AN OUTCROP TO SUBSURFACE STRATIGRAPHIC ANALYSIS OF THE NIOBRARA FORMATION, SAND WASH BASIN, COLORADO

by

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ABSTRACT

The Niobrara Formation is an unconventional oil and gas play containing continuous petroleum accumulations. In the Sand Wash Basin, historical production from the formation has largely occurred at the flanks of the basin from vertical wells that were drilled into swarms of natural fractures associated with Laramide deformation. However, as oil and gas companies explore further basinward, away from natural fracture swarms, the understanding of lateral and stratigraphic variations in mineralogy and TOC in the Niobrara Formation is critical for successful future development. This study combines information gathered from core descriptions, outcrop descriptions, XRD analysis, XRF analysis, geochemical data, and electric well log data to describe how the Niobrara Formation changes from a chalkier lithology in the eastern region of deposition to a marlier lithology in the western region of deposition.

Based on the whole rock and well log data analyzed, peak carbonate deposition and TOC preservation in the Niobrara Formation of the Sand Wash Basin are interpreted to be associated with periods of maximum transgression. These periods occur in the Buck Peak Bench, Tow Creek Bench, and (to a lesser extent) the Wolf Mountain Bench. Peak TOC preservation also correlates to a discrete mineral assemblage in both the Sand Wash and DJ Basins (50 wt.% carbonates, 30 wt.% clays, and 20 wt.% quartz). This mineral assemblage represents the optimal conditions for the preservation of TOC in the Western Interior Seaway during the deposition of the Niobrara Formation. Consequently, the most prospective lateral targets in the Niobrara Formation appear to be associated with maximum transgressive events in the Buck Peak Bench and Tow Creek Bench, and possibly in the Wolf Mountain Bench. These intervals are predicted to be both high quality sources and reservoirs in the formation. The high TOC values associated with these intervals suggest favorable conditions for hydrocarbon generation. Additionally, the high carbonate content suggests favorable brittleness characteristics that make the rocks prone to fracturing (both naturally and from hydraulic stimulation).
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Table 8-2  Summary of the submembers, lithofacies, mineralogic facies, carbonate content, and TOC associated with early regressive periods in the Western Interior Seaway during the deposition of the Niobrara Formation. Associations are drawn for both the Sand Wash Basin and the DJ Basin. ..................................................................................... 100

Table 8-3  Summary of the submembers, lithofacies, mineralogic facies, carbonate content, and TOC associated with periods of maximum regression (lowstand) in the Western Interior Seaway during the deposition of the Niobrara Formation. Associations are drawn for both the Sand Wash Basin and the DJ Basin. ..................................................................................... 101

Table 8-4  Summary of the submembers, lithofacies, mineralogic facies, carbonate content, and TOC associated with early transgressive periods in the Western Interior Seaway during the
deposition of the Niobrara Formation. Associations are drawn for both the Sand Wash Basin and the DJ Basin.

Table A-1 API numbers and well names of all wells used in this study. Data provided courtesy of IHS Global Inc.
ACKNOWLEDGEMENTS

Before all else, this work is dedicated to my family. To my parents and biggest fans, Thomas and Julie Dellenbach, you have been behind me every step of the way, with everything I have done in this life. Without you, any and all of my accomplishments would be left for fulfillment by another. To Joe, without the challenge to become better you have presented me with as my younger brother (even if, at times, it was so you couldn’t rub winning in my face) I would not be at the same place I am now. I hope that your final studies at Mines go smoothly so that we can both attack the world as rock jocks in the coming years. Emily, without your bright attitude and willingness to share fun with me, I would not be the same person. You are going to go far lil’ sis. You’re attitude, work ethic, and joy you take in your work are inspiring. Finally to my grandmother, Glenyce Petersen, you have been more than a major influence on my life. Thank you for helping to raise my brother, my sister, and myself; for exhibiting what it means to take on life with love, joy, and good humor; and for gathering the family under your roof every year so that we may enjoy the good company. Thank you all and I love you.

Next, I would like to express my gratitude to my advisor, Dr. Steve Sonnenberg. Upon completing my undergraduate studies at Mines I did not have a clear plan of what to do next and you provided the opportunity to continue my education at the institution. I thank you for your continued support of all of my work, for your willingness to discuss any questions I have had, and for consistently leading me in the right direction without batting an eye. I greatly enjoyed working with you and will miss the lively discussions we shared on geology, as well as any other subject.

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industry perspective. Without the work I was able to complete under you in Houston, it would have been very difficult to finish in a timely manner.

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I am indebted to the Colorado School as Mines as an institution. My time here has been very challenging and very fulfilling. I believe it has prepared me for almost anything that may cross my path in the coming years. Specifically, the experiences I gathered as a member of Colorado School of Mines Football have forged who I am today. They have given me memories and friendships that will last a lifetime.

Finally, I would like to thank my fiancée, Casie Ratzlaff. Ever since you entered my life, you have made it better. Thank you for all of the love and support you have shown me over the years. I would not be the same person without you and I would not have accomplished as much without you. You motivate me to better myself every day. I love you and I look forward to our lives together.

GO ‘DIGGERS!!
CHAPTER 1
INTRODUCTION

Fine-grained marine deposits make up the vast majority of sedimentary rocks found in the geologic record. Historically, many fine-grained rocks that were deposited offshore in low-energy marine environments (e.g. chalks, marls, and shales) have been identified as prolific source rocks for petroleum systems. With recent advancements in directional drilling and hydraulic fracturing techniques, many of these rocks have been targeted as self-sourced petroleum reservoirs, otherwise known as resource plays. The Niobrara Formation of the Cretaceous Western Interior Seaway is one such target.

1.1 Motivation and Importance

Historically, the Niobrara Formation has served as the major source rock in the Niobrara Petroleum System of the Rocky Mountain Region (Lockridge, 1977; Lockridge and Scholle, 1978; Clayton and Swetland, 1980; Rice 1984a, 1984b; Lockridge and Pollastro, 1988; Pancost et al., 1998; Landon et al., 2001; Finn and Johnson, 2005; Luneau et al., 2011; Sonnenberg, 2011, 2015; Estes-Jackson and Anderson, 2011; and others). As of recent, it has become a reservoir target for lateral wells in the region as a continuous petroleum accumulation (Schmoker, 2005).

The Sand Wash Basin, located in the northwest corner of Colorado (Fig. 1-1), is part of the greater Southwestern Wyoming Province. Historically, it has produced over 26 million barrels of oil (MMBO) from vertical Niobrara wells drilled into fracture plays on anticlinal and monoclinal structures associated with Laramide deformation (Vincelette and Foster, 1992). Still, large volumes of hydrocarbons are estimated to remain within the formation (Table 1-1) in the region (Fig. 1-2). To access the remaining hydrocarbon volumes, oil and gas companies have begun to explore deeper within the basin, away from flexural fracture plays. However, for companies to successfully produce basin-centered petroleum resources, optimal stratigraphic targets must be identified for lateral well placement within the Niobrara Formation. Consequently, a detailed understanding of the history of deposition and stratigraphic nature of
the formation is essential. In the Sand Wash Basin, little information has been documented on the
Niobrara Formation regarding these subjects. The work completed in this study aims to improve upon this
lack of information by documenting the nature of organic richness, mineralogy, lithology, elemental
occurrence, and thermal maturity of the Niobrara Formation within the Sand Wash Basin.

Figure 1-1: Map of the major basins and oil and gas fields of Colorado, taken from the Colorado Oil and
Gas Conservation Commission (COGCC) website (COGCC, 2016). The Sand Wash Basin is labeled as
the basin of focus for this study.
Table 1-1: Summary of assessment results for the Niobrara Total Petroleum System (Fig. 1-2). [MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 denotes a 95-percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable] (Finn and Johnson, 2005).

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<td>66.90</td>
<td>100.50</td>
<td>151.00</td>
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</table>

Figure 1-2: Map of the Southwestern Wyoming Province showing the extent of the Niobrara Total Petroleum System (TPS) and major structural elements. Contours represent the approximate depth in feet to the base of the Niobrara Formation (Modified from Kirschbaum and Roberts, 2005). Contour intervals = 2,000 feet. (Modified from Finn and Johnson, 2005).
1.2 Objectives and Purpose

The main objective of this study is to provide a better understanding of how, why, and where the Niobrara Formation changes from a chalky lithology in the eastern region of deposition to a marly lithology in the western region of deposition (Fig. 1-3). Within the regional context, the study also aims to improve upon the understanding of why higher accumulations of organic matter and carbonate material occur in certain stratigraphic intervals.

Figure 1-3: Schematic diagram of the Cretaceous Western Interior Seaway during the time of Niobrara deposition (modified from Roberts and Kirschbaum, 1995). Basinal trends in depth, clay, sand, %TOC, and carbonate are overlain on the diagram (Longman et al., 1998). The Sand Wash Basin is denoted by the green circle and the DJ basin is denoted by the red circle. The greater Southwestern Wyoming Province is outlined in red.
The aforementioned objectives will be attained with the purpose of aiding with the exploration for and production of hydrocarbons from the Niobrara Formation in the Sand Wash Basin, northwestern Colorado, as well as elsewhere in the Rocky Mountain Region. A better understanding of the horizontal and vertical variations within the Niobrara Formation will provide insight on what stratigraphic intervals of the formation are optimal for production of large volumes of hydrocarbons and therefore, lateral well placement.

1.3 Dataset and Methodology

Several types of data (well logs, core, XRD, XRF, geochemical, and outcrop) were supplied by multiple donors for use in this study (Table 1-2). The locations of the data are shown in Figure 1-4.

Table 1-2: Data used for this study. Wells used, sample types, and the sources of the data are listed. Well locations are displayed in Figure 1-4. RSWC = rotary sidewall core, SWN = Southwestern Energy, BEG = Bureau of Economic Geology.

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Figure 1-4: Diagram displaying the location and extent of data used for this study. All data is located in northwestern Colorado in Routt, Moffat, and Rio Blanco Counties. The locations of all 111 wells with well logs used for this study are displayed with differing well symbols according to the status of each well. Key wells (those containing core, XRD, XRF, spectral GR, and/or geochemical data) are outlined with black circles and labeled. The location of the Niobrara outcrop used in this study is shown by the yellow box. Oil and gas fields of Colorado are shown in red.
CHAPTER 2
GEOLOGIC OVERVIEW

This chapter discusses the regional and structural setting of the Sand Wash Basin. In addition, the internal stratigraphy, depositional setting, regional nomenclature, and source and reservoir rocks of the Niobrara Formation are addressed.

2.1 Sand Wash Basin

The Sand Wash Basin covers an area greater than 3,000 square miles in northwestern Colorado. Historically, it has been an important location for hydrocarbon production within the Rocky Mountain region. Included within the greater Southwestern Wyoming Province (SWWP), it is an asymmetric, Laramide-age (70-40 Ma) intramontane basin. It is structurally bounded by the Sierra Madre and Park Ranges to the east, the Axial Basin and Uinta Mountain Uplifts to the south and west, and the Cherokee Ridge anticline to the north (Fig. 2-1). Structurally, the basin exhibits an average dip of 3° to the W-NW. The dip flattens as it reaches the basin center and steepens towards the basin flanks to the east and south. It is along the areas of the steepest dip where maximum flexure of the formation is reached, extensive faulting occurs, and the majority of historical Niobrara production (> 26 MMBO) has been achieved (Vincelette and Foster, 1992). Structural features (faults and folds) within the basin trend primarily N-S, as exhibited by the Tow Creek and Sage Creek anticlines, and NW-SE, as exhibited by the Buck Peak and Axial Basin anticlines (Fig. 2-1). Depths to the Niobrara Formation range from surface exposures on the eastern and southern flanks to greater than 20,000 feet in the northwestern part of the basin. With such great variations in depth, the source rock maturity of the formation is within both the oil and gas generation windows (Finn and Johnson, 2005).
2.2 Regional Structural Setting and Stratigraphy

Early to Late Cretaceous sedimentation in the interior of North America occurred within a broad, asymmetric foreland basin referred to as the Western Interior Basin (WIB) (Kauffman, 1977). The basin formed as a result of crustal flexure produced by the Sevier Orogeny; a consequence of the subduction of the Farallon Plate beneath the North American craton (Humphreys et al., 2003) (Fig. 2-2a). Structurally bounding the basin was the Sevier Orogenic thrust belt to the west and a low relief stable craton to the east (Kauffman, 1977; Longman et al., 1998) (Fig. 1-3). Cretaceous sedimentation in the WIB began with the deposition of the Cedar Mountain Sandstone and was complete with the deposition of the Fox Hills Sandstone and Lance formations (Fig. 2-3). Accumulations of sediment were thickest in the deepest parts of the basin, along its western margin (Fig. 2-4). The thickness and spatial distribution of the strata were controlled by flexure of the North American craton from the loading by the Sevier Orogenic thrust belt to the west (Longman et al., 1998).
Figure 2-2: A schematic cross-section of the western United States showing the changes in the geometry of the Farallon Plate through time. a) Geometry of the Farallon Plate during the Sevier Orogeny. The WIB is shown to the east of the Sevier Orogenic thrust belt. b) Geometry of the shallowing Farallon Plate during the Laramide orogenic event (modified from Humphreys et al., 2003).

Figure 2-3: Generalized stratigraphic chart of Cretaceous rocks in the Southwestern Wyoming Province. The Sand Wash Basin (basin of study) is outlined in bold and the Niobrara Formation is outlined in blue (modified from Ryder (1988)).
The end of the Cretaceous was marked, in part, by the onset of the Laramide Orogeny (70-40 Ma), which was a result of the shift of the Farallon Plate to low angle subduction (Longman et al., 1998) (Fig. 2-2b). Consequently, the originally flat-lying rocks of the WIB were uplifted, faulted, and folded, creating the modern Rocky Mountains and the present day sedimentary basins of Colorado.

2.3 Deposition of the Niobrara Formation

The sediments of the Niobrara Formation were deposited during the Late Cretaceous (Coniacian-Santonian) in an epeiric seaway known as the Cretaceous Western Interior Seaway (WIS) (Weimer, 1959; 1978, 1983; Hattin, 1982; Kauffman, 1969, 1977; Weimer and Flexer, 1985; Kauffman and Caldwell, 1993; Roberts and Kirschbaum, 1995; Longman et al., 1998; Kirschbaum and Roberts, 2005; Locklair
Deposition of chalks, marls, and calcareous shales in the WIS were a result of a major 3rd-order transgressive-regressive (T-R) cycle, which is called the Niobrara Cyclothem (Fig. 2-5). The transgressive cyclothem was created by combined crustal subsidence in the Western Interior Basin and high eustatic sea level (Kauffman, 1977; Longman et al., 1998). Within the Niobrara Cyclothem, four climatically driven 4th-order T-R cycles (T-R7a – T-R7d) occurred and cyclically deposited the lithologies that are observed within the Niobrara Formation (Kauffman, 1967, 1969, 1977, 1984, 1985a, 1985b) (Fig. 2-5). Carbonate-rich lithologies were deposited during 4th-order transgressive phases T7a – T7d. Alternatively, carbonate-starved lithologies were deposited during regressions R7a – R7d.

Figure 2-5: a) Regional sea level trends of the Late Cretaceous in the Western Interior Basin (modified from Kauffman and Caldwell, 1993). b) The submembers of the Niobrara Formation in the DJ Basin are shown on the reference well Libsack 43-27 (NESE sec. 27 T4N R65W) (modified from Drake and Hawkins, 2012). c) Generalized 4th order T-R cycles that resulted in the cyclic deposition of Niobrara Formation lithologies (modified from Kauffman, 1977).
In addition to fluctuations in sea level, deposition of the Niobrara Formation in the WIS was influenced by the interaction of warm northern-flowing currents from the ancestral Gulf of Mexico to the south and cooler southern-flowing currents from the Arctic Sea to the north. The interplay of these currents created a counter-clockwise flow across much of the Rocky Mountain Region (Slingerland et al., 1996, Longman et al., 1998). Longman et al. (1998) concluded that the warmer northern-flowing currents facilitated the majority of carbonate deposition in the Niobrara Formation by bringing an abundance of coccoliths and planktonic forams into the seaway. Contrastingly, the cooler Arctic currents contributed little carbonate material to the seaway, and instead reworked siliciclastic sediments southward along the western margin of the seaway (Fig. 2-6).

Figure 2-6: The Cretaceous Western Interior Basin during the deposition of Niobrara Formation. The source for clastics was dominantly to the west. Total organic carbon (TOC) in the Niobrara increases to the east. Carbonate content generally increases to the east and southeast. Black rectangles represent the location of the study area (modified from Longman et al., 1998).
2.4 Niobrara Formation Stratigraphy and Nomenclature

The rise and fall of the relative sea level in the WIS resulted in the cyclical deposition of chalky and marly bedding in the Niobrara Formation. Although the cyclic deposits are consistent across the Rocky Mountain Region, the lithostratigraphic nomenclature of such deposits is not. In western Kansas and eastern Colorado (DJ Basin), the Niobrara Formation is divided into two members. The basal member, known as the Fort Hays Limestone, was deposited unconformably on the Carlile Shale and conformably underlies the Smoky Hill Member of the Niobrara Formation (Hattin, 1982; Longman et al., 1998). The Smoky Hill Member contains three to four chalk benches with three intervening marls. In ascending order, the chalk benches and marls of the Smoky Hill Member in western Kansas and eastern Colorado are named as follows: D Chalk/Marl (where present), C Marl, C Chalk, B Marl, B Chalk, A Marl, and A Chalk (Fig. 2-7). The Smoky Hill Member in western Kansas and eastern Colorado is overlain unconformably by the Pierre Shale.

The Niobrara Formation of the Sand Wash Basin unconformably overlies the Carlile Shale and unconformably underlies the Mancos Shale (equivalent to the Pierre Shale). Current nomenclature in the region of the Sand Wash Basin also identifies the two members of Niobrara Formation as the Fort Hays Limestone and the Smoky Hill Member. However, the naming of the submembers is inconsistent with the aforementioned chalks and marls of Kansas and the DJ Basin. The difference in nomenclature is rooted in the lithologic variation of the Niobrara Formation from east to west. At the western end of Niobrara deposition, the chalks and marls of western Kansas and eastern Colorado change facies to marls and calcareous shales. The informal naming convention in the Sand Wash Basin identifies the Buck Peak Bench, Tow Creek Bench, Wolf Mountain Bench, and Rangely Bench as equivalents to the A Chalk, B Chalk, C Chalk, and C Marl, respectively (Vincelette and Foster, 1992; Finn and Johnson, 2005) (Fig. 2-7). It is proposed in this study that the Rangely Bench should be divided into “Upper” and “Basal” classifications. Also proposed for this study is the use of “Upper Marl” and “Middle Marl” in the Sand Wash Basin as equivalents to the A Marl and B Marl, respectively (Fig. 2-7). In summary, the following
The nomenclature will be used for the remainder of this study (listed in ascending order): Fort Hays Limestone, Basal Rangely Bench, Upper Rangely Bench, Wolf Mountain Bench, Middle Marl, Tow Creek Bench, Upper Marl, and Buck Peak Bench.

