously in this study. OAE II represents a shift in anoxic conditions in the Cenomanian during Hartland deposition to oxic conditions recorded in the Bridge Creek during the Turonian. This is supported by the elemental data provided in this chapter.

Figure 4.8 Elemental data for the organic (Cr, Zn, Cu, V, Mo, U, and Ni), anoxic (V, Mo, U, Ni, Fe, and S), and oxic (Mn) suites plotted against the Noble Aristocrat PC H11-07 core description and depth. Elemental concentrations are in parts per million (ppm). See figure 4.6 for legend.
Mineralogical and elemental data support the depositional model provided in the previous chapter. Each method of analyses enhances the initial facies descriptions to provide insight into the depositional restraints that occurred during the Cretaceous. Bulk mineralogy reflects the differences in carbonate production vs. the availability of clastic sediments. Clay characterization also provides information about clastic sedimentation, as well as information about diagenesis. Elemental indicators enhance these descriptions and also suggest constraints on paleo-oceanic anoxia. Each of these analyses are important for overall reservoir characterization of the Greenhorn Formation.

4.3 Petrophysical Characterization

Extensive petrophysical characterization has not been published on the Greenhorn Formation. Petrophysical properties and characteristics of the Greenhorn Formation from the Aristocrat PC H11-07 well are described in this chapter. Changes in petrophysical character between the Aristocrat well in Wattenberg, the SM Patriot 1-19H in Silo Field and EOG Big Sandy 132-33M in Fairway are also documented. Gamma ray (GR), resistivity (RT), neutron porosity (Nphi), bulk density (RhoB), compressional sonic (DTC) and spectral gamma ray for potassium, uranium, and thorium (POTA, URAN, and THOR) logs assisted in petrophysical correlations in the Greenhorn throughout the study area. Furthermore, petrophysical models can be used to calculate water saturation and ultimately contribute to understanding of the hydrocarbon potential of the Greenhorn Formation.

Typical log responses for the Greenhorn Formation from Wattenberg Field are shown on a type log from the Noble Aristocrat PC H11-07 core in Figure 4.9. Distinct gamma ray, resistivity, porosity, bulk density, sonic, and spectral gamma ray signatures characterize each unit. The core description from the Aristocrat core allows for facies characterization to be continued at a petrophysical level. The Bridge Creek Member is comprised of carbonate-rich chalk and marl sequences. Chalks tend to have lower gamma ray, higher resistivity, and higher neutron-density crossover than shaly intervals due to their increased carbonate content. Gamma ray logs measure the natural radioactivity of a formation by combining the radioactive responses of uranium (U), thorium (Th), and potassium (K). GR can be used as a proxy for facies mapping because it
distinguishes radioactive shale intervals from non-radioactive carbonate or sandstone. Gamma ray signatures are lowest in the Bridge Creek and the gamma ray interpretation accurately follows the core description facies. GR signatures are highest in the Hartland, and again mimic the character of the core description. The gamma ray in the Lincoln Member is consistently higher than the Bridge Creek but lower than the Hartland, despite there being carbonate-rich grainstones interbedded with mudstone. This suppressed gamma ray in the carbonate-rich intervals is the result of the interbedded nature with clastic-rich mudstones.

Figure 4.9. Type log for the Noble Aristocrat PC H11-07 well. Typical log responses for the Greenhorn Formation are shown. Dotted horizontal lines indicate bentonites.
Resistivity, measured in ohm-meters, determines hydrocarbon- and water-bearing zones and can be used to calculate porosity and water saturation (Asquith et al., 2004). XRD and XRF data from the previous section determined that clay and quartz content increases from chalks of the Bridge Creek into the marls and mudstones of the Lincoln and the Hartland. Clay bound water is generally present in intervals with increased clay content and ultimately suppresses resistivity. Thus, resistivity is elevated in the Bridge Creek and relatively lower in the Hartland and the Lincoln members. This information, combined with the interbedded nature of the Lincoln, supports the suppressed resistivity seen in the logs.

Bulk density (RHOB in g/cc) is a function of matrix density, porosity and fluid density in pore space. Decreased bulk density readings can result from elevated calcite content, decreased clay content, or increased content of organic matter. Organic matter is less dense in source rocks than in surrounding carbonate or clay matrixes, resulting in suppressed bulk density readings. It has already been proven that the Bridge Creek member is high in calcite, so the elevated bulk density in this member suggests a lack of organic matter. This is supported by TOC data, which shows that the Bridge Creek is organic-poor compared to the other Greenhorn members. Bulk density is suppressed in the Hartland and Lincoln members, and is probably tied to the increase of organic material or clay in these intervals.

Porosity is shown with neutron porosity logs. DLIM refers to the density porosity corrected for a limestone and NPHI is measured neutron porosity. Neutron porosity measures the concentration of hydrogen. Neutron porosity is suppressed when pores are filled with gas because there is less hydrogen in gas than in oil or water. As such, this log follows a similar trend to density porosity and sometimes experiences crossover due to lithology differences. Generally, chalks will approach neutron-density crossover than mud-rich facies due to elevated calcite content and suppressed clay content. Neutron porosity is suppressed in the Bridge Creek, highest in the Hartland, and fluctuates in the Lincoln, but crossover is not seen in any of these intervals. This is likely the result of the thinly bedded nature of these intervals. Clay-bound water in a formation will increase the NPHI readings and probably explains the lack of crossover in the Hartland and the Lincoln.
Sonic tools measure the interval transit time of compressional sound waves traveling through a formation along a borehole axis. Lithology, porosity, and organic matter content can affect the interval transit time of a rock formation. DTC appears to be most affected by organic matter and lithology. Organic matter can increase the DTC log response, while carbonates can decrease it. This is seen in the Noble Aristocrat PC H11-07 well. The Bridge Creek member shows lower sonic signatures than the Hartland or the Lincoln. This not only says a lot about the lithology of the interval, but also has geomechanical implications that will be discussed later in this study.

Bentonites exhibit distinct petrophysical characteristics that can be correlated throughout the Greenhorn Formation (Fig. 4.9). Each bentonite identified in the Noble Aristocrat PC H11-07 core shows extremely high (>150 API units) GR signatures associated with increased thorium spikes, as well as suppressed resistivity, bulk density, and neutron porosity readings. Some of these bentonites represent surfaces that can be correlated throughout the study area.

Spectral gamma ray logs show individual components of potassium, uranium, and thorium concentrations within the formation. These logs help determine clay typing and suggest organic content. Potassium can be used to indicate clay concentrations, thorium is associated with heavy clay minerals and volcanic ash, and uranium can be used as a proxy for organic content (ElGhomy, 2015). The Bridge Creek shows relatively low concentrations of uranium, potassium, and thorium, indicating that this member is low in organic matter and clay, which was confirmed through XRD analysis. The Hartland and the Lincoln members show elevated concentrations of these elements due to higher clay content and organic matter. The TOC curve shows that organic matter is in fact elevated in portions of the Hartland and Lincoln (Fig. 4.10).

The petrophysical properties described above can be correlated throughout the study area (Fig. 4.11). The first observation is that the Greenhorn Formation decreases in thickness from Fairway to Wattenberg. The Bridge Creek decreases the most, while the Hartland and the Lincoln remain relatively similar in thickness. The decrease in thickness within the Bridge Creek from north to south is the result of lithology changes from more proximal marls close to deltaic sources to more distal pelagic chalks. Gamma ray signature decreases from the north to the south, while resistivity increases, indicating that the overall facies in the Greenhorn become shalier and more
clay-rich in the north. Neutron porosity and bulk density is relatively high and stable throughout the Greenhorn in the Big Sandy well but approaches crossover with bulk density in the Aristocrat well. In addition, the sonic log does not fluctuate as much in the Bridge Creek of the Big Sandy core as it does in the Aristocrat core. This suggests that the Bridge Creek is mainly marls in Fairway and Silo instead of the clean, carbonate chalk beds seen in Wattenberg.

