STRUCTURAL AND FACIES CHARACTERIZATION OF THE NIOLBRARA FORMATION IN GOSHEN AND LARAMIE COUNTIES, WYOMING

by

Nicholas Devereux Kernan
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Golden, Colorado

Date ________________

Signed: ____________________________
Nicholas D. Kernan

Signed: ____________________________
Dr. Stephen A. Sonnenberg
Thesis Advisor

Golden, Colorado

Date ________________

Signed: ____________________________
Dr. Paul Santi
Professor and Head
Department of Geology and Geological Engineering
ABSTRACT

The Niobrara Formation is a fine-grained marine rock deposited in the Western Interior Seaway during the Late Cretaceous. It is composed of fossil-rich interlayered shale, marls, and chalks. Recent interest in the Niobrara has grown due to the advent of lateral drilling and multi-stage hydraulic fracturing. This technology allows operators to economically extract hydrocarbons from chalkier Niobrara facies. Yet two aspects of the Niobrara Formation have remained enigmatic. The first is the occurrence of abundant, randomly oriented, layer-bound, normal faults. The second is the large degree of vertical heterogeneity. This research aimed to increase understanding in both these aspects of the Niobrara Formation.

Randomly oriented normal faults have been observed in Niobrara outcrops for nearly a hundred years. Recent high resolution 3D seismic in the Denver Basin has allowed investigators to interpret these faults as part of a polygonal fault system (PFS). PFS are layer bound extensional structures that typically occur in fine-grained marine sediments. Though their genesis and development is still poorly understood, their almost exclusive occurrence in fine-grained rocks indicates their origin is linked to lithology. Interpretation of a 3D seismic cube in Southeast Wyoming found a tier of polygonal faulting within the Greenhorn-Carlile formations and another tier of polygonal faulting within the Niobrara and Pierre formations. This research also found that underlying structural highs influence fault growth and geometries within both these tiers.

Core data and thin sections best describe vertical heterogeneity in fine-grained rocks. This investigation interpreted core data and thin sections in a well in Southeast Wyoming and identified 10 different facies. Most of these facies fall within a carbonate/clay
spectrum with clay-rich facies deposited during periods of lower sea level and carbonate-rich facies deposited during periods of higher sea level.

Because the average operator will typically have little core but abundant well logs, this investigation used three different methods of describing facies variability with logs. Facies interpreted with these methods are referred to as electrofacies. First, a conventional interpretation of Niobrara sub-units was done using gamma ray and resistivity logs. Then a cluster analysis was conducted on an extensive petrophysical log suite. Finally, a neural network was trained with the previous core interpretation so that it learned to identify facies from logs. The research found that when little core is available a cluster analysis method can capture significant amounts of vertical heterogeneity within the Niobrara Formation. But if core is available then a neural network method provides more meaningful and higher resolution interpretations.
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Figure 8.5: Pictures from Tewksbury et al. (2011). [A] Satellite image of a polygonal fault network in the Western Desert of Egypt. Lineations are protruding chalk and calcite veins that fill in fault gaps. [B] A ground-level picture of a calcite vein protruding from its host rock. Fault dip directions, rakes, and offset of dipping layers indicate normal slip.
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CHAPTER 1
INTRODUCTION, PURPOSE, AND OBJECTIVES

The purpose of this investigation is to increase understanding of the Niobrara Formation by characterizing its structure and facies using 3D seismic, geophysical well logs, and a core, located in Goshen and Laramie Counties, Wyoming.

1.1 Introduction

In the last ten years the on-shore petroleum industry of the United States has experienced a renaissance spurred by the advent of horizontal drilling and multistage hydraulic fracturing. These techniques permit the economic production of tight reservoirs out of the developmental scope of traditional technology. The result is revitalized production in mature hydrocarbon basins.

The Denver Basin is no exception to this trend. In 2001 no horizontal wells were permitted in the state of Colorado, but in 2013 alone a total of 2,261 horizontal wells were permitted (Figure 1.1) (COGCC, 2013). Oil production more than doubled in Colorado from an average 66.4 thousand bbl/day in 2006 to an average 135.3 thousand bbl/day in 2013 (Figure 1.2). The main target for a lot of this new production has been the Niobrara Formation.

Since the 1920’s the Niobrara Formation has been known to contain layer bound, randomly oriented, normal faults (Twenhofel, 1920; Lupton et al., 1922; Prescott, 1955; Fentress 1955). Traditionally geologists attributed their occurrence to underlying Permian salt dissolution (Merriam, 1963; Siguaw and Estes-Jackson, 2011). More recently Sonnenberg and Underwood (2013) have reinterpreted the normal faults as a polygonal fault system.
The Niobrara Formation has a high degree of vertical heterogeneity. This variability has been the recent focus of many researchers (Deacon et al., 2013; Humphrey et al., 2013; McDonough et al. 2012; Luneau et al., 2011; and many others). Niobrara facies can be characterized on a clay/carbonate spectrum. The most carbonate-rich rocks are chalks while the most clay-rich rocks are marls and calcareous shales. Most previous research has focused in areas where there is abundant data and, therefore, concentrated in existing hydrocarbon fields such as Wattenberg and Silo fields. Few have approached the characterization of the Niobrara Formation using multivariate statistical methods to identifying vertical heterogeneity.

Figure 1.1: Number of oil and gas well permits for wells drilled directionally and horizontally from common well pads in Colorado (from Colorado Oil and Gas Conservation Commission (COGCC))).
Figure 1.2: Colorado oil production between 1995 and 2012 in thousands of barrels per day (from COGCC).

1.2 Purpose

Because the Niobrara Formation has become a prolific producer of hydrocarbons in recent years increasing understanding of this formation is of great interest to the petroleum geology community. This investigation aimed to characterize the polygonal fault system within the Niobrara. This is valuable because these fault and fracture networks may enhance or reduce permeability and add complications to geosteering when drilling lateral wells. This investigation also aimed to characterize the vertical facies variability of the Niobrara in a previously uninvestigated area. This is valuable because it provides a new data point away from where most previous investigations have focused. As part of this facies characterization this research also aimed to test different multivariate statistical techniques for facies characterization of the Niobrara. This is valuable because it would allow operators to interpret fine scale facies variability without the cost of acquiring a lot of core data.
1.3 Objective

In order to accomplish the previously stated aims a data set was donated by Fidelity Exploration and Production that includes a small (4 section) 3-D seismic survey and two wells, both with petrophysical logs and one with core data. The data set is located across Goshen and Laramie Counties (Figure 1.3). The objective of this investigation is to interpret structure on the seismic cube and facies with core and well data.

Figure 1.3: Township and range map of southwest Wyoming. Silo field is locally the most productive Niobrara accumulation. Location of Rocky Hollow seismic survey in grey box.
CHAPTER 2
GEOLOGIC OVERVIEW

The following geologic overview is divided into three sections: 1) the geology of the Denver Basin, 2) a summary of the Niobrara Formation, and 3) a summary of polygonal fault systems. For readers generally familiar with these topics it is recommended that they skip to Chapter 3, “Previous Work,” which covers previous research specifically focused on Niobrara faults and on the Niobrara Formation of Southeastern Wyoming.

2.1 The Denver Basin

The Denver basin covers an area of approximately 70,000 square miles spanning from eastern Colorado and western Kansas into southeastern Wyoming and southwestern Nebraska (Figure 2.1). It is an asymmetrical structural basin that started forming as early as 300 million years ago during the development of the Ancestral Rockies. Its axis runs parallel to the Rocky Mountain and Laramie ranges. It is has a steeply dipping western flank, is deepest near the Front Range, and has a shallow dipping eastern flank (Figure 2.2). It is constrained to the west by the Front and Laramie ranges, to the northwest by the Hartville Uplift, to the northeast by the Chadron Arch, to the southeast by the Las Animas Arch, and to the southwest by the Apishapa Uplift. At its deepest point the Denver basin counts with a sequence of over 13,000 ft. of sedimentary rock (Martin, 1965). Precambrian basement rocks have been dated at about 1.6 billion years old (Weimer, 1996). The basin’s sedimentary package hosts several petroleum systems (Figure 2.3).
Figure 2.1: Structural contour map of the Denver basin after Sonnenberg (2011a). Datum is the top of the Niobrara Formation. Contour interval is 1000 feet and labels are subsea depths. Major oil fields are green and major gas fields are red. Schematic cross section A to A’ in Figure 2.2.
Figure 2.2: Schematic east-west cross section of the Cretaceous strata in the Denver Basin modified from Kauffman (1977).
Figure 2.3: A stratigraphic column of Denver Basin stratigraphy modified from Sutton et al. (2004). White dots indicate conventional hydrocarbon reservoirs. Black dots indicate source rocks/unconventional reservoirs.
2.1.1 Paleozoic-Jurassic

Early research on the Denver Basin suggested that Early Paleozoic deposition in Colorado was restricted to the westernmost part of the state and that little to none occurred in the Denver basin prior to the Pennsylvanian. Then, Chronic and Ferris (1963) described a geologic anomaly: Cambrian to Silurian outcrops in the southern Laramie Range of Wyoming, further east than anyone would have expected rocks of such an age to be present. These outcrops were composed of extremely fossiliferous carbonates that indisputably carried fossil assemblages of the early Paleozoic and were interpreted to have been deposited in a shallow marine environment. This introduced the possibility that the Early Paleozoic seas (to the west) penetrated deeper into the North American continent than previously thought.

The current lack of Early Paleozoic rock is explained by two Precambrian epeirogenic features: the Siouxia and Sierra Grande highs (2.1). These structures controlled the initial deposition of Early Paleozoic sediments, but more importantly, their uplift sometime between the end of the Silurian and the beginning of the Pennsylvanian subaerially exposed and eroded almost all Early Paleozoic rocks of eastern Colorado and Wyoming (McCoy, 1953).

Towards the end of the Paleozoic tectonic plates where sutured together into Pangea. The western North American continent formed the north-western edge of the supercontinent. Volcanic arches originating from the spreading proto-Pacific collided with the North American continent. This caused orogenic events that developed the Ancestral Rocky Mountains. The suturing of Pangea resulted in a change from primarily marine to primarily terrestrial deposition. A continues sedimentary
sequence from the Pennsylvanian until the Triassic is composed of these sediments. Periodic rises in sea level would allow marine encroachment into the basin resulting in terrestrial deposits being reworked and the deposition of salt. Salt deposition was especially prevalent during the Permian. By the Jurassic the sea had completely retreated leaving behind fresh-water lakes and swamps. These resulted in the deposition of variegated shales, marls, limestones, and sandstones of the Morrison formation.

2.1.2 Cretaceous

The Cretaceous package of the Denver basin is best described as a massive transgressive sequence. Large sea-level fluctuations held important constraints on rates and environments of deposition, nevertheless, a general drowning of the basin persisted throughout this time. This is attributed to the combined effects of three events: the first, and most influential, is the Sevier Orogeny to the west which started in the Jurassic and Early Cretaceous and resulted in a deepening foreland basin. Second, global temperatures were warm, resulting in the melting of polar ice caps and high eustatic sea levels. Third, high tectonic activity at ocean spreading centers resulted in more buoyant oceanic crust and the spill-over of ocean waters onto continents.

The first incursions of a rising sea level resulted in the infilling of incised valleys. Estuarine environments developed in which the sandstones of the Dakota Formation were primarily deposited. Continued deepening deposited the Colorado Group, composed mostly shales and marls with occasional thin sandstone units. The base of the Colorado group is composed of the Carlile Shale and Greenhorn Limestone.
The top is composed of the Niobrara chalks and marls. Finally, at the end of the Cretaceous sea level was highest and the shales of the Pierre Formation were deposited. Periodic drops in sea level during Pierre deposition resulted in the progradation and reworking of thin sands on the marine shelf. These are the Hygiene/Shannon and Terry/Sussex sandstones units within the Pierre Formation.

