ROCK QUALITY INDEX FOR NIOBRARA HORIZONTAL
WELL DRILLING AND COMPLETION OPTIMIZATION,
WATTENBERG FIELD, COLORADO

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

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ABSTRACT

The Niobrara Formation in Wattenberg Field has been successfully drilled over the last several decades, but largely from vertical wells. Successful horizontal well drilling in Wattenberg began in 2009, where operators quickly discovered lateral wells yielded drastically greater returns on hydrocarbon production. This discovery in the field set off a new round of drilling. Subsequently, major lateral advancements have occurred within the field over the last decade, including increasing lateral lengths, stage densities, and perforation clusters for hydraulic stimulation. While fracturing the reservoir is costly, the benefits include a substantial increase in initial production within tight shale reservoirs, such as the Niobrara Formation at Wattenberg Field.

By stimulating as much of the reservoir as possible along the lateral wells, operators are neglecting the conditions that exist at the wellbore, in terms of rock quality and stresses. Modern analogs in major unconventional reservoirs, including the Eagleford and Montney Shale, have discovered that initial production increases as wells are designed based on the in-situ conditions present at the wellbore. By accounting for rock quality and stresses, communication between near and far fracture networks is improved as the reservoir heterogeneity is recognized and better understood.

Chalk and marl benches within the Smoky Hill Member of the Niobrara are extremely variable. I combined various parameters that define each of the Niobrara chalk and marl benches in a Rock Quality Index (RQI). This methodology was developed in order to incorporate the depositional, petrographic, and hydraulic state of the reservoir rock. The RQI is a measurement of what rock is worth targeting and where the rock is most likely to fail when hydraulically stimulated. As the RQI was developed in vertical wells with core data, lateral targets were discovered not only in the chalk benches, but also in the marl benches of the Niobrara Formation. In order to successfully apply the RQI to lateral wells where
available well logs were limited, cluster analysis and neural networks were designed in order to incorporate synthetic logs within this methodology.

Geometrically spaced stages and perforation clusters along lateral wells are shown to affect the completion workflow. Areas of high heterogeneity within a single stage combine differentiating rock quality and stresses. Selectively spacing the stages and perforation clusters aids in targeting zones of homogenous rock types that will exhibit similar completion parameters throughout the stage. Additionally, as the RQI was validated with the available completion and seismic data, driving mechanisms for production within the study area were explored. Lateral wells that are further spaced apart, exhibit clustered microseismic trends along the wellbore that correlate directly with increasing RQI per stage (in the absence of intersecting faults). For the case where lateral wells are tightly spaced and faults are critically stressed (as they are aligned with maximum horizontal stress ($\sigma_H$)), factors greater than the rock quality are controlling production. These factors consist of critically stressed faults, fractures, and pressure compartmentalization.
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LIST OF SYMBOLS

Stress ......................................................... $\sigma$

Maximum Principal Stress ................................ $\sigma_V$

Maximum Horizontal Stress ................................ $\sigma_H$

Minimum Horizontal Stress ................................ $\sigma_h$

Young’s Modulus ............................................. $E$

Poisson’s Ratio ............................................... $\nu$

Shear Modulus ............................................... $\mu$ or $G$

Bulk Modulus ............................................... $K$

Compressional Velocity ................................... $V_P$

Shear Velocity .............................................. $V_S$

True Vertical Depth Below Ground Level ............... $TVD_{bgl}$

Brittleness Index .......................................... $BI$

Fabric Brittleness .......................................... $B_F$

Composition Brittleness ................................... $B_C$
LIST OF ABBREVIATIONS

Colorado School of Mines ................................................. CSM
Reservoir Characterization Project ........................................ RCP
Anadarko Petroleum Corporation ........................................... APC
Source Rock ................................................................. SR
Gas-Oil Ratio ................................................................. GOR
Horizontal ................................................................. HZ
Stimulated Reservoir Volume ............................................... SRV
Shear Wave Splitting ........................................................ SWS
Gamma Ray ................................................................. GR
Deep Induction Resistivity .................................................. ILD
Bulk Density ............................................................... RHOB
millidarcy ................................................................. mD
One Dimensional ........................................................... 1D
Three Dimensional .......................................................... 3D
Four Dimensional ............................................................ 4D
Time-Lapse ................................................................. 4D
Million cubic feet of gas per day ........................................ MMCFD
Rock Quality Index ........................................................ RQI
Horizontal Transverse Isotropy ............................................ HTI
Instantaneous Shut In Pressure ........................................... ISIP
<table>
<thead>
<tr>
<th>Term</th>
<th>Abbreviation</th>
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<tr>
<td>Trillion Cubic Feet Equivalent</td>
<td>Tcfe</td>
</tr>
<tr>
<td>Barrel</td>
<td>bbl</td>
</tr>
<tr>
<td>Billion Cubic Feet Equivalent Per Day</td>
<td>Bcfe/d</td>
</tr>
<tr>
<td>Barrel Oil Equivalent</td>
<td>BOE</td>
</tr>
<tr>
<td>Million Barrels of Oil Equivalent Per Day</td>
<td>MMboepD</td>
</tr>
<tr>
<td>Billions of Barrels of Oil Equivalent</td>
<td>Bboe</td>
</tr>
<tr>
<td>Trillion Cubic Feet Equivalent</td>
<td>Tcfe</td>
</tr>
<tr>
<td>Leeb Hardness</td>
<td>HLD</td>
</tr>
<tr>
<td>Western Interior Seaway</td>
<td>WIS</td>
</tr>
<tr>
<td>Pore Pressure</td>
<td>PP</td>
</tr>
<tr>
<td>Total Organic Carbon</td>
<td>TOC</td>
</tr>
<tr>
<td>Field Emission Scanning Electron Microscope</td>
<td>FE-SEM</td>
</tr>
<tr>
<td>Mercury Injection Capillary Pressure</td>
<td>MICP</td>
</tr>
<tr>
<td>Nitrogen Adsorption</td>
<td>$N_2$</td>
</tr>
<tr>
<td>X-ray Powder Diffraction</td>
<td>XRD</td>
</tr>
<tr>
<td>Confined Compressive Strength</td>
<td>CCS</td>
</tr>
<tr>
<td>Unconfined Compressive Strength</td>
<td>UCS</td>
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<tr>
<td>Normal Atmospheric pressure</td>
<td>psi</td>
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For Helen Cserney Mabrey (1921-2009)
This thesis is part of an integrated study by the Reservoir Characterization Project (RCP) in conjunction with Anadarko Petroleum Corporation (APC) that allows students from multiple disciplines to investigate the factors controlling production in Wattenberg Field. The Wattenberg Project is part of Phases XV and XVI of the RCP. The ultimate goal of these phases is to guide well spacing and completions in order to improve overall hydrocarbon recovery in Wattenberg Field. The data includes a 4D 9-component time-lapse seismic survey, microseismic, FMI data, core, and a multitude of production and completion data. The goals of this thesis is to define and characterize the heterogeneity within the Niobrara Formation through core and well log analysis. Additionally, identifying potential zones for re-fracturing the rock based on heterogeneity and rock quality in this particular study area.

1.1 Motivation

Currently, oil prices have reached an extreme low in recent history. In doing so, many companies are desperate to slash completion and production costs. Being the 4th largest oil field and the 9th largest gas field in the U.S., Wattenberg Field is one of the top unconventional reservoirs in the U.S., as displayed in Figure 1.1. Based on the U.S. Energy Information Administration (EIA) 2013 report, Wattenberg Field had produced 47,259 MMBO and 304,540 MMcf gas in one year. In order to reach equilibrium, companies need to find how to produce more while minimizing costs across the board.