Figure 4.10. TOC, TMAX, and HI logs shown with gamma ray (GR), resistivity (ILD), and limestone porosity.
Figure 4.11. Cross section showing petrophysical differences between the EOG Resources Big Sandy 132-33M and the Noble Aristocrat PC H11-07 wells.
Porosity is an important measurement in hydrocarbon exploration. It can either be derived from grain and bulk density values or through mercury injection methods. This study utilizes porosity values obtained through mercury injection capillary pressure (MICP) which directly measures pore volume by forcing mercury (Hg) into pore space on crushed core samples. Pore networks in mudrocks are nanometer- to micrometer-size pores (Loucks et al., 2012). The combination of pores and natural fractures form a fluid flow-path that allows for hydrocarbon migration. Tortuosity of the pore network is referred to as permeability. Porosity and permeability are significant constraints on storage and flow capacity and must be taken into account when evaluating reservoir potential.

5.1 Porosity and Permeability from Mercury Injection Capillary Pressure (MICP)

MICP analysis was completed on 10 core samples from different facies of the Greenhorn Formation in the Noble Aristocrat PC H11-07 well. EOG Resources provided MICP data for an additional 22 samples from the Greenhorn Formation from the Big Sandy 132-33M. The data for the Noble Aristocrat well show that porosity values are highest in the marl facies of the Bridge Creek, with values over 5%. The lowest porosity values are in the Hartland mudstone facies and are around 1.25-1.34%. The Lincoln shows a range of porosity values, from 2.79-5.07% in the foraminifera-rich grainstone facies and 4.73% in the homogeneous mudstone facies. Permeabilities are highest in the chalk grainstones and lowest in the mudstones and marls. Bulk grain densities range from 2.55-2.67 g/cc. It is important to note the limited dataset for this well. Each sample represents a different facies so there is only one sample per facies. In the future, it would be important to explore multiple samples per facies to eliminate the possibility of error.

Interesting trends exist in the porosity, permeability, and grain density values (Fig. 5.1). These values are all relatively low when evaluating reservoir quality. With the exception of the chalk, porosity increases from chalkier to marlier facies. Porosity shifts when the system switches from pelagic dominated to detrital dominated. In the detrital dominated system, porosities are lowest in the Hartland mudstone facies and increase again with depth into the foraminifera
Figure 5.1. Results of MICP porosity (%), permeability (mD), and grain density (g/cm³) in the Noble Aristocrat PC H11-07 well.
grainstones and the homogeneous mudstone at the base of the Lincoln. Increased porosity in the Lincoln grainstones can be attributed to orientation of spherical foraminiferal grains in laminations creating large pores that have partially been filled in by clay and other detrital material.

Permeability trends can also be separated by pelagic and detrital dominated systems. Permeability is highest in both of the carbonate-rich chalk grainstones at either end of the spectrum. Permeability decreases towards the mudstone facies. The pelagic dominated Bridge Creek has the highest permeability in its bioturbated chalks. Bioturbation generally destroys permeability. However, vertical burrowing in the Bridge Creek chalks influences biogenically enhanced permeability allowing vertical transmissibility of an otherwise impermeable matrix (Pemberton and Gringras, 2005). Permeability decreases as the system becomes more mud- and clay-rich. Clay-rich rocks have decreased permeability but commonly have higher micro-porosity, while effective porosity is generally low. The system switches at the base of the Bridge Creek and becomes detrital dominated. Permeability is lowest in the laminated mudstone and increases as the facies transition into the foraminifera-rich grainstone. Although a trend can be seen in the graphs, it is important to note that these variations are miniscule and permeability is still incredibly low in all facies.

Grain density follows a similar trend to porosity and is highest in the marls and grainstones and lowest in the laminated mudstone. Mudstones and limestones generally grain densities of 2.07-2.67 g/cm$^3$ and 2.75 g/cm$^3$ respectively (Daly et al, 1974). Chalk typically has a density around 2.23 g/cm$^3$. These values match the values seen in the data.

The data for the Big Sandy well is more extensive than that for the Lincoln and Hartland members but cannot be separated by facies. The Bridge Creek has an average porosity of 3.23%, the Hartland member 4.68% and the Lincoln member 5.05%. Overall, these data show higher porosity values but significantly lower permeability values than the Aristocrat well (Fig. 5.2). The Greenhorn Formation is almost 2000 feet deeper in the Big Sandy well; therefore, burial may be affecting the permeability values. The data values differ by orders of magnitude. This is the result of different methods of permeability determination. The Aristocrat values are based off crushed sample MICP; the Big Sandy values are calculated values based on pore size distribution. Regardless of difference in the magnitude of the data points, the trends within the data are still
prominent (Fig 53). The chalks are consistently highest in permeability and porosity and the mudstones are the lowest in both wells. Error between different machines completing the analyses for each well must also be considered.

**Figure 5.2.** MICP Porosity vs. permeability for the Noble Aristocrat PC H11-07 and Big Sandy 132-33M wells. Permeability for the Aristocrat well is from MICP whereas permeability for the Big Sandy well is calculated. Trends within the data still exist regardless of order of magnitude.
5.2 Pore size distribution

The reported permeability values are derived from the mean pore throat entry radius during MICP analysis. Mercury saturation is recorded as it enters pore space. Large pores are filled first and smaller pores are filled as pressure increases and more mercury is forced into pore space. Graphs corresponding to incremental records of pore size values have been created for each facies (Fig. 5.3). Mercury saturation rarely exceeds 12% in these tight reservoirs. As such, pore throat entry radii are on the order of 0.001 to 0.1 microns.

Differences between the facies are recorded in pore throat entry size measurements. In the chalk and marl facies of the Bridge Creek, mercury saturation almost immediately filled pore space, resulting in a skewed left distribution where the data peaks and then tapers off. Pore throat entry radii start at 0.0165 microns in the chalk and drop down to .0058 in the marls. Peak pore throat entry radii is 0.008 microns for the chalk facies and drops to 0.002-0.0025 microns for the marls. For comparison, pore throat entry radii in the mudstones start between 0.01 and 0.02 microns, similar to the chalk, but display a skewed right distribution. The mudstones peak between 0.003 and 0.004 microns. This ultimately shows that while all the facies contain pores of similar size, the distribution of pore throat sizes is higher in the chalks than in the mudstones. The foraminiferal packstone-grainstone is more variable and reflects large fluctuations in pore throat entry radius and mercury saturation. This can be attributed to the interbedded nature of foraminifera grainstone facies with thin clay-rich mudstone laminations. Therefore, this graph practically reflects pore throat entry radius sizes for two separate facies.

Normalized composite pore size distribution shows similar trends to the incremental data (Fig. 5.4). The facies that are rich in carbonate have overall higher pore throat sizes than mudstone facies with elevated concentrations of clay and detrital material. This suggests that the calcareous chalks and grainstones have larger pore throat sizes and thus have higher permeabilities than clay-rich mudstones. The size of the pore throat is more important than porosity (Olson and Grigg, 2008). This implies that the calcareous facies are better reservoirs in terms of permeability.
Figure 5.3. Incremental pore size distribution graphs for the 10 samples from the Noble Aristocrat PC H11-07.
Figure 5.4. Composite pore size distribution graph for the 10 samples from the Noble Aristocrat PC H11-07.
5.3 Pore network

Matrix related pore types can be subdivided into three different categories according to Loucks et al., 2012. Two of these pore types relate to the mineral matrix, while the third type is associated with organic matter (OM) (Fig. 5.5). Fractures are not included in this classification. Mineral matrix pores consist of interparticle pores found between grains and intraparticle pores within grains. Organic matter pores are intraparticle pores located inside organic matter. Interparticle pores are more reliable as an effective pore network because the pores are interconnected. OM pores are also generally part of an interconnected network despite being intraparticle. Burial and compaction can decrease a reservoir’s volume by up to 88% and consequently destroys pore networks, specifically in ductile clay-rich mudstones (Loucks et al., 2012). Hydrocarbon thermal maturation conversely creates organic matter pores when kerogen is transformed to hydrocarbons.