2.1.3 Tertiary

Tertiary of the Denver Basin is best described as a massive regressive sequence. Laramide orogenic activity fragmented the Cretaceous seaway and formed the mountain ranges that now span from southeastern Wyoming, through central Colorado, to northern New Mexico. Environments of deposition transitioned from open marine, to restricted marine, to lacustrine, and finally terrestrial. Tertiary sediments vary from lacustrine to aeolian and from conglomerates to siltstones and coals.

2.2 Petroleum Systems

Oil was first found in the Denver Basin in 1901 within the fractured Pierre Shale by the McKenzie Well drilled in Boulder, Colorado. Since then over a billion barrels of oil and over 4 trillion cubic feet of gas have been produced from the Denver basin through 2007 (Higley and Cox, 2007).

Production has historically been primarily from stratigraphically trapped, conventional, Cretaceous, marine sandstones and to a lesser extent from combined stratigraphically/structurally trapped, Permian, eolian sandstones. More recently Cretaceous age source rocks, the Niobrara Formation specifically, and tight,
Cretaceous age sandstones, such as the Codell, have been targeted as unconventional reservoirs. Figure 2.4 outlines the hydrocarbon producing units within the Denver basin.

Source rocks for these plays are primarily Cretaceous organic-rich shales and marls such as the Mowry, Graneros, and Niobrara formations which tend to be mature along the basin axis. The Permian sandstone reservoirs may be sourced from the Phosphoria Formation of western Wyoming. Most conventional reservoirs require stratigraphic trapping mechanisms except for the Permian sandstones play which also depends on structuring near the Front Range.

The Niobrara and Pierre plays depend heavily on open, naturally occurring, fracture networks to improve permeabilities. Regional tectonics usually maintain these fractures dilated in a northwest-southeast direction. Even though a key limiting factor for these plays is the presence of open fractures, traps may require a fracture system to terminate in order to count with a lateral seal (Higley et al., 2007).

2.3 The Niobrara Formation

The Niobrara Formation was deposited in the Late Cretaceous (Turonian – Campanian) intercratonic seaway approximately 87 to 82 million years ago. It is composed of two members. At the base is the Fort Hays Limestone, which is an argillaceous chalk with rhythmically interbedded shales. The nature of this deposition has been tied to Milankovich cycles, which are clearly observed in distal environments of deposition, such as Kansas, but disappear towards the west due to increasing proximity to the Terrigenous detrital source of the Sevier orogenic belt (Laferriere, 1987).
<table>
<thead>
<tr>
<th>Reservoir Name</th>
<th>Age</th>
<th>Lithology</th>
<th>Environment of Deposition</th>
<th>Conventional or Unconventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hygiene/Shannon Mbr of the Pierre Shale</td>
<td>Upper Cretaceous</td>
<td>Sandstone</td>
<td>Shallow marine shelf</td>
<td>Conventional stratigraphic traps</td>
</tr>
<tr>
<td>Terry/Sussex of the Pierre Shale</td>
<td>Upper Cretaceous</td>
<td>Sandstone</td>
<td>Shallow Marine Shelf</td>
<td>Conventional stratigraphic traps</td>
</tr>
<tr>
<td>Pierre Shale</td>
<td>Upper Cretaceous</td>
<td>Shale</td>
<td>Marine</td>
<td>Unconventional, Relatively shallow, fractured reservoir</td>
</tr>
<tr>
<td>Niobrara (shallow)</td>
<td>Upper Cretaceous</td>
<td>Marl and chalk</td>
<td>Marine</td>
<td>Conventional biogenic gas production</td>
</tr>
<tr>
<td>Niobrara (deep)</td>
<td>Upper Cretaceous</td>
<td>Marl and chalk</td>
<td>Marine</td>
<td>Unconventional clean marls interbedded by shaly marls</td>
</tr>
<tr>
<td>Codell Fm (Wall Creek/Turner equivalents)</td>
<td>Upper Cretaceous</td>
<td>Sandstone</td>
<td>Inner neritic to supra tidal</td>
<td>Unconventional tight sands</td>
</tr>
<tr>
<td>Dakota Group, J and D members of the Muddy Sandstone</td>
<td>Cretaceous</td>
<td>Sandstone</td>
<td>Near shore marine</td>
<td>Conventional stratigraphic and combination traps</td>
</tr>
<tr>
<td>Deep J Sandstone</td>
<td>Lower Cretaceous</td>
<td>Sandstone</td>
<td>Near shore marine</td>
<td>Unconventional tight gas along basin axis in the deepest areas of the basin</td>
</tr>
<tr>
<td>Lyons Fm.</td>
<td>Permian</td>
<td>Sandstone</td>
<td>Eolian, fluvial and shallow marine</td>
<td>Conventional basin margin structural and combination traps</td>
</tr>
<tr>
<td>Lansing Fm.</td>
<td>Upper Pennsylvania</td>
<td>Carbonates</td>
<td>Shallow Marine</td>
<td>Conventional stratigraphic and structural</td>
</tr>
</tbody>
</table>

Figure 2.4: Hydrocarbon reservoirs in the Denver basin and their geologic characteristics.

Above the Fort Hays is the Smoky Hill Member which is composed of interbedded chalks and marls (Figure 2.5). In outcrop the Niobrara weathers into sparse, monumental white stacks and cliffs (Figure 2.6) but in core looks like variable shades of dark-gray marl and light-gray chalk. The Smoky Hill generally has cyclical variations between chalkier and marlier facies every few inches and larger scale
variations between chalk and marl facies every fifty feet (Locklair and Sageman, 2008). This stratigraphy is controlled by climate and orbital cycles and tectonic events. During higher sea levels the system was dominated biogenic activity which resulted in chalkier facies and less preservation of organic matter. During lower sea levels the system was dominated by clastic dilution from terrigenous sources resulting in marlier facies and increased preservation of organics.

Drake and Hawkins (2012) observed that during the Late Turonian, the environment of deposition was a broad shelf but in the Late Coniacian subtle NW-SW and E-W oriented submarine channels formed incising younger sequences. Starting in the middle Santonian paleobathymetric highs such as the Wattenberg High disrupted the orientation of these channel. In the Upper Santonian-Lower Campanian the prevalent sediment source is oriented SW-NE. The result of this transition, from a bathymetrically simple broad shelf to a bathymetrically variable shelf, is the Smoky Hill Member tends to be more laterally homogenous at the base and have more variable thicknesses and increased lateral heterogeneities at the top.

The stratigraphy of the Niobrara Formation has been described by many geologists (Weimer, 1960; Hattin, 1963; Kauffman 1977, Sonnenberg and Weimer 1981; Hattin 1981; 1982; Locklair and Sageman, 2008; and many others). As a result, many different classification systems for Niobrara lithofacies exist. Most of these are based on a carbonate-shale spectrum. One such system was used by Longman et al. (1998) whom created a simplified version of Pettijohn’s (1975) nomenclature and divided the Niobrara into five lithofacies (Figure 2.8). Contacts between these lithofacies are often hard to discern. This can lead to difficulty in correlation,
particularly at a fine scale level. Such a problem has been recently addressed by investigators using chemostratigraphic methods to better define lithostratigraphic boundaries (Humphry et al., 2013).

Figure 2.5: A stratigraphic column of the Cretaceous in the Denver Basin (Sonnenberg, 2011).
Figure 2.6: Outcrop of the Smoky Hills Member of the Niobrara Formation in Monument Rocks, Gove County, Kansas

Figure 2.7: Outcrop of the Smoky Hills Member of the Niobrara Formation in Castle Rock, Gove County, Kansas
Figure 2.8: Niobrara lithofacies classification using the carbonate-shale spectrum. Figure modified from Longman et al. (1998). Column A is Pettijohn (1975) classification and Column B is Longman et al. (1998) simplified version.

2.4 Polygonal Fault Systems (PFS)

Polygonal faults were first identified on 2D seismic by several authors in the 1980s (Williams, 1987; Henriet et al., 1989) but were only truly characterized with the development of 3D seismic (Cartwright and Lonergan, 1996). Since then a multitude of polygonal-fault studies have been conducted (Cartwright and Dewhurst, 1998; Dewhurst and Cartwright, 1999; Cartwright and Bolton, 2003; James and
Goulty, 2006; Gay and Berndt, 2007; Cartwright, 2011; and others). Index 1 organizes publications on polygonal faults by subject matter.

2.4.1 Background on PFS

Polygonal fault systems are layer bound, randomly oriented, normal faults, which occur almost exclusively in fine-grained rocks and are hypothesized to form during early burial (Cartwright, 2011). They have been observed only in marine sediments with the exception of Wattrus et al. (2003) who interpreted polygonal shaped soft-sediment deformation in Lake Superior as an immature PFS. Investigations into polygonal faulting have been heavily focused on their impact on fluid flow through impermeable layers (Berndt, 2003; Gay and Berndt, 2007; Ostanin et al., 2012). Faults in shales could have significant impact on reducing the capability of a seal to retain hydrocarbons in a trap, or conversely, improve vertical migration pathways through impermeable units. More recently investigations have also focused on combining the impact polygonal faults have on fluid migration with the occurrence of gas hydrates (Shiguo et al., 2011; Chen et al., 2011).

Relatively little work has been done investigating polygonal faults in outcrop. There are two reasons for this. First, because PFS exist in fine-grained rocks they often do not outcrop well or extensively. Second, PFS are best characterized by seeing fault patterns over a large region across a time equivalent surface and outcrops rarely are exposed in such a way. One exception to these conditions is an outcrop of polygonal faults in the Western Desert of Egypt described by Tewksbury et al. (2011; 2012). This PFS resides in chalks and is exposed at the surface over a broad area. This is the most extensive outcrop of polygonal faults observed in the world.
2.4.2 Classification of PFS

Not all polygonal fault systems are the same and Cartwright (2011) developed a nomenclature for describing these systems based on their vertical pattern, planform pattern, and maturity. Vertical patterns can either be a simple tier or a wedge type tier. In a simple tier faults do not have a preferential dip direction. In a wedge type tier a higher order structural trend will orient the dip direction of faults in the same general direction (Figure 2.9). The number of tiers is also characteristic be it a single tier, two, three, etc.

The word “polygonal” originates from fault geometries as seen in planform view. There are four planform (map view) patterns of polygonal faults: conjugate pairs, clusters around nuclei, locally preferentially aligned faults, and the classical hexagonal pattern first observed by Cartwright and Lonergan (1996) (Figure 2.10).

Maturity refers to the density of faulting. Mature systems are said to have more densely spaced faults while immature systems have widely spaced faults. The term, though used by Cartwright (2011), is unfortunately misleading as it implies that fault density is exclusively controlled by the passage of time. Though time could play an important role in increasing fault density, it may also be less significant in creating fault density than other factors such as lithology. As a result “density” may be a more adequate term rather than maturity. Density can be calculated as a ratio of fault tips that are connected to another fault versus fault tips that are free, or disconnected to another fault. In a denser system, most faults will be interconnected, while in sparse systems, most fault tips will be free (Figure 2.11).
Figure 2.9: Representative seismic lines indicating a simple tier and a wedge type tier of polygonal faults (modified from Cartwright, 2011).

Figure 2.10: Representative seismic time slices indicating four different end-members of polygonal fault planform geometries (modified from Cartwright, 2011).
Figure 2.11: Representative time slices indicating different levels of polygonal fault maturity (density) and how one can arrive to an 'interconnectivity index' (modified from Cartwright, 2011)

2.4.3 Genesis of PFS

Early attempts to explain polygonal fault genesis were made by Henriet et al. (1991) who considered over pressure build-up and release, and deformation related to density inversion, as the drivers for polygonal fault development. This hypothesis was opposed by Cartwright and Lonergan (1996) who claimed that the radially isotropic nature of faulting was not compatible with overpressuring and proposed that volumetric contraction is more likely the primary cause for faulting. Syneresis was posed as a possible cause for contraction (Cartwright and Dewhurst, 1998), but how shrinkage cracks at the sediment-water interface would grow into faults at depth has never been clearly explained and neither the occurrence of PFS in clean chalks that lack the clays necessary for syneresis-like behavior.
More recently support for the volumetric contraction hypothesis has grown due to laboratory experiments with unconsolidated sediments (Shin et al., 2008). These found that dissolution of unconsolidated sediments caused polygonal shaped fracturing. Volumetric contraction has been interpreted as mechanism for polygonal fault nucleation (Shin et al., 2010; Cartwright, 2011).
CHAPTER 3
PREVIOUS RESEARCH

While the previous chapter focused on the background geology of the Denver Basin, Niobrara Formation, and polygonal faulting, this chapter focuses specifically on previous investigations on the Niobrara Formation in Southeastern Wyoming and previous research specifically on faults within the Niobrara Formation.