2.5 Source Rocks and Reservoirs of the Niobrara Formation

In the Niobrara Formation of the DJ Basin, several authors have documented slightly higher total organic carbon (TOC) content in the marls (2-8%) than in the chalks (1-3%) (Landon et al., 2001; Sonnenberg, 2015). Type II (oil prone) kerogen is dominant in both lithologies (Landon et al., 2001; Sonnenberg 2011; and Jarvie, 2012). However, the chalks are much more brittle than the marls and are
more prone to fracturing (both naturally and from hydraulic stimulation). As a result, the marls have historically proven to be better source rocks while the chalks are better reservoirs.

In the Niobrara Formation of the Sand Wash Basin, TOC values decrease from what are found in the DJ Basin, ranging from 0.85-2.75% (Finn and Johnson, 2005). The decrease in TOC values from east to west is a result of dilution by clastic sediments that were shed off of the Sevier Orogenic thrust belt to the west of the Western Interior Seaway. In the Sand Wash Basin, type II kerogen remains dominant, but Rock Eval pyrolysis has shown that type III (gas prone) kerogen is present as well (Finn and Johnson, 2005). Type-III kerogen was derived from terrestrial sources along the western shoreline of the WIS, and (or) from cavings from the overlying Mancos Shale (Finn and Johnson, 2005). According to Vincelette and Foster (1992), the majority of historical Niobrara Formation production in the Sand Wash Basin was derived from the carbonate-rich Buck Peak, Tow Creek, and Wolf Mountain benches. The relatively high carbonate content of these benches facilitates both natural and hydraulically-induced fracturing, making them the highest quality reservoirs in the Niobrara Formation section of the Sand Wash Basin. These benches also contain the highest concentrations of TOC throughout the section, making them the highest quality source rocks as well. Stratigraphic accumulations of TOC and carbonate material in the Niobrara Formation of the Sand Wash Basin will be discussed in following chapters.
CHAPTER 3

SUBSURFACE MAPPING

This chapter discusses the identification of the Niobrara Formation lithologies in the subsurface from electric well logs. Subsequently, regional mapping of the subsurface in the Sand Wash Basin is addressed and results are displayed.

3.1 Identification of the Niobrara Formation in Well Logs

The Niobrara Formation and its submembers can be identified in the subsurface with the use of electric well logs. In the Sand Wash Basin, the top of the Niobrara Formation is marked by a sharp increase in the gamma ray (GR) log compared to lower GR values at the base of the Mancos Shale (Fig. 3-1). The base of the formation can be identified by a sharp increase in GR values that represent the Carlile Shale directly below the clean GR response that represents the Fort Hays Limestone.

The Buck Peak, Tow Creek, and Wolf Mountain benches of the Smoky Hill Member can be recognized by elevated resistivity values and slightly elevated GR values (Fig. 3-1). When available, spectral GR logs show a crossover (or convergence) of thorium/uranium (Th/U) values (low Th, high U) that is a common characteristic of these benches. The internal GR character exhibited within these benches is consistent enough that it is mappable across the region of study with high confidence.

The Upper Marl, Lower Marl, and Upper and Basal Rangely Bench can be identified by characteristically low resistivity and GR values compared to those of the Buck Peak, Tow Creek, and Wolf Mountain Benches (Fig. 3-1). The contact between the Upper and Basal Rangely Bench submembers is marked by a sharp upward increase in GR values that is accompanied by an increase in resistivity values. Spectral GR logs display a divergence of Th/U values (high Th, low U) in each of these submembers. Inconsistent internal GR character is observed the Upper and Lower Marls and Upper and Basal Rangely Bench and cannot be traced across the region with high confidence.
The Fort Hays Limestone can be easily identified on GR logs in the study area. Located beneath the Basal Rangely Bench of the Smoky Hill Member, it exhibits a sharp decrease in GR values compared to those of the overlying units (Fig. 3-1). Resistivity values exhibit an upward-increasing trend throughout the member. Spectral GR logs in the Fort Hays Limestone display a decrease in both uranium and thorium values compared to values seen throughout the Smoky Hill Member.

Figure 3-1: The Welker 42-11 wireline log (left) correlated to the type reference log from the Trigg #1-5X well (NWNW sec. 5 T6N R86W) (right). Welker 42-11: left track – GR (API), middle track – resistivity (ohms), right track – spectral GR (ppm). Note spectral U (green)/Th (purple) crossover (or convergence) in the Buck Peak, Tow Creek, and Wolf Mountain benches of the Welker 42-11 well. Trigg #1-5X: left track – GR, right track – resistivity. Reference well log modified from Vincelette and Foster (1992).
3.2 Subsurface Mapping: Lithostratigraphy

A set of 111 well logs (Appendix A) containing partial or complete sections of the Niobrara Formation were mapped across the region of interest. Lithologic picking and regional mapping from well logs were accomplished with the use of the computer software IHS Kingdom® and Petra®. The identification of each of the Niobrara lithologies was completed for each well supplied (Fig. 3-1). Following identification of Niobrara Formation lithologies across the region, structural and isochore maps, as well as a cross-section were created (Fig. 3-2 – 3-4).

3.2.1 Structure

In the study area, the Niobrara Formation shows > 14,000 feet of vertical relief from the southeast to the northwest and generally dips to the northwest (Fig. 3-2). The shallowest depths are along the Axial Basin Uplift and Park Range to the south and east, respectively. Outcrop of the formation is present in the eastern margin of the study area. The formation reaches the greatest depths in the northwest part of the study area, at the center of the Sand Wash Basin.

3.2.2 Thickness

The thickest intervals of the Niobrara Formation reside along the west-northwest fringes of the study area (Fig. 3-3). Thinning occurs towards the east-southeast as the formation is reduced from greater than 2,000 feet of true vertical thickness (TVT) to less than 1,000 feet in the southeast part of the mapping area. Cross-section A-A’ (Fig. 3-4) illustrates the variation in thickness of the Niobrara Formation as it gains over 850 feet in TVT over a lateral distance of approximately 73 miles. The calculated average gain in thickness from east to west is 11.6 feet/mile. The duration of Niobrara Formation deposition has been interpreted to have taken place from 88 to 82 Ma by Dyman et al. (1994) and 89.5-83 Ma by Dean and Arthur (1998). These dates correspond to significant differences in average sedimentation rates of approximately 4.7 – 5 cm/thousand years between the thickest and thinnest sections of the Niobrara Formation within the study area. The thickness increase from east to west reflects an influx of
siliciclastics from the Sevier orogenic thrust belt to the west during the time of deposition. Dilution of carbonate material and TOC was a result of the increasing siliciclastic content to the west. The effects of clastic dilution on bulk mineralogy in the Niobrara Formation of the Sand Wash Basin are discussed in Chapter 6: Mineralogy and Elemental Analysis.
Figure 3-2: Regional structure map of the study area. Depths are subsea true vertical depths (SSTVD) to the top of the Niobrara Formation (contour interval = 1000').
Figure 3-3: Regional isochore map showing true vertical thickness (TVT) of the Niobrara in the study area (contour interval = 50’). Cross sectional line A-A’ corresponds to Figure 3-4.
Figure 3-4: Regional cross-section A-A’ displaying thickness changes in the Niobrara Formation from east to west along eight selected wells in the Sand Wash Basin (Fig. 3-3).
CHAPTER 4
CORE STUDY

This chapter covers a complete overview and description of three Niobrara Formation cores that were analyzed over the course of this study. The identification of ten lithofacies that were distinguished from within the cores is discussed. Subsequently, facies associations are assigned and depositional environments are interpreted for each core section.

4.1 Core Locations and Intervals

Three cores taken from the Niobrara Formation in the Sand Wash Basin were used in this study (Fig. 4-1). They were described in detail at a half-foot interval, with special attention given to sedimentary structures, fossil occurrence, and bentonite occurrence. Two cores were donated for use by Southwestern Energy (SWN): the Welker 42-11 core and the RMCCS State #1 core. The Welker 42-11 core is comprised of part of the Upper Rangely Bench, the full sections of the Wolf Mountain Bench, the Middle Marl, and the Tow Creek Bench, and part of the Upper Marl, for a total core length of 615 feet. The RMCCS State #1 core is comprised of sections of the Tow Creek Bench and the Upper Marl for a total core length of 120 feet (with some missing sections lost during the core retrieval process). The USA 1-22 core was described with permission from the BEG, located at the Core Research Center (CRC) in Austin, TX. It is comprised of sections of the Fort Hays Limestone, Wolf Mountain Bench, Tow Creek Bench, Upper Marl, and Buck Peak Bench for a combined total core length of 251 feet. Initially, lithofacies from each core were identified and described. Subsequently, facies associations were drawn and used to interpret the depositional styles represented by the lithologies present in the Niobrara Formation of the Sand Wash Basin.
4.2 Summary of Results

Ten lithofacies were observed over the course of the core study. The facies were identified visually at hand-sample scale from slabbed core samples. They were categorized by presence of sedimentary structures, macrofossil content, and mineralogy. Facies A – I have similar mineralogical constituents. Silt-sized grains found in these facies are predominantly angular to subangular detrital quartz. Large carbonate grains represent biogenic materials present in the cores. They occur as bivalve fragments, pellets, and planktonic foramin tests. Clay-sized material in these facies is composed of micrite, as well as mixed-layer illite/smectite, illite/mica, chlorite, and kaolinite. Approximately 15-25% of the mixed illite/smectite clays contain expandable interlayers. The clay-sized material was identified via XRD analysis performed on selected samples from the cores. Framboidal pyrite is also a common feature of Facies A – I. Facies J (the bentonite facies) contains mineral assemblages that differ greatly from Facies A – I. Mixed-layer illite/smectite is the most common mineral in Facies J, followed by plagioclase, kaolinite, and small amounts of chlorite, illite, biotite, calcite, quartz, K-feldspar, and pyrite. Approximately 30-40% of the
mixed illite/smectite clays in the bentonite beds contain expandable interlayers. Mineral constituents of Facies J were identified by XRD analysis and visual observation at the petrographic thin section scale.

4.3 Lithofacies Classification Scheme

Traditionally the lithofacies of the Niobrara Formation have been compositionally classified along a carbonate-shale spectrum that utilizes chalk nomenclature; i.e. chalks, marls, and shales (Longman et al., 1998; Stout, 2012) (Fig. 4-2a,b). However, the lithologies of the Niobrara Formation in the Sand Wash Basin are undifferentiated under these schemes, as they are classified exclusively as marls. In addition, quartz, which accounts for >40% of the bulk mineralogy of the Niobrara Formation in the Sand Wash Basin in some cases, is ignored by the traditional classifications. Therefore, in order to better resolve lithologic variation in the Niobrara Formation in the Sand Wash Basin, the mudrock classification scheme proposed by Gamero-Diaz et al. (2012) (Fig. 4-2c) will be used to classify the lithofacies of the formation for the remainder of this study (Fig. 4-3) (Table 4-1). Under this scheme, the continuum between the carbonate-shale spectrum is further refined from traditional classifications, and the quartz component of the lithologies is taken into account.

4.4 Facies Descriptions

Facies A is a dark-gray, well-laminated, foraminifera-rich mixed mudstone. It is characterized by planar to subplanar laminae that are easily distinguishable in hand sample (Fig. 4-3). Laminae may be sharp or diffuse. They are created by variations in silt and clay content and are typically normally graded, with silt bases that fine upwards into clay-sized particles. Bioturbation is evident in some petrographic thin section samples taken from this facies (Fig. 4-4a) and may be the cause of the diffuse texture. Flattened, elongate pellets are sparsely scattered throughout the facies (Fig. 4-4a). Framboidal pyrite is a common feature of the facies and exists as small, subrounded opaque minerals (Fig. 4-4b). Observed microfossils consist exclusively of planktonic foraminifera. Rare organic matter is dark-brown to black amorphous material (Fig. 4-4b).
Figure 4-2: Comparison of mineralogical classification schemes used by various authors. a) Carbonate-shale spectrum classification scheme used to describe Niobrara Formation lithologies by Longman et al. (1998) (modified from Pettijohn, 1975). b) Niobrara Formation scheme developed by the Colorado School of Mines Niobrara Consortium (Stout, 2012). c) Mudrock classification scheme used in this study, from Gamero-Diaz et al. (2012).
Facies B is a dark-gray, well-laminated, foraminiferal-molluscan mixed mudstone. It is identical to Facies A, except for the occurrence of fragmented bivalve shells (Fig. 4-3). All of the shells identified belong to either the large bivalves of the Inoceramidae family, with most belonging to the *Platyceramus platinus* (Logan, 1898) subgenus, specifically; or to the ostreid bivalve *Pseudoperna congesta* (Conrad, 1857), which are commonly found encrusting inoceramid shells. The bivalve macrofossils can be observed regularly in this facies at orientations parallel to laminae. The shells are commonly partially to completely pyritized.

Facies C is a light-gray to dark-gray, well-laminated, pelletal mixed carbonate mudstone. In hand sample this facies appears nearly identical to the well laminated nature of Facies A. Initially, the two facies were undifferentiated from each other during the description of core slabs. It was not until the microfabrics of each facies were studied at the petrographic thin section scale that obvious differences were recognized. Unlike the graded silt to clay beds that characterize Facies A, the rock fabric of Facies C exhibits a heavily pelleted texture in a matrix of clays and quartz silt (Fig. 4-5a). It may be classified as a true pelletal wackestone. Framboidal pyrite and small planktonic forams are present throughout the facies as well and organic matter occurs as black amorphous material (Fig. 4-5b).

Facies D is a light-gray to dark-gray, well-laminated, pelletal, mollusk-rich mixed carbonate mudstone. It is identical to Facies C, except for the occurrence of fragmented inoceramid (*P. platinus*) and ostreid bivalve (*P. congesta*) shells parallel to bedding planes (Fig. 4-3). These shells are commonly partially to completely pyritized.

Facies E is a dark-gray, poorly-laminated, pelletal-foraminiferal mixed mudstone. It is characterized by planar to subplanar laminae that are difficult, but possible to distinguish in hand sample (Fig. 4-3). The laminations are created by variations in silt and clay content. At petrographic thin section-scale, the facies is commonly represented by thinly laminated, fining-upward bedsets (< 1/5 in.). The bedsets commonly display basal silt lags, sometimes exhibiting scoured contacts, and show normal
grading upwards into clay-sized particles (Fig. 4-6a). Bioturbation was observed in a few petrographic thin sections. Elongated pellets are common and may form discrete laminae where particularly abundant. Framboidal pyrite is a common constituent throughout the facies. Planktonic foraminifera were the only microfossils identified in the provided petrographic thin sections. Amorphous dark-brown to black organic matter can be observed in some petrographic thin section samples as well (Fig. 4-6b).

Facies F is a dark-gray, poorly-laminated, pelletal-foraminiferal, mollusk-rich mixed mudstone. It is identical to Facies E, except for the occurrence of fragmented inoceramid (P. platinus) and ostreid bivalve (P. congesta) shells (Fig. 4-3). The bivalve macrofossils are found parallel to laminae and represent shell lags at the bases of normally graded bedforms. Where observed in the cores, the shells are commonly partially to fully pyritized.

Facies G is a black structureless, pelletal-foraminiferal mixed mudstone. At the petrographic thin section scale silt- and clay-sized particles are poorly sorted and laminae are either non-existent or faint (Fig. 4-7a). Bioturbation appears to be rare in this facies, but can be observed in a few petrographic thin section samples. Flattened, elongate pellets and planktonic foraminifera are a common constituent of the facies and are found dispersed throughout the sediment. Framboidal pyrite occurs frequently and appears as small opaques in petrographic thin sections. Organic material can be commonly found and usually appears as black amorphous material (Fig. 4-7b).

Facies H is a black structureless, pelletal-foraminiferal, mollusk-rich mixed mudstone. It is identical to Facies G, except for the occurrence of fragmented inoceramid (P. platinus) and ostreid bivalve (P. congesta) shells (Fig. 4-3). The bivalve fossils commonly display random orientations, and appear to be “floating” in the sediment. They are commonly partially to completely pyritized.

Facies I is a dark-gray bioturbated foraminiferal-molluscan mixed carbonate mudstone. It is characterized by disrupted, bioturbated bedding that is visually identifiable in core sample (Figs. 4-3, 4-8a). Fragmented inoceramid (P. platinus) and ostreid bivalve (P. congesta) shells are commonly observed
at random orientations. At the petrographic thin section scale, bedding appears massive as a result of the extensive bioturbation (Fig. 4-8b). Laminae are absent from this facies. Planktonic foraminifera are abundant, and in some petrographic thin section samples phosphate fragments are present and probably are fragmented fish fossils. Organic matter is rare, but appears as black amorphous material where present.

Facies J is comprised of ¼ inch to 2 ½ inch thick yellow-gray volcanic ash beds. The majority of the ash beds observed are altered to bentonite, although some unaltered beds were observed as well. Basal and upper contacts of ash beds with the other facies are planar to wavy to disrupted and discontinuous (Fig. 4-9a-e). However, thin (< 1 in.), planar beds are the most common (Fig. 4-9b). Some beds have diffuse upper contacts where they appear to mix with other sediments. Several unaltered volcanic ash beds display normal grading of crystals, while others display no grading. Petrographic analyses performed on a few sampled beds revealed that mixed-layer illite/smectite is the most common mineral in Facies J, followed by plagioclase, kaolinite, and small amounts of chlorite, illite, biotite, calcite, quartz, K-feldspar, and pyrite. Approximately 30-40% of the mixed illite/smectite clays contain expandable interlayers in these ash beds.

4.5 Facies Associations and Depositional Interpretations

Following the identification and description of ten lithofacies in the three cores that were analyzed for this study, facies associations and depositional environments were interpreted (Table 4-2). All interpretations are based off of the presence and style of sedimentary structures, bioturbation, TOC content, and mineralogic content exhibited by each lithologic facies.