Figure 5.5. Pore types from Loucks et al., 2012
Matrix pore networks were investigated in the Noble Aristocrat PC H11-07 well with (1) blue-dye impregnated polished thin sections using an epi-fluorescent microscope; and (2) using FE-SEM imagery. The epifluorescent dye did not show any visible micropores because they are too small to be visible with this technique. FE-SEM imagery was used to view the general pore structure at micro-scales. Ion milled samples are better for determining micro-porosity within organic matter and were not used in this study. Therefore, only the matrix porosity was assessed.

The facies in the Greenhorn Formation exhibit both interparticle and intraparticle microporosity (Fig. 5.6). Intraparticle porosity is expressed in the chalk and laminated mudstone facies. This pore types are not ideal when evaluating a reservoir because pore space is not interconnected. The chalk facies has been bioturbated and contains a significant amount of carbonate grains with intraparticle porosity (Fig. 5.6a). In addition, the chalks have been heavily recrystallized during burial diagenesis which results in the precipitation of calcite cement in pore space, reducing overall porosity. The laminated mudstone facies also has extremely low porosity resulting from compaction of mixed-layer illite-smectite clay flakes (Fig. 5.6b). In contrast, the marl facies represents an interplay between carbonate and clastic sediment, which results in dispersed clay with interparticle porosity between platelets and carbonate grains (Fig. 5.6c). The homogeneous mudstone facies also exhibits favorable interparticle porosity (Fig. 5.6d).

An extensive pore networks characterization using ion-milled samples and FE-SEM imagery could potentially reveal more about intraparticle organic porosity in the Greenhorn Formation on nanometer scales. It is likely that the organic-rich mudstones with very low pore size distributions will maintain some organic porosity. Without this information, however, it appears that the best reservoirs in the Greenhorn Formation are those with the highest porosity, permeability, and larger interparticle pores. Because permeability is so low in each sample, it can be virtually ignored for purposes of determining the best reservoir within the sample set. When this is considered, the carbonate-rich chalks, marls, and grainstones have the highest porosities and should be evaluated further as potential reservoirs.
Figure 5.6. FE-SEM micrographs showing matrix pores in the Greenhorn Formation. Favorably pore space marked in yellow (solid lines) and unfavorable pore space marked in orange (dashed lines). (a) Intraparticle pores in coccoliths and coccolith spines in the bioturbated chalk facies. Significant recrystallization has reduced primary pore space due to burial compaction. (b) Porosity reduction in the laminated mudstone facies resulting from compaction of clay. (c) Interparticle pores in the marl facies. (d) Interparticle and intraparticle pores in the homogenous mudstone facies.
CHAPTER 6
RESERVOIR GEOMECHANICS

Reservoir geomechanics applies material science, structural geology, rock mechanics and soil mechanics to reservoirs in the oil and gas industry. Rocks will react when stress is applied. Geomechanics incorporates these reactions with applications to a hydrocarbon reservoir. Hydrocarbon production also results in changes in pore pressure, which results in a change in stress applied on the reservoir and surrounding rocks (Sayers and Schutjens, 2007). This information is important when evaluating a rock’s reservoir potential.

Depositional fabric and facies characterization are directly related to geomechanical properties and are important to understand and characterize the reservoir. All of the properties that have been previously described or measured in each facies - mineralogy, pore size and structure, sedimentary structures, clay content - have an effect on mechanical behavior and ultimately on reservoir and completion quality. Generally, load bearing, brittle targets with large pores make better reservoirs than ductile, clay-rich mudstones (May et al., 2012). These ideal types of reservoirs develop in different types of depositional environments and systems (May et al., 2012). Because the Greenhorn Formation represents a mixed-siliciclastic/carbonate system, the facies represent varying degrees of reservoir potential and geomechanical properties.

6.1 Elastic Behavior

Elastic behavior refers to the deformation of a material after a stress is applied to it. If a rock is brittle, it will break; if a rock is ductile, it will bend and may or may not experience permanent deformation. Stress and strain affect elastic behavior. Stress is force per unit area and strain is the deformation response of a material due to an applied stress. Elastic moduli are measurements of elastic behavior and allow all three strain directions to be calculated (Bailey, 2015).

Young’s modulus (YM) measures the stiffness of an isotropic elastic material. It is the ratio of uniaxial stress to uniaxial strain, measured in Pascals (Pa). Stress is measured in units of pressure, or force per unit area, and strain is dimensionless. YM can predict how much a material
will lengthen or shorten in the direction parallel to stress when under tension or compression. It also relates to the material’s ability to return to its original shape after deformation has occurred due to an applied load. A material with a low YM will easily deform but will bounce back after deformation, whereas a material with a high YM will resist deformation but will eventually break. Rigid materials, such as concrete, have a higher YM than ductile materials, like rubber, and more force is required to deform a stiff material compared to a soft material. Therefore, it is important to understand reservoir composition to be able to predict its reservoir and completion quality. For example, clay and detrital quartz and silt are often lumped together and reported as siliciclastic content. However, they each have different elastic properties, and their individual concentrations should be quantified to understand their effect on the elastic moduli and therefore the geomechanical behavior of the rock. In reservoir applications, it can be expected that reservoirs that are high in detrital quartz will have a higher YM than ductile clay-rich mudstones. The same is true for reservoirs that are high in calcite.

Poisson’s ratio (PR) is unitless and is the ratio of transverse contraction strain to longitudinal extension strain. In other words, it is the material’s ability to be “squished” and represents a volumetric change that a material experiences once stress is applied; a material will expand in the two directions perpendicular to the direction it is compressed and vice versa. For example, rubber becomes thinner once it is stretched and thicker when it is compressed. Rubber has a PR of nearly 0.5 and cork is close to 0 because its lateral expansion is minimal when compressed. Most materials have a Poisson’s ratio between 0.1 and 0.5. Ultimately, this has implications on a rock’s reservoir potential in that a material with a low PR is able to withstand significant force without serious deformation. Clay-rich mudrocks will compress easier, ultimately reducing porosity, than a rock with high concentrations of detrital quartz or biogenic carbonate. Thus, PR and YM are important geomechanical properties that influence reservoir and completion quality.

Brittleness is a unitless measurement of the rock’s breakability when stressed. The brittleness index (BI) is a measurement of stored energy before failure and is a function of rock strength, lithology, texture, effective stress, temperature, fluid type, diagenesis and TOC (Perez and Marfurt, 2013). In this study, brittleness index is defined as Young’s modulus divided by
Poisson’s ratio (YM/PR) and is a good reference when determining a rock’s response to fracture (Perez and Marfurt, 2013). This measurement is also useful in determining fracture barriers against a potential reservoir (Perez and Marfurt, 2013). Based on this, an ideal reservoir from a completion’s standpoint will have a high Young’s Modulus and a low Poisson’s Ratio because it will be brittle and will shatter like glass (May et al., 2016). In contrast, the least ideal situation is a reservoir with a low Young’s Modulus and a high Poisson’s Ratio because it will absorb a fracture instead of shatter.

Young’s modulus and Poisson’s ratio were provided in the log suites for the Noble Aristocrat PC H11-07. Additionally, YM, PR and BI were calculated for the EOG Big Sandy 132-33M and SM Patriot 1-19H using the shear and sonic logs in the following equations:

1. \[ PR = \frac{\left(\frac{DTS}{DTC}\right)^2 - 1}{\left(\frac{DTS}{DTC}\right)^2 - 1} \]

2. \[ YM = 1000 \times \rho \left(\frac{1}{DTS}\right)^2 \left(\frac{3}{DTC} - 4 \left(\frac{1}{DTS}\right)^2\right) \]

3. \[ BI = \frac{YM}{PR} \]

Where DTS is fast shear sonic, DTC is compressional sonic velocity, and \( \rho \) is bulk density. Because of the close proximity (~5 mi) between the Big Sandy and the Patriot wells, only the Big Sandy well is shown for simplicity.