3.1 Characterization of the Niobrara Formation in Southeastern Wyoming

The bulk of research on the Niobrara in Southeastern Wyoming has focused around Silo Field, the second largest accumulation of Niobrara hydrocarbons outside of Wattenberg Field. A report has also been published by Fidelity Exploration and Production on the Niobrara Formation in Rocky Hollow, Wyoming, northeast of Silo. Following are summaries of both these areas.

3.1.1 Silo Field

Silo Field was discovered in 1981 by Amoco Corporation. The field is a basin-centered accumulation that to date has produced over 10 MMBO and over 9 BCFG from the Niobrara Formation alone. The first horizontal well was drilled in 1990 and in recent years essentially all wells drilled are horizontal. The main target for the Niobrara at Silo is the Niobrara B chalk. Reservoir properties for this unit are described as having less than 8% porosity, less than 0.1 md permeability, 30-60 feet of pay, a gas-oil-ratio of 1030 cubic feet of gas per barrel of oil and an oil gravity of 35° API (Sonnenberg, 2011b). High resistivities have been linked to the presence of oil and as a result isoresistivity mapping has been one of the most practical tools for the delineation of the hydrocarbon accumulation in Silo (Sonnenberg and Weimer, 1993). Naturally occurring fractures within
the Niobrara have been essential in making Silo field an economic operation. Many investigators have attempted to explain the occurrence of these natural fractures. These investigations can generally be grouped into those that believe that fractures form due to basement influences (Thomas, 1992; Davis and Lewis, 1990), those who believe they are mostly due to tectonic influences (Sonnenberg and Weimer, 1991; Vincelette and Foster, 1992; Svoboda, 1995), those that believe they are due to Permian salt dissolution (Saint and Campbell, 1991) and those that believe they are due internal processes such as high pore pressures (Meissner, 1978). Most recently Finley (2013) found that basement structure has an effect on faulting and fracturing and that differential compaction over the dissolved Permian salt edge is partially responsible for structure of overlying strata including the natural fracture network. In this investigation potential polygonal faults within the Niobrara were also observed.

3.1.2 Rocky Hollow

Fidelity Exploration and Production acquired the Rocky Hollow acreage in 2009 and in 2011 drilled two lateral wells that yielded low production results (Grau et al., 2013). Poor results were attributed to low maturity of the area. The data acquired over this area was then donated to the Colorado School of Mines and is the foundation of this Masters thesis.

In the Grau et al. (2013) investigation the structural complexity of the Niobrara Formation was interpreted on a 3D seismic data (Figure 3.1) but the cause for this complexity was not explained. A fracture network was interpreted from an FMI tool run on the Jethro 44-19H pilot hole. A large number of these fractures were open with the SH max direction being NW-SE (Figure 3.2). This defined the orientation of the lateral well.
bores drilled and played a key role in changing the orientation of the Jethro 44-19H lateral well plan to be more northwards than previously intended. The Niobrara B chalk was chosen as the target for landing their lateral wells and had a gross thickness of 21 ft., of which 10 ft. were considered net pay. The characteristics of the Niobrara B pay-zone were an average porosity of 8.9%, an average water saturation of 13%, and a TOC of 2.45%.

A traditional core and several rotary side-wall cores were collected in the Jethro 44-19H well. A graphical representation of the traditional core XRD data was published by Grau et al. (2013) and can be seen in Figure 3.3. Values of porosity, permeability, and grain density were acquired for each sample. The majority of these values are from the Niobrara B1 and B2 Chalk units. Fidelity E&P also purchased a thin section petrography report from CoreLab Petroleum Services which was donated to the Colorado School of Mines for this investigation. A summary of samples available from this report are outlined in Figure 3.4.
Figure 3.1: Map from Grau et al. (2013) showing a structural interpretation on the Niobrara Formation surface from the Rocky Hollow survey. Warm colors indicate structurally higher terrains while cool colors indicate structurally lower terrains. Note the pattern of the faults. All these faults are interpreted as being normal and some form grabens. The two wells drilled in this acreage are labeled. In dashed lines is the final direction of the Jethro 44-19H while the solid line was the proposed drilling direction prior to a fracture network study.
Figure 3.2: FMI log interpretations in Rocky Hollow (modified from Grau et al., 2013). [A] SH Max. [B] Open fractures. [C] Healed fractures.
Figure 3.3: Mineralogy by XRD of the conventional core taken in the Jethro 44-19H well. Figure from Grau et al. (2013). This core mostly spans the Niobrara B unit. Note the interplay between changes in quartz, calcite, and clay.
Figure 3.4: Summary table of petrographic analysis of conventional and rotary sidewall core samples conducted by CoreLab on the Jethro 44-19H well. This data set was donated by Fidelity E&P to the Colorado School of Mines for this investigation.
3.2 Faults in the Niobrara Formation

Faulting within the Niobrara was first described in Kansas outcrops (Twenhofel, 1920). In 1955 faults were first interpreted in the subsurface intersecting wells of the Little Beaver Field, Washington County, Colorado (Fentress, 1955). They were first described on 2-D seismic by Davis (1985) within the Wattenberg Field. Not until 2011 were these faults described in 3-D seismic (Siguaw and Estes-Jackson, 2011). In 2013 they were described on a high resolution 3-D survey in Morgan County, Colorado (Sonnenberg and Underwood, 2013). The following subsections cover each of these investigations in greater detail.

3.2.1 Faults in Kansas Outcrops

Normal faults in Kansas were first recognized by Twenhofel (1920), and subsequently described by a series of other geologists (Lupton, 1922; Prescott, 1955; Merriam, 1963; Johnson, 1958; Sawin et al., 1990). All of these researchers describe these faults as normal, layer bound (restricted to the Niobrara), randomly oriented, unrelated to structural trends, with relatively little displacement (only as much as 40 ft. recorded), containing rotated blocks and localized folding, and containing striated calcite filling. Some observations were made that the Pierre Formation may have similar types of faults, but due to poor outcrop exposure, these were never truly investigated.

The general consensus between investigators was that these faults were caused by underlying Permian salt dissolution which resulted in differential subsidence and compaction of overlying sediments. Permian salt dissolution had been
observed to cause collapse structures and sinkholes in eastern Kansas (Merriam, 1963). Salt dissolution was interpreted to occur at great depths.

Figure 3.5: Photograph from Johnson (1958) showing a normal fault in outcrop, Logan County, Kansas. Fault dips to the right of picture. Shovel to the left for scale. Note the rotation of strata as one crosses the fault plane.

3.2.2 Faults in Wells

Subsurface normal faults within the fine-grained Cretaceous strata of the Denver Basin were first identified by Fentress (1955) while investigating the Little Beaver Field. Faults were interpreted from missing section in well logs. Fentress (1955) also recognized these faults as being randomly oriented and layer-bound. He recognized two tiers of faulting: one in the Niobrara and Pierre formations and the other in the upper part of the Greenhorn Formation.
Figure 3.6: Cross-section of the Little Beaver Field by Fentress (1955) showing two tiers of faulting, one in the Niobrara and one in the Greenhorn. This was the first instance that faults in these formations were described in the subsurface.

Figure 3.7: Isopach map of Little Beaver Field by Fentress (1955). ‘Bulls-Eyes’ thins indicate missing section due to the occurrence of abundant, randomly oriented, normal faults.
3.2.3 Faults in Seismic

Davis (1985) interpreted 2D seismic lines over Wattenberg Field, Colorado, and observed widespread layer-bound normal faults in the Niobrara-Carlile-Greenhorn along the flanks of fault-bounded basement-controlled paleo-structures (Figure 3.8). Davis (1985) concluded that recurrent movement on basement-controlled faults triggered development of listric normal faults in tectonically sensitive stratigraphic intervals of the Cretaceous. The Niobrara-Carlile-and Greenhorn section was considered one such interval. The listric nature of the faults was suggested by Davis (1985) as an explanation for the layer bound nature of faulting, but careful observations suggest they very well could be linear.

Siguaw and Estes-Jackson (2011) conducted the first detailed 3D seismic investigation of faulting within the Niobrara. Observations were made across three 3D seismic surveys within the Denver basin. Siguaw and Estes-Jackson (2011) recognized a layer bound, randomly oriented, set of normal fault within the Niobrara. They interpreted the occurrence of these faults to be related to post-Cretaceous dissolution of Permian salt beds and Laramide reactivation of shear zones in Precambrian basement (Figures 3.9 and 3.10).

Sonnenberg and Underwood (2013) investigated a 3D seismic data set in the central Denver Basin. They saw similar faulting as Siguaw and Estes-Jackson (2011) but reinterpreted these faults as a polygonal fault system (Figures 3.11 and 3.12). The structural style seemed to perfectly fit all the qualifications of polygonal faulting: layer-bound in fine grained rocks, normal faults with 45° dips, non-tectonic, and randomly oriented.
Figure 3.8: Modified figures from Davis (1985). [A] Interpreted seismic line displaying normal faults at the Niobrara, Hygiene zone, and Upper Pierre levels. Events labeled are top of Niobrara (Kn), top of Dakota (Kd) and approximate basement level (pE). [B] Schematic relationship between basement-controlled faults (bf) and listric normal faults (Inf). Faults were interpreted as listric but careful observations suggest they very well could be linear.
Figure 3.9: Arbitrary line across Mildred West Field, Colorado, from Siguaw and Estes-Jackson (2011)

Figure 3.10: Comparison of Precambrian shear zones and faulting within the Niobrara Formation (Siguaw and Estes-Jackson, 2011).
Figure 3.11: Time slice on the top of Niobrara interpreted by Sonnenberg and Underwood (2013). Note the classical hexagonal polygonal pattern of the PFS.

Figure 3.12: Arbitrary 2D seismic line from the 3D volume interpreted by Sonnenberg and Underwood (2013). Note the two tiers in the Pierre Shale and the Niobrara Formation.
CHAPTER 4
INTERPRETATION OF SEISMIC

A 3-D seismic data set was interpreted in order to characterize the structural geology of the study area. This data set was of approximately four square miles in area and located over Goshen and Larimer Counties (Figure 1.3). The data was collected by GeoKinetics on behalf of Fidelity Exploration and Production Co. Interpretation was done on a zero-phase time domain.

4.1 Seismic Units

Thirteen seismic units were identified named B, Pz1, Pz2, UC1, UC2, UC3, UC4, UC5, UC6, UC7, UC8, and UC9 (Figure 4.1). These units vertically stack on one another from the interpreted ‘Basement’ horizon up to the interpreted ‘Pierre Event’ horizon. A few of these units exhibit on-lapping, down-lapping, and erosive surfaces as well as other forms of discontinuities but most are composed of parallel internal reflectors with a gentle dip towards the NW. Interpretation of formations corresponding to seismic units was guided by Finley (2014) who conducted a 3-D seismic characterization of Silo Field just south of this report’s study area.

The B unit is the Precambrian basement composed of discontinuous, low amplitude, low frequency, reflectors. The reflector at the surface of this unit broadly displays a NW dipping trend with minor local variability towards the SE.

The Pz1 unit is the lowermost Paleozoic strata below the Permian salt but above basement. It is composed of semi-continuous, medium amplitude, low frequency, reflectors. Internal reflectors are parallel. A reflector within this unit is interpreted to be the top of the
Wolfcamp Formation and displays a NW dipping trend that is less steep than the Basement horizon.