4.5.1 Facies A, B, E, F – Deposition and Associations

The mixed mudstones of Facies A, B, E, and F exhibit graded laminasets, silt and shell lags, sparse pellets, amorphous organic matter, frambooidal pyrite, and occasional bioturbation. The normally graded, often basally eroded laminasets present in these facies are inconsistent with deposition by suspension
Figure 4-3: Lithofacies (A – J) identified and described from the Welker 42-11, RMCCS State #1, and USA 1-22 cores
Table 4-1: List and descriptions of identified lithofacies in the Niobrara Formation in the Sand Wash Basin from the Welker 42-11, RMCCS State #1, and USA 1-22 cores.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Facies Name</th>
<th>Geologic Description</th>
<th>Micro Fabric</th>
<th>Relative Detrital Content (Quartz and Clays)</th>
<th>Relative Biogenic Content (Carbonates)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Well-laminated, foraminifera-rich mixed mudstone</td>
<td>Dark-gray; well-defined to diffuse normally graded planar and subplanar lamina sets (&lt; 1/5 in. thick); bioturbated in areas; sparsely pelleted; contains frambooidal pyrite, planktonic foraminifera, and amorphous organic matter</td>
<td>laminated, sometimes bioturbated</td>
<td>High (&gt; 70 wt.%)</td>
<td>Low (&lt; 30 wt.%)</td>
</tr>
<tr>
<td>B</td>
<td>Well-laminated, foraminiferal-molluscan mixed mudstone</td>
<td>Identical to Facies A, except for the occurrence of fragmented bivalve shells (<em>Inoceramus</em> sp. and <em>Pseudoperna congesta</em>) that lie parallel to bedding planes. The bivalve fragments are commonly partially to fully pyritized</td>
<td>laminated, sometimes bioturbated</td>
<td>High (&gt; 70 wt.%)</td>
<td>Low (&lt; 30 wt.%)</td>
</tr>
<tr>
<td>C</td>
<td>Well-laminated, pelletal mixed carbonate mudstone</td>
<td>Light-gray to dark-gray; heavily pelleted (pelletal wackestone); pellet accumulations appear to create well-defined laminations at the hand sample scale; contains frambooidal pyrite, planktonic foraminifera, and amorphous organic matter</td>
<td>&lt; 1/50 in. (5 mm) dia. pellets in a matrix of clays, quartz silt, and carbonate materials</td>
<td>Low (&lt; 40-50 wt.%)</td>
<td>High (&gt; 50-60 wt.%)</td>
</tr>
<tr>
<td>D</td>
<td>Well-laminated, pelletal, mollusk-rich mixed carbonate mudstone</td>
<td>Identical to Facies C, except for the occurrence of fragmented bivalve shells (<em>Inoceramus</em> sp. and <em>Pseudoperna congesta</em>) that lie parallel to bedding planes. The bivalve fragments are commonly partially to fully pyritized</td>
<td>&lt; 1/50 in. (5 mm) dia. pellets in a matrix of clays, quartz silt, and carbonate materials</td>
<td>Low (&lt; 40-50 wt.%)</td>
<td>High (&gt; 50-60 wt.%)</td>
</tr>
<tr>
<td>E</td>
<td>Poorly-laminated, pelletal-foraminiferal mixed mudstone</td>
<td>Dark-gray; poorly-laminated at hand sample scale; well-defined normally graded planar and subplanar lamina sets (&lt; 1/5 in. thick) at the petrographic thin section scale; rare bioturbation; sparsely pelleted; contains frambooidal pyrite, planktonic foraminifera, and amorphous organic matter</td>
<td>laminated, rarely bioturbated</td>
<td>Moderate (50-70 wt.%)</td>
<td>Moderate (30-50 wt.%)</td>
</tr>
<tr>
<td>F</td>
<td>Poorly-laminated, pelletal-foraminiferal, mollusk-rich mixed mudstone</td>
<td>Identical to Facies E, except for the occurrence of fragmented bivalve shells (<em>Inoceramus</em> sp. and <em>Pseudoperna congesta</em>) that lie parallel to bedding planes. The bivalve fragments are commonly partially to fully pyritized</td>
<td>laminated, rarely bioturbated</td>
<td>Moderate (50-70 wt.%)</td>
<td>Moderate (30-50 wt.%)</td>
</tr>
<tr>
<td>G</td>
<td>Structureless, pelletal-foraminiferal mixed mudstone</td>
<td>Black; structureless (massive) bedding; poorly sorted quartz silt, clays, and carbonate materials; rare bioturbation; pelleted; contains frambooidal pyrite, planktonic foraminifera, and amorphous organic matter</td>
<td>massive</td>
<td>Moderate (50-70 wt.%)</td>
<td>Moderate (30-50 wt.%)</td>
</tr>
<tr>
<td>H</td>
<td>Structureless, pelletal-foraminiferal, mollusk-rich mixed mudstone</td>
<td>Identical to Facies G, except for the occurrence of fragmented bivalve shells (<em>Inoceramus</em> sp. and <em>Pseudoperna congesta</em>) that are observed “floating” at random orientations. The bivalve fragments are commonly partially to fully pyritized</td>
<td>massive</td>
<td>Moderate (50-70 wt.%)</td>
<td>Moderate (30-50 wt.%)</td>
</tr>
<tr>
<td>I</td>
<td>Bioturbated foraminiferal-molluscan mixed mudstone</td>
<td>Dark-gray; extensively bioturbated; contains frambooidal pyrite, planktonic foraminifera, phosphate fragments, and rare amorphous organic material; fragmented bivalve shells (<em>Inoceramus</em> sp. and <em>Pseudoperna congesta</em>) that are observed “floating” at random orientations</td>
<td>bioturbated</td>
<td>Unknown (no XRD data available), but is predicted to be low</td>
<td>Unknown (no XRD data available), but is predicted to be high</td>
</tr>
<tr>
<td>J</td>
<td>Volcanic ash bed</td>
<td>Yellow-gray volcanic ash beds; 1/4 to 2 1/2 inches thick; planar to wavy to disrupted basal and upper boundaries; commonly normally graded; minerals include (in order of abundance) mixed-layer illite-smectite, plagioclase, kaolinite, chlorite, illite, biotite, calcite, quartz, K-feldspar, and pyrite.</td>
<td>massive to normally graded crystals (where unaltered)</td>
<td>100 wt.%</td>
<td>NA</td>
</tr>
</tbody>
</table>
Figure 4-4: Petrographic thin section sample images that are representative of lithofacies A and B. Images were taken from the Welker 42-11 core and are in plane-polarized light. a) Thin section image displaying laminated and bioturbated nature of Facies A and B. Laminasets are numbered 1, 2, and 3. Each laminaset exhibits a subplanar silty base that fines upward. The laminated structure of bedset 1 has been disrupted by bioturbation. Black, elongated pellets are scattered sparsely throughout the sample. Framboidal pyrite is present as small opaque grains. b) Thin section image displaying the lenticular, thread-like organic matter in Facies A and B. Framboidal pyrite grains and a terrestrial mica grain are labeled as well.
Figure 4-5: Petrographic thin section sample images that are representative of lithofacies C and D. Images were taken from the Welker 42-11 core and are shown in plane-polarized light. a) Thin section image displaying the abundant pellets typical of facies C and D. The matrix is composed of clays and quartz silt. An artificial fracture is present that was created during the creation of the thin section sample b) Thin section image displaying the lenticular, thread-like organic matter in Facies C and D. Framboidal pyrite grains and a small foram test are labeled as well.
Figure 4-6: Petrographic thin section sample images representative of lithofacies E and F. Both images were taken from the Welker 42-11 core and are shown in plane-polarized light.  

a) Thin section image displaying laminated nature of Facies E and F. Laminasets are numbered 1, 2, and 3. Each laminaset exhibits a subplanar silty base that fines upward. The base of bedset 1 has a scoured base that cuts into underlying sediment. Black, elongated pellets can be observed throughout the sample. 

b) Thin section image displaying the lenticular, thread-like organic matter in Facies E and F. Framboidal pyrite grains and pellets are also labeled.
Figure 4-7: Petrographic thin section sample images that are representative of lithofacies G and H. Both images were taken from the Welker 42-11 core and are shown in plane-polarized light. a) Thin section image displaying massive nature of Facies G and H. Black, elongated pellets can be observed throughout the sample, and form weak laminae. Forams are abundant in these facies and are labeled in this image. b) Thin section image displaying the nature of organic matter in Facies G and H. Pellets are present throughout the image, appearing as dark brown, elongated forms. Planktonic foraminifera and frambooidal pyrite are present as well.
Figure 4-8: Petrographic thin section sample images that are representative of lithofacies I. Both images are photos of petrographic thin sections that were viewed at the BEG with the USA 1-22 core. a) Thin section image displaying the completely bioturbated nature of Facies I. Image is in plain light. b) Thin section image displaying massive bedding that is a result of extensive bioturbation. Planktonic foraminifera are abundant and are calcite-filled. Phosphate fragments are relatively common in this facies. Image is in plane-polarized light.
Figure 4-9: Images displaying the different styles of bentonite beds in the Niobrara Formation. All images were taken from the Welker 42-11 core. Basal and upper ash bed contacts are outlined by red dashed lines in each image. a) A ~2 1/2 inch thick ash bed. The basal contact with underlying sediment is planar and the upper contact is disrupted and nonplanar. A fracture is present along the upper contact of the ash bed. The bed exhibits normal grading with larger, gray crystals at the base and finer, yellowish grains near the top. The upper contact of the ash bed is diffuse in nature as it is mixed with overlying sediments. b) A ~1/4 inch thick ash bed that exhibits planar basal and upper contacts. It also displays normal grading and is partially pyritized. c) A ~1/4 inch thick ash bed. The bed exhibits a subplanar basal contact and a disrupted, nonplanar upper contact. No grading is evident. d) A ~1/4 inch thick ash bed. Basal and upper contacts with sediment are nonplanar and disrupted. No grading is evident and the bed is partially pyritized. e) An ~1/8 inch thick ash bed. The bed exhibits a disrupted, discontinuous nature. No grading is evident.

fallout. Instead, they are interpreted to have resulted from the deposition and/or reworking of sediments by: 1) storm-induced sediment-gravity flows, and possibly 2) thermohaline oceanic bottom currents.

Evidence for sediment-gravity flows is provided by the normally graded beds with silty lags observed in all four of these facies and additional shell lags observed in Facies B and F. These sedimentary structures are consistent with Bouma-type beds that are common in density-driven gravity flows, specifically turbidites. However, slope gradients in the Western Interior Seaway have been interpreted to be very low in the area of Niobrara Formation deposition (Hattin, 1982), so it is unlikely that any sediment-gravity flows were created by slope collapse. Additionally, given the central basinal location of the study area in the Western Interior Seaway, sediment-gravity flows in association with hyperpycnal flows created by
terrestrial river systems emptying into the basin are also unlikely. The most probable initial mechanisms that induced sediment-gravity flows in the Niobrara Formation in the study area were storm waves. These events, sometimes referred to as wave enhanced sediment-gravity-flows (WESGF) (Macquaker et al., 2010), are created when storm waves suspend enough fine-grained sediment to produce a high density fluid that moves downslope (Myrow and Southard, 1996; Myrow et al., 2002; Macquaker et al., 2010; Harazim and McIlroy, 2015; Lazar et al., 2015). In mudrock successions, they are represented as texturally heterogeneous, fining-upward bedsets with distinct silty bases that fine upwards into mud-rich tops (Lazar et al., 2015). Such bedsets are evident in Facies A, B, E, and F (Fig. 4-4; Fig. 4-6), and are interpreted to represent storm-induced sediment-gravity flows.

In addition to sediment-gravity flows, a portion of the sediments in these facies are likely to have been reworked and redistributed by thermohaline oceanic bottom currents, creating deposits such as contourites. Although the effects of these currents on mudrock deposition aren’t fully understood, their common association with sediment-gravity flows in deep water environments has been discussed extensively (Stow, 1979; Stanley, 1993; Stow et al., 2002; and others) and the redistribution of fine-grained sediments from gravity flow deposits has been documented (Mutti et al., 2014). With the relatively constant mixing of cooler, lower-salinity waters from the Arctic Sea to the north and warmer, higher salinity waters from the ancestral Gulf of Mexico to the south of the Western Interior Seaway, it is highly likely that thermohaline bottom currents, driven primarily by differences in temperature and salinity, reworked the sediments of the Niobrara Formation at the sediment-water interface on a relatively consistent basis. However, there remains a lack of unambiguous and commonly accepted diagnostic criteria for distinguishing small-scaled thermohaline current deposits (such as contourites) from sediment-gravity flow deposits (such as turbidites) in fine-grained rocks (Rebesco et al., 2014). Modern thermohaline oceanic bottom currents usually exhibit very slow velocities (1-2 cm/s) but can commonly reach velocities of up to 10-20 cm/s when heavily influenced by the Coriolis Force, a product of Earth’s spin, along the western margin of seaways (Stow et al., 2002). With silt- and mud-size grains (< 0.0625
mm), flow velocities of up to 20 cm/s are expected to generate ripples (Middleton and Southard, 1984). Undulating scour surfaces (Fig. 4-6) may actually be representations of such ripples in the mudrocks of the Niobrara Formation. In addition to ripples, the waxing and waning of bottom currents would result in the normal gradation of sediments; a feature common in these facies (Fig. 4-4; Fig. 4-6). In conclusion, it is interpreted that both storm-induced sediment-gravity flows and thermohaline oceanic bottom currents reworked and redistributed sediments in Facies A, B, E, and F of the Niobrara Formation in the Sand Wash Basin. More definitive criteria regarding the differentiation of such processes in fine-grained systems must be established in order to accurately distinguish these processes in mudrocks, such as those present in the Niobrara Formation.

Where organic matter and frambooidal pyrite are present in these facies, they are associated with dysoxic to anoxic marine environments at the seafloor. However, TOC concentrations are relatively low and the occurrence of bioturbation is high in these facies when compared to Facies C, D, G, and H. Also, the concentration of detrital minerals (quartz and clays) are highest in these facies. Consequently, Facies A, B, E, and F are associated with periods of relatively low sea level (4th-order). Relative sea level lows allowed for large influxes of siliciclastic sediments from the west and occasional oxygenation of bottom waters, resulting in the dilution of carbonates and TOC, as well as the oxygenation of TOC. In addition, the processes of deposition represented in these facies (storm-induced sediment-gravity flows and thermohaline oceanic bottom currents) are also a result of relatively low sea levels, as the storm wave base was low and thermohaline currents were concentrated within relatively small water volumes.

4.5.2 Facies G and H – Deposition and Associations

The mixed mudstones of Facies G and H are interpreted to be pelagic to hemipelagic deposits that settled in relatively stagnant, dysoxic to anoxic bottom waters, as evidenced by the presence of frambooidal pyrite, moderate concentrations of TOC, and a general lack of bioturbation and sedimentary structures at the petrographic thin section scale (Fig. 4-7). However, the presence of fragmented, sometimes randomly oriented, ostreid bivalve and inoceramid shells provides evidence for the occasional
redistribution of sediments in Facies H, as the fragments are not consistent with pelagic settlement. Instead, the shell fragments and associated sediments were likely reworked and brought into the area of deposition by rare storm-induced sediment-gravity flows and/or thermohaline oceanic bottom currents, such as in Facies A, B, E, and F. Pellets are relatively common in the facies, although not as abundant as in Facies C and D. The lack of sedimentary structures and bioturbation, moderate TOC concentrations, and moderate detrital mineral content (Table 4-1) leads to an association of Facies G and H with periods of relatively high sea level (4th-order). As a result of the high sea levels, carbonate material and TOC were not heavily diluted by clastic materials, and exhibit moderate concentrations in these facies. The general lack of sedimentary structures such as ripples or graded bedding also provides evidence for relatively high sea levels in Facies G and H as the storm wave base was raised and thermohaline oceanic bottom currents were dispersed throughout greater volumes of water, decreasing their effect.

**4.5.3 Facies C and D – Deposition and Associations**

The pelletal mixed carbonate mudstones of Facies C and D are interpreted to have been dominated by pelagic to hemipelagic sedimentation in stagnant dysoxic to anoxic bottom waters, as evidenced by framboidal pyrite, high concentrations of TOC, and a lack of sedimentary structures and bioturbation at the petrographic thin section scale (Fig. 4-5). However, bedding-parallel inoceramid and ostreid bivalve shell fragments and planar laminations are easily distinguishable at the hand sample scale. The presence of the bedding-parallel shell fragments suggests that storm-induced sediment-gravity flows and/or thermohaline currents, although rare, occasionally reworked sediments during the deposition of these facies. The planar laminations are interpreted to have been created by the pelagic to hemipelagic settling and subsequent compaction of large fluxes of pellets. These pellets are far more abundant in these facies than any other (Fig. 4-5). They have been shown to be largely composed of calcareous coccolith fragments (Hattin, 1982; Luneau et al., 2011; others), and are associated with frequent, episodic coccolith blooms in the Western Interior Seaway. The high abundancy of calcareous pellets, high TOC content, low detrital mineral content (Table 4-1), and lack of bioturbation leads to an association of Facies C and D.
with periods of maximum transgression (4th-order) in the Niobrara Formation of the Sand Wash Basin. These maximum transgressive periods worked to restrict siliciclastic detritus to the western part of the basin, greatly reducing the dilution of carbonates and TOC. In addition, high sea levels limited the reworking of sediments by raising the storm wave base and dispersing thermohaline oceanographic currents throughout large volumes of water, decreasing their effect. They also may have even facilitated carbonate production, as warm waters from the ancestral Gulf of Mexico flowed strongly northward into the basin (Kauffman and Campbell, 1993; Longman et al., 1998)

4.5.4 Facies I – Deposition and Associations

The mixed carbonate mudstones of Facies I are associated with the possible pelagic to hemipelagic (?) deposition of sediments in persistently oxygenated bottom waters. Thoroughly bioturbated sediments throughout the facies suggest that oxygen was present at, and below, the sediment-water interface for long periods of time in order to allow for burrowing organisms to completely disrupt the sediment. Still, small amounts of organic matter managed to be preserved in the facies. Facies I is also associated with the highest ratios of carbonates to siliciclastics in the study area. Deposition of the facies occurred during rare instance of high sea level and carbonate deposition combined with persistently oxygenated bottom waters in the Western Interior Seaway.