The Bridge Creek has higher calculated YM and BI values in log data than the Hartland and the Lincoln in the Aristocrat well (Fig. 6.1). Young’s modulus is more variable than the other moduli, indicating a contrast in the overall rigidity between members. This ultimately affects the brittleness of the unit. The Bridge Creek is significantly more brittle than the other Greenhorn Members in this well. In contrast, the elastic moduli in the Big Sandy and Patriot well remain relatively constant throughout the Greenhorn Formation with limited variability (Fig. 6.2).
Figure 6.1. Geomechanical properties and elastic moduli of the Greenhorn Formation in the Noble Aristocrat PC H11-07 well in Wattenberg. Gamma Ray, bulk density, neutron porosity, shear and compressional sonic logs, YM, PR, and Brittleness are shown.
Figure 6.2. Geomechanical properties and elastic moduli of the Greenhorn Formation in the EOG Resources Big Sandy 132-33M well in Fairway and the SM Patriot 1-19H in Silo. Gamma Ray, bulk density, neutron porosity, shear and compressional sonic logs, YM, PR, and Britteness are shown.
Averages of geomechanical properties are summarized in Table 6.1. YM and PR vary greatly between the Noble Aristocrat PC H11-07 well in Wattenberg and the SM Patriot 1-19H and EOG Big Sandy 132-33M wells in the northern Denver Basin (Fig. 6.3). Values for the Patriot and Big Sandy cores are similar. Averages for the Noble Aristocrat well are higher than in the other wells. This results from the higher YM in the Bridge Creek Chalk facies.

**Table 6.1.** Average geomechanical properties for each member in the three study area wells.

<table>
<thead>
<tr>
<th>Wells</th>
<th>PR</th>
<th>YM</th>
<th>BI</th>
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<tbody>
<tr>
<td><strong>Noble Aristocrat PC H11-07</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridge Creek</td>
<td>0.28</td>
<td>5.38</td>
<td>19.82</td>
</tr>
<tr>
<td>Hartland</td>
<td>0.28</td>
<td>3.20</td>
<td>11.37</td>
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<tr>
<td>Lincoln</td>
<td>0.26</td>
<td>3.29</td>
<td>12.50</td>
</tr>
<tr>
<td><strong>EOG Big Sandy 132-33M</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridge Creek</td>
<td>0.29</td>
<td>3.18</td>
<td>10.97</td>
</tr>
<tr>
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<td>2.44</td>
<td>8.08</td>
</tr>
<tr>
<td>Lincoln</td>
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<td>2.57</td>
<td>8.95</td>
</tr>
<tr>
<td><strong>SM Patriot 1-19H</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Bridge Creek</td>
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</tr>
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<tr>
<td>Lincoln</td>
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<td>2.46</td>
<td>8.46</td>
</tr>
</tbody>
</table>

**Figure 6.3.** Cross plot showing YM to PR for the Noble Aristocrat PC H11-07, EOG Big Sandy 132-33 M, and SM Patriot 1-19H.

There is a clear distinction between the elastic moduli for each member in the Aristocrat well (Fig. 6.4a). The Bridge Creek maintains the highest YM with variable PR. The Hartland and the Lincoln members have similar YM values, but Hartland generally has a higher PR. Data from the Big Sandy well show a tight cluster of all values, with YM<3.5 and PR>0.27 (Fig. 6.4b). The cluster of values in the Big Sandy well is the result of similar facies with elevated clay contents, resulting in a higher PR value throughout. In contrast, the variation in values in the Aristocrat well is the result of variable facies. The elevated YM values from the Bridge Creek member in the Noble Aristocrat PC H11-07 well can be attributed to the rigidity of the dominant bioturbated chalk facies.
Figure 6.4. Cross plots showing Young’s Modulus to Poisson’s Ratio. (a) Noble Aristocrat PC H11-07 (b) Big Sandy 132-33M.
Mineralogy data from XRD analysis can sometimes reveal interesting information about elastic behavior. However, XRD data from the Noble Aristocrat well and the Big Sandy well were plotted against geomechanical properties and did not show a correlation between any of the variables (Fig. 6.5). It is important to note that XRD is measured on a direct point on a core, whereas calculated geomechanics represent an average over an interval. This ultimately should be treated as a guideline and not a scientific conclusion. A strong linear relationship ($R^2$ between 0.6 and 0.8) appears to exist between bulk mineralogy (clay and carbonate wt. %) and YM and Brittleness in the Aristocrat well but does not in the Big Sandy well (Fig. 6.5a-d). This is due to an outlier effect caused by the chalk facies. The fact that there is a strong relationship in the Aristocrat well and not in the Big Sandy well implies that bulk mineralogy, specifically carbonate, can have an effect on the stiffness of the unit and is especially dominant in the chalk facies. Rocks that are high in carbonate and low in clay express higher YM values and ultimately higher brittleness than clay-rich rocks. This positively affects reservoir and completion quality. Thus, the Bridge Creek is more brittle and will respond to fracture more positively than the other Greenhorn members.

Organic matter can also affect geomechanical properties. Again, a weak linear relationship exists between TOC wt. % and brittleness in the Big Sandy well (Fig. 6.6). The elastic behavior of organic matter is similar to clay. Units with more organic matter have lower brittleness indices than units that are low in organic carbon. As expected, the Hartland and the Lincoln have more organic matter and therefore have a lower brittleness index than the organic-poor Bridge Creek member.

Average calculated brittleness based on well logs for each Greenhorn Member in the Noble Aristocrat PC H11-07, EOG Big Sandy 132-33M and SM Patriot 1-19H wells is shown in Figure 6.7. The Bridge Creek is the most brittle unit in both wells, followed by the Lincoln, with the Hartland the least brittle. Brittleness values in the Big Sandy well are lower for each member overall than in the Aristocrat well. The Bridge Creek shows the most variability between the wells, whereas the Hartland and the Lincoln remain more similar. The difference in brittleness between the two wells further suggests that the Bridge Creek in the Big Sandy well consists of more marls than in the Noble Aristocrat well.
Figure 6.5. Cross plots showing XRD mineralogy data plotted against elastic moduli in both the Noble Aristocrat PC H11-07 and the EOG Big Sandy 132-33M wells. The circles indicate location of Bridge Creek chalk facies that have a major effect on the relationship. Legend shown in b. (a) Young’s modulus vs. Total carbonate wt. %. (b) Young’s modulus vs. total clay wt. %. (c) Britleness vs. total carbonate wt. %. (d) Britleness vs. total clay wt. %. (e) Poisson’s ratio vs. total carbonate wt. %. (f) Poisson’s ratio vs. total clay wt. %.
Figure 6.6. A weak negative correlation exists between TOC and Brittleness in the EOG Big Sandy 132-33M well.

Figure 6.7. Average brittleness for each member of the Greenhorn Formation in the Noble Aristocrat PC H11-07, EOG Big Sandy 132-33M and SM Patriot 1-19H wells.
Differences in brittleness also exist between facies (Fig. 65). The bioturbated chalk and marl facies in the Bridge Creek are more brittle than the Hartland and the Lincoln due to elevated carbonate content. The Hartland and the Lincoln both contain high values of clay wt. %, but the Lincoln contains interbedded foraminifera-rich grainstones that are high in carbonate. Although the Lincoln contains carbonate-rich grainstones, thin interbeds of clay and mud are present and ultimately lower the unit’s brittleness index. Furthermore, the Bridge Creek is a biogenic pelagic dominated system and the Hartland and the Lincoln represent a mixed carbonate-siliciclastic detrital dominated system. The changes in brittleness between the facies follows the same trend as the facies distribution discussed in chapter 3 (Fig. 3.25), indicating that the type of system and depositional fabric both have an effect on geomechanical properties.