The Pz2 unit is the uppermost Paleozoic strata and is interpreted to be composed predominantly of Permian age salt. It is composed of continuous, high amplitude, low frequency, reflectors. Internal reflectors are extremely parallel. A horizon at the base of this unit indicates it is also NW dipping and is even less steep than the Wolfcamp horizon. The top of this unit is a major unconformity.

The UC1 unit is the lowermost Upper Cretaceous strata and is composed of semi-continuous, low amplitude, high frequency, reflectors. Internal reflectors are subparallel to divergent and appear to be composed of NW prograding clinoforms with a shallow basin hinge at about the middle of the survey which correlates with the edge of the basement high observed in the B unit. These are interpreted to be the deltas and estuaries deposited during the initial deposition of the Upper Cretaceous. Reflectors become more parallel towards the top of the unit as the basin appears to be in-filled.

The UC2 unit lies above UC1 and is composed of continuous, high amplitude, low frequency, reflectors. Internal reflectors are parallel. This unit, together with UC1, is interpreted to be composed of the Dakota and Sundance Formations. A reflector at the top of UC2 indicated it has a continuous NW dipping trend.

The UC3 unit lies above UC2 and is composed of faintly continuous, medium amplitude, medium frequency, reflectors. Internal reflectors are parallel but thin slightly onto the NW dipping at about the middle of the seismic survey. These reflectors are interpreted to be composed of the Graneros/Mowry Shale.
The UC4 unit lies above the UC3 unit and is composed of mostly discontinuous, low amplitude, high frequency, reflectors. Internal reflectors are parallel. This unit is interpreted to be the Greenhorn Limestone and Carlile Shale.

The UC5 unit lies above the UC4 unit and is composed of mostly continuous, medium amplitude, high frequency reflectors. Internal reflectors are parallel. This unit is interpreted to be the Lincoln Limestone, Codell Sandstone, and Fort Hays Limestone.

The UC6 unit is a thin unit that lies above the UC5 unit and is composed of discontinuous, low amplitude, medium frequency, reflectors. This unit is interpreted to be the lower part of the Smoky Hills Member of the Niobrara Formation (Niobrara C and B) composed mostly of chalk and marls. The uppermost reflector of this unit (blue/peak) is interpreted as the top of the Niobrara B Chalk.

The UC7 unit lies above the UC6 unit and is composed of 3 continuous, high amplitude, low frequency, reflectors. Internal reflectors are very parallel. This unit is interpreted to be composed of the upper part of the Smoky Hills Member of the Niobrara Formation (Niobrara B and A) at its base and the lowermost Pierre Shale (including the Sharron Spring’s member) and its top. The highly variable lithology results in very bright velocity contrasts. The middle reflector (blue/peak) is interpreted as the top of the Niobrara Formation.

The UC8 unit lies above the UC7 unit and is composed of semi-continuous, low amplitude, variable frequency, reflectors. Internal reflectors are somewhat subparallel. This unit is interpreted to be composed of the lower part of the Pierre Shale.
The UC9 unit lies above the UC8 unit and is composed of mostly continuous, medium amplitude, high frequency, reflectors. Internal reflectors are parallel but appear to be thickening slightly towards the NW. This unit is interpreted to be within the Pierre Shale.

The UC10 unit lies above the UC9 unit and is composed of three, continuous, high amplitude, low frequency, reflectors. This unit contains the “Pierre Event” horizon also identified by Finley (2014).

4.2 Seismic Interpretation

The top of the basement is poor or nonexistent because the acoustic impedance of the overlying section can be identical to the basement. The interpreted Basement horizon (Figure 4.2) is, therefore, approximate. This horizon has a gentle NW dipping direction. This is to be expected since the study area is east of the Denver Basin axis and in the Northern Denver Basin. More interestingly is the presence of local basement highs and lows. These may be paleo-basement topography or generated by basement faults. An interpretation of the basement fault hypothesis can be seen in Figure 4.23. All horizons above the basement drape over these basement features.

Paleozoic to Dakota strata fills in the structural lows and on-lap onto the structural highs (Figures 4.3 through 4.11). These progressively ‘flatten’ as one goes up-section. Yet signs of increasing structural complexity appear within the seismic unit UC3 composed of the Graneros and Mowry Shale (Figure 4.11). A set of faults flanking the basement structure can then be seen in the time structure map of the Greenhorn Event (Figure 4.12) at the top of seismic unit UC4.

Seismic unit UC4 (Figure 4.13) is comprised of the Greenhorn and Carlile formations and provides a particularly intriguing structural signature. It hosts a dense set of
randomly oriented, layer bound, normal faults (Figure 4.24). These are interpreted to be a polygonal fault system. As one moves up-section into seismic unit UC5, comprised of Codell Sandstone and Fort Hays Limestone, this fault system terminates. This fault system could be propagating downward into the Graneros and Mowry Shale.

A second polygonal fault tier is observed within the Niobrara and Pierre formations (Figures 4.14 through 4.22). Unlike the faults restricted to the Greenhorn and Carlile these faults are larger and less dense (Figure 4.25). This tier of faulting terminates somewhere within the Pierre Formation.

The largest faults in this study area cut across both the above mentioned polygonal fault tiers. They occur almost exclusively along the flanks of underlying structural highs in a relationship similar to that observed by Davis (1985) in Wattenberg Field.

Growth strata within the Pierre Formation suggest that these faults occurred early after burial (Figure 4.20). On-lapping of seismic reflectors onto the crest of these faults suggests that they interacted with the sediment-water interface (Figure 4.27) but it is possible that these features are simply caused by differential compaction.
Figure 4.1: East-West X-Line displaying the different seismic units identified and the horizons that bind them. Polarity of data is EG Normal (Blue = Peak). Vertical exaggeration is approximately 20:1.
Figure 4.2: Top basement time structure map. Note the NW dip direction with a slight porpoising of the reflector suggesting occurrence either NE-SW trending faults and folds, or paleo-topography. A discreet basement high can be observed in the middle of the survey (dashed black line), with another possible basement high just barely visible to the south. These highs form a shallow space on the eastern portion of the survey. Contour interval is 2 milliseconds.
Figure 4.3: Time structure map of Permian horizon (top of Pz1 seismic unit). Note that the dip direction continues to be towards the NW but the reflector is much more continuous, suggesting that basement faults do not extend into the sedimentary cover. The basement high can be observed in the middle of the survey, but some infilling around this structure has taken place. Contour interval is 2 milliseconds.
Figure 4.4: Isochron map of seismic unit Pz1. This unit contains all the strata from the basement until the Permian. Thinning over the several basement highs can be observed. Thickening occurs in the shallow space to the east of the basement high. Contour interval is 2 milliseconds. Cool colors are thins, warm colors are thicks.
Figure 4.5: Time structure map of the upper-most Paleozoic reflector (top of Pz2 seismic unit). Note that this reflector looks very similar to the Permian horizon. Contour interval is 2 milliseconds.
Figure 4.6: Isochron map of seismic unit Pz2. This unit is essentially isopachus across the area under investigation. In other words, there are no real changes in the thickness of the Permain salt beds. Contour interval is 0.5 milliseconds. Cool colors are thins, warm colors are thicks.
Figure 4.7: Time structure map of the uppermost reflector of the seismic unit UC1. The NW dipping structure is observed with a structural high in the middle of the seismic survey and the N-S trending shallow to the East. Contour interval is 2 milliseconds.
Figure 4.8: Isochron map of seismic unit UC1. This unit appears to be mostly filling the area to the NW of the seismic survey. A N-S thin is observed on the eastern part of the survey. This is interpreted to occur due to the underlying structural high that reduces accommodation. Contour interval is 0.5 milliseconds. Cool colors are thins, warm colors are thicks.
Figure 4.9: Time structure map of Dakota horizon (top of seismic unit UC2). This map looks very similar to underlying time structure maps with a gently dipping NW trend and a slight high in the middle of the seismic survey (edge of high displayed as a black, dashed, line). Contour interval is 2 milliseconds.
Figure 4.10: Time structure map of the uppermost reflector of seismic unit UC3. Though the general trend continues to be NW dipping, a higher amount of texture can be observed in this horizon suggestive of increasing structural complexity. The N-S trending shallow-basin on the eastern portion of the survey has been completely filled in. Contour interval is 2 milliseconds.
Figure 4.11: Isochron map of seismic unit UC3. Small, randomly oriented, changes of seismic thickness can be observed similar to the isochron of seismic unit Pz2. Unlike seismic unit Pz2 the changes in this seismic unit are at a larger scale and some influence of the underlying structure can be observed. For example, the overall thickness of the unit increases towards the SW and a thin, curved band, of thinning can be observed along the NW edge of the underlying structural high. This randomly oriented variability in thicknesses could be an early expression of a polygonal fault system. The curved band of thinning is likely a product of enhanced slip along the pre-existing structural hinge. Some E-W lineations in the SW portion of the survey appear to be seismic artifacts. Contour interval is 0.5 milliseconds. Cool colors are thins, warm colors are thicks.
Figure 4.12: Time structure map of the Greenhorn Event horizon (top of seismic unit UC4). The general NW structural dip is retained in this horizon but subtle normal faulting occurs along the edge of the structural hinge. These faults follow the contour of the basement structure and do not appear to have a generally preferred NW dip direction. The largest of these faults has a throw of approximately 20 milliseconds. Contour interval is 2 milliseconds.
Figure 4.13: Isochron map of seismic unit UC4. Elongate, randomly oriented, changes in seismic thickness can be observed. These are very similar to those seen in the isochron of seismic unit UC3, however they are larger and longer. This structural pattern is characteristic of a polygonal fault system. A normal fault could be interpreted to exist everywhere an elongate thinning is observed. Faults that follow the edge of the first order structural high appear to have enhanced slip resulting in more missing section. Variations in thickness in the underlying seismic unit UC3 could be caused by the downward tipping-out of this fault system. Contour interval is 0.5 milliseconds. Cool colors are thins, warm colors are thicks.
Figure 4.14: Time structure map of the Fort Hays horizon (top of seismic unit UC5). Note the NW dipping and the presence of faults along the perimeter of structural highs and lows. Black dots and lines indicate lateral wells drilled within the Niobrara B Chalk. Slight NW-SE trends are observed developing in the NW corner of the seismic survey. Contour interval is 2 milliseconds.
Figure 4.15: Isochore map of seismic unit UC5 (containing the Fort Hays and Codell units). A few faults from seismic unit UC4 cut clean through unit UC5 but most of the underlying polygonal faults do not. This seismic unit is a baffal to polygonal fault growth except along the edge of the underlying structural high. Contour interval is 0.5 milliseconds. Cool colors are thins, warm colors are thicks.
Figure 4.16: Time structure map of the Niobrara B horizon (top of seismic unit UC6). A new tier of polygonal faulting appears to be present. This tier is strongly controlled by underlying structural features making it appear less random (polygonal) than the Greenhorn-Carlile PFS.