4.5.5 Facies J – Deposition and Associations

Facies J is associated with volcanic activity that took place in the Sevier orogenic thrust belt to the west of the study area. Each volcanic ash bed was deposited as a geologically instantaneous event, resulting from ash settling through the water column following a volcanic eruption. However, the differences in occurrence of each ash bed (planar to disrupted to discontinuous) are associated with differing dynamics at the seafloor during the time of deposition. Beds that are disrupted or discontinuous are associated with thermohaline bottom currents that flowed with enough force to winnow away and redistribute sediments that were originally present with the ash bed. O’Neal (2015) suggests that ash beds in the Niobrara Formation may also be disrupted by extensive bioturbation, which is also likely, although
it was not observed over the course of this study. Ash beds with planar surfaces suggest that they were deposited on the seafloor during a period when bottom water currents were absent.

Table 4-2: Facies associations and depositional interpretations for each of the ten lithofacies described (Table 4-1).

<table>
<thead>
<tr>
<th>Facies</th>
<th>Depositional Interpretations</th>
<th>Association</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, B, E, F</td>
<td>Storm-induced sediment-gravity flows, Thermohaline oceanic bottom currents; occasionally oxygenated bottom waters</td>
<td>Low relative sea level (4th order), low TOC concentrations</td>
</tr>
<tr>
<td>G,H</td>
<td>Pelagic to hemipelagic sedimentation; rare reworking of sediments; dysoxic to anoxic bottom waters</td>
<td>High relative sea level (4th-order), moderate TOC concentrations</td>
</tr>
<tr>
<td>C,D</td>
<td>Pelagic to hemipelagic sedimentation; rare reworking of sediments; dysoxic to anoxic bottom waters</td>
<td>Maximum transgressions (4th-order), high TOC concentrations</td>
</tr>
<tr>
<td>I</td>
<td>Pelagic settlement (?); oxygenated bottom waters</td>
<td>High relative sea level (4th-order), low TOC concentrations</td>
</tr>
<tr>
<td>J</td>
<td>Pelagic settlement of volcanic ash through water column; occasionally reworked</td>
<td>Volcanic eruptions in the Sevier orogenic highlands</td>
</tr>
</tbody>
</table>

4.6 Core Descriptions

Each core was described at a half-foot scale for lithologic facies and sedimentary features (Fig. 4-10). The identified lithologies in the cores are nearly all mixed mudstones to mixed carbonate mudstones, as determined by XRD analysis of core plugs (Fig. 4-11). Total organic carbon values from the Welker 42-11 and RMCCS State #1 are plotted with depth and are shown next to the core descriptions. Only the slabbled core samples and photos of petrographic thin sections were available from the USA 1-22 core. Therefore, no mineralogic facies or TOC correlations are included with the core description.
Figure 4-10: Core description legend for the three cores described over the course of this study. Column A displays the color designation scheme of each lithofacies described in the cores. Column B displays symbols that represent sedimentary structures and shell fragments that were observed in each core.
Figure 4-11: Ternary plot displaying XRD data from the Welker 42-11 and RMCCS State #1 wells. The data is shown with the mudrock classification scheme from Gamero-Diaz et al. (2012). Weight percent quartz, carbonates, and clays from XRD data are normalized and plotted on the diagram. Mineralogic facies for the Welker 42-11 and RMCCS State #1 cores were identified using this classification scheme.

4.6.1 Welker 42-11 Core

The first core described over the course of this study was taken from the Welker 42-11 well (SENE sec. 11 T6N R92W) located in Moffat County, CO. The core consists of a total of 615 feet of continuous Niobrara section. It extends downward from the bottom section of the Upper Marl through the complete sections of the Tow Creek Bench, Middle Marl, and Wolf Mountain bench, and terminates in the upper part of the Upper Rangely Bench (Fig. 4-1). The core contains the lithofacies A, B, C, D, E, F, G, H and J (Fig. 4-12). Facies A and B are only found in the Upper Rangely Bench and represent a period
Figure 4-12: Welker 42-11 core descriptions. The Niobrara Formation submembers are shown to the left. Column A displays identified facies. Column B displays the sedimentary features and shell fragments observed in the core. To the right of the core descriptions, mineralogy and TOC values (wt.%) are plotted against depth. To the left of the core descriptions is a 4th-order relative sea level curve interpreted from facies occurrences observed in the core.

of relatively low sea level. Moving stratigraphically upwards, the facies change from A and B to a small section displaying Facies E and F, to a large section of Facies G and H in the Wolf Mountain Bench. The transition of facies represents a rise in sea level across the Upper Rangely Bench and Wolf Mountain lithologic boundary. Peak TOC content in the Wolf Mountain Bench correlates to structureless, pelletal-
foraminiferal mollusk-rich mixed mudstones (Facies H), near the base of the Bench (Fig. 4-12). Approximately halfway through the Wolf Mountain Bench, the lithologic facies change back into Facies E and F from Facies G and H, representing a drop in sea level. Facies E and F are observed through the top half of the Wolf Mountain Bench and continue into the Middle Marl. Halfway through the Middle Marl a rise in sea level is interpreted, as the lithofacies transition back to Facies G and H from Facies E and F. Facies G and H continue into the base of the Tow Creek Bench. A maximum transgression is represented in the Tow Creek Bench around depths of approximately 7235-7275 feet. This maximum transgression is represented by Facies C and D, which correlate directly to maximum carbonate and TOC contents observed in the core (Fig. 4-12).

Facies J (the bentonite facies) is found throughout the core, but occurs with the greatest frequency in the lower half of the Wolf Mountain Bench. The data suggests that volcanic activity in the Sevier orogenic thrust belt was more common during the deposition of the lower half of the Wolf Mountain Bench.

Mineralogic facies in the Welker 42-11 core classify most of the section as a mixed mudstone (Fig. 4-12). However, mixed carbonate mudstones are present in some small intervals of the core as well. A single instance of the mixed argillaceous mudstone mineralogic facies is also present in the Wolf Mountain Bench. A higher resolution XRD data set is desired to better model fluctuations in mineralogic facies in the Welker 42-11 core. For this study, samples were collected approximately every ten feet for XRD analysis. If samples were collected every foot, a much more comprehensive, high resolution mineralogic model could be created and correlated to lithofacies.

The Welker 42-11 core exhibits TOC values that range from 0.9-2.25 wt.% with an average of 1.65 wt.% (Fig. 4-12). The Tow Creek Bench has the highest average TOC content (1.84 wt.%), leading to an association of TOC with Facies C and D. It is followed by the Middle Marl (1.68 wt.%), the Wolf Mountain Bench (1.61 wt.%), the Upper Marl (1.51 wt.%), and the Upper Rangely Bench (1.08 wt.%).
4.6.2 RMCCS State #1 Core

The second core described over the course of this study was taken from the RMCCS State #1 well (SWSE sec. 34 T6N R91W) located in Moffat County, CO. The core consists of a total of 120 feet (with some missing sections lost during core retrieval from downhole). It extends from the bottom section of the Upper Marl down through the majority of the Tow Creek Bench and terminates a few feet above the contact between the Tow Creek Bench and the Middle Marl (Fig. 4-1). Facies C and D compose most of the section, while Facies A and E are only found in a small section near the top of the core (Fig. 4-13). A maximum transgressive surface is likely present in the Tow Creek Bench of this core. It is represented by Facies C and D, and correlates directly to the same facies that were observed in the Tow Creek Bench of the Welker 42-11 core (Fig. 4-12). The presence of Facies A and E near the top of the core in the Upper Marl reflects a drop in sea level.

Only one occurrence of Facies J is present in the RMCCS State #1 core at a depth of 6640 feet in the Tow Creek Bench. Ash beds are uncommon in the same section of the Welker 42-11 core as well, suggesting that volcanic activity was less common during the deposition of the interval.

Mineralogic facies identified from XRD analysis classify this section of described core as a mixed mudstone to a mixed carbonate mudstone (Fig. 4-13). The RMCCS State #1 core exhibits much higher TOC values than those observed in the Tow Creek Bench of the Welker 42-11 core. They range from 2.35-4.10 wt.%, with an average of 3.29 wt.% (Fig. 4-13). It is possible that because the RMCCS State #1 well is located further to the east than the Welker 42-11 well, TOC was less diluted by siliciclastic detritus from the west during the deposition of the Tow Creek Bench. Another possibility is that the slight difference in burial depth (~600 ft) experienced by the Tow Creek Bench in the Welker 42-11 well resulted in depressed TOC values as a result of increased thermal maturity. It is probable that both possibilities contributed to some degree.
Figure 4-13: RMCCS State #1 core descriptions. The Niobrara Formation submembers are shown to the left. Column A displays identified facies. Column B displays the sedimentary features and shell fragments observed in the core. To the right of the core descriptions, mineralogy and TOC values (wt.%) are plotted against depth. To the left of the core descriptions is a 4th-order relative sea level curve interpreted from facies occurrences observed in the core.

4.6.3 USA 1-22 Core

The third, and final core described was that from the USA 1-22 well (SENE sec. 22 T6N R90W) located in Moffat County, CO. It consists of a total of 251 feet of non-continuous Niobrara section. Sections of the Fort Hays Limestone (Core 5), Wolf Mountain Bench (Core 4), Tow Creek Bench (Core 3), Upper Marl (Core 2), and Buck Peak Bench (Core 1) were recovered (Fig. 4-1). The core sections contain all of the lithofacies described over the course of this study (A-J) (Fig. 4-14).

Core 5 encompasses part of the Fort Hays Limestone. It is composed of Facies E, F, I, and J (Fig. 4-14). There is a large fault that cuts across the core at a depth of approximately 7455 feet. Below the fault, Facies I was the only lithofacies observed. This facies represents sediments in this part of the Fort Hays Limestone that are heavily bioturbated and contain abundant fragmented bivalve shells. The Fort Hays Limestone is the only section of described cores that contains Facies I. This suggests that deposition
Figure 4-14: USA 1-22 core descriptions. The Niobrara Formation submembers are shown to the left. Column A displays identified facies. Column B displays the sedimentary features and shell fragments observed in the core. To the left of the core descriptions is a 4th-order relative sea level curve interpreted from facies occurrences observed in the core.
of this member occurred in waters that had much higher oxygen contents than the waters in which any part of the Smoky Hill Member was deposited. Above the fault, there is a facies change from Facies I into Facies E and F. No bioturbation is visible above the fault, suggesting that part of the Smoky Hill Member was juxtaposed next to the Fort Hays Limestone in Core 5. Facies J is present as two ash beds in Core 5. The beds occur on either side of the fault that cuts the core. They suggest that some volcanic activity took place during the deposition Facies I in the Fort Hays Limestone, as well as in Facies E and F in the Smoky Hill Member.

Loucks and Rowe (2014) were able to take TOC measurements from selected sections of the USA 1-22 core. Core 5 has TOC values that range from < 0.5-3.0 wt.% However, below the fault, TOC content rarely exceeds 1.0 wt.% and never exceeds 1.5 wt.% This observation is consistent with what would be expected in Facies I. Oxygenated bottom waters and bioturbation are not conducive conditions for the preservation of organic matter. Above the fault, TOC values increase significantly in Facies E and F of the Smoky Hill Member.

Part of the Wolf Mountain Bench was recovered in Core 4. The section is composed of Facies E, F, G, H, and J (Fig. 4-14). Facies E and F compose most of the recovered part of the Wolf Mountain Bench, while Facies G and H are present in the top part of the section. This suggests that a slight rise in sea level is represented in the cored section. Facies J is observed at the highest frequency in Core 4. This observation is concurrent with the observed frequency of ash beds in the Wolf Mountain Bench of the Welker 42-11 core (Fig. 4-12).

Total organic carbon values in Core 4 range from about 2.0-3.6 wt.% (Loucks and Rowe, 2014). These values are much higher than what is observed in the Wolf Mountain Bench in the Welker 42-11 core (1.61 wt., average). It is possible that because the USA 1-22 well is located further to the east than the Welker 42-11 well, TOC was less diluted by siliciclastic detritus from the west during the deposition of the Wolf Mountain Bench. Another possibility is that the slight difference in burial depth (~700 ft)
experienced by the Wolf Mountain Bench in the Welker 42-11 well resulted in depressed TOC values as a result of increased thermal maturity. It is probable that both possibilities contributed to some degree.

Core 3 recovered part of the Tow Creek Bench. The section is composed of Facies C, D, E, F, and J (Fig. 4-14). The presence of Facies C and D reflects a near maximum transgression that is represented in the Tow Creek Bench of the USA 1-22 core. This observation is consistent with what is observed in the Tow Creek Bench in the Welker 42-11 and RMCCS State #1 cores. There is only one occurrence of Facies J that was observed in this section of the USA 1-22 core, suggesting that volcanic activity was minimal during the deposition of the Tow Creek Bench. This observation is concurrent with what was documented in the same section of the Welker 42-11 and RMCCS State #1 cores. No TOC values were reported by Loucks and Rowe (2014) for Core 3.

Core 2 encompasses part of the Upper Marl. It is composed of Facies A, E, and F (Fig. 4-14). The occurrences of these facies suggest that the Upper Marl was deposited during a period of relatively low sea level. Facies J was not observed in the core, indicating that little to no volcanic activity took place over the deposition of this part of the Upper Marl.

Loucks and Rowe (2014) reported TOC values from Core 2 that range from about 1.3-2.6 wt.%. The TOC values reported from Core 2 are slightly higher than those obtained from the Upper Marl in the Welker 42-11 core (1.51 wt.%, average). The difference in TOC values may reflect different levels of siliciclastic dilution in each core, differences in thermal maturity experienced by in each core, or both.

Part of the Buck Peak Bench is represented in Core 1. It is composed of Facies C, D, E, G, and J (Fig. 4-14). The presence of Facies C and D suggests that the Buck Peak Bench was deposited during periods of high sea level, if not during a maximum transgression. Facies J is present near the top of Core 1, indicating that there was some active volcanism during the deposition of the Buck Peak Bench.

Total organic carbon values from Core 1 range from about 1.5-3.5 wt.% (Loucks and Rowe, 2014). The highest values, found near the top of the core, are associated with Facies E.
CHAPTER 5
OUTCROP STUDY

This chapter provides an overview of the locations of Niobrara Formation outcrops that were used for this study. The nature of the Smoky Hill and Fort Hays Limestone members of the Niobrara Formation in outcrop is described. In addition, the occurrence of large bivalves from the Inoceramidae family in the Niobrara Formation is discussed in detail.

5.1 Location

Outcrops of the Niobrara Formation on the eastern flank of the Sand Wash Basin in northwestern Colorado were identified and selected for use in this study. The outcrops are located at the western edge of the city of Steamboat Springs, CO along Colorado State Highway 40 and the Yampa River (40°30’30"N, 106°53’23"S) (Fig. 5-1). Undifferentiated parts of the Smoky Hill Member as well as the Fort Hays Limestone Member are present at this location. The outcrops occur as large, highly weathered, cliffs on both public and private property. Sections of the outcrops are generally strike-parallel, although some oblique-cut sections are present as well. The height and steep gradient (nearly vertical) of the cliffs made the detailed measurement of the outcrops impossible without rappelling; an action not readily undertaken by the author. In addition, without the use of a handheld scintillometer, the identification of the Niobrara Formation submembers within the Smoky Hill strata was impossible. Consequently, instead of measured sections in a format similar to those of described core in Chapter 4, a more qualitative description of the outcrops is provided in this work.
Figure 5-1: Location of Niobrara outcrop in Steamboat Springs, CO. The inset map displays the Sand Wash Basin outlined in red and the approximate location of the outcrop outlined in black. The larger aerial image displays outcrop locations in blue. Black arrows denote Colorado State Highway 40 and the Yampa River. The city of Steamboat Springs, CO is located just outside of the picture to the east.

5.2 Smoky Hill Member

Several undifferentiated sections of the Smoky Hill Member of the Niobrara Formation are exposed along the Yampa River and Colorado State Highway 40 in northwestern Colorado, just west of the city of Steamboat Springs. At this locality, the various sections of the Smoky Hill Member are present as large, highly weathered cliffs. The outcrops range in color from light tan to light gray to dark gray to orange, and are generally very fissile. Inoceramids and ash beds are common and are commonly observed as orange to red as a result of oxidation of associated pyrite grains (Fig. 5-2). The ash beds are commonly laterally extensive and may be used as marker beds within individual outcrops. However, some ash beds
are discontinuous over short lateral distances (< 100 ft), illustrating the ability of bottom currents to
winnow away sediments on the paleo-seafloor during Niobrara deposition.

Two generalized rock types can be easily distinguished in the member at this outcrop location: 1) resistant and 2) highly weathered (Fig. 5-3). The resistant rock type is associated with higher carbonate contents than the highly weathered rock types. In the resistant sections of rock, planar cyclic bedding is recognized as alternating layers of more resistant and less resistant lithologies (Fig. 5-3a). The alternating lithologies are representative of fluctuations in carbonate content related to small changes in relative sea level (≥ 5th-order cycles). More resistant, carbonate-rich layers are associated with relative sea level highs. The cyclicity of the bedding and relative sea level changes likely correspond to Milankovitch cycles at 21-, 42-, 100-, and 400-k.y. intervals, as described by Kauffman and Caldwell (1993). The same bedding cycles cannot be observed in the highly weathered sections of rock, as an increase in clay content creates structureless masses (Fig. 5-3b).

Figure 5-2: Ash beds and inoceramids in outcrop of the Smoky Hill Member of the Niobrara Formation, west of Steamboat Springs, CO. Pencil (~5.5 in.) is shown for scale.
Figure 5-3: Generalized rock types observed in the Smoky Hill Member of the Niobrara Formation, west of Steamboat Springs, CO. a) Image of the resistant rock type. Note the cyclic bedding style, easily recognized by differences in weathering profiles. b) Image of the highly weathered rock type. Note how the planar bedding is difficult to recognize due to the extent of weathering.
5.3 Fort Hays Limestone Member

One occurrence of the Fort Hays Limestone Member of the Niobrara Formation is present in outcrop west of the city of Steamboat Springs, along the Yampa River and Colorado State Highway 40 (Fig. 5-4). At this locality, the member forms a resistant ledge (~10 feet thick) that sits unconformably atop the less resistant Montezuma Valley Member of the Carlile Shale. The lithologies present in the member have been weathered to light tan to orange to light gray. This member appears to have much higher carbonate contents than any part of the Smoky Hill Member that was described in outcrop. In a fashion similar to that of the resistant rock types of the Smoky Hill Member outcrops, planar cyclic bedding was observed in the Fort Hays Limestone (Fig. 5-4). The cycles can be recognized as thick resistant (carbonate-rich) layers that alternate with thinner, less-resistant (clay-rich) layers. The alternating lithologies are representative of fluctuations in carbonate content related to small changes in relative sea level ($\geq 5^{th}$-order cycles). The more resistant, carbonate-rich layers are associated with relative sea level highs. As in the Smoky Hill Member, these cycles likely correspond to Milankovitch cycles at 21-, 42-, 100-, and 400-k.y. intervals, as described by Kauffman and Caldwell (1993).