Figure 6.8. Britteness by facies in the Noble Aristocrat PC H11-07 well.
6.2 Depositional Fabric

Depositional fabric and composition affect the mechanical properties of a rock. As determined in chapter 3, the Greenhorn Formation represents two different mixed carbonate-siliciclastic systems. The Bridge Creek and the associated facies are characteristic of a pelagic dominated system that is high carbonate concentrations with lower values of detrital quartz while the Hartland and the Lincoln and the associated facies represent a mixed siliciclastic-carbonate detrital dominated system with more silt and clay. As shown in previous cross plots, brittleness corresponds to the facies that derive from these depositional systems. Clay and carbonate concentrations, organic matter, diagenesis, bioturbation, lithology framework, fractures, and sedimentary structures all have an effect on geomechanics. Each of the depositional systems maintains the following geomechanical properties, summarized in Table 6.2. Figure 6.9 corresponds to facies seen in a pelagic dominated system, and figure 6.10 corresponds those found in a detrital dominated system.

Table 6.2. Relative geomechanics organized by depositional system defined in chapter 3.

<table>
<thead>
<tr>
<th>System</th>
<th>Biogenic Pelagic Dominated</th>
<th>Detrital Dominated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Member</td>
<td>Bridge Creek</td>
<td>Hartland and Lincoln</td>
</tr>
<tr>
<td>Facies</td>
<td>Facies 1-4</td>
<td>Facies 5-7</td>
</tr>
<tr>
<td>Clay</td>
<td>Low (0-25%)</td>
<td>High (30-40%)</td>
</tr>
<tr>
<td>Carb</td>
<td>High (&gt;40%)</td>
<td>Low (&lt;30%)</td>
</tr>
<tr>
<td>Qz</td>
<td>Low (&lt;20%)</td>
<td>Low (&gt;20%)</td>
</tr>
<tr>
<td>YM</td>
<td>High (5.38)</td>
<td>Low (3.25)</td>
</tr>
<tr>
<td>PR</td>
<td>Variable</td>
<td>Variable</td>
</tr>
<tr>
<td>BI</td>
<td>High (20+)</td>
<td>Low (11-14)</td>
</tr>
<tr>
<td>TOC</td>
<td>0-5 wt. %</td>
<td>2-4 wt. %</td>
</tr>
</tbody>
</table>
Figure 6.9. Depositional fabric in core, thin section, and FE-SEM of Bridge Creek facies from a pelagic dominated system. (a) Bioturbated chalk. (b) Laminated marl.
**Figure 6.10.** Depositional fabric in thin section of Hartland and Lincoln facies from detrital dominated system. (a) Fossiliferous laminated mudstone shows pellets and organic matter concentrated in laminae. (b) Foraminifera grainstone shows clay and mud concentrated in laminae.
Each system has different depositional fabrics that ultimately affect geomechanical properties. Depositional fabric and sedimentary structures are significant in evaluating rock strength (May et al., 2015), but it is difficult to determine based solely on core description. Figure 6.11 shows core photographs and thin sections for both the laminated marl and fossil-rich laminated mudstone. Both facies are laminated in core and appear very similar in thin section. However, the laminated marl facies is richer in carbonate and lower in clay than the mudstone and has a higher brittleness index. As stated previously, clay and carbonate ratios have an effect on brittleness. Thus, it is important to assess bulk mineralogy when evaluating rock mechanical strength.

**Figure 6.11.** Depositional fabric of laminated marl (a) and fossiliferous laminated mudstone (b) in core and thin section. Both facies look very similar in core and thin section, but carbonate/clay ratio is the major distinction, causing the laminated marl to be more brittle.
Clay volume alone does not determine overall geomechanics. The distribution of clay also influences geomechanics (Fig. 6.12). Clay content is 33-40% in each of the mudstone facies. Brittleness 11-13 in the laminated mudstone facies but is 9-12 in the fossiliferous laminated mudstone. This suggests that clay content not only negatively influences brittleness, but the distribution of clay has an effect as well. This can be partially attributed to the orientation of dispersed clay mineral grain flakes vs. laminated clay. In the laminated mudstone, the visible laminations as seen in thin-section are predominantly composed of foraminifera or other carbonate material. In FE-SEM, clay flakes are dispersed around other grains in variable orientations in the laminated mudstone facies (figure 6.12a). In contrast, FE-SEM imagery shows that clay flakes are aligned in layers in the homogeneous mudstone (figure 6.12b). Ultimately, this affects completion quality of a reservoir. Stimulated fractures in reservoirs with laminated clay will not fracture easily. These fractures over time will close back together which accelerates production decline.

Bioturbation may also have an effect on reservoir quality and geomechanics. The data suggests that the bioturbated chalk facies are more brittle than the laminated mudstone and marl facies (Fig. 6.13). However, a bioturbated reservoir will likely not have as many interconnected pores as a laminated reservoir and suggests bioturbation might have both positive and negative effects on reservoir and completion quality based on depositional fabric.

Diagenesis can have a positive or negative affect on brittleness, and thus on reservoir and completion quality depending on the type of diagenesis. For example, facies that have been recrystallized with calcite are more brittle than facies that have not undergone recrystallization. Chapter 3 concluded that burial compaction is the main form of diagenesis present in the Greenhorn Formation. This form of diagenesis ultimately decreases porosity and permeability by closing existing pore space. Therefore, diagenesis should be taken into account when evaluating reservoir quality from both a geomechanics and porosity and permeability standpoint.
Figure 6.12. Clay distribution in mudstone facies in core and FE-SEM. (a) Laminated mudstone (b) Homogeneous mudstone.
Occurrence of carbonate limestone beds plays a role in the mechanical behavior of the unit. In a recent Eagle Ford study, intervals with higher occurrences of limestone beds with interbedded marls resulted in higher production rates than intervals with thick limestone beds (Breyer et. al, 2015) (Fig. 6.14). The ideal frequency of limestones is over 0.3/ft with more than 60% marl (Breyer et. al, 2015, Denne, 2016, personal communication). This allows for hydrocarbons to be generated in the organic rich marls and mudstones with added brittleness from the limestone beds, creating the perfect zone for a stimulated fracture. There must not be too much or too little marl or mudstone; similarly, there must be the right amount of limestone to enhance brittleness. This ideal balance of limestone and marl is referred to as the “Goldilocks Zone” (Denne, 2016, personal communication).
communication). Thus, the perfect amount of interbedded limestone and marls of mudstone is necessary to create the right conditions for a frackable carbonate reservoir.

Figure 6.14. Effect of frequency of limestone beds from stimulated fracture. Both sections are 10 ft thick and contain 70% marl and 30% limestone. The section on the left has a limestone frequency of 0.1/ft and the section on the right has a limestone frequency of 0.3/ft. (Modified from Breyer, 2015).
6.3 Fracture characterization

Fractures also reveal a lot about geomechanical properties. They expose past states of strain which can help confirm stress calculations and notions of PR and YM for given rock types. The Bridge Creek does not bear many natural fractures, despite the fact that the chalks are more brittle than the other Greenhorn facies. This lack of fractures might negatively affect fluid flow in the Bridge Creek. Instead, natural fractures exist in the mud-rich facies of the Greenhorn. Mineralized natural vertical fractures occur in the Lincoln Member at the base of the Greenhorn in the SM Patriot core in the homogeneous and laminated mudstone facies (Fig 6.15). The Lincoln is more siliceous, but it is also more clay rich than the other Greenhorn Members. Furthermore, more fractures were recorded during core description in the Patriot core than in the Aristocrat core. The Patriot core is paleogeographically shallower in terms of deposition but is currently deeper in the basin. This implies that fracturing could be the result of burial compaction.

One must be careful not to mistake inoceramid filaments or drilling induced fractures for natural fractures. Drilling induced fractures look like natural horizontal fractures in core but are not mineralized (Fig. 6.16a). Inoceramid filaments look like calcite-filled horizontal fractures and are present in the interbedded mudstone and grainstone facies of the Lincoln Member in thin section (Fig. 6.16b-c). These filaments are the planktonic larvae of benthic inoceramids (Denne, 2016, personal communication). These filaments are ductile and do not break during compaction (Denne, 2016, personal communication). It would be interesting to discover if these ductile filaments affect the brittleness of the units where they exist in high concentrations. Additionally, these filaments may have an influence on porosity.