Black dots and lines indicate lateral wells drilled within the Niobrara B Chalk. The Cowgirl Premium 31-18H was drilled into a narrow tilted fault block. Operator (Fidelity E&P) hoped that proximity to faulting might create additional fracturing which in turn would result in better secondary permeabilities. The Jethro 44-19H was drilled into a broad plunging nose. Operator hoped that the complex up-dip faulting would create a trapping mechanism. Contour interval is 2 milliseconds.
Figure 4.17: Time structure map of the Niobrara horizon (top of seismic unit UC7). This map appears very similar to the Niobrara B horizon but shows increased slip along normal faults. Faults flanking the structural highs have greater slip. Contour interval is 2 milliseconds.
Figure 4.18: Isochron map of the Niobrara Formation (from the Top Niobrara reflector to the Fort Hays reflector). Thinning indicates the occurrence of normal faults. Contour interval is 1 milliseconds. Cool colors are thins, warm colors are thicks.
Figure 4.19: Time structure map of the top of the seismic unit UC8. Note that horizons become less structured as one moves up-section and again the NW dipping horizon with a local high in the middle of the seismic survey can be seen. Contour interval is 2 milliseconds.
Figure 4.20: Isochron map of seismic unit UC8. Note thicker packages (green) adjacent to faults (blue and purple due to missing section). This is suggestive of fault-growth strata which would insinuate that the faults were active soon after burial so that they may interact with sedimentation. Contour interval is 0.5 milliseconds. Cool colors are thins, warm colors are thicks.
Figure 4.21: Time structure map of the uppermost reflector of seismic unit UC9. Note that the reflector has very little structural complexity, The local high is still present and regional dip is towards the NW. Contour interval is 2 milliseconds.
Figure 4.22: Isochron map of seismic unit UC9. No drastic changes in thickness variations are observed suggesting a near termination of fault growth within or below this unit.
4.3 Summary of Seismic Interpretation

1. The basement high in the south-central portion of the survey, and the basement low in the north-west portion of the survey, are structural features that control shallower structures well into Late Cretaceous time. These structures may be generated by paleo-topography or due to basement faulting. A possible interpretation of basement faults can be seen in Figure 4.23. These are not easily interpreted on the seismic survey.

2. No Permian salt dissolution or mobilization was observed negating the possibility that polygonal faulting in Upper Cretaceous strata is caused by these mechanisms. It is possible that Permian salt could decouple basement structure from post-salt strata, but as the previous point states, the basement highs and lows appear to have a persistent control on structure into Late Cretaceous time.

3. A polygonal fault system is first vaguely observed within seismic unit UC3, composed of the Graneros and Mowry Shale. It is distinctly observed in seismic unit UC4, composed of the Greenhorn and Carlile Formations, in the form of polygonal shaped thinning. This thinning is due to missing section caused by normal faulting. Figure 4.24 is an interpretation of faults within seismic unit UC4. Faults seem to have a generally random (polygonal) pattern. The faults on flanks of basement structures have greater slip and link into longer faults. This fault tier terminated within seismic unit UC5.
4. A second polygonal fault tier exists within the Niobrara and Pierre Formations. Underlying structure appears to have a stronger influence on these faults than in the deeper Greenhorn-Carlile tier.

5. A few faults cross-cut across both the deeper Greenhorn-Carlile tier and the shallower Niobrara-Pierre tier. These tend to be aligned along the flanks of structural highs.

6. Some growth stratum was observed adjacent to normal faults in the Niobrara-Pierre tier. This suggests that polygonal faults grow primarily up section and were active after early burial. Some component of downward fault propagation may have occurred as well. It is possible, however, that these features are caused by differential compaction.

7. Antithetic faults form grabens and may develop due to the rotation of the hanging wall block. Alternatively, changes in the dip of the normal faults could be causing the development of the antithetic faults (Figure 4.25).
Figure 4.23: Interpretation of basement structure based on the basement horizon and the seismic unit Pz1 isochron maps. Northwest-Southeast trending faults could produce local structural highs and lows. The overlying sedimentary cover drapes over these features. Contour interval is about 4 millisecond.
Figure 4.24: Fault interpretation from the seismic unit UC4 isochron which includes the Greenhorn and Carlile formations.
Figure 4.25: Niobrara time-structure map with interpreted faults. X-Line 94 in red is displayed in Figure 4.26. X-Line 41 in blue is displayed in Figure 4.27. Contour interval is 2 milliseconds.
Figure 4.26: X-Line 94 (as displayed in figure 4.25). Note that an antithetic fault has developed. This antithetic fault could develop due to the rotation of the hinging wall block or due to a change in dip in the main fault. 10X vertical exaggeration.

Figure 4.27: X-Line 41. Note on-lapping onto fault scarps (indicated by arrows). Similar on-lapping can be observed in Figure 4.1. This suggests that the faults could have been interacting with the sediment-water interface. Alternatively, they might be generated from differential compaction. Vertical exaggeration is approximately 7:1.
4.4 Fault in Core

A core was collected from the Jethro 44-19H well and interpreted in this investigation (Chapter 6, Facies Characterization). One of the most startling discoveries made during the interpretation of the core was the presence of a fault at 7602 feet depth (Figure 4.25). This fault has no seismic expression (Figure 4.26) resulting in three possible theories for its occurrence (Figure 4.28). This fault has a moderate angle (50 degrees) of dip and is filled with calcite. Coming off the fault are thin, perpendicular, fractures. The facies through which this fault intersects is a thin bed of the hummocky cross-stratified marl. Since the facies the fault intersects is hardly displaced it is likely that this fault is simply an incredibly small, independent, subseismic, fault.

Figure 4.28: Fault as seen in the Jethro 44-19H core at a depth of 7602 ft. Note the calcite fill in between fault planes and the perpendicular fractures originating from this surface. End of mechanical pencil for scale.
Figure 4.29: Seismic line between the two wells in the study area. Note that no fault within the Niobrara appears to be present at the Jethro 44-19H. On the Cowgirl Premium 31-18H well the gamma ray log has been plotted with warm colors indicating high API values and cool colors indicating low API values. Niobrara horizons are interpreted and labeled.
Figure 4.30: Three possible interpretations for the presence of the fault in the Jethro 44-19H core are possible. The box labeled “A” suggests a subseismic extension of the fault south of the well. The box labeled “B” suggests a subseismic extension of the fault directly east of the well. A third, and more likely, option is that this fault is independent of any fault interpreted on seismic.
CHAPTER 5
PRELIMINARY OBSERVATIONS IN OUTCROPS

Because polygonal fault systems exist in fine-grained rocks they rarely crop out. The Niobrara Formation is unique in that it crops out in certain areas of West Kansas and Nebraska. Additionally, these regions have not experienced significant tectonism so all structures can be interpreted to be non-tectonic in nature. Because this is such a unique situation this investigation set forth to make some preliminary observations of the Niobrara Formation in West Kansas outcrops, particularly in Gove County. The Niobrara Formation is the first instance of a polygonal fault system that crops out identified within North America, and one of the few polygonal fault systems seen in outcrop in the world. Following are preliminary observations made in the field. Since these observations were made a more detailed investigation on distributed normal faults in Niobrara outcrops of Kansas and Nebraska has been completed by Maher (2014).

- The best outcrops found were in Monument Rocks National Natural Landmark, West Gove County, and at Castle Rock, East Gove County (Figure 5.1). Exposures may still be too small to adequately characterize the polygonal planform pattern of a polygonal fault system.

- Faults closer to the eastern edge of Niobrara outcrops (within stratigraphically deeper section) tended to be smaller and denser. Bedding within these fault blocks was sometimes rotated and folded. Slip on these faults is in the order of only a few feet (Figure 5.2)
Faults closer to the western edge of Niobrara outcrops (within stratigraphically shallower section) tended to be larger and not dense, but rather, single independent features. These larger faults exhibit a slight listric geometry and have slips on the order of several tens of feet (Figure 5.3).

Large amounts of striated calcite in the form of veins and float were observed in eastern outcrops (Figure 5.4). This calcite had grooved and corrugated surfaces suggestive of rakes at approximately 90 degrees indicating dip slip.

Strong parallels can be found between the work done by Tewksbury et al. (2012) on polygonal faults in outcrops of Khoman chalk of the Western Desert of Egypt and this investigation (Figure 5.5.).

Figure 5.1: Map of Niobrara outcrops in Kansas modified from Meriam (1963) with interstate I-70 for reference. Blue star indicates general location of Monument Rock outcrops. Red star indicates general location of Castle Rock outcrops, and white star indicates location of outcrops investigated North of Hays.
Figure 5.2: Faults observed towards the eastern edge of Niobrara outcrops (within stratigraphically lower section) tended to have large numbers of small, randomly oriented faults. [A] Two sub-parallel faults in outcrops north of Hays. Hammer for scale. [B] Three faults at Castle Rock. Two parallel faults dip towards the left and one fault dips towards the right. Dr. Maher for scale stands between these faults of opposing dips.
Figure 5.3: Faults observed towards the western edge of Niobrara outcrops (within stratigraphically shallower section) are larger, independent, faults. [A] Two faults dipping in different directions within outcrops of Monument Rocks. One fault is indicated with blue arrows and the other with red arrows. The blue arrow fault can be seen on the left of the picture and it dips towards the right. It continues along strike into the buttress with the white star over it. The red arrow fault can be seen on the right of the picture and it dips towards the left and continues along strike until it also arrives to the buttress with the white star. Here both faults connect at a slightly oblique angle. [B] Close-in picture of the blue fault as seen on the leftmost buttress.
Figure 5.4. Calcite veins will often fill faults observed within the Niobrara. [A] Veins consist of coarse calcite up to 10 inches thick. Some of these veins protrude out of the surface at steep dips. [B] Veins are strongly grooved and corrugated and have rakes of approximately 90 degrees indicating dip slip (6-inch ruler for scale). [C] Veins appear to have grown perpendicular to vein margins and into dilatant space. This suggests high pore fluid pressures and an element of ‘strain-hardening’ during vein development. Kinks in faults can amplify the dilatant space and result in coarser calcite crystals, some as much as 4 inches long.
Chapter 6
Facies Characterization

Facies characterization of the Niobrara was based on interpreting a conventional core and rotary side-wall cores from the Jethro 44-19H well. The core interpretation was paired with XRD and thin section analysis of 28 samples (Figure 3.7 and 3.8). A total of 9 facies were identified within the Smoky Hills Member and one facies within the Fort Hays Member. Most of these can be organized in a spectrum from high calcite/low clay content to low calcite/high clay content. The exceptions are facies 10 which is Bentonite, and facies 6, Silty Marl, which is a more quartz-rich variety of facies 5, Marl. The facies nomenclature applied is similar, though not exactly, like that used by Deacon et al. (2013), and Luneau et al. (2011) whom both have described Niobrara facies in the Denver Basin. Figures 6.1 and 6.2 show how the volume of clay changes with volume of carbonate and the volume of silt.

![Clay v. Carbonate graph](image)

Figure 6.1: Graph of the relationship between the volume of clay and carbonate in the Niobrara Formation in the Jethro 44-19H core. XRD analysis by CoreLab.
Figure 6.2: Graph of relationship between the volume of clay and silt (quartz + feldspar) in the Niobrara Formation in the Jethro 44-19H core. XRD analysis by CoreLab.

6.1 Facies Identification

The following list is organized from facies with abundant carbonate and little clay to facies with abundant clay and little carbonate. The Bentonite and the Fort Hays Limestone facies are described last.

1. Chalk (Figure 6.3)
   - Observed within the Niobrara B Chalk unit interbedded with the Slightly Argillaceous Chalk facies
   - Contains over 90% carbonate with the remainder being equal amounts of clay and quartz
   - Usually faintly laminated and light grey in color

2. Slightly Argillaceous Chalk (Figure 6.4)
   - One of the most common facies in the core. Observed within the Niobrara C chalk unit interbedded with the Argillaceous Chalk facies and within the Niobrara B chalk unit interbedded with the Chalk facies.
   - Chalk: contains 80-90% carbonate with the remainder being equal amounts of clay and quartz
   - Usually bioturbated and light grey in color

3. Argillaceous Chalk (Figure 6.5)
   - Observed predominantly within the Niobrara C Chalk unit interbedded with the Slightly Argillaceous Chalk facies but also as a thin bed within the middle of the Niobrara B Chalk in what is often referred to as the “Niobrara B1 Marl.”
- Contains 70-80% carbonate with the remainder being equal amounts of clay and quartz
- Usually faintly laminated and slightly bioturbated

4. **Fossiliferous Marl (Figure 6.6)**
   - Observed at base of the Niobrara B Marl
   - Contains 50-70% calcite with the remainder being equal amounts of clay and quartz
   - Is characterized by abundant planktonic foraminifers and brachiopods

5. **Marl (Figure 6.7)**
   - Observed in a side-wall core within the Niobrara A Marl and interpreted to be more common at the top of the unit and interbedded with the Calcareous Shale facies.
   - Contains 30-60% carbonate, ~15% quartz, ~30% clay, and ~15% pyrite.