![Figure 5-4: Outcrop of the Fort Hays Limestone Member of the Niobrara Formation atop the Montezuma Valley Member of the Carlile Shale, west of Steamboat Springs, CO. Note the highly resistant nature of the member and the planar cyclic bedding that is evident. The dashed red line depicts the undulating contact between the Fort Hays Limestone and the underlying Montezuma Valley Member of the Carlile Shale.](image)
5.4 Inoceramids in the Niobrara Formation

Large bivalves of the Inoceramidae family are ubiquitous throughout the Late Cretaceous Niobrara Formation, as has been described and discussed in detail by many authors including Hattin (1982), Seilacher (1982), Stewart (1990), and Kauffman et al. (2007). They are easily identified in outcrop and core by the prismatic appearance of their shell in cross-sectional view. Several genera have been identified by Hattin (1982) at Niobrara Formation outcrop locations in western Kansas, including the highly inequivalved, bowl-shaped, thick-shelled *Inoceramus (Volviceramus) grandis*; the giant-sized, equivalved, slightly biconvex *Inoceramus (Platyceramus) platinus* and *Inoceramus (Cladoceramus) undulatoplicatus*; and the small- to medium-sized, thin-shelled, elongate, biconvex *Inoceramus stantoni* and *Inoceramus balticus*. Commonly associated with the inoceramids are ostreid bivalves assignable to the species *Pseudoperna congesta* (Conrad, 1857). These ostreids are commonly found to be densely encrusting inoceramid valves, especially on articulated specimens.

It is highly likely that inoceramids and associated *P. congesta* are the only benthic body fossils present in the facies of the Niobrara Formation (Kauffman et al., 2007). The low diversity of benthic fauna is attributable to the style of depositional environment that existed at the seafloor during the deposition of the formation. Dominant facies in the Niobrara can be described as basinal, organic-rich, commonly pyritiferous, well-laminated to microbially turbated argillaceous/siliceous mudstones, mixed mudstones, mixed carbonate mudstones, and carbonate-dominated lithotypes. The nature of these facies suggests that low benthic oxygen and possibly high levels of H₂S and/or methane seepage were present at the seafloor, greatly restricting benthic habitats and limiting bioturbation (Kauffman et al., 2007). Therefore, the presence of the inoceramids and *P. congesta* in the Niobrara Formation reflects ecological opportunism, as these organisms filled a niche unoccupied by any other species at the time.

At the Steamboat Springs outcrop locality, only the species *Platyceramus platinus* (Logan, 1898) was identified by the author over the course of this study. The morphology of this subgenus (*Platyceramus*) is described in great detail by Seitz (1962). In general, it is characterized by its large size,
low shell convexity, normal inflation limited mostly to the umbonal area, and flattened flanks (Kauffman et al., 2007). Specimens commonly exhibit axial lengths of greater than 3 ft, and sometimes reach sizes of greater than 6.5-10 ft (Hattin, 1982; Stewart, 1990; Kauffman et al., 2007). They are extremely thin-shelled relative to their axial length. At the Steamboat Springs outcrop, *P. platinus* specimens typically are observed to be articulated, flat-lying (parallel to bedding), and encrusted by *P. congesta* (Fig. 5-5). However, disarticulated, fragmented, and randomly oriented specimens may be found on occasion as well. Large specimens are commonly observed to occur with high frequency over short stratigraphic intervals (< 5 ft). Although not observed in this study, it is predicted that within those short stratigraphic intervals, the platyceramids occur in large groups laterally across individual bedding planes. To confirm this hypothesis, large trenches would have to be dug into the outcrop at the Steamboat Springs locality. Such observations have been made by Kauffman et al. (2007) in Lyons, CO. These large accumulations of platyceramids are interpreted as bivalve “beds” that reflect optimal environmental conditions for the growth, reproduction, and colonization of these organisms. Articulated specimens at the Steamboat Springs outcrop range from less than 0.3 ft to greater than 6.5 ft in axial length. They commonly have both valves pressed tightly together, and may be slightly deformed and/or fragmented (sometimes imbricated) as a result of compaction (Figure 5-5). Many specimens, both articulated and disarticulated, are stained orange and/or red as a result of oxidation of frambooidal pyrite grains that are associated with the shells.

There is current debate over the life habits and living position of *P. platinus*. An epibenthic recumbent to semi-recumbent living position is suggested for the species by several authors including Hattin (1982) and Kauffman et al. (2007). However, common thick, dense encrustations of *P. congesta* on the outsides of both valves of articulated *Platyceramus* specimens present a perplexing observation when considering a recumbent living position for the species. Hattin (1982) and Kauffman et al. (2007) suggest that the platyceramids may have been overturned by predatory, bottom-feeding fish (such as hybodontiform ptychodid sharks) and/or by storm-generated currents to allow for encrusters to access the
Figure 5-5: Images displaying the occurrence of *Platyceramus platinus* in the Smoky Hill Member of the Niobrara Formation, west of Steamboat Springs, CO. a) Image of large platyceramid specimens found parallel to bedding (along measuring tape). The black rectangle corresponds to the location of image (b). b) Image of two large articulate *P. platinus* specimens. Both specimens have valves that are pressed tightly together and are heavily encrusted by *Pseudoperna congesta*. Parts of the specimens are stained orange and red as a result of the oxidation of associated pyrite grains. c) Image of a small *P. platinus* specimen. Both valves are present, although they are slightly deformed. Pencil (~5.5 in.) is shown for scale.
undersides of specimens. An additional, alternative explanation is given by Hattin (1982) when he states that the platyceramids may have been colonized on both valves simultaneously as they lay flat on the seafloor. He suggests that at the time of deposition, the seafloor muds of the Niobrara Formation were “soupy”, consisting of mostly water, so that the *P. congesta* that encrusted the bottom-sides of *P. platinus* lived in a predominantly aqueous environment.

Contrastingly, Stewart (1990) suggests that *Platyceramus platinus* was actually a nonrecumbent bivalve, and exhibited an erect to suberect growth mode. With this interpretation, it is assumed that the platyceramids were attached to the sediment by a stout byssus and possibly had the shell anterior partially buried in the substrate.

One other possibility concerning the life habits and growth mode of *P. platinus* is suggested by Seilacher (1985). He interprets that platyceramids were pseudoplanktonic on floating logs, ammonites, and other sizeable objects in the upper parts of the water column. It is then interpreted that their presence in the sediments of the Niobrara Formation reflects deposition of the organisms following death, as they fell out of the water column to the seafloor.

Based on observations made at outcrop and from core of the Niobrara Formation over the course of this study, it is interpreted (in agreement with Hattin (1982), Kauffman et al. (2007), and others) that *P. platinus* was an epibenthic recumbent bivalve. It, along with the encrusting *P. congesta*, filled an ecological niche created in a deep marine environment characterized by low benthic oxygen levels and possibly H$_2$S and/or methane seepage.

The possibility that platyceramids were nonrecumbent and exhibited erect growth modes facilitated by strong byssal attachments to the seafloor is rejected because not a single articulated specimen has been observed to be preserved in an erect, upright position. All articulated specimens present at the Steamboat Springs outcrop locality are preserved parallel to the bedding planes in the Niobrara Formation (Fig. 5-5). Similar observations have been made by Hattin (1982) and Kauffman et al. (2007) at outcrop locations in
western Kansas and Lyons, Colorado, respectively. Furthermore, Hattin (1982) has noted that *P. platinus* valves preserve no evidence of byssal attachment.

The possibility that platyceramids were pseudoplanktonic on floating objects such as logs is rejected because they occur in “beds” that show evidence of colonization at the seafloor. These colonies would not exist if platyceramids fell through the water column to the seafloor after death. Additionally, as noted by Hattin (1982), objects such as logs, which are common in other Cretaceous marine strata, such as the Greenhorn Limestone, are exceedingly rare in the strata of the Niobrara Formation.

A common feature associated with *P. platinus* in the Niobrara Formation is the occurrence of fragmented platyceramid shell debris (Fig. 5-6). Samples depicting the nature of these fragmented platyceramid shells from the Niobrara Formation in the Sand Wash Basin were collected from the Steamboat Springs outcrop locality (Fig. 5-6a,b). In this sample, broken platyceramid fragments are observed on top what appears to be a piece of an adult specimen. The fragmented pieces are subrounded and randomly oriented, and range in size from pieces ~ 1 in. across to individual shell prisms. A similar sample displaying shelly debris from northwestern Kansas (Graham County) was collected by the author over the course of this study (Fig. 5-6c). This sample also displays rounded to subrounded, randomly oriented inoceramid fragments. It is unclear to what subgenus and species these fragments belong. What is clear is that similar processes were active across the entire region of Niobrara Formation deposition in the Western Interior Seaway. These processes worked to break up inoceramid shells and redeposit them rapidly in random orientations on the seafloor. The question as to how the inoceramid shells were disarticulated and fragmented is up for debate. One possibility is that the shells were crushed by bottom-feeding fish, such as hybodontiform ptychodid sharks. With this hypothesis, it is suggested that the hard parts of inoceramids were ejected from the intestines of sharks through the mouth, as they do not appear as coprolites. It is likely that this process accounts for at least some of the shelly inoceramid debris, if not the majority of it. This hypothesis is supported by the fact that ptychodid sharks had knoblike teeth for crushing of materials such as shells; and that these teeth are a common fossil that can be found in the
Figure 5-6: Fragmented inoceramid samples from Niobrara Formation outcrop locations in Steamboat Springs, CO and Graham County, KS. 

a) Side view of part of a *Platyceramus platinus* valve with shelly debris on top. The sample was collected from the Smoky Hill Member of the Niobrara Formation, west of Steamboat Springs, CO. 

b) Top view of the same sample displayed in (a). Notice the random orientation and size distribution of fragmented platyceramid shells. 

c) Top view of a sample displaying fragmented inoceramid debris. Notice the rounded to subrounded nature of the inoceramid fragments, as well as their random orientation. The sample was collected from an undifferentiated section of the Niobrara Formation in Graham County, KS. 

d) Schematic diagram illustrating the locations from which the fragmented inoceramid samples were gathered. The green star represents outcrop in Steamboat Springs, CO and the red star represents outcrop in Graham County, KS. Note that the two locations are separated by over 500 miles (Modified from Hattin, 1982).
Niobrara Formation (Kauffman et al., 2007). The hypothesis is also supported by an action observed in modern sharks known as gastric eversion. Gastric eversion is an extremely rapid action used by modern sharks as a “cleansing” function for removing indigestible food particles from the stomach lining (Brunnschweiler et al., 2005). Modern sharks execute this technique by orally ejecting their stomach tissue. It is suggested that the Cretaceous Ptychodontid sharks used a similar technique to rapidly eject hard, fragmented inoceramid shells from their intestines to be deposited on the seafloor.

Another possibility that may explain the occurrence of shelly inoceramid debris is that the shells were fragmented by current and/or wave energy. With this hypothesis it is suggested that the shells were mechanically broken in environments with consistently higher current and/or wave energy than what was present in the depositional environments of the Niobrara Formation. It is unlikely that enough energy existed at any point during the deposition of the Niobrara to mechanically smash and break large inoceramid shells into tiny pieces. Kauffman et al. (2007) notes that inoceramids may be found in oxygenated shoreface sandstones, although they are sparse and of smaller sizes than when found in basinal facies. It is possible that inoceramid shells in the shoreface facies could have been mechanically fragmented by wave energy and subsequently transported further basinward.

Regardless of the process of fragmentation of inoceramid shells, it is interpreted in this study that the presence of the shelly debris in outcrop (and core) represents lag deposits. These deposits are thought to be a result of the subsequent reworking of shell materials by very large storms and/or bottom flowing currents after the fragmentation process.

The occurrence of articulated and fragmented inoceramids in the Niobrara Formation suggest that the depositional environment was complex and dynamic. Seafloor dysoxia is associated with whole, articulated specimens that were interpreted to be discovered preserved in living position. Additionally, the existence of fragmented inoceramid shell lags is evidence for persistent bottom flowing currents and/or episodic large storms were able to rework sediment at the seafloor in the Western Interior Seaway.
CHAPTER 6
MINERALOGY AND ELEMENTAL ANALYSIS

This chapter examines the mineralogy of the Niobrara Formation in the Sand Wash Basin. Ternary
diagrams are utilized to demonstrate concentrations of quartz, total clays, total carbonates, and total
organic content. Both spatial and stratigraphic mineralogic trends are analyzed. In addition, elemental
concentrations in the Niobrara Formation are discussed and correlated to the mineralogy in the formation.

6.1 Mineralogy of the Niobrara Formation

Samples of the Niobrara Formation were collected from seven wells in the Sand Wash Basin for
mineralogical analysis by XRD (Fig. 6-1). Whole core plugs were sampled from the RMCCS State #1
and Welker 42-11 wells. Rotary sidewall cores were sampled from the Bulldog 20-12H, Bulldog 22-41V,
Dill Gulch 1-22, North Hayden 1-26, and Weber Federal 32-04 wells. Data gathered from whole core
plugs sampled from the Aristocrat PC H11-07 well in the DJ were compared against data from the Sand
Wash Basin. Each member and submember of the Niobrara Formation is represented by the mineralogical
data. Using the organic mudstone classification scheme described by Gamero-Diaz et al. (2012), six
mineralogical facies can be observed in the formation in study area (Fig. 6-2). The majority of the
mineralogical data plots in the argillaceous/siliceous mudstone, mixed mudstone, and mixed carbonate
mudstone facies. A few anomalous data points fall into the mixed argillaceous mudstone, mixed siliceous
mudstone, and argillaceous/carbonate mudstone, mineralogic facies (Fig. 6-2). The data display a linear
trend on quartz-carbonate-clay ternary diagrams. Normalized quartz and total clay data show a consistent
ratio to one another throughout the study area; about 2 parts quartz to 3 parts clay. As a result, varying
ratios of carbonate content are responsible for the major mineralogic changes displayed by the XRD data.
Figure 6-1: Locations of Niobrara Formation wells with samples taken for XRD analysis. The locations are plotted on an isochore map of the total Niobrara Formation (contour interval = 100').

The linear trend of data points between carbonate-rich endmembers (mixed carbonate mudstones) and siliciclastic-rich endmembers (argillaceous/siliceous mudstones) reflects a major geographical trend exhibited by the mineralogy of the Niobrara Formation in the study area. During the deposition of the formation, clastic shedding from the Sevier Orogenic highlands to the west of the study area diluted carbonate production in the Western Interior Seaway. As a result, data from wells in the western-northwestern part of the study area display lower carbonate mineral percentages than wells further to the east-southeast. Concurrently, as the thickness of the Niobrara Formation decreases in the study area, carbonate ratios increase in the system. Where the formation is much thinner in the DJ Basin, carbonates make up a much higher mineral percentage of Niobrara Formation lithologies (Fig. 6-2). Carbonate-
dominated lithotype, mixed carbonate mudstones, and argillaceous/carbonate mudstones are the primary mineralogic facies displayed by the XRD data from the DJ Basin. Still, even in eastern regions of Niobrara deposition such as the DJ Basin, quartz to total clay ratios remain relatively constant. This suggests that siliciclastic dilution occurred in a decreasing fashion from west to east across the Western Interior Seaway during the deposition of the Niobrara Formation. Carbonate production may have been relatively constant across the region at any given time, with siliciclastic input being the main control on the thickness of the formation and mineralogic facies at a given locality.

Figure 6-2: Mineralogic data gathered from XRD analysis on samples taken from the Niobrara Formation in the Sand Wash Basin (plotted as diamonds) and DJ Basin (plotted as circles). Mineralogic data from the Aristocrat PC H11-07 well is modified from ElGhonimy, 2015.
Mineralogy in the Niobrara Formation also varies stratigraphically throughout the section. The formation has long been recognized to be composed of alternating carbonate-rich and siliciclastic-rich lithologies throughout its area of deposition. In the Sand Wash Basin, the same cyclical nature of Niobrara Formation lithologies can be recognized in mineralogical data (Figs. 6-3, 6-4).

The Buck Peak Bench, Tow Creek Bench, and Wolf Mountain Bench have the highest carbonate contents found in the entire Niobrara Formation section (Figs. 6-3a,c, 6-4a). These benches correlate to the A, B, and C chalks that have been described in the Niobrara Formation of the DJ Basin. However, in the Sand Wash Basin, the normalized carbonate fraction of these benches rarely exceed 70 wt.% and average less than 50 wt.%%. Therefore, instead of being classified as chalks, they are most commonly classified as mixed carbonate mudstones and mixed mudstones.

The Upper Marl, Middle Marl, Upper Rangely Bench, and Basal Rangely Bench have lower carbonate fractions than the benches that they alternate with (Figs. 6-3b,d, 6-4b,c). These submembers correlate to the A, B, and C marls, and the D chalk/marl that have been described in the Niobrara Formation of the DJ Basin. In the Sand Wash Basin, these submembers rarely exhibit normalized carbonate contents greater than 50 wt.% and average less than 40 wt.%%. They are most commonly classified as mixed mudstones and argillaceous/siliceous mudstones in the study area.

The Fort Hays Limestone displays low carbonate values in the Sand Wash Basin (Fig. 6-4d). Contrastingly, in the DJ Basin, the member is described as a clean limestone and the most carbonate-rich interval in the Niobrara Formation (Longman et al., 1998). The reason for the low carbonate fraction represented by the provided data is probably due to a sampling bias. Only two data points were collected from the member, so the values gained from XRD analysis are statistically insignificant. However, the low carbonate percentages suggest that the Fort Hays Limestone Member, like the Smoky Hill Member, was at least somewhat diluted by clastic sediments in an increasing fashion from east to west in the Western Interior Seaway.
Figure 6-3: a) Histogram displaying the occurrence of carbonates in the Buck Peak Bench. b) Histogram displaying the occurrence of carbonates in the Upper Marl. c) Histogram displaying the occurrence of carbonates in the Tow Creek Bench. d) Histogram displaying the occurrence of carbonates in the Middle Marl.