Production milestones within companies active in Wattenberg have reached an all time high. Anadarko produced 101,000 BOPD in Wattenberg Field during the second 2015 quarter, while also increasing efficiency during this down turn (APC, 2015). Being one of the top producers in Wattenberg Field, Anadarko is constantly striving to minimize productions
costs, stating that they are currently drilling lateral wells in the field for approximately $1 million per well (APC, 2015). On the other hand, PDC Energy, another strong competitor in Wattenberg Field, stated in their second quarterly 2015 report that they have reduced standard and extended laterals to approximately $3.1 and $4.1 million per well, respectively (PDC Energy, 2015). For PDC Energy, this is an improvement of 25-28% based on the type of lateral wells they are drilling. PDC also determined that they saw a 43.7% increase in MBbls and 53.3% MMcf production when comparing the difference between second quarter for 2014 and 2015.

In terms of price of production, hydraulic fracturing comes at a large cost. The benefits of hydraulic fracturing are tremendous and has allowed for a substantial increase in initial production within tight shale reservoirs, including the Niobrara Formation in Wattenberg Field. During the down turn, many companies are drilling wells and not hydraulically
stimulating them until oil and gas prices increase. Hydraulic fracturing these reservoirs has proven extremely effective, but during this critical time companies may not be able to afford the heavy price tag. Another solution for cutting costs for companies has been increasing the lateral lengths and stage density in order to stimulate more reservoir without having to drill another well. This is not always the best solution.

A study in the Eagle Ford Formation, a tight shale reservoir, was conducted in 2012 in order to identify the best quality rock to stimulate (Cipolla et al., 2012). Understanding what is occurring between the wellbore, hydraulic fracture and the reservoir is key to effectively stimulating the reservoir. Within this study, two nearby wells are put to the test by spacing perforation clusters along the lateral geometrically or selectively based on rock quality and stresses (Figure 1.2). The selectively placed perforation cluster wells had an increase in initial production by 20% compared to the geometrically spaced well (Cipolla et al., 2012). The goal of this thesis is to develop a Rock Quality Index (RQI) for the Niobrara reservoir interval based on previous work done in Pouce Coupe Field (Davey, 2012). Stimulated reservoir volumes (SRV) and completion data will prove how effective the RQI is along the lateral wells within this study area. Accounting for the heterogeneity within these unconventional reservoirs is key to improving overall production, while also decreasing production costs.

1.2 Geologic Setting

The Niobrara Formation extends over parts of Colorado, Wyoming, and Nebraska within the Denver Basin, covering over 70,000 square miles. The highest producing portion of the Niobrara is located within Wattenberg Field, Colorado part of the Denver Basin. The Niobrara is considered a basin-centered, low permeability, gas reservoir (Higley and Cox, 2007). The asymmetrical, foreland Denver Basin is steeply dipping to the west and gently dipping to the eastern side.

The Niobrara Formation is subdivided into two separate members: Smoky Hill and Fort Hays. The Smoky Hill Member refers to the interbedded limestones and calcaerous shales, respectively chalks and marls, ranging in descending order from A to D (Figure 1.3). In
Figure 1.2: Two nearby lateral wells in the Upper Eagle Ford Formation with varying completion designs, geometrically spaced and selectively spaced stages based on reservoir and completion quality (Cipolla et al., 2012). The top figure displays geometrically spaced stages and perforation clusters, neglecting rock quality. The figure below displays the newly designed lateral based on where “good” completion quality is located along the wellbore. This lower lateral exhibited an increase in initial production by 20%.
the study area the Smoky Hill Member starts with the D Chalk/Marl and ends with the A Marl, as the A chalk is assumed to be eroded away in this portion of Wattenberg Field (due to a paleohigh). The second member, Fort Hays, is a limestone that has completely different reservoir quality and characteristics than the Smoky Hill Member. Fort Hays will be mentioned throughout this research, as it is a potential barrier between the reservoirs in the Smoky Hill chalks and marls and the underlying Codell Sandstone. Overall the Niobrara Formation ranges from 200 to 400 ft thick, while each chalk and marl bench may range from 30 to 50 ft in thickness.

Figure 1.3: Stratigraphic column of Wattenberg Field, Colorado (Sonnenberg and Weimer, 2003).

The chalks and marls of the Niobrara Formation have distinct log signatures. The chalks yield a lower gamma ray response (due to lower clay volume), faster sonic, and higher resistivity compared to the marls Figure 1.4. Through core analysis, the chalk and marl
lithofacies are extremely interbedded with one another, and can be hard to distinguish at times. The Niobrara is considered a tight gas due to the low porosities (<10%) and permeabilities (0.1 mD) (Sonnenberg, 2015).

![Figure 1.4: Type log of the reservoir intervals, displaying the variations between lithofacies within the Niobrara chalk and marl benches within Wattenberg Field. From left to right: gamma ray, resistivity, compressional and shear velocity.](image)

Due to the interbedded nature of the Niobrara Formation, the reservoir is prolific throughout the field. The marls are generally considered the source rocks, while the chalks are considered the reservoir rocks. Generally, the chalks have higher porosity and permeability than the marls (this will be further discussed in the Previous Research section of Chapter 2). The Niobrara Formation is consumed of varying micro-organisms based on the type of lithology.
and time of deposition (Kauffman et al., 1993). The Codell Sandstone is comprised of cross-stratified and bioturbated clay-rich siltstone. The Niobrara, Codell and Pierre Shale are all acting as a seal for the individual reservoir intervals (Figure 1.5). The varying mineralogy and fossils of the reservoir intervals will be further discussed in the Core Analysis section of Chapter 3.

![Diagram of petroleum system events](image)

**Figure 1.5:** The petroleum system events within the Denver Basin based on geologic time. Gray represents primary events, green marks the time of oil generation, and the wavy black lines represent presumed unconformities (Higley and Cox, 2007).

### 1.2.1 Depositional Environment

The Niobrara was deposited in the Western Interior Seaway (WIS) during the Late Cretaceous, during a time of fluctuating sea-level and climatic conditions, with multiple periods of transgressions and regressions. These oscillations in sea-level are the reason that the Niobrara is made up of alternating chalks and marls throughout the reservoir (Figure 1.3).

During the Late Cretaceous, the WIS extended over the vast majority of present day western interior portion of North America, connecting cold Boreal and warm Tethyan water, respectively what is now known as the Arctic Ocean to the Gulf of Mexico (Roberts and Kirschbaum, 1995). Surrounded by landmasses on the east and west, there was also a large input of clastic sediment input within the WIS. During the time of deposition, Wattenberg Field was located in the southern portion of the WIS (Figure 1.6).
As sea level rose during the Late Cretaceous, coccolith-rich carbonate chalk deposition dominated due to circulation of cold Boreal and warm Tethyan water. During these times of transgression, preservation of organic carbon was low and dilution of chalks by input of siliciclastic material was low (Locklair and Sageman, 2008). When sea level began to fall, retreat of warm Tethyan waters evoked an anoxic environment for the marls to accumulate. During these times of regression, preservation of organic carbon was high, while the rate of deposition was also much higher (Kauffman, 1977).
1.2.2 Tectonic History

During time of deposition, to the west of the WIS existed a subduction zone known as the Sevier Orogenic Belt, with a subsequent volcanic arc paralleling the large seaway. Subsequently, there was an influx of ash beds throughout the Niobrara Formation due to the active tectonics at the time. These ash beds are also known as bentonite, and will be further discussed in Chapter 3.

Lasting from the time of deposition (Late Cretaceous) and into the Early Eocene, the Laramide orogeny caused a multitude of tectonic events to occur during the extended amount of time. The WIS was divided into present day basins known as the Denver Piceance and Uinta Basins (Sonnenberg and Underwood, 2012). The Laramide orogeny caused uplift of the Rocky Mountains (west of the Denver Basin), folding and faulting of originally flat lying rocks (Higley and Cox, 2007). Structural and stratigraphic traps were formed during this widespread time of major tectonic events.

Wattenberg Field is composed of two different types of faulting systems, both of which are associated with the Laramide orogeny and basement uplift. The two types of fault systems consist of the primary wrench fault system, trending northeast, and a secondary fault system situated between the large wrench faults (Higley et al., 2003). Weimer (1960) first discovered the wrench fault systems by field mapping. The RCP study area is located between the Lafayette and Longmont wrench fault systems, as seen in Figure 1.7. Faults identified within the Niobrara Formation consist of: wrench, listric normal, polygonal faults, and large graben structures (Davis, 1985; Sonnenberg and Underwood, 2012; Weimer et al., 1986). The faults within the field are contributing to the generation of fracture networks, hydrocarbon migration to the reservoir through conduit faults, and trapping hydrocarbons with sealing faults (Davis, 1985).