6. **Hummocky Cross-Stratified Marl (Figure 6.8)**
   - Observed as thin (1-2 inches) beds at the base of the Niobrara B Chalk
   - Interpreted to be storm deposits

7. **Silty Marl (Figure 6.9)**
   - Observed at the across the entire Niobrara B Marl and interbedded in the middle of the Marl facies.
   - Contains ~40% carbonate, ~25% quartz, and ~30% clay.

8. **Calcareous Shale (Figure 6.10)**
   - Observed at the top of the conventional core within the base of the Niobrara A Marl and interpreted to be more common at the base of that unit becoming interbedded with the Marl facies
   - Contains 10-30% carbonate, with the remainder being quartz and clay
   - Has very fine laminations and little poker-chipping of core.
   - Sub-vertical sylolite observed

9. **Bentonite (Figure 6.11)**
   - 21 observed within the conventional core. These are typically very thin (less than half an inch) but occasionally can be as thick as 2-3 inches.

10. **Fort Hays Limestone (Figure 6.12)**
    - At the base of the Niobrara. Observed only in a side-wall core.
    - A highly bioturbated argillaceous chalk
6.3: **Chalk Facies.** [A] Picture of facies in core at 7593 ft. depth. Laminations (L) can be observed at top of core. [B] Thin section of facies from sample 14 at core depth 7593.25 ft. Note calcite-cemented vertical microfractures (Fr_ca), abundant foraminifer tests, and an oyster shell fragment (Br). [C] Calcite cement (ca) fills foraminifer tests. There is moderate amounts of plant fragments and almost no quartz silt. Matrix is micritic and has a mottled texture.

Sample 14 XRD-Whole Rock Mineralogy (Weight %):
Calcite: 92.4%
Total Clay: 3.5%
Quartz: 2.5%
Figure 6.4: **Slightly Argillaceous Chalk Facies.** [A] Picture of facies in core at 7590 ft. depth. Sample is bioturbated. Inoceramus fragment visible near the bottom of the picture. [B] Thin section of facies from sample 11 at core depth 7590.05 ft. Planktonic foraminifers are abundant and there is a bivalve shell (Br). [C] Calcite cement (ca) fills foraminifer tests (fp). Elongate plant fragments (pf) can also be observed. Matrix is micritic with a mottled texture.

Sample 11 XRD-Whole Rock Mineralogy (Weight %):
Calcite: 86.8%
Total Clay: 5.8%
Quartz: 5.1%
Figure 6.5: Argillaceous Chalk Facies. [A] Picture of facies in core at 7580 ft. depth. Note the fine scale laminations. [B] Thin section of facies from sample 6 at core depth 7579.50 ft. Sample is organic-rich and contains abundant microstylolites. [C] Foraminifer tests (fp) are less common than in previous two facies. Pyrite (py) found in matrix. Horizontal microfracture (Fr) present and may be natural or induced.

Sample 6 XRD-Whole Rock Mineralogy (Weight %):
Calcite: 75.9%
Total Clay: 9.5%
Quartz: 7.3%
Figure 6.6: **Fossiliferous Marl Facies.** [A] Picture of facies in core at 7604 ft. Oyster shells are abundant. [B] Thin section of facies from sample 21 at core depth 7604.75 ft. Note the abundant planktonic foraminifera and oysters (Br), some of which have been replaced with fluorite (fl). Organic matter (om) concentrated in microstylolites and compaction seams. [B] Foraminifer tests are cemented by calcite (ca) and ferroan dolomite (df). Pyrite (py) present in matrix. Facies interpreted as a storm deposit.

Sample 21 XRD-Whole Rock Mineralogy (Weight %):
Calcite: 66.2%
Total Clay: 15.6%
Quartz: 10.5%
Figure 6.7: Marl Facies. [A] Thin section of facies from sample 3, a rotary side-wall core collected at 7424 ft. depth within the Niobrara A Chalk unit. Sample is mostly pellets (p) with some planktonic foraminifers (fp) and silt sized grains being mostly quartz. [B] Pyrite (py) occurs as small framboids throughout the matrix and partially cementing some foraminifer tests. Calcite (ca) and ferroan dolomite (fd) commonly cement foraminifer tests. Matrix consists of micrite and detrital clay and is rich in organic matter.

Sample 29 XRD-Whole Rock Mineralogy (Weight %):
Calcite: 67.8%
Total Clay: 11.5%
Quartz: 12.1%
Figure 6.8: Hummocky Cross-Stratified Marl facies. [A] Picture of facies in core at 7592 ft. depth. Note the distinct cross-bedding composed of scour bases and truncation surfaces separating individual undulating lamina. Interpreted as a storm deposit. [B] Detrital and organic matter concentrates along microstylolites (sty). [C] Abundant planktonic foraminifers (fp) and pyrite (py) in matrix with calcite (ca) cement in tests and quartz (Q). Horizontal microfracture (Fr) observed but unclear if natural or induced.

Sample 17 XRD-Whole Rock Mineralogy (Weight %):
Calcite: 54.6%
Total Clay: 27.2%
Quartz: 7.2%
Figure 6.9: Silty Marl Facies. [A] Picture of facies in core at 7613 ft. depth. Note the faint laminations, bioturbation, and microfractures (mf). [B] Thin section of facies from sample 24 at 7613.00 ft. Note the matrix is composed mostly of pellets and quartz. [B] Pellets (p) and quartz (Q), and abundant clay make up most of the matrix. The few foraminiferal tests are cemented with ferroan calcite (cf) or ferroan dolomite (df). Abundant plant fragments (pf) also observed.

Sample 24 XRD-Whole Rock Mineralogy (Weight %):
Calcite: 41.0%
Total Clay: 27.5%
Quartz: 24.5%
Figure 6.90: **Calcereous Shale Facies.** [A] Picture of facies in core at 7594 ft. Note the presence of two bentonites (b) at the top and bottom of picture and the fine scale laminations. [B] Thin section of facies from sample 5 at 7494.25 ft. depth. Laminations are obvious including a quartz lamina at the base of picture. Phosphatic bone fragment (ph) in upper-right hand corner. [C] Pellets (p), framboidal pyrite (py), and quartz are abundant. Not very organic-rich and few plant fragments.

Sample 5 XRD-Whole Rock Mineralogy (Weight %):
Calcite: 35.0%
Total Clay: 29.8%
Quartz: 15.4%
Figure 6.101: Bentonite Facies. Picture of facies in core at 7564 ft. depth. This is the thickest bentonite (B) observed in core. The rest are usually less than a quarter inch to a half inch.
Figure 6.112: **Fort Hays Limestone Facies.** [A] Picture of facies from sample 30 collected in a rotary side-wall core at 7746.00 ft. depth. Sample stained (alizarin red) for calcite. Note the presence of burrows (bu) and the abundant planktonic foraminifers. Dark areas are burrows. An echinoderm fragment (E) can also be observed. [B] There is a moderate amount of quartz (Q) and agglutinated foraminifers (agg). A pelecypod (py) shell fragment can be observed.

Sample 30 XRD-Whole Rock Mineralogy (Weight %):  
Calcite: 73.0%  
Total Clay: 12.3%  
Quartz: 10.1%
6.2 Core Interpretation

The only sidewall core sample of the Niobrara ‘A’ Chalk subunit was identified to be a marl indicating that in this part of the Denver Basin this unit, besides being very thin, is also very clay-rich. The three sidewall cores taken from the upper Niobrara ‘A’ Marl indicate that the upper portion of this subunit is mostly composed of the marl facies. The upper part of the conventional core is composed of the base of the ‘A’ Marl subunit and is exclusively the calcareous shale facies. Thus, we can interpret the ‘A’ Marl subunit to be more clay-rich at its base but then more carbonate-rich towards the top. This suggests that sea level was rising during the deposition of the ‘A’ unit.

The Niobrara ‘B’ Chalk subunit is sampled by the conventional core and is interpreted to be composed of alternating beds of Chalk, Slightly Argillaceous Chalk, and Argillaceous Chalk facies. The base of this subunit is more carbonate-rich resulting in a 10 foot and 6 foot bed of clean chalk divided by a 6 foot bed of slightly argillaceous chalk. Above this package, and composing the rest of this subunit, is a 52 foot package of mostly slightly argillaceous chalk with a 14 foot bed in the middle of argillaceous chalk. This middle bed is often referred to as the ‘B1’ Marl since it is a more clay-rich bed within the ‘B’ Chalk subunit. This sedimentary sequence suggests that sea level started high at the base of the ‘B’ Chalk subunit, then swallowed until the top of the ‘B1’ Marl, and then began to deepen again.

The top of the Niobrara ‘B’ Marl subunit contains a 4 foot bed of the fossiliferous marl facies. This is the only occurrence of this oyster-rich rock type and is interpreted as being deposited by a storm event. This bed also appears to have the highest concentration of organic matter (mostly in the form of plant fragments) suggesting that storm events may
be an important mechanism for organically enriching the Niobrara. Bellow this bed is a thin (5 foot) marl bed and then the rest of the 61 foot ‘B’ Marl subunit is composed of relatively homogenous silty marl with thin (0.5-1 foot), interbedded, marl beds. They relatively higher amount of silt in this marl suggests that the ‘B’ Marl subunit was deposited in a more proximal environment than the ‘A’ Marl, implying that an overall deepening of the environment occurred between these two packages. The transition in this subunit from silty marl to marl in this subunit suggests that either the source of silt moved away from this environment or that the sea level rose and made this environment more distil. This subtle trend from more clastic-rich to more carbonate-rich parallels the more obvious trend of the ‘A’ Marl subunit.

The base of the conventional core samples the top of the Niobrara ‘C’ Chalk subunit. This 6 foot bed is composed of argillaceous marl. Sidewall core at the base of this subunit are composed of slightly argillaceous chalk suggesting that this subunit generally becomes more clay-rich from base to top. This is a similar trend that was observed in the ‘B’ Chalk subunit but opposite to the trend seen in the ‘A’ Marl subunit. We can, therefore, conclude that Niobrara Chalk subunits tend to be shallowing upward packages as reflected by the vertically increasing quantity of clay and that the Niobrara Marl subunits tend to be deepening upward packages as reflected by the vertically increase quantity of carbonate.

The Niobrara ‘C’ Marl was not sampled but can be interpreted to be mostly the marl facies. One can observe that a total of 3 phases of decreasing sea level and 4 phases of rising sea level can be observed in the Smoky Hills member of the Niobrara Formation in the study area. The interpretation of the conventional core from the Jethro 44-19H well can be seen in figure 6.13.
Figure 6.12: Interpretation of the Jethro 44-19H core. Left edge corresponds to the gamma ray log. Depth are in feet.
6.3 Summary of Facies Characterization

Following is a summary of observations made while interpreting these facies from a conventional core a sidewall core.

- A total of 10 different lithologic facies were identified.
- Facies in the Niobrara can be classified in a carbonate/clay spectrum, but this will not account for all facies. In this investigation the silty marl and fossiliferous marl facies were exceptions to this trend.
- They base of the ‘A’ Marl is mostly calcareous shale while the ‘B’ marl is mostly silty marl. The ‘A’ Chalk is a marl, the ‘B’ Chalk is interbedded chalk, slightly argillaceous chalk, and argillaceous chalk, and the ‘C’ Chalk is interbedded argillaceous chalk and slightly argillaceous chalk.
- Niobrara Chalk subunits become more clay-rich from base to top suggesting they are shallowing up-ward sequences while Niobrara Marl subunits become more carbonate-rich from base to top suggesting they are deepening upward sequences.
- Any form of intra-particle porosity, such as voids within formanifer tests, has been cemented, mostly with calcite.
- All but the chalk facies have substantial amounts of organic matter. The most organic-rich facies is the hummocky cross-stratified marl, which was observed interbedded with the chalk facies. This suggests that the organic richness of the Niobrara Formation may be in part dependent on storm events transporting organic matter into the deeper basin.
CHAPTER 7
ELECTROFACIES CHARACTERIZATION

Well logs can identify rock types, or electrofacies. The term “electrofacies” was introduced by Serra and Abbott (1980) and was defined as “the set of log responses which characterizes a bed and permits this to be distinguished from others.” Any rock classification that is described with well logs is an electrofacies while classifications made on rocks described in core or outcrop are simply facies. Fine-grained rocks tend to have a high degree of vertical heterogeneity. Conventional methods of well log interpretation tend to underestimate electrofacies variability. The application of multivariate statistical techniques may be a solution to this problem.