Figure 6-4: a) Histogram displaying the occurrence of carbonates in the Wolf Mountain Bench. b) Histogram displaying the occurrence of carbonates in the Upper Rangely Bench. c) Histogram displaying the occurrence of carbonates in the Basal Rangely Bench. d) Histogram displaying the occurrence of carbonates in the Fort Hays Limestone.
Total organic carbon values from the Niobrara Formation also vary with mineralogy in the Sand Wash Basin. The highest TOC values (> 3.0 wt.%) cluster around the intersection of the mixed mudstone, argillaceous/carbonate mudstone, and mixed carbonate mudstone mineralogical facies (Fig. 6-5). The clustering centers around a mineral assemblage of approximately 50 wt.% carbonates, 30 wt.% clays, and 20 wt.% quartz. Mineralogical data from the marls in the DJ Basin also tend to cluster around the same point (Fig. 6-2b). As was mentioned earlier, several authors have documented significantly higher total organic carbon (TOC) content in the marls (2-8%) than in the chalks (1-3%) in the DJ Basin (Landon et al., 2001, Sonnenberg, 2015). Therefore, the same mineral assemblage corresponds to the highest organic matter preservation potential in both basins. As mineralogical facies trend away from this intersection towards the siliciclastic-rich endmember, TOC content decreases as it becomes diluted by clastic sediments. As the mineralogic facies trend towards the carbonate-rich endmember of the system, TOC values also decrease, as the lithologies become too clean with carbonates. Hence, it is interpreted that the mineral assemblage centered around the intersection of the three aforementioned mineralogic facies represents a depositional environment in which TOC was best preserved in the Western Interior Seaway during the deposition of the Niobrara Formation. Additionally, the data points representing the highest TOC concentrations in the Sand Wash Basin display a trend in quartz to total clays ratios that decreases slightly from what was displayed in Fig. 6-2 (Fig. 6-5). This suggests that organic matter preservation correlates to depositional environments that had minimal quartz input in the system.

Stratigraphically, TOC can be found at higher concentrations in certain intervals in the Niobrara Formation than others (Figs. 6-6, 6-7). The Buck Peak Bench, Tow Creek Bench, and Basal Rangely Bench exhibit the highest average TOC values from the given data (Figs. 6-6a,c, 6-7c). However, because only four samples were acquired from the Basal Rangely Bench, the TOC data may display anomalous values. Specifically, the highest TOC concentration recorded from the entire Niobrara Formation came from a data point taken out of the Basal Rangely Bench. The sample that was used to generate the data was retrieved from the greatest depth of any sample used in the project at 12053 feet (TVD) from the
Figure 6-5: Total organic carbon values correlated to mineralogical percentages from the Niobrara Formation in the Sand Wash Basin. Data outlined in green represents the concentration of highest TOC values (> 3.0 wt.%). Data outlined in red represents data with lower TOC concentrations (< 3.0 wt.%).

Bulldog 22-41V well. As total organic carbon values typically decrease with depth and increasing thermal maturity, it is doubtful that the data from the sample is reliable. One possibility is that the samples taken from this well were contaminated by oil-based mud that was used during drilling. However, it is possible that the Bulldog 22-41V well penetrated a pocket of deposition in the Basal Rangely Bench that retained anomalously high amounts of TOC. In either case, it is concluded based off of the provided data that the highest concentrations of organic carbon consistently reside exclusively in the Buck Peak Bench and Tow
Creek Bench. These benches also contain the highest concentrations of carbonate material in the Niobrara Formation (Fig. 6-3a,c).

Based off of the previous interpretations that these benches were deposited during transgressive events and sea level highs, it is suggested that peak deposition of carbonate materials and peak preservation of organic matter coincide with highstand periods observed in the Buck Peak Bench and Tow Creek Bench in the Sand Wash Basin. Data from the Upper Marl, Middle Marl, Wolf Mountain Bench, and Upper Rangely Bench also display significant TOC concentrations that all average over 1.50 wt.% (Figs. 6-6b,d, 6-7a,b). It is evident that organic material was being delivered to the seafloor of the Western Interior Seaway over the entire course of Niobrara Formation deposition. Yet, the organic matter in these submembers was either not delivered in as high of concentrations as in the Buck Peak and Tow Creek Benches, or it was not well-preserved. The Fort Hays Limestone displays the lowest TOC concentration values in the Niobrara Formation (Fig. 6-7d). This observation is consistent with what would be expected from the member, as it is interpreted as a relatively clean limestone and was observed to be heavily bioturbated in the USA 1-22 core. However, only two data points represent the TOC content from the Fort Hays Limestone and average values may be even lower. Additional data is required in order to more accurately represent the occurrence of organic matter in the member.

6.2 Elemental Analysis

The Welker 42-11, Dill Gulch 1-22, North Hayden 1-26, and Bulldog 20-12H wells were sampled for elemental analysis of the Niobrara Formation by XRF. Data from the Welker 42-11 well was gathered from whole core plug samples, while data from the Dill Gulch 1-22, North Hayden 1-26, and Bulldog 20-12H wells were gathered from rotary sidewall cores. All elemental data points used correlate to locations sampled for XRD and TOC analysis in this study. Each well was analyzed for concentrations of the elements Mg, Al, Si, Ca, K, Ti, Fe, S, Th, and U. Nakamura (2015) showed that the elements Mg, Al, Si, Ca, K, Fe, and S displayed high coefficients of determination (R²-values) when plotted against mineralogical data and total organic carbon values from the Niobrara Formation in the DJ Basin. For this
Figure 6-6: a) Histogram displaying the occurrence of TOC in the Buck Peak Bench. b) Histogram displaying the occurrence of TOC in the Upper Marl. c) Histogram displaying the occurrence of TOC in the Tow Creek Bench. d) Histogram displaying the occurrence of TOC in the Middle Marl.

Figure 6-7: a) Histogram displaying the occurrence of TOC in the Wolf Mountain Bench. b) Histogram displaying the occurrence of TOC in the Upper Rangely Bench. c) Histogram displaying the occurrence of TOC in the Basal Rangely Bench. d) Histogram displaying the occurrence of TOC in the Fort Hays Limestone.
study, the same elements were plotted against mineralogical data and TOC from the Niobrara Formation in the Sand Wash Basin (Figs. 6-8, 6-9). Additionally, data from the elements Ti, Th, and U were plotted against mineralogical data in this study (Figs. 6-8, 6-9). The elements Si, Ti, Th, Al, and K display high $R^2$-values ($> 0.65$) when plotted against quartz and total clays, suggesting that they are good detrital sediment indicators in the Niobrara Formation in the study area (Fig. 6-8a-e). High $R^2$-values are also exhibited by calcium when plotted against calcite (Fig. 6-8f), suggesting that the element is a good proxy for carbonate deposition. Magnesium correlates slightly with dolomite values and does not correlate with total clays (Fig. 6-8g). Low $R^2$-values between magnesium and dolomite are probably caused by the incorporation of the element into high-Mg calcite and/or ankerite. Iron and sulfur exhibit high $R^2$ values when plotted against pyrite (Fig. 6-9a,b). No correlation was found between iron and total clays. TOC shows no good correlation with any of the elements analyzed. Uranium shows a slight positive correlation with calcite, a very slight negative correlation with total clays, and no correlation with TOC or pyrite (Fig. 6-9c,d).
Figure 6-8: Element-phase relationships utilizing XRF elemental measurements, XRD mineral phase measurements, and TOC organic phase measurements. a) Silicon plotted against total clays and quartz. b) Titanium plotted against total clays and quartz. c) Thorium plotted against total clays and quartz. d) Aluminum plotted against total clays. e) Potassium plotted against total clays. f) Calcium plotted against calcite. g) Magnesium plotted against total clays and dolomite.
Figure 6-9: Element-phase relationships utilizing XRF elemental measurements, XRD mineral phase measurements, and TOC organic phase measurements. a) Iron plotted against total clays and pyrite. b) Sulfur plotted against pyrite and TOC. c) Uranium plotted against calcite and TOC. d) Uranium plotted against total clays and pyrite.
CHAPTER 7
ORGANIC GEOCHEMISTRY

This chapter discusses the geochemical properties of the Niobrara Formation in the Sand Wash Basin. Kerogen types and source rock quality in the formation are interpreted from the provided data. In addition, the thermal maturity of the formation is examined with respect to depth.

7.1 Geochemical Data

Six wells containing the Niobrara Formation in the Sand Wash Basin were sampled for geochemical analysis (Fig. 7-1). Rock Eval bulk pyrolysis was performed on samples from the Bulldog 20-12H and Bulldog 22-41V wells. For the RMCCS State #1, Welker 42-11, North Hayden 1-2, and Dill Gulch 1-22 wells, bulk pyrolysis was performed by a HAWK analyzer (hydrocarbon analyzer with kinetics). All bulk pyrolysis data from well samples was provided for this project courtesy of Southwestern Energy (SWN).

In addition, four samples were collected from the Niobrara Formation outcrop in Steamboat Springs, CO (Fig. 7-1). Three of the samples were from undifferentiated parts of the Smoky Hill Member, while one sample was from the Fort Hays Limestone. All of the samples collected from outcrop were moderately weathered. The samples underwent bulk pyrolysis using the Source Rock Analyzer™ (SRA) at the Colorado School of Mines. The procedure for bulk pyrolysis that was performed on outcrop samples is detailed in Appendix B.

The bulk pyrolysis performed on each sample in this study provided S1, S2, and S3 peaks and $T_{\text{max}}$ values, as well as TOC. Several ratios were calculated from these values, including the hydrogen index (HI), oxygen index (OI), and production index (PI). From these calculations, various qualities of the source rocks in the Niobrara Formation of the Sand Wash Basin were able to be estimated and interpreted.
Many authors have demonstrated that the Niobrara Formation contains enough organic carbon to classify it as a fair (1-2 wt.% TOC) to good (2-4 wt.% TOC) to excellent (> 4% wt.% TOC) quality source rock (Landon et al., 2001; Sonnenberg, 2015). Additionally, it has been shown that type-II (oil prone) kerogen is dominant in the Niobrara Formation, especially in the DJ Basin (Landon et al., 2001; Sonnenberg 2011; and Jarvie, 2012). However, in the Sand Wash Basin, Finn and Johnson (2005) have shown that while type-II kerogen remains dominant, type-III (gas prone) kerogen is present as well. They suggest that the type-III kerogen was most likely derived from terrestrial sources along the western shoreline of the WIS, and (or) from cavings from the overlying Mancos Shale.

Data from this study concerning the source rock potential in the Niobrara Formation show similar results to what has been noted by previous authors (Fig. 7-2a,b). Total organic carbon values range from
less than 1 wt.% to greater than 6 wt.% in the given dataset (Fig. 7-2a). However, the majority of the data ranges between 1 wt.% TOC and 4 wt.% TOC, classifying the Niobrara Formation source rocks in the Sand Wash Basin as fair to good in quality. It is likely that some organic matter was oxidized at outcrop locations and, as a result, samples collected from outcrop may display depressed TOC values. It is predicted that if the samples were collected from unweathered surfaces, TOC content would be greater in each one of the samples, possibly classifying some of the source rocks in the Niobrara Formation as excellent in quality. In general, the TOC content displays a decreasing trend with increasing depth (and increasing thermal maturity) as hydrocarbons were generated, cracked, and expelled from the formation.

The remaining hydrocarbon potential of the Niobrara Formation source rocks, represented by S2 peak values, is classified as good to excellent (> 5 mg HC/g) for most data points taken from above 7,000 feet (TVD) in the Sand Wash Basin (Fig. 7-2b). Only data from outcrop of the Fort Hays Limestone displays an S2 peak less than 5 mg HC/g. All of the data points collected from outcrop may have depressed S2 peaks as a result of weathering processes, and may actually have higher quality oil potential than the data suggests. As is expected, S2 values decrease with increasing depth. The S2 peak is a measurement of the hydrocarbons produced under the pyrolysis of kerogen and is used to estimate the potential of a source rock to generate hydrocarbons. Thermally immature samples produce the greatest S2 peaks because little to none of the kerogen in the samples has been converted to bitumen, oil, condensate, or gas. Therefore, immature samples best characterize the original oil potential of a source rock at deposition. As the thermal maturity of samples increases with depth, S2 values decrease due to the fact that the kerogen, once present in the rock, has been cracked to produce oil, condensate, and gas. In turn, the samples taken from great depths (> ~7,500’ TVD) are not representative of the original quality of the source rocks, and should not be considered when classifying the oil potential of the Niobrara Formation.

Analyses completed with the bulk pyrolysis data regarding kerogen type is interpreted to show that type-II (oil prone) kerogen and type-III (gas prone) kerogen are both present in significant quantities in the Niobrara Formation of the Sand Wash Basin (Figs. 7-2c, 7-3). These findings are consistent with what
has been shown on kerogen types in the Niobrara Formation of the Sand Wash Basin by Finn and Johnson (2005). The type-III kerogen present in the system was most likely brought in as terrestrial organic material with siliciclastic detritus from the Sevier orogenic thrust belt to the west of the Western Interior Seaway. Type-II kerogen was present as algal marine organic matter that was generated in the water column. The two types of organic matter were deposited together in the sediment and underwent diagenesis, resulting in the two kerogen types that can be observed in the data.

The hydrogen index (HI) calculated from bulk pyrolysis values (S2/TOC) from immature samples may be used as a proxy for kerogen types in the source rocks of the Niobrara Formation, as well as for their generation potential. Above 7000 feet (TVD), HI values plot as mixed type-II/III kerogen to type-II kerogen (Fig. 7-2c). Although the most immature samples from the outcrop plot only as mixed type-II/III to type-III (gas prone) kerogen, weathering of the samples may have depressed HI values. It is predicted that if the samples were collected from unweathered surfaces, the data would have plotted as mixed type-II/III to type-II kerogen, following the upward-trend displayed by the rest of the data (Fig. 7-2c). With increasing depth and thermal maturity, the HI of Niobrara Formation samples decreases so that they are plotted as gas prone. This observation is a result of a decreasing ratio of S2 values to TOC contents with increasing depth, and is not indicative of the types of kerogen that are actually present in the formation.

Another method for interpreting kerogen types in source rocks can be accomplished by plotting TOC content against S2 peaks from bulk pyrolysis on a chart known as a kerogen quality plot. Data points that were sampled from the Niobrara Formation in the Sand Wash Basin at depths above 7,000 feet TVD (RMCCS State #1 and outcrop) plot as mixed type-II/III to type-II kerogen on the kerogen quality plot (Fig. 7-3). As the depth at which the samples were taken from increases, the data displays a decreasing trend in remaining hydrocarbon potential (S2) as well as TOC. On the kerogen quality plot, this trend is displayed as a clockwise shift in data points, as they plot from mixed type II/III down to type III and dry gas prone kerogen (Fig. 7-3). The data points that plot as type III and dry gas prone kerogen are
a result of increasing thermal maturity and are not indicative of the types of kerogen that are actually present in the formation.

Considering the aforementioned geochemical data and interpretations concerning source rock potential and kerogen types, two strong conclusions may be drawn about the Niobrara Formation in the Sand Wash Basin. First, based off of TOC content and S2 peak values, the Niobrara Formation should be considered a good to excellent source rock in the Sand Wash Basin. Second, it is evident that both type-II (oil prone) and type III (gas prone) kerogen are present in the Niobrara Formation in the Sand Wash Basin. The presence of both types reflects a mixing of marine and terrestrial components during the deposition of the formation in the Western Interior Seaway.

**7.3 Thermal Maturity**

Geochemical data regarding the thermal maturity of the Niobrara Formation in the Sand Wash Basin can be interpreted using a kerogen type and maturity plot (Fig. 7-4). In this plot, $T_{\text{max}}$ values are plotted against the hydrocarbon index of Niobrara Formation samples. Note that the pathway of data points trends down and to the right, with the majority of points being interpreted as a mixture of type II (oil prone) and type-III (gas prone) kerogen. This observation is concurrent with previously mentioned interpretations on kerogen type from this study.

In the DJ Basin, Thul (2012) concluded that the onset of hydrocarbon generation occurs between $T_{\text{max}}$ values of 432 °C and 440 °C in the Niobrara Formation. Based off of that conclusion, the geochemical data from this study is interpreted to show that the Niobrara Formation resides in both the oil and gas generation windows in the Sand Wash Basin. Data from outcrop and the RMCCS State #1 and Welker 42-11 wells plot solely in the oil generation window. The fact that data from the outcrop plots in the oil generation window means that the rocks present at the outcrop location must have been buried to a sufficient depth before being uplifted and exposed during the Laramide Orogeny. Data that was taken from the deeper North Hayden 1-26 and Dill Gulch 1-22 wells shows a transition into the gas generation
window (Fig. 7-4). This transition occurs at a depth of approximately 9,100 feet (TVD), suggesting that at least some dry gas generation occurs in the Niobrara Formation below that depth in the Sand Wash Basin. Nearly all of the data points from the Bulldog 20-12H and Bulldog 22-41V wells plot to the right of interpreted oil to gas transition lines, suggesting that the Niobrara Formation is fully into the gas generation window in these wells.