Fullmore Formation Micro-imaging (FMI) logs were available for the SM Patriot 1-19H core (Fig. 6.17). Low-angle mineralized fractures occur at the upper and lower contacts of the Bridge Creek Member. Mineralized vertical fractures also exist in the Lincoln Member. In addition, low- to high- angle expulsion fractures exist in the Hartland and the Lincoln members based on the FMI interpretations in Figure 6.17. Pressure released during hydrocarbon expulsion is responsible for the formation of this type of fracture. This suggests that Greenhorn source beds might have higher fracture porosity due to hydrocarbon expulsion.
Figure 6.15. Natural and induced fractures in the Lincoln Member of the SM Patriot 1-19H core.
Figure 6.16. Horizontal fractures in the Greenhorn Formation. (a) Induced horizontal fractures. (b) Mineralized natural horizontal filaments. (c) Filaments.
Figure 6.17. FMI logs and fracture interpretation for the SM Patriot 1-19H core provided by SM Energy.
6.5 Mechanical stratigraphy

Mechanical stratigraphy uses mechanical properties to stratigraphically correlate units. The previous section discussed differences between each member of the Greenhorn formation in terms of elastic moduli. These mechanical properties can then be tied to the facies descriptions and elemental data in the Noble Aristocrat PC H11-07 well in order to determine distinct geomechanical zones (Figure 6.18). As such, four geomechanical zones have been determined:

**Zone 1**  Carbonate zone: This zone consists of alternating chalk and marl sequences which are representative of the Bridge Creek chalk and marl cycles comprised of facies 1-4. Fluctuating YM, PR, and brittleness correlates to the transitional parasequences of chalk to marl described in chapter 3. Overall, brittleness is highest in this zone, over 15 with an average of 19.82. This zone contains low concentrations of Aluminum, indicating low clay, elevated concentrations of Calcium, indicating carbonate, and elevated Manganese content resulting from bioturbated intervals formed under oxic conditions. Uranium is low, which is consistent with low TOC.

**Zone 2**  Mudstone Zone: This zone corresponds to the mudstone facies 5 a, b, and c. YM, PR, and Brittleness are relatively homogeneous. Brittleness is 10-12. Uranium and aluminum are elevated due to increased organic matter and clay. Calcium and manganese are low because this unit is not carbonate rich and formed under anoxic conditions.

**Zone 3**  Bentonite Zone: The bentonite zone is characterized by decreased brittleness and YM values and increased PR. Thorium is elevated. Spikes in brittleness values occur above and below bentonite beds. Brittleness is less than 10.

**Zone 4**  Interbedded Zone: This zone consists of facies 5, 6 and 7. It is very similar to the carbonate zone but fluctuations in PR are more drastic between carbonate and mudstone intervals due to the interbedded nature of the unit. Brittleness ranges from 12-16. Aluminum and carbonate vary more than in zone 1. Uranium is higher due to increased organic content.
Figure 6.18. Geomechanical zones in the Noble Aristocrat PC H11-07 well. Facies are tied to elastic moduli and elemental data.
6.6 Geomechanical Implications

Geomechanical zones will respond differently to fracture based on elastic moduli and elemental data. From a completions standpoint, ideal carbonate reservoirs should have a high YM and a low PR, with low clay and higher carbonate content. This ultimately affects the brittleness of the rock and will fracture easier. The Bridge Creek is the most brittle Greenhorn member, followed by the Lincoln and then the Hartland. Carbonate zone 1 contains the least amount of clay, detrital material, and organic matter and is high in carbonate with interbedded organic-rich marls, making it the most brittle zone that will fracture easiest close to source beds. Interbedded zone 4 is similar, but has higher amounts of organic matter, making it a possible source rock reservoir. Additionally, this zone is likely to have some added organic porosity due to the nature of organic pores. Both of these zones (1 and 4) have the potential to have the conditions necessary for a “Goldilocks Zone.” The mudstone Zone 2 remains relatively low in all elastic moduli. This makes it less ideal from a completions standpoint. The Bentonite zone 3 has a low YM and a high PR, with the lowest brittleness of all the zones. Bentonite is not very stiff and is very compressible, making it the least favorable in terms of geomechanics. Based on this information, Zone 1 and Zone 4 are the most viable targets in terms of completion quality.

Depositional fabric also has a significant effect on geomechanical properties. The Greenhorn Formation represents two major depositional systems. The Bridge Creek represents a pelagic dominated system, and the Lincoln and the Hartland represent detrital dominated systems. Bulk mineralogy, bioturbation, sedimentary structures, diagenesis, and grain distribution affect depositional fabric which ultimately affect geomechanics. Bioturbated units, such as the Bridge Creek chalks, are very brittle but might not have interconnected pores. Laminations can either positively or negatively affect brittleness. In some of the facies of the Greenhorn Formation, such as the laminated marl and mudstone facies, laminations are predominately carbonate grains, and thus have higher brittleness than other units. However, if internal laminations are predominantly clays, like in the homogeneous mudstone, the unit will be very ductile and will not positively respond to fracture. Diagenesis from burial compaction ultimately enhances the brittleness but might have a negative impact on porosity. All of these factors are important to consider when evaluating a rock’s reservoir potential.
CHAPTER 7

COMPARISON TO NIOBRARA

In addition to understanding the differences between reservoir and completion qualities of each member within the Greenhorn Formation, it is also important to recognize similarities that exist between the Greenhorn Formation and the Niobrara Formation. The chalk beds in the Niobrara Formation are a significant contributor to oil production in the Denver Basin, and any similarities could indicate opportunities for stacked-play scenarios in existing fields. The Niobrara Formation represents a sequence of alternating chalk and marl successions with similar facies seen in the Greenhorn Formation. Both the Niobrara Formation and the Greenhorn Formation represent fluctuations in climate and sea level that resulted in the deposition of chalks and marls.

The Bridge Creek Member of the Greenhorn exhibits similar characteristics to the chalks in the Niobrara on the basis of petrophysical, XRF Elemental and geomechanical data. The chalk beds in both the Niobrara and the Bridge Creek Members have relatively low abundances of detrital elements (Al, Ti, K, and Si) and elevated values of biogenic calcium, indicating chalk (Fig. 7.1). In contrast, the Lincoln and Hartland members have higher concentrations of detrital elements and lower Ca values due to elevated clay content and decreased carbonate production.

One major difference between the Bridge Creek and the Niobrara is Mn content. Most of the Niobrara has low concentrations of Mn, indicating anoxic to suboxic deposition. The Bridge Creek and the Fort Hays Member of the Niobrara both have elevated Mn concentrations, indicating oxic conditions resulting from the highly bioturbated nature of both of these rock units. The Fort Hays is similar to the Bridge Creek in that it consists of recrystallized bioturbated microfossil grainstone or coccolith-rich chalk and marlstone couplets. The fact that the Bridge Creek has a lower Mn concentration than the Fort Hays. This is possibly the result of the more transitional marlstone beds into small chalk sequences in the Bridge Creek to the thick bioturbated chalks with small marlstone sequences in the Fort Hays. The chalk sequences in the Bridge Creek in the 1 Portland core are thicker and more prominent than the chalk sequences in Wattenberg. Unfortunately, XRF data is not available for the Bridge Creek in this core. In the future, it would be interesting to see if a correlation exists between bioturbated chalk bed thickness and Mn content.
Figure 7.1. Detrital indicators in the Niobrara and Greenhorn Formations in the Noble Aristocrat PC H11-07 well (Sonnenberg, 2015).
Differences exist between the Greenhorn Formation and the Niobrara formation on the basis of anoxic and organic indicators (Fig. 7.2). The Niobrara has higher concentrations of anoxic and organic elements than the Greenhorn. Even the organic-rich Hartland and Lincoln members exhibit lower volumes of these elements than most of the marls in the Niobrara. This suggests that the Niobrara source rocks are higher in total organic carbon.