Both wells in this project’s study area had extensive petrophysical log suites across the Niobrara Formation and one of them had a core within the Niobrara B unit (Chapter 6). These log suites were analyzed in three different ways. First, electrofacies were interpreted in a conventional fashion using just gamma ray and deep resistivity logs. Then they were interpreted using cluster analysis of many logs. Finally, a neural network was trained with the previous core interpretation so that it learned to identify facies form logs. Each of these methods for generating electrofacies provided a different perception of vertical heterogeneity and insights into the stratigraphy of the Niobrara Formation.

7.1 Interpretation with Gamma Ray and Deep Resistivity Logs

Operators drilling the Niobrara often subdivide the Niobrara into Marl and Chalk subunits. These can be considered electrofacies. They are often interpreted using gamma ray and resistivity logs. Thus this investigation started interpreting electrofacies in the same way. The top of the Niobrara formation was interpreted at the base of a sharp, 10 foot, peak in the gamma ray log which corresponds to the Sharron Springs Member of the Pierre
Formation. The Sharron Springs is a ‘hot’ shale and the base member of the Pierre. The upper Niobrara corresponding to the Smoky Hills Member is composed of alternating chalks and marls which were broken out into six units: the A Chalk, A Marl, B1 Chalk, B1 Marl, B2 Chalk, B2 Marl, C Chalk, and C Marl. At the base of the Niobrara is the Fort Hays Member which is composed of a relatively clean chalk. All low gamma ray and high resistivity values are interpreted as being chalks while high gamma ray and low resistivity values are interpreted as being marls. Figure 7.1 shows the electrofacies interpretation based on this method for the two wells in the study area.

![Graph showing electrofacies interpretation based on gamma ray and deep resistivity values.](image)

Figure 7.1: Correlation across the two wells in study area with electrofacies interpretation based on gamma ray and deep resistivity values. Gamma ray is on the left track with a linear scale from 0 to 300 API. Deep resistivity is on the right track with logarithmic scale from 0.1 to 100 ohmm. The Chalk facies is blue while the Marl facies is black.
7.2 Electrofacies Generation with Cluster Analysis Method

An elemental capture spectroscopy (ECS) tool was run in both these wells. This tool measures the weight percent of different elements. A cluster analysis of these, and other, logs was applied to generate an alternative electrofacies interpretation. Figure 7.2 and 7.3 show the results of this method for each well in the study area.

Cluster analysis is based on a principle component analysis and a k-means algorithm. K-means algorithm is a type of centroid-based clustering that groups data such that the average values of each cluster is as different as possible from the average values of every other cluster (Figure 7.5). When applied to well logs this technique groups log responses into a pre-defined number of clusters. The optimal number of pre-defined clusters must be established through trial and error.

For this investigation 10 logs where chosen: gamma ray, density, neutron, resistivity, and six logs from the ECS tool (dry weight percent aluminum, calcium, silicon, iron, titanium, and sulfur). A total of 7 clusters best capture the statistically meaningful vertical heterogeneity of the Niobrara. Any more clusters resulted in significant overlap between clusters. Each resulting cluster is as an electrofacies. The lithology of each electrofacies was interpreted primarily on changes of calcium, silicon, and aluminum. How the values of each input trend across each cluster can be seen in Figure 7.4.

The finest scale unit identified through this method was 1 ft. thick but the majority of the units were thicker than 10 ft. As expected from the previous core interpretation the Slightly Argillaceous Chalk and Argillaceous Chalk facies were typically interbedded. The Marl and the Calcareous Shale facies also occur in association of one another. The Silty Marl facies compromises the majority of the B
Marl unit and expressed the least amount of vertical heterogeneity. The Fort Hays limestone was identified as being an electrofacies of its own.

Of significance is that the facies compromising the ‘A’ Marl unit and the ‘B’ Marl unit were clustered distinctly from one another. These rocks are clearly quite different. The interpretation of these facies with just a gamma ray and resistivity log would not suggest this difference.

Also of interest are the differences between the ‘B’ Chalk and the ‘C’ Chalk. The ‘B’ Chalk, like the ‘A’ Marl, is composed of alternating beds of end members with some being relatively clean chalks, and others being argillaceous chalk. The ‘C’ Chalk unit, however, is more consistently an argillaceous chalk and, therefore, expresses less variability. When combined, both these trends highlight that at the base of the Niobrara vertical heterogeneity is lower than at the top of the Niobrara.
Figure 7.2: Interpretation of 7 electrofacies within the Jethro 44-19H well generated through a cluster analysis of 9 different well logs. These electrofacies are (1) Calcareous Shale, (2) Silty Marl, (3) Marl, (4) Slightly Argillaceous Chalk, (5) Argillaceous Chalk, (6) Chalk, and (7) Fort Hays Limestone.
Figure 7.3: Interpretation of 7 electrofacies within the Cowgirl Premium 31-18H well generated through a cluster analysis of 9 different well logs. These electrofacies are (1) Calcareous Shale, (2) Silty Marl, (3) Marl, (4) Slightly Argillaceous Chalk, (5) Argillaceous Chalk, (6) Chalk, and (7) Fort Hays Limestone.
Figure 7.4: Box-and-whisker plots showing the distribution of values of each log for each cluster. Note that Al, Ca, Si, Fe, and Ti have very strong trends while gamma ray, density, resistivity, and neutron porosity have weaker trends. These plots were used to interpret the 7 clusters as electrofacies.
Figure 7.5: A graphical representation of clustering. The X-axis has values of the 1st principle component while the Y-axis has values of the second principle component. These two initial principle components encompass 86% of variance. Grey stars indicate the average value for each cluster. A total of six out of nine principle components were used in this method accounting for 99% of the variance in the data set.

7.3 Core Supervised Neural Network Method

In the previous section well logs were used to generate electrofacies through a cluster analysis. An alternative system would employ neurocomputing. Hecht-Nielsen (1990) defines neurocomputing as, “the technology discipline concerned with information processing systems that autonomously develop operational capabilities in adaptive response to an information environment.” Artificial neural networks replace the idea of one large, single, fast processor, with two or more massive parallel slower processors that are highly interconnected. Connections between nodes (neurons) in the processors can be weighted in order to group data into meaningful results. Prior to the 1960s neural network systems had limited capabilities and could not solve even relatively simple problems (Braunshweig and
Day, 1995). Then backpropagation learning algorithms, also referred to as feed-forward networks, were developed and these made neurocomputing, not only functional, but powerful. These methods were made particularly popular by a seminal paper in *Nature* by Rumelhar et al. (1986). Backpropagation allows a program to use a training set of correct possible outcomes to learn how to best change weights between neurons across processors. Progressive iterations lead to a better distribution of weights and more accurate answers. The larger the training set, the more benefit one sees from this learning capability. The final weighted network is as called an “estimation model.”

In this investigation a backpropagation artificial neural network was used to create an estimation model that was trained with the Jethro 44-19H core interpretation in order that it might identify electrofacies from the same nine logs used previously in the cluster analysis. The estimation model was then applied to the log suites of both wells in the study area and electrofacies were interpreted (Figure 7.6).

Like in the cluster analysis method, the first step in creating the estimation model involved a principle component analysis. Again a total of six out of the nine principle components were used accounting for over 99% of the variance in the data set. These principle components were input to an artificial neural network and four different estimation models were generated, one for each Niobrara sub-unit (‘A’ Marl, ‘B’ Chalk, ‘B’ Marl, and ‘C’ Chalk). Separating the estimation models by sub-unit was an important step that prevented spill-over of facies within one sub-unit into another where their occurrence would be unrealistic.

The resulting training error for each estimation model is shown in Figure 7.7. Training error is the value of how closely the estimation model could generate facies
identical to the training set, in this case, the core interpretation. When the training set was small, as in the case of the ‘A’ Marl and ‘C’ Chalk, which mostly counted with few side-wall cores, the training error tended to be small as well because it was easier for the estimation model to make sure it interpreted the few training data points correctly. All estimation models become more accurate with every iteration, or epochs, as seen by the decreasing training error in the graphs. Each model was run through 500 iterations.

The result of this methodology can be seen in Figure 7.6. This method was able to effectively fill-in gaps between the conventional core and the side-wall cores. It also generated a geologically reasonable electrofacies for the Cowgirl Premium 31-18H well which had no core at all. This methodology also handled facies that may not fall within the clay/carbonate spectrum. For example, the fossiliferous marl facies has the same petrophysical response to the marl facies. As a result the cluster analysis method failed to distinguish this unit as a different facies but the neural network method improved the odds of it being interpreted. Even so, one can notice that this facies begins to be encroached by the underlying marl facies in the Jethro 44-19H electrofacies log, and within the Cowgirl Premium 31-18H it is even thinner. Some facies are just too thin, or rare, to be picked up by the neural network. Such was the case of the hummocky cross-stratified marl, and this investigation did not even attempt to generate bentonite electrofacies. Yet this method brings with it the confidence that whatever electrofacies is being generated it is founded on a true understanding of the rock, and as such may provide a greater sense of confidence than the cluster analysis method which requires interpretations to be made post electrofacies generation.
Figure 7.6: Results from the logs trained by a neural network method. The left-most track displays each well’s environmentally corrected gamma ray. In the Jethro 44-19H well the central track are the facies as interpreted from core. Note that the bulk of the interpretation came from the conventional core collected from the middle of the Niobrara ‘A’ Marl until the top of the Niobrara ‘C’ Chalk. Above a bellow this core several rotary sidewall cores were collected and their interpretation is displayed as 1 to 4 foot thick interpretations. The right-most track contains the electrofacies generated from the estimation models created through artificial neural networks.
Figure 7.7: Graphs of training error by epoch (or iteration). Note that the training error generally sharply decreases with the first 10 epochs. This decrease is due to the artificial network learning to make better facies interpretations.
7.4 Summary of Electrofacies Interpretation

Even though the data set available for this investigation contained only two wells and a modest core, it provided a valuable exercise in electrofacies generation. There are 6 main points that are worth emphasizing:

- The Niobrara Formation has significant fine scaled recurring facies. Conventional methods of well log interpretation will generally underestimate this vertical variability.

- The ECS tool is invaluable for the generation of electrofacies through cluster analysis. Elemental trends are much stronger than trends seen in triple combo well logs. This was clearly observed in Figure 7.4.

- The cluster analysis method typically subdivided Niobrara sub-units into two electrofacies per sub-unit and only identified facies that fell within a trend of petrophysical responses such as the clay/carbonate spectrum.

- The neural network method interpreted some finer scale variability and identified facies that did not fall in a trend of petrophysical responses.

- A major pitfall for the neural network method is that it can only interpret facies from which it has a training data set. As a result, this method should only be applied when there is full confidence that all possible rock types have been identified.

- A major pitfall of the electrofacies methodology is that it does not provide as reliable a facies interpretation as core or neural networks because it is not based on actual observations of rocks.
CHAPTER 8
DISCUSSION

This investigation had two major components, structural characterization and facies characterization. Each of these components had a side project, respectively, observations in outcrop and electrofacies generation. The following discussion covers these four subjects.