In the Sand Wash Basin, depths to the Niobrara Formation range from surface exposures on the eastern and southern flanks to greater than 20,000 feet in the northwestern part of the basin. Finn and Johnson (2005) have shown that the source rock maturity of the Niobrara Formation can be found in both the oil and gas generation windows. Building upon the work completed by Finn and Johnson (2005), Cumella et al. (2014) have stated that three different Niobrara plays currently exist in the study area: 1) a shallow, underpressured, fracture-controlled oil play; 2) an intermediate depth wet gas play; and 3) a deeper dry gas play. Production data (Table 7-1) and thermal maturity data (Fig. 7-4) suggests that the transition from play type 1 (shallow, oil) to play type 2 (intermediate, wet gas) occurs at a depth of ~8600 feet (TVD) in the Sand Wash Basin, near the North Hayden 1-26 and Dill Gulch 1-22 wells (Fig. 7-5). The transition from play type 2 (intermediate, wet gas) to play type 3 (deep, dry gas) occurs at depths between 10235 feet and 10690 feet (TVD) in study area near the Bulldog 20-12H and Bulldog 22-41V wells (Fig. 7-5), as suggested by production data (Table 7-1) and thermal maturity data (Fig. 7-4).
Figure 7-2: Source potential and kerogen type plots for the Niobrara Formation in the Sand Wash Basin. a) Total organic carbon plotted against depth. b) The S2 peak (remaining hydrocarbon potential) plotted against depth. c) Hydrogen index (S2/TOC*100) plotted against depth. Range of TVDs for all samples is listed in the key.
Figure 7-3: Kerogen quality plot for samples collected from the Niobrara Formation in the Sand Wash Basin. The image displays TOC data plotted against S2 peaks (remaining hydrocarbon potential).
Figure 7-4: Plot displaying kerogen type and thermal maturity interpretations for the Niobrara Formation in the Sand Wash Basin. $T_{\text{max}}$ values are plotted against the hydrogen index (S2/TOC*100). The onset of oil generation is interpreted to occur at $T_{\text{max}}$ values of 432 °C. Gas generation is interpreted to occur at $T_{\text{max}}$ values of approximately 460 °C. The locations from which each of the samples was taken are listed with increasing depth in the key.
Table 7-1: Production data from wells sampled for geochemical analysis in this study. Data was obtained from the Colorado Oil and Gas Conservation Commission (COGCC) website (COGCC, 2016). Gas type (wet or dry) was reported by producers to the COGCC. [NA = information not available, BBL = barrel(s), MCF = thousand cubic feet, GOR = gas-oil ratio (cubic feet of gas (CFG)/BBL), DA = dry and abandoned, PR = producing, SI = shut-in].

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>NA</td>
<td>DA</td>
</tr>
<tr>
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<td>11/1/2014</td>
<td>12/31/2014</td>
<td>74</td>
<td>369</td>
<td>77</td>
<td>4,986</td>
<td>Wet</td>
<td>PR</td>
</tr>
<tr>
<td>North Hayden 1-26</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>PR</td>
</tr>
<tr>
<td>Bulldog 20-12H</td>
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<td>10/1/2012</td>
<td>10/31/2015</td>
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<td>1,034,285</td>
<td>51,679</td>
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<td>PR</td>
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<td>12/1/2013</td>
<td>10/31/2015</td>
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<td>228,121</td>
<td>11,768</td>
<td>1,520,807</td>
<td>Dry</td>
<td>PR</td>
</tr>
</tbody>
</table>

Figure 7-5: Generalized interpretation of the areal extent of the three Niobrara Formation play types described by Cumella et al. (2014): 1) a shallow, underpressured, fracture-controlled oil play; 2) an intermediate depth wet gas play; and 3) a deeper dry gas play. Interpretations are based off of production data from wells completed in the Niobrara Formation and their locations with respect to regional structure. All wells shown on the figure were completed in the Niobrara Formation. Wells with geochemical data used in this study are shown as black circles and are labeled Contours shown are SSTVD to the top of the Niobrara Formation (contour interval = 1000'). All wells shown were completed within the Niobrara Formation (production data from IHS Global Inc.).
CHAPTER 8
DISCUSSION

Following the examination of cores, outcrop, and petrographic data (thin sections, XRD, XRF), several interpretations regarding the deposition of the Niobrara Formation in the Sand Wash Basin, with respect to relative sea level, have been stated. In this chapter, these interpretations are linked to well log data in order to create basin-wide maps that display the deposition of the member with respect to 4th-order trends in sea level (T-R cycles). Trends in total GR and spectral GR that reflect relative sea level trends are examined. Finally, as a culmination off all interpreted data presented in this study, a regional depositional model for the Niobrara Formation is presented in this chapter.

8.1 Deposition and Sea Level

Following the examination of all whole rock data, an attempt to link 4th-order transgressive-regressive relative sea level cycles to the deposition of the Niobrara Formation in the Sand Wash Basin was accomplished. Previous work on this subject has been completed by Kauffman, 1967, 1969, 1977, 1984, 1985a, 1985b; Longman et al., 1998; Drake and Hawkins, 2012; and others, with the use of reference logs from the DJ Basin (Fig. 2-5). All of these studies have interpreted peak carbonate deposition to have occurred during sea level highs and peak siliciclastic deposition to have occurred during sea level lows. Similarly, in this study, peak carbonate deposition has been interpreted to have occurred during 4th-order maximum transgressions and peak siliciclastic deposition occurred during 4th-order maximum regressions.

In well logs from the Sand Wash Basin, GR peaks are generally present in the carbonate-rich intervals and are interpreted to represent 4th-order transgressive periods. Regressive periods, present in siliciclastic-rich intervals, are generally marked by GR minimums. However it is suggested in this study that trends in the uranium and thorium curves from spectral GR logs are higher quality sea level indicators than total GR on well logs. As was shown in Chapter 6 of this study, thorium is a high quality indicator of detrital minerals in the Niobrara Formation with R² values of greater than 0.8 and 0.75 for
quartz and clays, respectively (Fig. 6-8). Therefore, thorium values from spectral GR logs are interpreted to be direct indicators of siliciclastic input into the depositional system of the Niobrara Formation. As is expected, with every interpreted transgressive period, thorium values drop dramatically and with each interpreted regressive period, thorium values increase, suggesting an inverse correlation between thorium values and relative sea level. These patterns reflect siliciclastic depositional cycles that are linked to sea level that have been discussed previously in this work; when sea level was high, clastic input was restricted to the western part of the Western Interior Seaway and when sea level as low, clastic input was carried further eastward into the basin. Uranium values display trends that are exactly opposite of thorium values on spectral GR logs. This suggests a tie between uranium values and the deposition of carbonates and TOC, and a positive correlation between uranium and relative sea level. Despite this observation, in Chapter 6 of this study, uranium did not correlate well with carbonates, TOC, or any other minerals. The correlation discrepancy between the two data sets may be linked to the methods in which the data was gathered. Uranium values gathered from XRF analysis have been shown to be largely inaccurate in the Niobrara Formation (Nakamura, 2015). However, authors such as Adams and Weaver (1958) have documented high correlations between uranium values and carbonates in marine settings. So, it is suggested that uranium values gathered from spectral GR data are more accurate than when gathered from XRF analysis, and that uranium does indeed express a tie to carbonate deposition, and possibly TOC, in the Niobrara Formation of the Sand Wash Basin. Furthermore, trends in Th/U ratios have been shown to correlate to sea level fluctuations in other basinal marine rocks, such as the Greenhorn Limestone (Doveton, 1991). In the Greenhorn Limestone, relatively high uranium contents accompanied by low thorium contents (low Th/U ratios) were shown to be associated with strongly reducing environments that were present during transgressive events (Doveton, 1991). Alternatively, regressive events were associated with relatively high Th/U ratios.

Using total GR and thorium and uranium values from spectral GR in combination with depositional interpretations made from whole rock data, four 4th-order T-R cycles (T-R7a – T-R7d) are interpreted in the...
Niobrara Formation in the study area (Fig. 8-1). The first transgressive event (T7a) deposited the entirety of the Fort Hays Limestone unconformably above the Montezuma Valley Member of the Carlile Shale. The Basal and Upper Rangely Benches were deposited during the first regressive event (R7a). The carbonate-rich Wolf Mountain, Tow Creek, and Buck Peak Benches were each deposited over T-R cycles T-R7b, T-R7c, and T-R7d, respectively. Maximum transgressive surfaces were interpreted near the middle of each of these benches. Maximum regressive surfaces at the top of events R7b and R7c are interpreted to be within the Middle Marl and Upper Marl, respectively.

Figure 8-1: Relative 4th-order sea level trends made on the Welker 42-11 well. The interpretations depicted here correlate to four 4th-order T-R cycles (T-R7a – T-R7d) that have been interpreted in the Niobrara Formation in areas outside of the study area (Fig. 2-6). The image to the left has been modified from Kauffman and Caldwell (1993).
8.2 Depositional Mapping

Each T-R cycle was mapped across the study area using the available well logs and interpreted sea level trends (Fig. 8-1). To model deposition during each T-R cycle, isochore maps were created for each event (Figs. 8-2 – 8-9). Note that each transgressive and regressive event displays similar thicknesses in lineaments from the northeast to the southwest, except for T7a, which deposited the Fort Hays Limestone. The consistent directional trends in thickness reflect the existence of a large sediment source to the west/northwest of the study area. However, as can be observed from the thickness maps, different transgressive and regressive events display differing depocenters in the area of study. The shifting of depocenters through time can be explained by two possibilities: 1) differing sediment transport directions during transgressive and regressive phases, or 2) compensational stacking of large volumes of sediment during deposition.

The first possibility is supported by the fact that two events that display depocenters towards the southeast part of the study area are both transgressive events (T7b and T7c) (Figs. 8-4, 8-6). As peak carbonate deposition is associated with transgressive events, the locations of the depocenters exhibited by these two events suggest that carbonate sediment may have been transported from areas further east during sea level highs. Longman et al. (1998) interpreted variations in current flow from the north and south in the Western Interior Seaway that correspond to variations in sea level. During sea level highs, warmer currents from the ancestral Gulf of Mexico to the south of the Western Interior Seaway heavily influenced the deposition of the Niobrara Formation. These warmer currents tended to flow along the eastern part of the basin. During sea level lows, cooler, lower-salinity currents from the Arctic Sea to the north had a large influence on deposition in the Western Interior Seaway, transporting sediments from the western edge of the seaway further basinward. The interaction of these two opposite-flowing currents could have created variations in dominant sediment transport directions (large thermohaline currents). During sea level highs, the warmer, northward flowing currents may have interacted with cooler, weaker southern flowing Arctic currents (Fig. 2-6) to create counterclockwise gyres in the WIS, as described by
Slingerland et al. (1996). These gyres could have redistributed sediments from the eastern platform and deposited them further westward. However, an absence of depocenters located in the southeast during transgressive events $T_{7a}$ and $T_{7d}$ suggests that eastward transport of large volumes of sediment during sea level highs was not the main control on sediment distribution in the study area.

A more reasonable explanation of the shifting of depocenters in the Niobrara Formation throughout time is compensational stacking. As was stated earlier, large volumes of siliciclastic sediment were shed into the basin from the Sevier Orogenic thrust belt to the west, resulting in an overall thickening of the Niobrara Formation from east to west. The only isochore map that does not display a northeast-southwest trending thickness lineament that evidences a clastic source to the west-northwest is that of $T_{7a}$ (Fig. 8-2). This transgressive event deposited the Fort Hays Limestone unconformably on the Carlile Shale. The presence of the basal unconformity may account for the strange thickness trends observed in the event. In this instance, the Fort Hays Limestone could have filled in topographic lows associated with the unconformity. The first regressive event ($R_{7a}$) displays a large depocenter in the western part of the study area and a strong thinning trend to the east-southeast (Fig. 8-3). The second 4th-order transgressive event ($T_{7b}$) exhibits a depocenter that appears to have shifted to the southeast (Fig. 8-4). This suggests that sediment build-up and decreasing accommodation space in the western part of the study area during the first T-R cycle resulted in the deposition of sediments further east during event $T_{7b}$. The sediment associated with this event was likely deposited in areas with greater accommodation space and gentler gradients. Regressive event $R_{7b}$ proceeded to accumulate sediments in the west-northwest part of the study area (Fig. 8-5). The isochore of the event displays a thinning towards the center of the study area and additional thickening in the very southeaster and eastern most portions of the study area. This suggests that sediment was deposited on both sides of the high created during transgressive event $T_{7b}$. It was followed by the events $T_{7c}$ and $R_{7c}$, which both deposited sediments further to the east in areas with more accommodation space (Figs. 8-6, 8-7). The final 4th-order T-R cycle ($T_{7d}$-$R_{7d}$) observed in the Niobrara Formation once again deposited sediments in the west-northwest part of the study area (Figs. 8-
Although, event $R_{7d}$ displays a thick sediment accumulation in the southeast part of the study area where deposition may have filled in a topographic low created by previous events.

In reality, both compensational stacking and variations in sediment transport direction probably played significant roles in how and where sediment was deposited in the study area. While subsurface mapping data suggests that compensational stacking was the main control on where sediments were accumulated, variations in current flow and subsequent changes in sediment sourcing and transport directions in the Western Interior Seaway probably had a greater effect on the types of sediments being deposited (i.e. siliciclastics vs. carbonates).

Figure 8-2: Isochore map of the first transgressive event ($T_{7a}$) in the Niobrara Formation. The event displays a depocenter in the central part of the study area. Thinning is to the east and west.
Figure 8-3: Isochore map of the first regressive event ($R_{7a}$) in the Niobrara Formation. The event displays a depocenter in the western-northwestern part of the study area. The thinning trend is from west to east.

Figure 8-4: Isochore map of the second transgressive event ($T_{7b}$) in the Niobrara Formation. The event displays a depocenter across the middle part of the study area. The thinning trend is from the center of the map to the northwest and southeast.
Figure 8-5: Isochore map of the second regressive event (R$_{7b}$) in the Niobrara Formation. The event displays depocenters in the northwest and southeast parts of the study area. The thinning trend is from the northwest and the southeast to the center of the map.

Figure 8-6: Isochore map of the third transgressive event (T$_{7c}$) in the Niobrara Formation. The event displays a depocenter across the middle part of the study area. The thinning trend is from the center of the map to the northwest and southeast.
Figure 8-7: Isochore map of the third regressive event ($R_{7c}$) in the Niobrara Formation. The event displays a depocenter across the middle part of the study area. The thinning trend is from the center of the map to the northwest and the southeast.

Figure 8-8: Isochore map of the fourth and final transgressive event ($T_{7d}$) in the Niobrara Formation. The event displays a depocenter in the northwest part of the study area. The thinning trend is from the northwest to the southeast.
Figure 8-9: Isochore map of the fourth and final regressive event (R$_{7d}$) in the Niobrara Formation. The event displays depocenters in the northwest and southeast parts of the study area. The thinning trend is from the northwest and the southeast to the center of the map.

8.3 Depositional Model

Detailed analysis completed on the Niobrara Formation in the Sand Wash Basin over the course of this study has allowed for several observations to be made regarding the timing and style of sedimentation in the Western Cretaceous Seaway. The submembers, lithofacies, mineralogic facies, and variations of TOC in the Niobrara Formation can be correlated to 4$^{th}$-order T-R cycles (Tables 8-1 – 8-4, Figs. 8-10 – 8-13). In the Western Interior Seaway, maximum transgressive periods restricted siliciclastic sediments along the western edge of the basin, limiting the dilution of carbonate sediments and TOC. In addition, these periods were characterized by large influxes of warm, northward flowing waters from the ancestral Gulf of Mexico which facilitated peak carbonate (coccolith) production across the seaway (Fig. 8-10). In the Sand Wash Basin, these periods are reflected by the presence of well-laminated, pelletal mixed carbonate mudstones and structureless, pelletal-foraminiferal mixed mudstones (Facies C, D, G, and H) in the Buck Peak Bench, Tow Creek Bench, and (to a lesser degree) the Wolf Mountain Bench (Table 8-1). Pelagic to hemipelagic sedimentation in dysoxic to anoxic bottom waters dominated these periods. As a
result, the highest relative TOC contents (2-4 wt.%) in the Smoky Hill Member of Niobrara Formation in the Sand Wash Basin are associated with maximum transgressions. However, the Fort Hays Limestone was also deposited during a 4th-order transgressive period, yet it exhibits low TOC values (< 2 wt.%) as a result of highly oxygenated waters evidenced by the presence of bioturbated lithofacies I in the member (Table 8-1). Further to the east in the DJ Basin, maximum transgressive events are characterized by carbonate-dominated lithotypes (chalks) of the A Chalk, B Chalk, C Chalk, and Fort Hays Limestone. However, unlike in the Sand Wash Basin, relative TOC contents associated with maximum transgressions in the Niobrara Formation of the DJ Basin are minimal (1-3 wt.%).

Following maximum transgressions, the relative sea level in the Western Interior Seaway began to drop. As a result the carbonate fraction in the Niobrara Formation began to drop as well. Warmer waters from the ancestral Gulf of Mexico started to recede out of the basin as cooler, lower-salinity Arctic currents from the north began to have a larger effect on deposition (Fig. 8-11). These Arctic currents flowed along the western part of the seaway and helped to carry siliciclastic detritus from the Sevier orogenic thrust belt further eastward into the basin. With a drop in sea level, the storm wave base was lowered and storm-induced sediment-gravity flows became more prevalent. In addition, the interaction of the northward and southward flowing currents may have created clockwise gyres that contributed to increased thermohaline current energy and sediment distribution in the seaway. In the Sand Wash Basin, these periods are reflected by the presence of structureless to poorly-laminated foraminiferal-pelletal mixed mudstones (Facies E, F, G, and H) near the top parts of the Buck Peak Bench, Tow Creek Bench, and Wolf Mountain Bench; near the basal parts of the Upper Marl, Middle Marl, and Upper Rangely Bench; and with the entirety of the Basal Rangely Bench (Table 8-2). Relative TOC content in stratigraphic intervals associated with early regressions decrease from those of maximum transgressions to display moderate values (1-3 wt.%) in the Niobrara Formation of the Sand Wash Basin. The total decrease in both carbonate content and TOC content with early regression is largely a result of dilution from siliciclastic influx. In addition to dilution, the cooler, lower-salinity northern Arctic waters probably
inhibited carbonate production in the seaway. In the DJ Basin, these events are characterized by mixed carbonate mudstone mineralogic facies near the top parts of the A Chalk, B Chalk, and C Chalk and the basal parts of the A Marl, B Marl, and C Marl. However, these stratigraphic intervals exhibit relative TOC contents that increase from minimal values with maximum transgressive events to moderate values (2-4 wt.%) in the DJ Basin.