The intricate fault system and continuous tectonic activity has lead to the formation of an extensive fracture system within the Niobrara Formation (Davis, 1985). As these faults within the formation are reactivated, the fracture networks grow in complexity (Figure 1.8).
1.3 Field Background

The largest and most productive field in the Denver Basin is the Wattenberg Field located just north of the Denver metropolitan area, displayed in Figure 1.9 (Sonnenberg and Weimer, 2003). The field has been active since 1970, extending over 81 townships (1.9 million acres) in northeast Colorado. The Niobrara Formation produces both oil and gas, from the alternating chalk and marl benches. Within Wattenberg Field, the B and C chalk, as well as the Codell, are the main targets within the reservoir intervals. This tight, self-sourced reservoir is extremely complex, varying both laterally and vertically across Colorado (Sonnenberg,
Figure 1.8: Schematic relationship between basement-controlled faults and listric normal faults in creating fracture systems (Davis, 1985).

Figure 1.9: Wattenberg Field is located to the northeast of Denver, Colorado. Wattenberg Field is highlighted in green, while the study area is highlighted in red. The Wishbone section is represented by the white box within the study area (RCP, 2015).

Another factor that has lead Wattenberg Field directly into the hydrocarbon window is the thermal anomaly associated with the underlying Colorado Mineral Belt. Wattenberg Field lies directly over the deepest part of the synclinal Denver Basin (Sonnenberg, 2015). The extra heat flow provided by the Colorado Mineral Belt has sped up the process...
of thermal maturity for the hydrocarbons subsiding in Wattenberg, as well as forming an overpressured system with the Niobrara and Codell Formations. Thermal maturity of the Niobrara Formation varies significantly across the Denver Basin, therefore, understanding geologic and structural variability is key in targeting the best reservoir.

Understanding the rock quality within this reservoir is key to successful drilling and production. The 45-year-old-field has undergone complete renovation through the advancement of technologies. Currently, lateral extension, increasing stage density, and downspacing have allowed for a large amount of increase in initial production. Wattenberg currently has over 22,000 producing wells, and is currently producing approximately 1.2 billion cubic feet per day (Bcfe/d) with cumulative production at approximately 4.2 trillion cubic ft (Tcfe) and is estimated to have over 4 Bboe of recoverable oil.

1.4 Objectives

The objectives for this thesis was to define and characterize the heterogeneity within the Niobrara Formation through core and well log analysis. Additionally, identifying potential zones for re-fracturing the rock based on heterogeneity and rock quality. Through these objectives I will answer the following questions:

- Should the Niobrara chalk benches be the only main horizontal well targets? Or is there also potential for targeting laterals within the marl benches?

- How is heterogeneity within the Niobrara affecting completion and production results based on available data?

- How has geometrically spaced stages and well spacing affected the available completion and production data?

Methodologies from previous work, Davey (2012) and Cipolla et al. (2012), has encouraged me to apply the rock quality index (RQI) to the Niobrara Formation in the Wishbone section of Wattenberg Field. I will apply the RQI equation designed by Davey (2012), in
order to incorporate 3 different rock types: petrographic, depositional and hydraulic. By adjusting the variables of the RQI to cater to the lithologies and stress regime of the Niobrara, the RQI is then applied to lateral wells within the Wishbone section, where data necessary for the equation is limited.
CHAPTER 2
AVAILABLE DATA AND PREVIOUS RESEARCH

The available data for Phase VX and VXI of the RCP has been provided by APC, with the exception of the joint acquisition of the time-lapse, 9 component (9C) seismic survey. The primary study area is within the Wishbone section of the Turkey Shoot seismic survey, although the amount of available data extends well beyond the four square mile survey. The following data has been provided by APC:

- 3 seismic surveys (1 component; 3 component; 9 component, time-lapse*)
- Completion, production, and tracer data for the 11 lateral wells within the Wishbone Section
- Surface microseismic during the completion of the 11 lateral wells
- Core from 4 vertical wells surrounding the seismic surveys
- FMI logs within a select amount of vertical and lateral wells

* jointly acquired by RCP and APC

The timeline in which this data was acquired by APC and RCP is displayed in Figure 2.1. Through integration of this large dataset provided by APC, we can begin to investigate the primary objectives for this substantial project:

1. Characterize how the faults and natural fracture system is affecting the reservoir
2. Resolving the controls of the changing stress state within the reservoir
3. Analyzing how the heterogeneity of the reservoir is affecting overall production and stimulation along the wellbore
2.1 Well Spacing

For this study, I am utilizing both vertical and lateral wells to integrate the available core data with the production and engineering data available in the lateral wells. The 11 lateral wells are located within the Wishbone section, situated within the Turkey Shoot seismic survey (Figure 2.4). These horizontal wells were drilled prior to the baseline Turkey Shoot survey, and were not completed until after the baseline survey was acquired. The wells were completed in a series from east to west with the completion summary displayed in Table 2.1. All of the horizontal wells have 20 to 32 hydraulic fracture stages, spanning the 4,000 foot laterals. The spacing between the laterals ranges from 600 to 1200 ft, as depicted in Figure 2.2.

Completion of the laterals was done utilizing several different methods, including sliding sleeve, plug and perf, as well as a zipper frac between 7N, 8C and 9N. Figure 2.2 also shows that 7 of the wells targeted the C Chalk (1N, 2N, 4N, 6N, 7N, 9N), 1 targeted the B Chalk (11N), and 4 targeted the Codell (2C, 5C, 8C, 10C). The wells are undulating throughout
the Wishbone section, therefore the laterals are not consistently in the same lithology. The structural geology, especially the centrally located NE-SW trending graben in the center of the survey, causes significant displacement along the wellbore depicted by the dotted stages in Figure 2.3. Each dot along the lateral represents the lithology determined from the drilling reports for each stage.

Table 2.1: Summary of Well Completions

<table>
<thead>
<tr>
<th>Well</th>
<th>Stimulation</th>
<th>Flowback</th>
<th>Method</th>
<th>Stages</th>
<th>Fluid Injected (Ratio of Well to Average)</th>
<th>Proppant Injected (Ratio of Well to Average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1N</td>
<td>Day 1</td>
<td>Day 12</td>
<td>Method 1</td>
<td>32</td>
<td>0.87</td>
<td>0.88</td>
</tr>
<tr>
<td>2N</td>
<td>Day 3</td>
<td>Day 15</td>
<td>Method 1</td>
<td>32</td>
<td>0.87</td>
<td>0.88</td>
</tr>
<tr>
<td>3C</td>
<td>Day 5</td>
<td>Day 15</td>
<td>Method 1</td>
<td>32</td>
<td>0.98</td>
<td>0.88</td>
</tr>
<tr>
<td>4N</td>
<td>Day 8</td>
<td>Day 21</td>
<td>Method 1</td>
<td>32</td>
<td>0.91</td>
<td>0.88</td>
</tr>
<tr>
<td>5C</td>
<td>Day 10</td>
<td>Day 22</td>
<td>Method 1</td>
<td>32</td>
<td>0.93</td>
<td>0.92</td>
</tr>
<tr>
<td>6N</td>
<td>Day 13</td>
<td>Day 21</td>
<td>Method 1</td>
<td>32</td>
<td>0.92</td>
<td>0.97</td>
</tr>
<tr>
<td>7N</td>
<td>Day 14</td>
<td>Day 33</td>
<td>Method 1</td>
<td>zipper</td>
<td>32</td>
<td>0.96</td>
</tr>
<tr>
<td>8C</td>
<td>Day 14</td>
<td>Day 34</td>
<td>Method 1</td>
<td>zipper</td>
<td>32</td>
<td>0.97</td>
</tr>
<tr>
<td>9N</td>
<td>Day 14</td>
<td>Day 30</td>
<td>Method 2</td>
<td>zipper</td>
<td>27</td>
<td>1.03</td>
</tr>
<tr>
<td>10C</td>
<td>Day 22</td>
<td>Day 45</td>
<td>Method 1</td>
<td>20</td>
<td>0.81</td>
<td>0.92</td>
</tr>
<tr>
<td>11N</td>
<td>Day 23</td>
<td>Day 45</td>
<td>Method 1</td>
<td>32</td>
<td>1.75</td>
<td>2.01</td>
</tr>
</tbody>
</table>