Figure 7.2. Anoxic and organic indicators in the Niobrara and Greenhorn Formations in the Noble Aristocrat PC H11-07 well (Sonnenberg, 2015).
Spectral gamma ray shows similar trends between the Bridge Creek and the Niobrara chalks (Fig. 7.3). Uranium concentrations are highest in the marls and mudstones and lowest in the chalks, indicating organic content. Clay indicators potassium and thorium are low in both the Niobrara chalks and the Bridge Creek, and are elevated in the marls and mudstones. A spike of potassium and thorium at the base of the Bridge Creek is consistent with OAE II. Thorium concentrations are higher in the Greenhorn due to the frequency of bentonite beds.

Figure 7.3. Spectral gamma ray curves (Uranium, potassium, thorium) in the Noble Aristocrat PC H11-07 well (Sonnenberg, 2015).
From a petrophysical standpoint, the Bridge Creek and Niobrara chalk beds reflect similar gamma ray signatures (Fig. 7.4). The chalks in the Niobrara also exhibit elevated resistivity and neutron density separation which reflect carbonate content (Fig. 7.4). Suppressed neutron density

Figure 7.4. Gamma ray, resistivity (shaded over 15 ohms), neutron and density porosity, and bulk density logs for the Noble Aristocrat PC H11-07 well.
resulting in separation may be a reflection of gas saturation, thin beds, calcite, and/or organic matter. Neutron density separation is not seen in the chucks of the Bridge Creek, which may be due to its thinly interbedded nature and a higher proportion of clay. Niobrara source rocks are rich in organic matter and contain fractures that allow for hydrocarbons to travel into the surrounding chalk beds. The source rocks in the bridge creek marls are less rich in TOC and thus, bulk density remains elevated. The Hartland and the Lincoln Members exhibit the opposite: low resistivity and no neutron-density separation, a reflection of higher clay content. High clay content implies higher ductility, and thus lower brittleness and response to fracture.

The Niobrara and the Greenhorn are comparable in terms of elastic moduli (Fig. 7.5). There is some overlap between the Niobrara and the Greenhorn Formations in the chalk and marl facies. Young’s modulus is elevated in the Niobrara Chalks and Bridge creek and is low in the marls and mudstones. The brittleness index follows the same trend as Young’s modulus and is significantly higher in the chalk beds than in the marls and mudstones (Fig. 7.6). This confirms that the chalks are significantly more brittle and will fracture more easily than the marls and mudstones. Fractures in mud-rich facies will have a tendency to close early and/or throughout the life of the well, resulting in production decline over time. In addition, contrasts in the brittleness index indicate fracture barriers that may exist. The Bridge Creek is bounded by the Carlile and the Hartland, which both have decreased brittleness characteristics. The Lincoln Member has been exploited as a source rock reservoir in the Denver Basin and has had both favorable and unfavorable production. However, this data combined with information about the Niobrara Chalks suggests that the Bridge Creek Member may actually be a better target than the Lincoln from a geomechanical standpoint.

A summary of the Niobrara and Greenhorn Formation reservoir properties can be found in Table 7.1. The two formations are very similar except porosity and permeability values are much lower in the Greenhorn. The porosity of the Niobrara Formation averages between 8 and 10% (Sonnenberg, 2012). While the numbers are still very small, porosity values above 5% are more favorable. Based on this information, the Greenhorn Formation may not be as viable as a reservoir target.
Figure 7.5. Cross plot of Young’s Modulus and Poisson’s Ratio for the Noble Aristocrat PC H11-07 well. There is some overlap between the Niobrara and the Greenhorn Formations in the chalk and marl facies (Sonnenberg, 2015).
Figure 7.6. Gamma ray, neutron density, bulk density, compressional sonic, Young’s modulus, Poisson’s ratio and Brittleness for the Noble Aristocrat PC H11-07 well.
Table 7.1. Summary of the Greenhorn and Niobrara reservoir properties.

<table>
<thead>
<tr>
<th></th>
<th>Greenhorn</th>
<th>Niobrara</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong></td>
<td>Late Cretaceous</td>
<td>Late Cretaceous</td>
</tr>
<tr>
<td><strong>Stage</strong></td>
<td>Cenomanian-Turonian</td>
<td>Coniacian-Santonian</td>
</tr>
<tr>
<td><strong>Lithology</strong></td>
<td>Chalks, marls and mudstones</td>
<td>Chalks and Marls</td>
</tr>
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<td><strong>Depth</strong></td>
<td>8000 ft</td>
<td>7000 ft</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
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<td>100-300 ft</td>
</tr>
<tr>
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<td><strong>Perm</strong></td>
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<td>&lt;0.1 mD</td>
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<tr>
<td><strong>TOC</strong></td>
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<td>2-8%</td>
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</tbody>
</table>
CHAPTER 8
RESERVOIR AND COMPLETION QUALITY

Reservoir, source, and completion quality are the last steps to evaluating a potential reservoir. Reservoir quality (RQ) refers to the characteristics that make up a good reservoir and completion quality (CQ) generally refers to geomechanical properties that affect the ability of a reservoir to be completed. Source quality (SQ) analyzes the unit as a source rock reservoir. Table 8.1 summarizes these qualities for the Greenhorn Formation in the Denver Basin.

**Table 8.1.** Greenhorn Formation reservoir, source and completion quality in the Denver Basin.

<table>
<thead>
<tr>
<th></th>
<th>WATTENBERG</th>
<th>N. DENVER BASIN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Noble Aristocrat PC H11-07</td>
<td>BIG SANDY 132-33M</td>
</tr>
<tr>
<td></td>
<td>Bridge Creek</td>
<td>Hartland</td>
</tr>
<tr>
<td>Reservoir Quality</td>
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<td>Lithology</td>
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<tr>
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</table>
Each member was rated qualitatively from 1-3 (3=best) for each category (RQ, SQ, and CQ; Table 9) and summarized by totaling the scores. In the analysis, the Lincoln Member scored highest overall in both wells, largely due to good scores in RQ and SQ. The Bridge Creek Member tied with the Lincoln Member in Wattenberg, but came in second to the Lincoln in the Northern Denver Basin based on its high completion quality scores. The Hartland scored the lowest.

The Lincoln Member has the highest average porosity in both wells, leading to the greatest hydrocarbon storage potential of the three members. However, the high clay content negatively affects RQ and CQ, ultimately bringing the score down. In spite of this, favorable production has been reported for a recent well (Rocky Mountain Oil Journal, 2016). The high clay content may pose a problem in the future for production decline based on current recovery techniques. If technology evolves and advances over time, issues with high clay content may be addressed, and hopefully these reservoirs will become easier and more cost effective to exploit.

The Bridge Creek Member scores highest in CQ due to its high brittleness associated with high carbonate content relative to the other members. The chalk facies within the Bridge Creek bring down the porosity average due to significant recrystallization of the matrix in addition to highly bioturbated fabric. However, the marls within the Bridge Creek have the highest porosity values of all the facies, which brings the average up. Furthermore, the Bridge Creek shows that permeability is highest because of its pore throat size distribution (Chapter 5). While the Bridge Creek scores highest in CQ, this factor alone does not predict success or failure. Hydrocarbon saturation must also be considered for all members.

The Hartland Member has mixed, but generally low scores according to the rating system. Of all the qualities, the Hartland Member scores highest in SQ. This member has the lowest porosity and permeability due to its high clay content, giving it a low RQ and CQ score.

The analysis and conclusions of Kaiser (2013) suggest that the Greenhorn Formation has source rock qualities needed to be a successful unconventional play. This study suggests that if charged, the Lincoln Member holds the most promise while the Bridge Creek Member is also a potential target. Limited production data from Greenhorn tests suggest that various operators are testing the Lincoln. The targeted members are not publicly available.
CHAPTER 9

CONCLUSIONS

1. The Greenhorn Formation represents a complex mixed siliciclastic-carbonate depositional setting. Identified facies represent a transition from chalk to marl to mudstone. Facies 1-4 are representative of low energy pelagic sedimentation with some clastic influx and are only present in the Bridge Creek. Facies 5-7 siliciclastic are representative of a detrital dominated system with reworking from storm beds and are present in the Hartland and Lincoln. Facies 1 and Facies 7 are both carbonate microfossil chalk grainstones, but facies 1 is a pelagic grainstone consisting predominantly of coccoliths while facies 7 is an allograinstone with mainly foraminiferal grains.