Maximum regressions (lowstands) in the Western Interior Seaway correlate to maximum siliciclastic contents in the Niobrara Formation. During these periods, cooler, lower-salinity Arctic currents from the north had the greatest effect on deposition in the seaway, while warmer Gulfian waters recessed to a maximum extent out of the basin (Fig. 8-12). As a result, low sea levels distributed large amounts of siliciclastic detritus from the west to be deposited in the eastern part of the seaway, extensively diluting any existing carbonate production and TOC accumulation. In addition, carbonate production was likely decreased to a minimum in the seaway as a result of the Arctic currents. In the Sand Wash Basin, these periods are reflected by the presence of poorly- to well-laminated, foraminiferal argillaceous/siliceous mudstones and mixed mudstones (Facies A, B, E, F) in the Upper Marl, Middle Marl, and Upper Rangely Bench (Table 8-3). These facies are reflective of the highest energy depositional environments in the Niobrara Formation of the Sand Wash Basin. They represent increases in storm-induced sediment-gravity flow deposits as well as increased thermohaline current energy. Stratigraphically, the lowest relative TOC contents (< 2 wt.%) in the Niobrara Formation of the Sand Wash Basin are also associated with maximum regressions. In the DJ Basin, these events are characterized by mixed mudstones in the A Marl, B Marl, and C Marl. However, unlike in the Sand Wash Basin, the highest relative TOC contents associated with maximum regressions in the Niobrara Formation of the DJ Basin (4-8 wt.%).

As sea levels rose following periods of maximum regression, carbonate production and TOC accumulation in the Niobrara Formation became less diluted by siliciclastics in the area of study. In addition carbonate production began to increase as cooler, lower salinity northern Arctic waters receded
and warmer Gulfian waters began to have more of an effect on deposition in the Western Interior Seaway (Fig. 8-13). The rise in waters worked to raise storm wave base and dissipate thermohaline current energy throughout greater volumes of water. In the Sand Wash Basin, these periods are reflected by structureless to poorly-laminated foraminiferal-pelletal mixed mudstones (Facies E, F, G, and H) near the basal parts of the Buck Peak Bench, Tow Creek Bench, and Wolf Mountain Bench and near the top parts of the Upper Marl, Middle Marl, and Upper Rangely Bench (Table 8-4). These stratigraphic intervals exhibit moderate relative TOC values (1-3 wt.%). In the DJ Basin, these events are characterized by mixed carbonate mudstone mineralogic facies near the basal parts of the A Chalk, B Chalk, and C Chalk and the top parts of the A Marl, B Marl, and C Marl. However, the stratigraphic intervals associated with early transgressions exhibit moderate relative TOC contents (2-4 wt.%).
Table 8-1: Summary of the submembers, lithofacies, mineralogic facies, carbonate content, and TOC associated with periods of maximum transgression in the Western Interior Seaway during the deposition of the Niobrara Formation. Associations are drawn for both the Sand Wash Basin and the DJ Basin.

<table>
<thead>
<tr>
<th>Maximum Transgression</th>
<th>Submembers</th>
<th>Associated Lithofacies</th>
<th>Mudstone Mineralogic Facies</th>
<th>Relative Carbonate Content</th>
<th>Relative TOC Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Wash Basin</td>
<td>Buck Peak Bench, Tow Creek Bench, Wolf Mountain Bench</td>
<td>C, D, O, H</td>
<td>Mixed carbonate mudstones</td>
<td>High (&gt; 50 wt.%)</td>
<td>High (2-4 wt.%)</td>
</tr>
<tr>
<td>Sand Wash Basin</td>
<td>Fort Hays Limestone</td>
<td>I</td>
<td>Mixed carbonate mudstones</td>
<td>High (&gt; 50 wt.%)</td>
<td>Low (&lt; 2 wt.%)</td>
</tr>
<tr>
<td>DJ Basin</td>
<td>A Chalk, B Chalk, C Chalk, Fort Hays Limestone</td>
<td>NA</td>
<td>Carbonate-dominated lithotypes (chalks)</td>
<td>High (&gt; 70 wt.%)</td>
<td>Low (1-3 wt.%)</td>
</tr>
</tbody>
</table>

Figure 8-10: Schematic diagram, quartz-carbonates-clays ternary diagram, and 4th-order sea level curve displaying interpreted conditions during the deposition of the Niobrara Formation in the Western Interior Seaway throughout periods of maximum transgression. On the schematic diagram to the left and the ternary diagram to the upper right, the green and red circles correspond to the Sand Wash Basin and DJ Basin, respectively. The red outline on the schematic diagram to the left represents the greater Southwestern Wyoming Province. Mudstone classification scheme from Gamero-Diaz et al. (2012).
Table 8-2: Summary of the submembers, lithofacies, mineralogic facies, carbonate content, and TOC associated with early regressive periods in the Western Interior Seaway during the deposition of the Niobrara Formation. Associations are drawn for both the Sand Wash Basin and the DJ Basin.

<table>
<thead>
<tr>
<th>Regression</th>
<th>Sand Wash Basin</th>
<th>DJ Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submembers</td>
<td>Top of: Buck Peak Bench, Tow Creek Bench, Wolf Mountain Bench</td>
<td>Top of: A Chalk, B Chalk, C Chalk</td>
</tr>
<tr>
<td></td>
<td>Base of: Upper Marl, Middle Marl, Upper Rangeley Bench</td>
<td>Base of: A Marl, B Marl, C Marl</td>
</tr>
<tr>
<td>Associated Lithofacies</td>
<td>E, F, G, H</td>
<td>Mixed Mudstones</td>
</tr>
<tr>
<td>Mudstone Mineralogic Facies</td>
<td>Moderate (30-50 wt.%)</td>
<td>Moderate (2-4 wt.%)</td>
</tr>
<tr>
<td>Relative Carbonate Content</td>
<td>Moderate (1-3 wt.%)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8-11: Schematic diagram, quartz-carbonates-clays ternary diagram, and 4th-order sea level curve displaying interpreted conditions during the deposition of the Niobrara Formation in the Western Interior Seaway throughout regressive periods. On the schematic diagram to the left and the ternary diagram to the upper right, the green and red circles correspond to the Sand Wash Basin and DJ Basin, respectively. The red outline on the schematic diagram to the left represents the greater Southwestern Wyoming Province. Mudstone classification scheme from Gamero-Diaz et al. (2012).
Table 8-3: Summary of the submembers, lithofacies, mineralologic facies, carbonate content, and TOC associated with periods of maximum regression (lowstand) in the Western Interior Seaway during the deposition of the Niobrara Formation. Associations are drawn for both the Sand Wash Basin and the DJ Basin.

<table>
<thead>
<tr>
<th>Submembers</th>
<th>Associated Lithofacies</th>
<th>Mudstone Mineralogic Facies</th>
<th>Relative Carbonate Content</th>
<th>Relative TOC Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Wash Basin</td>
<td>Upper Marl, Middle Marl, Upper Rangely Bench</td>
<td>A, B, E, F</td>
<td>Argillaceous/Siliceous Mudstone</td>
<td>Low (&lt; 20-30%)</td>
</tr>
<tr>
<td>DJ Basin</td>
<td>A Marl, B Marl, C Marl</td>
<td>NA</td>
<td>Mixed Mudstones</td>
<td>Low (&lt; 50-60%)</td>
</tr>
</tbody>
</table>

Figure 8-12: Schematic diagram, quartz-carbonates-clays ternary diagram, and 4th-order sea level curve displaying interpreted conditions during the deposition of the Niobrara Formation in the Western Interior Seaway throughout periods of maximum regression (lowstand). On the schematic diagram to the left and the ternary diagram to the upper right, the green and red circles correspond to the Sand Wash Basin and DJ Basin, respectively. The red outline on the schematic diagram to the left represents the greater Southwestern Wyoming Province. Mudstone classification scheme from Gamero-Diaz et al. (2012).
Table 8-4: Summary of the submembers, lithofacies, mineralogic facies, carbonate content, and TOC associated with early transgressive periods in the Western Interior Seaway during the deposition of the Niobrara Formation. Associations are drawn for both the Sand Wash Basin and the DJ Basin.

<table>
<thead>
<tr>
<th>Submembers</th>
<th>Associated Lithofacies</th>
<th>Mudstone Mineralogic Facies</th>
<th>Relative Carbonate Content</th>
<th>Relative TOC Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Wash Basin</td>
<td>Base of: Buck Peak Bench, Tow Creek Bench, Wolf Mountain Bench Top of: Upper Marl, Middle Marl, Upper Rangely Bench</td>
<td>E, F, G, H</td>
<td>Mixed Mudstones</td>
<td>Moderate (30-50 wt.%</td>
</tr>
<tr>
<td>DJ Basin</td>
<td>Base of: A Chalk, B Chalk, C Chalk Top of: A Marl, B Marl, C Marl</td>
<td>NA</td>
<td>Mixed Carbonate Mudstones</td>
<td>Moderate (60-70 wt.%</td>
</tr>
</tbody>
</table>

Figure 8-13: Schematic diagram, quartz-carbonates-clays ternary diagram, and 4\textsuperscript{th}-order sea level curve displaying interpreted conditions during the deposition of the Niobrara Formation in the Western Interior Seaway throughout regressive periods. On the schematic diagram to the left and the ternary diagram to the upper right, the green and red circles correspond to the Sand Wash Basin and DJ Basin, respectively. The red outline on the schematic diagram to the left represents the greater Southwestern Wyoming Province. Mudstone classification scheme from Gamero-Diaz et al. (2012).
CHAPTER 9
CONCLUSIONS

The main objectives outlined for this study were 1) to provide a better understanding of how, why, and where the Niobrara Formation changes from a chalky lithology in the eastern region of deposition to a marly lithology in the western region of deposition and 2) within the regional context, to improve upon the understanding of why higher accumulations of organic matter and carbonate material occur in certain stratigraphic intervals.

The first objective was accomplished by demonstrating that the variations in mineralogy observed in the Niobrara Formation are largely a result of the proximity of any given location to the western shoreline of the Western Interior Seaway. Mineralogical information gathered from XRD data was plotted on ternary diagrams to show that the carbonate fraction of the Niobrara Formation decreases to the west as a result of siliciclastic dilution. Total organic carbon is also diluted in an increasing fashion to the west, as is evidenced by the decrease in TOC values from the DJ Basin (1-8 wt.%) (Landon et al., 2001) to the Sand Wash Basin (1-4 wt.%). The dilution resulted from the shedding of clastic sediments from the Sevier orogenic thrust belt eastward into the basin.

The second objective was accomplished by linking the stratigraphic variations of organic matter and carbonate material to conditions associated with the sequence stratigraphic framework of the Niobrara Formation. In the Sand Wash Basin, peak carbonate deposition and TOC preservation are both associated with periods of maximum transgression in the Buck Peak Bench, Tow Creek Bench, and (to a lesser extent) the Wolf Mountain Bench. Contrastingly, minimal carbonate and TOC fractions are associated with periods of maximum regression in the Upper Marl, Middle Marl, and Upper Rangely Bench. Accumulations of carbonate materials in the Niobrara Formation of the DJ Basin display the same stratigraphic trends as in the Sand Wash Basin; peak carbonate production occurred during maximum transgressions represented in the A, B and C Chalks and minimal carbonate production occurred during
maximum regressions represented within the A, B, and C Marls. However, accumulations of TOC exhibit stratigraphic trends that are opposite of those in the Sand Wash Basin. The largest preserved accumulations of TOC are associated with periods of maximum regression in the A, B, and C Marls, while minimal TOC values are associated with maximum transgressive periods in the A, B, and C Chalks.

Despite the contrasting periods of peak TOC preservation from east to west, it was noted that the mineral assemblages associated with high TOC values in the Niobrara Formation are very similar in both the Sand Wash and DJ Basin. The mineralogical data associated with high TOC content clusters around a mineral assemblage of approximately 50 wt.% carbonates, 30 wt.% clays, and 20 wt.% quartz on ternary diagrams. Therefore, the same mineral assemblage corresponds to the highest organic matter preservation potential in both basins. As mineralogical facies draw away from this intersection towards the siliciclastic-rich endmember, TOC decreases as it becomes diluted by clastic sediments. As the mineralogic facies trend towards the carbonate-rich endmember of the system, TOC values decrease as the lithologies become too clean with carbonates. Hence, it is interpreted that the mineral assemblage centered around the intersection of the three aforementioned mineralogic facies represents a depositional environment in which TOC was best preserved in the Western Interior Seaway during the deposition of the Niobrara Formation.

Aside from addressing the two main objectives that were outlined, several other conclusions were able to be drawn over the course of this work:

1.) The most prospective lateral targets in the Niobrara Formation appear to be associated with maximum transgressive events in the Buck Peak Bench and Tow Creek Bench, and possibly in the Wolf Mountain Bench. These intervals are associated with combined high carbonate and TOC contents. High TOC values suggest favorable conditions for the generation of hydrocarbons in these intervals. Additionally, high carbonate contents suggest favorable brittleness characteristics that make the rocks prone to fracturing (both naturally and from hydraulic stimulation). On well
logs, these intervals are associated with relatively high resistivity values and minimal Th/U ratios on spectral GR logs.

2.) Traction currents were a common occurrence at the seafloor during the deposition of the Niobrara Formation in the Western Interior Seaway. Sedimentary structures that resulted from these currents (normally graded beds, scour surfaces, and silt and shell lags) are present in multiple lithofacies and are likely the result of density driven bottom currents and/or very large storms.

3.) Gravity flows also likely deposited sediments in the Niobrara Formation, as evidenced by randomly oriented shell fragments observed “floating” in structureless sediments.

4.) Interpretations of deposition with sea level made from the analysis of electric well log signatures display shifting depocenters in the area of study. The shifting of the depocenters probably reflects compensational stacking patterns of large volumes of sediment.

5.) The large bivalve species *Inoceramus (Platyceramus) platinus* retained a recumbent lifestyle on the seafloor of the Western Interior Seaway. These large bivalves, where present as articulated specimens in the Niobrara Formation, provide evidence for the existence of at least small amounts of oxygen (dysoxia) at the sediment-water interface.

6.) The elements Si, Ti, Th, Al, and K are good proxies for deposition of detrital minerals in the Niobrara Formation of the Sand Wash Basin. Calcium is a good proxy for the deposition of carbonate material. TOC and Uranium do not correlate well with any other minerals or elements in the formation.

7.) The Niobrara Formation should be considered a good to excellent source rock in the Sand Wash Basin.

8.) Type II (oil prone) kerogen and Type III (gas prone) kerogen are both present in the Niobrara Formation in the Sand Wash Basin.
CHAPTER 10

RECOMMENDATIONS FOR FUTURE WORK

1.) Complete a petrophysical analysis on the Niobrara Formation in the subsurface of the Sand Wash Basin using available well logs. Such an analysis would greatly improve upon current understanding of hydrocarbon vs. water occurrence, porosity, permeability, and lithologic variation in the subsurface.

2.) Complete a comprehensive study of the porosity and permeability of the Niobrara Formation in the Sand Wash Basin using FESEM (field emission scanning electron microscope) data and subcritical nitrogen adsorption data generated from outcrop and core samples, and petrophysical data generated from well log analysis.

3.) Identify higher resolution sea level trends within the 4th-order framework that was constructed over the course of this study. Higher resolution interpretations would help to improve upon current understanding of the deposition of the Niobrara Formation in the Sand Wash Basin with respect to time.

4.) Perform a biostratigraphic study on the Niobrara Formation in the Sand Wash Basin in order to better understand deposition with respect to time.

5.) Acquire any available seismic data from the Sand Wash Basin and interpret the Late Cretaceous strata in order to better understand the structural characteristics associated with the Niobrara Formation in the basin.

6.) Collect XRD and XRF samples at high stratigraphic frequencies (1 sample/ft) from Niobrara Formation cores taken from the Sand Wash Basin. This would provide data that could be used to model variations in mineralogy and depositional environment at a high resolution that may be linked to sea level trends interpreted from well logs.
7.) Obtain organic and anoxic suite elements from XRF analysis (Cr, Zn, Mo, V, Ni). These elements may be used to model the deposition of organic matter as well as periods of anoxia in the Niobrara Formation.

8.) Complete a comprehensive study on the geomechanical stratigraphy of Niobrara Formation in the Sand Wash Basin using sonic logs and an instrument such as the Proceq Bambino hand-held rebound hammer.

9.) Perform a detailed fracture analysis of the Niobrara Formation in the Sand Wash Basin using outcrop and core data as well as any available image logs.

10.) Better refine the locations of the three Niobrara Formation play types present in the Sand Wash Basin as described by Cumella et al. (2014) by integrating geochemical data with additional production data and an improved structural analysis generated from seismic interpretations.

11.) Study the possible occurrence of differing organo-facies in the Niobrara Formation using Type II/Type III kerogen ratios.
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APPENDIX A

Table A-1: API numbers and well names of all wells used in this study. Data provided courtesy of IHS Global Inc.

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APPENDIX B

The complete analytical procedures used with Source Rock Analyzer™ (SRA) at the Colorado School of Mines (Figure B-1) can be found in the Weatherford SRA-TPH/TOC™ Manual Version 1.1 (Weatherford Laboratories Instruments Division, 2010). Additionally, a short summary of the analytical procedures has been given by Jin (2013), and is provided below.

Samples for SRA analysis are first pulverized so that they may pass through a 40-mesh sieve. Next approximately 60-100 mg of pulverized sample is accurately weighed into an SRA crucible, which is then placed in the SRA auto-sampler. The crucible is then transferred by the auto-sampler to the SRA pedestal, which raises the sample into the 300 °C oven. The sample is held at an isothermal condition of 300 °C for 5 minutes. During this isothermal heating, free hydrocarbons (HCs) are volatilized and quantitatively detected by the FID detector in SRA, reported as milligrams (mg) of HC per gram of rock. Simultaneously, the liberated free CO2 is detected by the IR cell at temperature up to 400 °C and reported as milligrams (mg) of CO2 per gram of rock. After the isothermal condition, the temperature is programmed to increase up to 600 °C at a temperature ramp of 25°C/minute. From 300 °C to 600 °C, organic hydrocarbons are thermally generated by pyrolytic decomposition of the kerogen in the rock and are roughly equivalent to the generative potential of the rock. FID is able to quantitatively detect these bulk hydrocarbons, which are labeled as S2 and reported as milligrams (mg) of HC per gram of rock. The oven is then cooled to 580 °C at the end of pyrolysis, and the carrier lines are purged for 5 minutes. The oven is cooled below 600 °C so that no pyrolysis components are released during oxidation. Subsequently, the oven is held at an isothermal condition of 580°C with purge of oxygen to oxidize the remaining residual organic carbon. During this time carbon monoxide (CO) and carbon dioxide (CO2) are released and measured by the IR cells and determined as S4. A typical SRA pyrogram is shown in Figure B-2.
Figure B-1: The Source Rock Analyzer™ (SRA, by Weatherford Ltd.) located at the Colorado School of Mines.
Figure B-2: A typical SRA™ pyrogram with pyrolysis S1-S4 and $T_{\text{max}}$ shown (from Jin, 2013).