2.2 Geophysical Surveys

Within this study area, there are three seismic surveys available to RCP Figure 2.4. As the size of the survey decreases, the quality of each survey increases, as the acquisition parameters were tighter in the smaller surveys, resulting in higher quality. Turkey Shoot is the main survey of interest in this study due to the survey being multi-component (9C), including individual PP-, PS- and SS-wave surveys. In addition to the multi-component surveys, Turkey Shoot also has a baseline and a monitor survey that was shot before production and 2 months post fracking, respectively.
Figure 2.2: Depth-view of the 11 lateral well spacing within the Wishbone section. The available data for each well is highlighted in the key (RCP, 2015).

Figure 2.3: Plan view of the 11 lateral wells within the Wishbone section with each stage (dots) color coated based on the formation. Wells are overlaying the coherence map of the seismic survey, showing large-scale faults intersected by the lateral wells (RCP, 2015).
Figure 2.4: Core well locations in relation to the seismic surveys surrounding the Wishbone section. Core Wells 1-4 have been provided by APC, while Core Well 5 has been provided by Noble Energy.

The surface microseismic data were acquired during the completion of the 11 lateral wells within the Wishbone Section. The microseismic was completed by Microseismic Inc. using their own FracStar array, between the acquisition of the baseline and first monitor Turkey Shoot seismic surveys.

For this study, the geophysical surveys will be utilized in order to investigate the time-lapse data and the controlling factors when stimulating the reservoir. This will be done by analyzing where the reservoir was stimulated in relation to faults, pressure compartmentalization, and stress orientation. Although there is plenty of overlap in the microseismic from well to well, the microseismic has a tendency to favor the geologic structure as the laterals intersect major structural features. This can be seen when the microseismic data is overlaying the structure map derived from the seismic data. The two main lateral wells that are under investigation for this study are the 2N and 6N, seen in Figure 2.5.
2.3 Core and FMI data

In this thesis, core has been described in the 4 available core wells. The locations in relation to the seismic surveys are depicted in Figure 2.4. Core wells 1 and 2 have incomplete core starting from the middle of the Niobrara to the Codell, and therefore the core analysis is deficient within these two wells. Overall, the core analysis has allowed for the following throughout the Niobrara Formation to the Codell Sandstone:

- Classification of interpreted facies
- Extent of laminations, bioturbation and fossils
- Identification of bentonite beds
- Observation of drilling induced vs. natural fracture, fractures, and slickenline locations
- Static geomechanical measurements using the Proceq Bambino
Well log data for Core Well 5 was received by Noble Energy during the development of the RQI. Although core has been made available to RCP students upon request, this data was not utilized in this study. Core Well 5 is located approximately 6 miles northeast of Core Well 3, and it therefore further away from seismic surveys and the wishbone section. The suite of logs available with this well include all of the data necessary to build the RQI, including the commonly lacking XRD data.

The FMI logs are present within 2 of the 11 wells, 2N and 6N. FMI work will be furthered discussed in the Previous Research section of this chapter.

2.4 Previous Research

Fellow RCP students have been developing methods in order to further characterize reservoir potential, in conjunction with industry standards. Students in the past have worked with similar tight gas shales that are currently under investigation in RCP (i.e. Niobrara Formation at Wattenberg Field). The following work discussed has contributed to this study on rock quality analysis of the Niobrara Formation in Wattenberg Field.

2.4.1 Rock Quality Index

Davey (2012) took an integrated approach to reservoir characterization by developing the Rock Quality Index (RQI) for the Montney Shale in Pouce Coupe Field in Western Alberta. In this tight gas play, Davey found that the principal factors driving the rock quality along the wellbore are natural fractures, orientation and magnitude of stresses and rock brittleness. These brittle zones along the wellbore correlates well with areas of high internal heterogeneity depicted by the RQI. Through observations in the microseismic data, the heterogeneity of the formation along the wellbore has a strong impact on where and how the hydraulic fracture propagates. This study determined that within homogenous zones of the RQI the reservoir was stimulated, while heterogeneous zones acted as fracture barriers.
2.4.2 Wattenberg Microseismic, Fractures and Stress State

FMI logs in this section of Wattenberg Field have shown small azimuthal changes in maximum horizontal stress from well to well, trending northwest to southeast. Dudley (2015) found that the linear microseismic events in this data set correspond directly to the maximum horizontal stress, while a cluster of events are associated with conjugate natural fractures, or a zone of brittle rock (Figure 2.6). The magnitude of the microseismic events tends to be influenced by the lithology and structure along the wellbore. Faults also play a key role in the propagation of microseismic events, where a large fault intersects the wellbore, the microseismic events are deferred from the near-wellbore stimulation efforts (Dudley, 2015).

![Linear and Clustered Microseismic Events](image)

Figure 2.6: Observations in the 6N well exhibiting delineated microseismic with linear trends associated with maximum horizontal stress, while clustered events in the 2N well correspond to multidirectional natural fractures, displayed in the rose diagrams (Dudley, 2015).

Tom Bratton, a PhD RCP student, analyzed the stresses occurring within Wattenberg Field (further discussed in the Stress Component section of Chapter 4). Bratton has been working with the overburden stress, pore pressure gradient, and fault stability within the
Wishbone section. The stability of faults is calculated through Mohr-Coulomb failure analysis by plotting the stress against the dip and strike along a fault. For a fault generally dipping at a 45 degree angle, the strike along the fault was found to be most unstable from 100 to 125 degrees, as seen in Figure 2.7. Applying this critical stress information based on Mohr-Coulomb theory, Bratton found that the range of unstable strike directions agreed with the underlying microseismic and incoherence fault map, displayed in Figure 2.8. From the figure, we observe that the western portion of the central graben is the main fault that is within the range of unstable strike direction.

![Stress on fault dipping at 45 degrees](image)

Figure 2.7: Representation of the stability of a general fault dipping at 45 degrees in relation to strike. The normal stress is shown in blue, shear stress in red, and stability (critical stress) in green. If the value exceeds a stability greater than 1.0, then the fault is considered highly stressed (or unstable) under in-situ conditions (RCP, 2015).

### 2.4.3 Geomechanical and Petrophysical Core Measurements in the Niobrara Formation

High-resolution geomechanical properties within Wattenberg Field have been tested in depth utilizing a non-destructive, micro-rebound hammer on core, known as the Proceq Bambino (Murray, 2015). The motivation behind this research was to identify the mechanical
stratigraphy within a Niobrara core through the Bambino measurements, returning Leeb Hardness (HLD) values. This micro-rebound hammer will be further discussed in Chapter 3 through the core analysis work. Murray was able to utilize the mechanical properties from the core tests, and extrapolate the results to surrounding wells without core in order to understand the relationship between the rock properties and production.

Through his studies, Murray found that the relationship between sonic logs and chalk HLD values were much stronger than the marl measurements. This was caused due to the sonic velocity measurements responding to anisotropy in the rock, while the HLD values are not affected by anisotropy. The marls are considered to be more anisotropic than the chalks, and therefore the relationship between chalks and sonic velocity was valid for this study (Murray, 2015). Murray also found that there was a much stronger relationship between
Petrophysical rock typing of the Niobrara Formation was performed on Core Well 3 (Kamruzzaman, 2015). The chalks and marls were split into three separate lithofacies: All Marls (A and B Marl), All Chalks (B and C Chalk), and Basal Chalk (D Chalk). The separation in lithology was due to the similarities in mineralogy based on XRD analysis. For each lithofacies groups, mineralogy analysis, pore characterization, source rock evaluation, micro-textural image analysis, and acoustic velocity interpretation were investigated within Core Well 3 of the study area. The amount of pore space, pore size and pore throat distribution was determined through the following laboratory tests: mercury intrusion capillary pressure (MICP), $N_2$ gas adsorption, and field emission scanning electron microscopy (FE-SEM) analysis.