8.1 Structural Characterization and Observations in Outcrop

Two tiers of polygonal faulting were observed. The first is mostly within seismic unit UC4 composed of the Greenhorn and Carlile Formations. This fault system can be classified according to Cartwright (2011) as a simple tier, classical hexagonal, dense on seismic, polygonal fault system. The second tier is within the Niobrara and Pierre Formations and can be classified as a simple tier, locally preferentially aligned, sparse on seismic, polygonal fault system. The deeper Greenhorn-Carlile tier stops growing within seismic unit UC5. The shallower Niobrara-Pierre tier stops growing within the middle of the Pierre Formation. On the flanks of structural highs and lows faults link-up across both these tiers and are unhindered by the Codell fault-growth-baffle. Fault growth is, therefore, controlled to some extent by underlying structure.

Several theories on the initiation of polygonal faults exist. These were covered in section 2.4.3. All of them link fault origin to lithology. Five rotary side-wall cores were collected in the well Jethro 44-19H within the seismic unit UC4. One of these samples is from the Carlile Formation and four from the Greenhorn Formation (Figure 8.1). These have average total clay content of 38% with a value as high as 48% and as low as 29%. The rest of this rock is typically 40% chalk and 20% quartz. This rock is incredibly fine grained...
and thick (~ 500 ft.). Similarly, the Niobrara and Pierre Formations are very fine grained and thick. Thus, polygonal faults in the study area develop within thick fine-grained rocks.

It was also observed that growth strata are present adjacent to the normal faults of the Niobrara-Pierre tier indicating that the faults were active during deposition. Yet growth strata does not truly start to form within the Niobrara Formation but more so within the Pierre Formation, therefore, it is likely that the faults were active during early burial, but did not form immediately after deposition.

The trigger for polygonal nucleation is likely a product of slightly burying thick sequences of fine-grained sediments. When burial of fine-grained sediment occurs two things happen: pore pressure increases and water is expelled. High pore pressures enlarge the mohr circle and set the stage for mechanical failure. In fine-grained rocks pore pressure can increase relatively early in the burial history of the sediment since they have incredibly high initial porosities but very low permeability. Yet simply raising pore pressures could also cause tensile failure rather than shear failure. Such fluid escape features are common in rapidly deposited sandstones. Something else must happen to trigger the development of an extensional regime and shear failure. Shin et al. (2008) demonstrated that volumetric contraction could produce such a regime (Figure 8.2). In the experiment of Shin et al. (2008) grains are dissolved and this drives volumetric contraction, thus diagenesis is the trigger for polygonal fault nucleation. Volumetric contraction, however, may occur without diagenesis. Consider the incompressibility of water. If confined in a fine grained rock it would be able to temporarily behave like a grain becoming part of the actual sediment framework as opposed to just being a pore fluid. But a continued rise in pressure will ultimately expel this pore fluid. Fine-grained rocks lose about half their pore water in the
first 3000-5000 feet of burial (Figure 8.3). This pressure build up followed by dehydration could cause the overall sedimentary body to experience three-dimensional volumetric contraction after burial. As seen in this investigation polygonal faulting initiates’ not immediately after deposition but soon after some burial has occurred supporting this hypothesis. The isotropic nature of this process results in the random orientation of faults.

Almost all faults in the deeper Greenhorn-Carlile tier terminate within seismic unit UC5. This also happens to be where a coarser grained unit is deposited, the Codell Sandstone. A sidewall core of the Codell sandstone was sampled and can be observed in Figure 8.4. The Codell would have been a layer of very permeable sediment that would have served as a pressure release valve in the system. With no build-up of high pressures water can no longer behave statically and the first polygonal fault tier would have ceased to grow. As a result we see few faults of the lower Greenhorn-Carlile tier grow past Seismic Unit UC5; the few that due are located on the flanks of structural highs.

The shallower Niobrara-Pierre tier of faults likely has a similar nucleation history as the deeper Greenhorn-Carlile tier, but a different mechanism for termination. Rather than being capped by a coarse grained unit this PFS seems to be more long lived and terminate due to burial and water expulsion. With sufficient burial and water expulsion no more volumetric contraction can occur, thus ending the driver for fault growth.

The largest faults in the study area cross-cut both of these fault tiers. These faults tend to be preferentially aligned along the flanks of structural highs. It is possible that fault slip is sensitive to underlying structure. This is similar to the findings made by Davis (1985) in the Wattenberg Field.
Faults in Niobrara outcrop were clearly an extension of the subsurface PFS. Their occurrence suggests that a dense, sub-seismic, PFS may exist independently of the deeper Greenhorn/Carlille PFS. The abundant amount of coarse grained calcite indicates massive fluid flow through these faults. This is logical considering they are impermeable fine grained rocks which will preferentially drain through fractures and faults and supports the notion that dehydration through the sediment framework was difficult. The changes seen in fault density from eastern to western outcrops parallel the changes between the two tiers of faulting seen on seismic. It may be that a lithologic variation is controlling fault density within outcropped Niobrara but more field work would need to be done to ensure that this trend is real.

Field observations are very similar to those of Tewksbury et al. (2011) who mapped a polygonal fault system in outcrops of the Khoman Chalk within the Farafra Anticline of the Western Desert of Egypt (Figure 8.5). Faults appear as ridge networks of calcite veins and a polygonal pattern can be made out in satellite images. Calcite veins, the random nature of faults, and the lack of strong tectonic influences make this study area the closest known analog to faulting in Kansas.
Figure 8.1: Example thin section of one of the Greenhorn Formation rotary sidewall cores. Note the vertical fracture (arrow). Elongate pellets (p) are aligned parallel to bedding. Planktonic foraminifera are common. Minor amounts of pyrite (py) found in matrix.

Sample 39 XRD-Whole Rock Mineralogy (Weight %):
Calcite: 18.5%
Total Clay: 43.7%
Quartz: 26.5%
Figure 8.2: Results from Shin et al. (2008) showing that volumetric contraction decreases the lateral stress coefficient relative to vertical strain resulting in a polygonal fault fracture system to develop.

Figure 8.3: Stages of water loss in fine-grained rocks from Sonnenberg and Underwood (2013) whom modified from Burst (1969). Note Stage A experiences the most significant amount of water loss during depositional compaction.
Figure 8.4: Example thin section of one of the Codell Formation rotary sidewall cores. This sample is a very fine-grained, well sorted argillaceous sandstone. Framework grains are mostly quartz (Q). Detrital clay is moderately abundant and distributed unevenly in association with bioturbation. There are minor quartz overgrowths (arrow), a volcanic rock fragment (VRF), and minor amounts of pyrite (py).
Sample 33 XRD-Whole Rock Mineralogy (Weight %):
Calcite: 1.0%
Total Clay: 19.3%
Quartz: 71.3%
Figure 8.5: Pictures from Tewksbury et al. (2011). [A] Satellite image of a polygonal fault network in the Western Desert of Egypt. Lineations are protruding chalk and calcite veins that fill in fault gaps. [B] A ground-level picture of a calcite vein protruding from its host rock. Fault dip directions, rakes, and offset of dipping layers indicate normal slip.
8.2 Facies and Electrofacies Characterization

There are multiple ways one can describe the Niobrara Formation. This investigation chose a carbonate/clay spectrum, with some consideration for sedimentary structures, the presence of silt, and bentonites. An alternative method could have used the Dunham classification of carbonates. With such a nomenclature the Argillaceous Chalk facies may be referred to as a Foraminiferal Pelletal Argillaceous Lime Packstone. This nomenclature, however, is not practical. It fails to focus on the key variations in the Niobrara, the composition of the rock, in favor of focusing on its micro-texture.

There are many scales at which the Niobrara can be interpreted but because it is fine grained it appears relatively homogenous when doing a visual core interpretation. As a result, one should constrain one’s self to the resolution of the thin sections and XRD data available. For this investigation XRD and core thin sections were at best collected every foot. If the interpretation is going to be used to generate electrofacies through a neural network the resolution should be no finer than one-foot since this is pretty close to well log accuracy. An even coarser (three to four foot) resolution may be more a reliable.

Clay-rich beds typically displayed signs of higher energy such as the fossiliferous marl bed and the hummocky cross-stratified facies. These units also had the most visible plant fragments suggesting that storm events play a critical role in supplying the distal basin with organic matter. Carbonate-rich beds had more chalk, which is a pelagic form of sedimentation, and were often finely laminated indicating that they were deposited in lower energy environments and a more distal environment.

Important to note is that Chalk Niobrara subunits were observed to be more carbonate-rich at their base and more clay-rich at their top. Marl Niobrara subunits were
observed to have more carbonate at their base and more clay at their top. One can, therefore, interpret the Niobrara as a whole to be a first order transgression and each chalk-marl pair is a second order cycle of transgression and regression.

Vertical heterogeneity of electrofacies within the Niobrara Formation was greater than the subunits typically interpreted with well logs. Multivariate statistical techniques can greatly aid the identification of electrofacies. When there is little or no core data a neural network approach should not be attempted. This method requires an extensive training data set to be accurate. Nevertheless, when the data is available this method is capable of identifying finer scale vertical heterogeneity than the cluster analysis method.

The cluster analysis method is an excellent first-pass method for generating electrofacies provided that an extensive petrophysical log suite is available, preferably one that contains ECS logs or some other sort of elemental or mineralogical data. It may fail to capture very thin electrofacies, but by not needing a training data set this method does not have any biases in interpretation. Setting a top and bottom of where clustering occurs is an essential step which excludes units outside of the zone of interest. Interpretation of the clusters generated does not account for sedimentary structures, bioturbation, or other textural components of the rock which one could try to identifying with the core-supervised neural network method. Ultimately, paring all three electrofacies characterization methods, together with abundant core data, will yield the best results and best capture vertical heterogeneity.
CHAPTER 9
CONCLUSIONS

This study aimed to characterize the structural geology of the Niobrara Formation in Goshen and Larmie Counties, Wyoming. It also attempted to characterize facies within the Niobrara Formation with core and well logs. This chapter lists the primary conclusions and then covers suggestions for future work.

9.1 Conclusions

The Niobrara Formation has layer–bound, randomly oriented, normal faults that are the product of polygonal faulting in the deeper Greenhorn and Carlile Formation. The largest of these are controlled by basement structure. This fault system extends to Niobrara outcrops of Kansas and Nebraska. This is the only known polygonal fault system recognized in outcrop in North America.

The Niobrara Formation has at least 10 different facies which can be described in a carbonate/clay spectrum from chalk to calcareous shale with some additional consideration to silt and fossil-rich beds. Deposition was highly cyclical resulting in units of chalk interbedded with argillaceous chalk and units of marl interbedded with silty marl or calcareous shale. When interpreted with well logs the Niobrara can be classified as having as few as two or as many as eight different electofacies. A cluster analysis method that uses logs from an ECS tool can greatly aid in improving ones understanding of Niobrara vertical heterogeneity. A neural network analysis that used core to train a log data set is a more reliable method.
9.2 Suggestions for Future Work

Future seismic work in the Niobrara Formation should focus keenly on the Seismic Unit UC4 which encompasses the Greenhorn and Carlile Formations in search of similar polygonal shaped patterns of missing sections. It is also essential that future researchers look for similarities between Niobrara structural patterns and the basement.

Future focus on the mechanics of burying fine grained rocks could yield supporting evidence as to whether or not high pore pressures paired with dehydration are the main cause for polygonal fault development.

More work can be done in Niobrara outcrops. Though exposures may not be great it would be useful to observe changes in faulting styles and density as one goes from the eastern to the western edge of Niobrara outcrops collecting samples along the way in order to link any structural changes to variations in lithology.

Concerning facies and electrofacies characterization it would be useful to link interpretations to reservoir properties such as oil-in-place values. This would help operators estimate volumes more accurately than just through conventional petrophysics. Future investigators could try to refine use of multivariate statistics to characterize the Niobrara Formation. A neural network generates a more accurate estimation model the larger the training data-set. Future researchers could acquire more core and see if this method yields better results. This would then set the platform for fine scaled electrofacies modelling of the Niobrara Formation across the Denver Basin.
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**Index 1:** Published polygonal fault studies organized by subject matter and listed in chronological order from oldest publications to the most recent.

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