2. Facies 1-4 in the Bridge Creek represent a fluctuating water column between vigorous vertical mixing depositing chalks and a stratified water column resulting in marl deposition. These cycles correspond to 41 Ka obliquity Milankovitch cycles. Facies 5-7 are representative of a stratified water column.

3. The ratio between foraminifera to micrite and mud ratio is a major control on lamination scale heterogeneity. Facies with higher carbonate content contain larger foraminifera than facies with low carbonate content.

4. Overall siliciclastic abundance increases from the Bridge Creek to the Lincoln, from less than 20 wt. % to over 30 wt. %. In contrast, carbonate material decreases from the Bridge Creek to the Lincoln. The Bridge Creek Member contains >50 wt. % carbonate, the Hartland is ranges from 30-45 wt. % and the Lincoln Member ranges from 20-30 wt. %. The Bridge Creek has the lowest abundance of clay (<25 wt. %), while the Hartland and the Lincoln have higher percentages of clay material (30-40 wt. %).

5. Based on XRD data, the Bridge Creek Member represents a mixed carbonate mudstone and the Hartland and the Lincoln members represent a mixed mudstone classification due to their elevated siliciclastic and clay contents.
6. Clays in the Bridge Creek have a total abundance of <25 wt. % and consist mainly of illite and mixed layer illite-smectite. The Hartland Member contains 30-40 wt. % clay and is predominantly illite and mixed layer illite-smectite, but low percentages of chlorite (1-2 wt.%) are introduced. Like the Hartland, the Lincoln member is also composed of 30-40 wt. % clay, mainly illite and mixed layer illite-smectite, low percentages of chlorite (1 wt. %), as well as small volumes of kaolinite (1-2 wt. %).

7. The Bridge Creek shows relatively low concentrations of uranium, potassium, and thorium, indicating that this member is low in organic matter and clay, which was confirmed through XRD analysis. The Hartland and the Lincoln members show elevated concentrations of these elements due to higher clay content and organic matter.

8. The decrease in thickness in the Bridge Creek throughout the study area is the result of differences in lithologies as the facies change from more proximal to more distal.

9. Gamma ray signature decreases from the north to the south, while resistivity increases, indicating that the overall facies in the Greenhorn become shalier and more clay-rich as the system moves north.

10. High clay content and thin interbeds are responsible for the low resistivity and neutron-density separation in the Greenhorn Formation.

11. The data for the Noble Aristocrat well show that porosity values are highest in the marl facies of the bridge creek with values over 5%. The lowest porosity values are in the Hartland mudstone facies and are around 1.25-1.34%. The Lincoln expresses a variable range of porosity values, with ranging from 2.79-5.07% in the foraminifera-rich grainstone facies and 4.73% in the homogeneous mudstone facies. Permeabilities are highest in the chalk grainstones and lowest in the mudstones and marls. Bulk grain densities range from 2.55-2.67 g/cc. Big Sandy: The Bridge Creek has an average porosity of 3.23%, the Hartland member 4.68% and the Lincoln member 5.05%.
12. The distribution of pore throat sizes is higher in the chalks than in the mudstones. The calcareous chalks and grainstones have larger pore throat sizes and have higher permeabilities than clay-rich mudstones.

13. The Greenhorn Formation contains both interparticle and intraparticle microporosity.

14. Burial cementation and diagenesis has reduced porosity and permeability in the Bridge Creek. The lack of mineralized fractures in the Bridge Creek member combined with low porosity in the chalk units suggests that burial compaction and diagenesis has affected this unit as a reservoir. Brittleness fluctuates due to the presence of interbedded marls. These marls have higher porosity than the chalks.

15. The Bridge Creek in Wattenberg is more brittle than the Bridge Creek in the northern Denver basin (Average 20, max >40 vs 10) due to elevated carbonate content. The Hartland and the Lincoln remain range from 8-10. The Bridge Creek is the most brittle of the Greenhorn Members and will fracture easiest. The Lincoln and Hartland have more clay and organic matter and are less brittle.

16. To summarize, each of the depositional systems maintains the following geomechanical properties:

- **Biogenic pelagic dominated system:** Bridge Creek chalks and marls (facies 1-4). Relatively low clay, high carbonate, low detrital quartz, high YM, varying PR, high brittleness. Organic content is low. Diagenesis causes chalk and marl facies to show evidence of recrystallization. Chalk units are bioturbated, while marls are more laminated. Laminations are predominantly foraminifera or other fossiliferous carbonate material instead of clay.

- **Detrital dominated system:** Hartland and Lincoln (facies 5-7). Relatively high clay, low carbonate, low detrital quartz, low YM, varying PR, low brittleness. Organic content is higher than in Bridge Creek. Less diagenesis and recrystallization. Bioturbation is cryptic and along laminations if present. Laminations of clay, detrital quartz and silt, and organic matter can be seen in all of the facies associated with this system.
17. Four geomechanical zones have been determined based on geomechanical properties. Based on this, Zones 1 and 4 are the best zones in terms of completion quality.

18. The Bridge Creek is similar to the Niobrara chalks, specifically the Fort Hays, on the basis of petrophysical, XRF elemental, and geomechanical data.

19. The Bridge Creek Member expresses the highest completion quality of the Greenhorn Formation due to its elevated brittleness values from high carbonate content. In Wattenberg, The Bridge Creek is a potential target. The marls have the highest porosity and the chalks provide brittleness for fracture.

20. The Lincoln Member appears to be the best target overall in both regions within the study area when reservoir quality, source quality, and completion quality are considered, despite its high clay content. If technology advances in the future account for production decline in clay-rich intervals, the Lincoln Member could be more successful.
CHAPTER 10

FUTURE WORK

1. Conduct more detailed, facies specific XRF on the Bridge Creek in the Portland or another south core to see if there is a correlation between bed thickness and Mn content.

2. Complete a more extensive clay characterization to understand clay anomalies and their effect on geomechanical character.

3. Evaluate ion-milled samples to check and quantify pore types and sizes.

4. Obtain more MICP and other porosity measurement techniques. Conduct analyses on more than one of each facies to eliminate error.

5. Use XRD/XRF on same sample locations.

6. Complete a study involving more extensive geomechanics. Use the Bambino or hand held micro-rebound hammer to determine rock strength.

7. Complete an in-depth fracture characterization to determine rock strength.

8. Calculate water and oil saturation to determine original oil in place.

9. Complete basin-wide mapping and interpretation of depositional patterns.
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USGS: Core Research Center: http://geology.cr.usgs.gov/crc/


Figure A1. Digitized core description of the full Aristocrat Angus H11-07 core. Gamma ray, resistivity, and neutron density logs are shown. RT90 shading over 15-ohms.
Figure A2. Digitized core description of the Bridge Creek Member from the Aristocrat Angus H11-07 core. Gamma ray, resistivity, and neutron density logs are shown. RT90 shading over 15-ohms.
Figure A3. Digitized core description of the Hartland Member from the Aristocrat Angus H11-07 core. Gamma ray, resistivity, and neutron density logs are shown. RT90 shading over 15-ohms.
Figure A4. Digitized core description of the Lincoln Member from the Aristocrat Angus H11-07 core. Gamma ray, resistivity, and neutron density logs are shown. RT90 shading over 15-ohms.
Figure A5. Digitized core description of the Lincoln Member of the SM Patriot 1-19H core. Gamma ray, resistivity, and neutron density logs are shown. RT90 shading over 15-ohms.
Table A1. MICP data for the Noble Aristocrat PC H11-07 well.

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**Table A2.** MICP data for the EOG Resources Big Sandy 132-33M.

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