Kamruzzaman (2015) found that the Basal Chalk was most similar to the marls within the Niobrara Formation, with a higher amount of clay content, higher porosity, smaller pore sizes (less than 1 $\mu$m) and pore throats. While the chalks have less overall porosity with larger pore sizes (nm to $\mu$m) and pore throats. Through this research, Kamruzzaman found that the Basal Chalk may have striking similarities to the All Marls lithofacies group, although when it comes to source rock potential the Basal Chalk has the lowest TOC and hydrocarbon content (S2) through a source rock analyzer (SRA), and therefore has the lowest source rock potential. From velocity analysis, he also found that the chalks have higher stiffness and pressure compliant pores, compared to that of the All Marls and Basal Chalk lithofacies groups.
CHAPTER 3
CORE ANALYSIS

This chapter focuses on the heterogeneity of the reservoir interval through depositional and petrographic rock typing of the Niobrara Formation. Cyclical patterns within the Niobrara Formation are represented by the interbedded chalk and marl benches within the Smoky Hill Member of the formation (Sonnenberg and Weimer, 2003). Each chalk and marl bench that make up the Niobrara Formation are distinctive based on varying depositional environments, mineralogy, pore size and diameter, sedimentary and biogenic features, and geomechanical properties. It is important to upscale from the micro- to macro-scale to predict the reservoir quality of the Niobrara Formation.

3.1 Core

In order to upscale the well logs to seismic, a concrete understanding of the reservoir lithology of the Niobrara Petroleum System is required. All four of the supplied core are located on each side of the seismic surveys at varying distances (ranging from 4 to 16 miles away from the Wishbone section), as seen in Figure 2.4. Each of the core descriptions includes identification of lithology type, facies, sedimentary structures, fossils and skeletal fragments, degree of laminations and bioturbation, bentonite beds, and fractures (displayed in the Appendix).

The alternating chalk and marl beds within the benches have varying degrees of laminations, bioturbation and microorganisms. The core-scale macro facies were identified based on the level of clay content and sedimentary structures (displayed in the Appendix). The chalk benches were deposited during an overall transgressive cycle, with high oxygen levels for organisms to thrive and grow, therefore preservation of organic matter is low (Drake and Hawkins, 2012). The marl benches are deposited during a time of overall regression with many storm events and terrigenous sediment deposition from the west, and high preservation
of organic matter. In conjunction to identifying the core-scale macro facies within the study area, bentonite beds and core brittleness have also become key variables in understanding the mechanical stratigraphy.

3.2 Bentonite Bed Identification

A key component from the core work is identifying where the commonly occurring ash beds are located within the Niobrara Formation. The ash beds, also known as bentonites, were deposited from the volcanic arc along the Sevier Orogenic Belt located west of the WIS during the Late Cretaceous (Figure 1.6). The ash deposits are considered marker beds as they may extend over larger parts of the basin in a cyclical pattern. Bentonite beds serve a purpose in age dating rock, determining sedimentation rates, and accessing the possible drilling hazards associated with drilling into or around these beds. Within the central portion of the Denver Basin, the Niobrara was dated between 6 bentonite beds. Through Ar-Ar age dating of the bentonite beds, the duration of sedimentation was determined to have occurred over the course of approximately 6.2 million years. Within each of the 6 bentonite beds, the sedimentation rate at this particular location was approximated at roughly 1.4 cm per thousand years (Locklair and Sageman, 2008). As for the drilling impacts, the thin beds are ductile and weak barriers that can potentially divide the unconventional reservoir into distinct flow units. The bentonite beds commonly are found in clusters, and clusters can indicate abundance at that particular zone. Specifically speaking about the Niobrara bentonite beds, clusters within marly beds may be analogous to areas where the thin beds may be hindering proppant fluid communication with the chalk (reservoir) intervals (Sonnenfeld et al., 2015).

The thin ash beds within the provided core range from 1 to 10 cm in thickness, and are, for the most part, concealed in the well logs because of the minimal thickness. The larger clusters of bentonite may be identified in the well logs due to the distinct spike with log responses of low sonic, low density, and high gamma ray, although, for the most part, they are overlooked by log measuring tools. Bentonite is unique because it fluoresces under
black light when studying the core, as displayed in Figure 3.1. The figure shows how evident identifying these zones of bentonite clusters, especially in the B Chalk core box. In Figure 3.2, throughout the core wells, bentonite clusters are commonly found at the base of the B Chalk interval. In Core Well 3, the closest core to the Wishbone section, bentonite clusters are absent within the C Chalk. This core well exhibited no bentonite beds within the Fort Hays or Codell, where Core Well 5 did exhibit minor bentonite beds within these intervals.

Figure 3.1: Bentonite beds in core boxes are identified from fluorescing under black light. Bentonite beds are identified in the A Marl and B Chalk within Core Well 3. Each core box contains 9 feet of core.

Identifying the extent of these bentonite beds throughout the available core in the study area will aid in identifying potential zones of weakness throughout the reservoir. Dudley (2015) previously picked bentonite beds in the 2N and 6N lateral FMI logs. The bentonite
Figure 3.2: Bentonite clusters for all 4 core wells. Core Wells 1 and 2 are incomplete, while Core Well 3 is closest to the Wishbone section, and Core Well 4 is greater than 10 miles away. Bentonite clusters can mean that they are abundant at that zone.

beds are generally striking at the same degree as the surrounding bedding planes picked within the FMI, as seen in the 2N lateral represented in Figure 3.3. Ideally, the thin bentonite beds within the target reservoirs should be compared to microseismic and proppant tracer data in order to determine how the bentonite beds are affecting completions and reservoir stimulation at the near-wellbore. Investigating this valuable information, in conjunction with bentonite bed locations, provides valuable information for improving completion strategy and future geosteering targets.

3.3 XRD Analysis

XRD data was provided by APC, and is only available in Core Wells 2 and 3. Most of the Niobrara Formation is absent in Core Well 2. Therefore, Core Well 3 will be the main reference for the XRD analysis section.
Figure 3.3: Bentonite beds (yellow) identified in FMI logs within 2N lateral well, along with bedding planes (green). The bentonite beds are generally dipping at the same orientation as bedding. The angle of the beds represented have been vertically stretched and are therefore not to scale, as the bentonite and bedding planes are relatively flat lying as the lateral well intersects them.

The total organic carbon (TOC) volume and total mineralogy content for clay, carbonate and other minerals is displayed in Figure 3.4. The TOC content conveys where the potential source rocks lie within the Niobrara Formation in this particular well. The C Marl exhibits the most TOC content throughout the reservoir, while the C Chalk also has a large amount of TOC content in the deepest portion of the interval. The D Chalk has an insufficient amount of TOC, which has previously negated this bench from being considered as a target interval, along with other petrophysical factors.

The total clay content is generally higher in the marls than it is in the chalks, as seen in Figure 3.4. The Fort Hays Limestone is remarkably distinct in comparison to the chalks and marls of the Smoky Hill Member, as the limestone nearly consists of all carbonate minerals, while lacking in all other minerals. The Codell Formation has less than 30% clay content, supporting that the sandstone is an ideal target reservoir. Based on the TOC and clay content, the Niobrara B Chalk, C Chalk, and Codell Sandstone reservoirs make for the best quality reservoirs within Core Well 3.
3.4 Mechanical Stratigraphy Analysis

In order to improve fracture propagation predictions, the driving mechanisms within the reservoir must be identified. Fractures may form due to a multitude of reservoir attributes, including lamination surfaces, sequence boundaries between chalks and marls, and fractures that may pass through the entire reservoir interval (Zahm and Hennings, 2009). Starting from the small scale core work, the fine detail characteristics are compared to dynamic log properties.

The variations in laminations and bioturbation throughout the core may be contributing to the anisotropy in a lateral and vertical sense. The mechanical stratigraphy found within the core will aid in understanding the variations within well log data and geomechanical
properties. By identifying these lateral and horizontal mechanical changes within the Niobrara Formation, drilling targets and overall production may be improved (Sonnenberg and Weimer, 2003).

Displayed in the appendix, the degree of laminations and bioturbation were noted throughout the core data. The degree of each category compared to the varying facies is displayed in Figure 3.5. Predominance of bioturbation within the core was scaled from 0-3, where 0 is absent and 3 is relatively high. On the other hand, laminations were scaled based on the separation between the consecutive laminae. In this sense, 3 represents laminae that are extremely thinly spaced (less than 2 mm separation), 2 represents laminae that range from mm to cm spacing, 1 represents laminae that are separated by 1 to 2 inches, and finally, 0 represents no visible laminations.

The varying scales of the mechanical stratigraphy were plotted against dynamic well log data within Core Well 3, in order to determine whether or not these fine-scale details are affecting anisotropy within the reservoir. The data was plotted in the form of box and whisker plots, in which varying populations (i.e. degrees of sedimentary structures) are plotted based on statistical distribution within the input frequency (i.e. well log values). The input logs that were used for comparisons to the degree of laminations and bioturbation have all been normalized from a scale of 0 to 2, as seen in Figure 3.6. The box and whisker plots display a multitude of information. The box itself represents the first (25th percentile) and third quartile (75th percentile), while the middle line represents the second quartile (50th percentile), also known as the median. The lines reaching beyond the box, above and below, are the “whiskers,” representing the possible alternative values (or outliers).

The degree of laminations and bioturbation from the core was compared to a significant amount of well logs, including \( V_P \), \( V_S \), resistivity (ILD), bulk density (RHOB), neutron porosity (NPHI), gamma ray (GR), Poisson’s ratio \( (\nu) \), and Young’s Modulus (E). As for the variations in the scale of laminations, a relationship was not established as the results were generally scattered as the degree of laminations ranged from 0-3. From Figure 3.6,
Figure 3.5: From left to right, GR (depicting the variations in shale), Young’s Modulus (higher values represent more brittle rock), Facies (lithofacies colors represented on right side), degree of laminations (ranging from 0-3), and bioturbation (ranging from 0-3). The relationships between the degree of bioturbation and certain well logs can be examined. These relationships may strengthen as more core wells are added to this analysis. For all of the displayed well logs, the determined relationship between logs and core was that as bioturbation increases, the values within the normalized logs also increases. The degree at which the increase occurs, varies from log to log. This relationship conveys that bioturbation affects the variation of anisotropy within the well logs.
3.5 Geomechanical Analysis of Core

After core-scale macrofacies, bentonite beds, XRD data and mechanical stratigraphy were evaluated, the heterogeneity of the interbedded Niobrara Formation was measured utilizing a hand-held micro-rebound hammer, known as the Proceq Bambino. The hammer consists of a 3 mm diameter ball that is launched from a spring against the sample. The screen on the Bambino reads a value of Leeb Hardness (HLD), which is the ratio of rebound velocity over initial velocity. The micro-rebound hammer was derived from its successor, the Schmidt hammer, which is a destructive tool that is generally used to measure rock strength properties of outcrops. Figure 3.7 depicts the Bambino in use as it is being measured along the flat core surfaces. The Bambino has been proven to be directly relatable to the mineralogy of the rock (Ritz et al., 2014). Additional research has found that the micro-rebound hammer can be correlated to dynamic geomechanical properties, such as Young’s Modulus (E), Bulk Modulus (K), and Poisson’s Ratio (ν) (McClave, 2014). These core measurements are observed on a much finer scale than what is seen in well logs, and the trend between core and log measurements is all relative, not exact. The Bambino is one of the least destructive techniques in directly measuring geomechanical properties of a core. These measurements may also be utilized as calibration points between well logs and core data.
Static core measurements aid in adjusting dynamic well logs to incorporate the essential core information.

![Figure 3.7: Bambino being measured along the core slab surface.](image)

### 3.5.1 Methodology

Bambino measurement locations were selected prior to viewing the four cores based on XRD measurements and corresponding well log responses for individual core. At each point of measurement, the Bambino apparatus was held firmly in the center of the core in order to maintain a directly perpendicular position to the testing surface. A total of 5 measurements along the flat core surface was made for each predetermined measurement site, as seen in Figure 3.8. Ritz found that as the measurements reached the edges of the core slab, the error in the HLD values increased (Figure 3.9). Ideally, the butt of the core, rather than the slabs or rockers, should be used for Bambino measurements in order to minimize error and acquire more accurate HLD values. For this study, the butts were not available, thus the error was minimized by measuring along the center of the slabs. An average was taken of the 4 to 5 values at each measurement site, in order to achieve a standard deviation of less than 10% error.
The HLD values from the Bambino have been converted to unconfined compressive strength (UCS) and confined compressive strength (CCS) through a previous study in the Niobrara. The study determined the relationship between HLD and confined compressive strength (CCS) from a triaxial-measured CCS test performed on the core (McClave, 2014). By converting the HLD values to CCS (equation 3.1), the static core values can then be correlated to dynamic properties, as both units are now in psi.

\[
\begin{align*}
UCS &= \frac{(HLD - 409)}{0.0261} \\
CCS &= \frac{UCS}{0.2659} 
\end{align*}
\]

### 3.5.2 Bambino Results

Based on the varying lithofacies within each chalk and marl bench, the Bambino will help unveil the contributing factors in the varying geomechanical properties whether it pertains to clay content, laminations, bioturbation, fractures, etc. These factors can only be determined through core work, and therefore, variations in geomechanical properties where core does not exist may be correlated to the wells with core (Murray, 2015). For this study, Core
Figure 3.9: HLD measurement values plotted against the cut surface of the core, butts (red) and slabs (blue). The values along the surface of the slab section decrease significantly as the measurements reach the edges of the slab at 1 and 20 (Ritz et al., 2014). This error is avoided by only measuring the center of the slabs, while error is minimum along the entire surface of the butt.

Well 3 will be the primary well of interest, as it has the most log information, core available throughout the reservoir intervals and is closest to the Turkey Shoot seismic survey and Wishbone section.

In Figure 3.10, the hammer-derived CCS values are found to be directly proportional to Young’s Modulus (E) and Bulk Modulus (K), while indirectly proportional to Poisson’s ratio (ν), as McClave (2014) discovered. From the Bambino results, the C Chalk HLD measurements are consistent with E, while the B Chalk measurements are inconsistent, possibly driven by heterogeneity in the B Chalk compared to the C Chalk. The facies within the B Chalk show that there is much more clay volume within the bench, contributing to lower HLD values.
Once the Bambino measurements have been correlated to the dynamic geomechanical properties within multiple core wells, then proper calibration points may be identified. These calibration points are a means of tying the heterogeneity identified in the static core measurements to the larger-scale well logs, in order to improve the geomechanical characterization of the Niobrara reservoir (Altamar and Marfurt, 2014). By identifying locations necessary for calibration, unpredicted breakouts in mud log reports may be improved as the well logs are adjusted to be more representative of the core data.

Figure 3.10: Determining correlations between Bambino measurements, geomechanical properties, bentonite beds, and core-scale macro facies in Core Well 3.
CHAPTER 4
COMPONENTS OF THE ROCK QUALITY INDEX

The rock quality index (RQI) aids in identifying geosteering targets, fracture barriers and predicting effectiveness of refracking wells that have been previously stimulated (Davey, 2012). There are three components of the RQI: rock composition, rock fabric, and the stress state. The combination of these three components of the RQI are designed to measure what rock is worth drilling and where is the optimal location for fracturing the reservoir. Davey (2012) discovered that the RQI in the Montney Formation highlighted distinct zones of reservoir homogeneity and heterogeneity. In the homogenous zones, conditions for hydraulic fracturing were more ideal due to fracture initiation and growth throughout the zone, examined through microseismic data and Diagnostic Fracture Injection Tests (DFIT). In this study, the RQI will be compared to completion data available within the lateral wells in the Wishbone Section. In addition, the stimulated reservoir based on time-lapse seismic and microseismic will aid in validating the applications of the RQI.

4.1 Rock Properties

Mechanical stratigraphy is defined as the present day rock after it has undergone mechanical and chemical changes, such as diagenesis and tectonic activity (Laubach et al., 2009). Through core analysis, the fine-detail mechanical stratigraphy of the reservoir has been upscaled to the log data. The architecture of these mechanical layers that are abundant throughout the Niobrara have a significant impact on fracture and fault development due to the heterogeneity throughout the reservoir (Hennings, 2009).

Many different factors contribute to the heterogeneity observed within the Niobrara. The RQI accounts for these factors by solving for these two components: rock fabric and rock composition (Figure 4.1). The fabric of the reservoir takes into account the depositional conditions of the reservoir, while the composition utilizes the petrographic information. Both
of these rock property components define the overall rock brittleness. Many of the brittleness index definitions used in the industry today are calculated either with log-derived elastic properties or mineralogy, and neither of the brittleness definitions take into account the stress state or pore pressure (Herwanger et al., 2015). While the brittleness index (BI) is mainly an indicator of lithology (rock quality), the RQI equation takes into account the stress state of the rock along the wellbore. Thus, this particular application of the RQI is unique compared to many of the current rock quality methodologies within the industry to date.

Figure 4.1: Primary factors affecting shale heterogeneity that aid in determining the most ideal hydraulic fracture location based on rock brittleness and where the fracturing will propagate (Davey, 2012).

4.1.1 Fabric

Mechanical stratigraphy relates to the time of deposition and burial history that the reservoir has undergone. The Niobrara was deposited in a relatively deep marine setting characterized by varying degrees of laminations and bioturbation (previously discussed in Chapter 3). Although these sedimentary structures are identified at such fine detail in the core, a relationship between these structures and well logs must be determined. Variations in bioturbation appear to have the strongest influence on well log data, compared to lami-
nations, based on the core analysis from Chapter 3.

Rock typing within the Niobrara in Core Well 3 has been performed through petrophysical and depositional analysis (Kamruzzaman, 2015). The rock types within the Niobrara Formation have been separated into 3 lithofacies groups: all marls (A-C), middle chalks (B and C), and the basal chalk (D). A fellow RCP student examined the pore structure between the lithofacies through $\text{N}_2$ gas adsorption indicating the presence of micro-, meso-, and macropores, as seen in Figure 4.2. The middle chalks exhibit larger pore structures (macro), while the marls and basal chalk display smaller pores (micro to meso). FE-SEM images within Core Well 3 were generated for each of the lithofacies (Figure 4.3). The representative FE-SEM images aids in identifying the variations between the lithofacies on a micro-scale. Through Kamruzzaman (2015) work, the middle chalks (B and C) exhibit significantly larger pore spaces and pore throat sizes, mostly hosted by calcite. The marls (A-C) exhibit a large amount of organic matter (OM) and clay hosted pores with finer pore spaces and throat sizes. Finally, the basal chalk (D) features negligible amounts of OM, with high amount of clay and finer pore spaces and throat sizes. These conclusions are conveyed in Figure 4.2 and Figure 4.3.

While the varying lithologies have been defined based on porosity, permeability and source rock potential, the reservoir has not yet been defined in terms of the most ideal locations for hydraulic stimulations within this study area (Kamruzzaman, 2015). The RQI exclusively accounts for these locations by additionally accounting for the hydraulic state of the reservoir.

The rock fabric brittleness establishes an empirical relationship between $V_P$ and unconfined rock strength ($C_0$) based on laboratory rock strength tests with core data (Holt et al., 2011). Additionally, through a study conducted by Stump and Flemings (2001), $V_P$ was determined to have an empirical relationship with past effective stress ($\sigma_{V_{max}}$), demonstrating that $V_P$ increases with $\sigma_{V_{max}}$. The available $V_P$ well logs are converted to ($C_0$), demonstrated in equation 4.1, in order to convert sonic velocity values in terms of stress and pressure units,
Figure 4.2: Based on the relative pressures that the isotherms reach from $N_2$ gas adsorption aids in determining the variations within the lithofacies of the Niobrara Formation (Kamruzzaman, 2015).

Once the $\sigma_{V_{\text{max}}}$ has been obtained, the OCR can be determined by dividing maximum past effective stress ($\sigma_{V_{\text{max}}}$) by present day effective vertical stress ($\sigma_V$), as displayed in equation 4.3. The fabric brittleness ($B_F$) empirical relationships have been determined from laboratory tests for seal leakage in shales and mudrocks (equation 4.4).

$$C_0[\text{MPa}] = 0.77V_F[\text{km/s}]^{2.93} \quad (4.1)$$

$$\sigma_{V_{\text{max}}}[\text{MPa}] = 0.86C_0[\text{MPa}]^{0.55} \quad (4.2)$$

$$OCR = \frac{\sigma_{V_{\text{max}}}}{\sigma_V} \quad (4.3)$$

$$B_F = OCR^{0.89} \quad (4.4)$$
Figure 4.3: Representative FE-SEM images of the 3 Niobrara lithofacies in Core Well 3: a.) all marls (A-C), b.) middle chalks (B and C), c.) basal chalk (D) (Kamruzzaman, 2015).

4.1.2 Rock Composition

From Davey (2012) work within the Montney Shale, the rock composition varied based on TOC, clay content, and mineralogy. The rock composition component of the RQI equation has been adjusted to accommodate for the distinct Niobrara mineralogy.

The compositional brittleness of the rock is generally defined utilizing XRD data from the core. The mineralogy essentially identifies the lithology, while the brittleness index defines where the lithology is most brittle or ductile (Herwanger et al., 2015). The harder the mineral, such as quartz, the more likely the rock will break when hydraulically stimulated is the idea behind the brittleness index. This assumption does not account for stress, which may inhibit or help fracture propagation. Quartz and dolomite are considered the stiffest minerals when defining a non-reservoir specific brittleness index based on mineralogy. Therefore equation 4.5 and 4.6 are defining the stiffest minerals as a fraction, in order to assign the
brittleness index with higher value when the mineralogy indicates a harder, more brittle rock (Jarvie et al., 2007; Wang and Gale, 2009). The two equations indicate that a high brittleness index is associated with a sandstone (or quartz) rich lithology, while a low brittleness index is associated with a high shale (or clay) rich lithology (Herwanger et al., 2015). The brittleness index, the stiffness fraction from mineralogy data, directly correlates to elastic properties defined by well log data. A high brittleness index corresponds to a high Young’s Modulus (E) and low Poisson’s ratio (ν) from well log data.

\[
BI = \frac{V_{Quartz}}{V_{Quartz} + V_{Calcite} + V_{Clay}}
\]  

(4.5)

\[
BI = \frac{V_{Quartz} + V_{Dolomite}}{V_{Quartz} + V_{Calcite} + V_{Clay} + V_{Dolomite} + V_{TOC}}
\]  

(4.6)

The compositional brittleness equation is based off of Wang’s brittleness index equation 4.6, accounting for quartz, dolomite and TOC. The chalks and marls within the Niobrara have varying amounts of carbonate and clay content. From the XRD data discussed in Chapter 3, the total clay content is higher in the marls, while the calcite content increases within the chalks. Dolomite and feldspar are of significantly higher content in the Codell, although minor in the Niobrara. Therefore, the most variable carbonate mineral within the reservoir interval is calcite. Illite and smectite make up the bulk of the clay volume, both of which follow the general trend of being high in the marls and low in the chalks (chlorite and kaolinite are virtually absent throughout the entire reservoir interval). As for other differentiating “hard” mineralogy within the reservoir interval, quartz, plagioclase and pyrite vary significantly throughout, with quartz having the highest influence on bulk “other” mineralogy. From the information gathered from the XRD data, the rock composition brittleness may be determined by solving for equation 4.7.

\[
B_C = \frac{V_{Quartz} + V_{Calcite} + V_{Plagioclase} + V_{Pyrite}}{(\text{numerator} + V_{Clay} + V_{Others})(1 - TOC_{pd}) + TOC_{pd}}
\]  

(4.7)
4.2 Stress Component

The maximum and minimum principal stresses ($\sigma_V$ and $\sigma_h$) are calculated for the stress component of the RQI. The third principal stress, maximum horizontal stress ($\sigma_V$), has less of an influence on rock failure compared to the other two principal stresses (Hillis, 2000). As previously discussed in the Previous Research section of Chapter 2, Tom Bratton, a fellow student in RCP, has developed general assumptions for the overburden stress and pore pressure in relation to depth within the Wishbone section. In order to apply these necessary variables to the RQI, I will first discuss his methodology in determining the stresses affecting the Wishbone section.

4.2.1 Overburden Stress

Bratton has solved for overburden stress, utilizing true vertical depth below ground level ($TVD_{bgl}$) and bulk density (RHOB) (equation 4.8). For the cases where vertical well logs did not have any data for shallow densities, basic earth model assumptions were made based on information within Wattenberg Field. Once the overburden stress was calculated using vertical well logs (Figure 4.4), a general equation was created by fitting an overburden stress model to the curve (equation 4.9). The four coefficients were generated by fitting the curve with a Morgan-Morgan Finney (MMF) model. Through this methodology, the overburden stress may be accurately predicted within the lateral wells in the Wishbone section. The only data necessary for these predictions are the log depth measurements, since density logs are unavailable within the laterals. Assuming that ground level is relatively flat in Wattenberg Field, the overburden stress calculated with depth is held constant within the Wishbone section based on the available data. Therefore, error within several feet is expected.

$$\sigma_{V2} = \sigma_{V1} + 0.4335 \times RHOB(TVD_2 - TVD_1) \quad (4.8)$$
Figure 4.4: The equation for overburden stress ($\sigma_V$) was determined by fitting the curve to the overburden stress results from (equation 4.8). The calculated overburden stress values from equation 4.8 are represented by the red data points, while the overburden stress model that was fit to the data is represented by the black line (work by Tom Bratton).

\[
y = \left(\frac{a \times b + c \times x^d}{b + x^d}\right)
\]

where:

\[
\begin{align*}
a &= 17.93 \\
b &= 918.00 \\
c &= 90.73 \\
d &= 0.4029
\end{align*}
\]  
(4.9)

4.2.2 Pore Pressure

Pore pressure (PP) plays a vital role in rock failure. Overpressured reservoirs exhibit effective stresses approaching shear failure, while as the reservoir is being depleted the stresses are assumed to decrease (Figure 4.5). This relationship between stress and rock failure leads to the critical impact of pore pressure (Hillis, 2000). By expressing $\sigma_h$ in terms of $\sigma_V$, pore pressure’s effect on the Mohr-Coulomb failure analysis becomes more clear (equation 4.10).
Figure 4.5: Mohr-Coloumb diagram depicting the relationship between shear and effective normal stress. An overpressured reservoir is likely to approach the failure envelope, while a reservoir undergoing depletion will become more stable (Hillis, 2000).

\[ \sigma_h = \frac{\nu}{1-\nu}(\sigma_v - PP) + PP \]  \hspace{1cm} (4.10)

The same standard is held for PP within this section of Wattenberg. As for PP, there are only two known data points near the Wishbone section in Well 1, where Bratton has assumed a linear trend between these two data points, as seen in Figure 4.6. The PP was then calculated within the vertical wells using $TVD_{bgl}$ alone (equation 4.11). The same approach for calculating overburden stress over the Wishbone section was then applied to PP by using the depth information from the lateral logs (equation 4.12).

\[ PP^{norm} = 0.447TVD_{bgl} \]
\[ PP = PP^{norm} + 1.25(\text{psi/ft})(TVD_{bgl} - TVD_{bgl0}) \]  \hspace{1cm} (4.11)
\[ TVD_{bgl0} = \text{Lower Pierre PP data point depth (ft)} \]

\[ y = 2643 + 1.31(x - 5920) \]
\[ x = TVD_{bgl} \]
\[ y = PP(\text{psi}) \]  \hspace{1cm} (4.12)

Unfortunately, the PP is only available in one well within the study area (Well 1). Therefore, to apply the PP gradient to nearby vertical wells, the wells were compared utilizing GR, RHOB, and $V_P$ logs. From Figure 4.7, these vertical well logs, even being 6 miles away from one another, are strikingly similar. The main difference between the two wells resides
Figure 4.6: Schematic diagram of the PP gradient based on the known data points in Core Well 1 (work by Tom Bratton).

in the A Marl. Studying the figure, the GR, $V_p$, and RHOB logs are all varying at the same point within the A marl, ruling out any gas affects and most likely caused by a difference in lithology. Utilizing equation 4.11, the relative PP was determined for Core Well 3, and will later be applied to the RQI equation. As for solving the RQI along the lateral wells, equation 4.12 will be used to determine the general PP trend over the Wishbone section based on the depth at which the laterals are undulating.
Figure 4.7: Core Well 3 is compared to Core Well in terms of GR, $V_p$ and RHOB logs, respectively.
Applying the RQI along the lateral wells within the Wishbone section will allow for validation and correlation to the available completion and production data. In order to develop the RQI along the lateral wells within the Wishbone section, this analysis must first be applied to the surrounding vertical wells. The vertical well that exhibits all of the available data necessary for the RQI equation is Core Well 3, which is also the closest core well to the Wishbone section. Due to limited logs existing within the laterals, cluster analysis and neural networks were applied in order to expand the RQI equation to the lateral wells. This process will be further discussed in the “RQI in Lateral Wells” section of this chapter.

The equation for the RQI is displayed in Figure 5.1, where the stress state is subtracted from the rock brittleness. The brittleness of the rock is based on the addition and normalization of the rock composition and fabric. The stress state is calculated by taking the difference between the maximum and minimum principal stresses ($\sigma_V$ and $\sigma_h$), and then normalized. After the stress differential is determined, the natural log of the normalized value is calculated. By taking the natural log of normalized stresses ranging from 0 to 1, the values will approach negative infinity as the input values approach 0. This process for the stress state component will amplify the stress results, as the natural log will display differential variability more rapidly (Davey, 2012).

Due to the distinct mineralogy within the varying lithofacies, the RQI is only determined within the Niobrara reservoir. For example, the rock composition equation is designed to assign higher values to stiffer rock. Calcite is extremely high in the Fort Hays Limestone compared to the Smoky Hill member of the Niobrara Formation. Additionally, clay content is approaching zero within the Fort Hays while the Niobrara varies from approximately 3 to 40 weight percent within the alternating chalks and marls of the Smoky Hill member. The
Figure 5.1: The three components that define the RQI. Rock fabric and composition are added together, and then subtracted from the differential stress in order to generate the RQI, modified from Davey (2012).

Result of the variations in mineralogy from the Smoky Hill Member to the Fort Hays, would assign a much higher weight to the Fort Hays compared to the other lithologies comprising the Niobrara. These relationship are displayed in the XRD data within the Core Well 3 in Figure 3.4. Therefore, all of the intervals outside of the alternating chalks and marls will be excluded from the RQI calculation.
5.1 RQI in Vertical Wells

The RQI was determined in Core Well 3 by utilizing compressional and shear velocities ($V_P$ and $V_S$, respectively), XRD data, pore pressure (PP) and overburden stress ($\sigma_V$). Ideally, the reservoir is lower in clay content, higher in TOC, lower in stress differential, and higher in rock fabric brittleness. All of these components in the RQI equation are considered the driving mechanisms for an ideal reservoir for hydraulic stimulation, where maximum fracture width and minimum breakdown pressure may be achieved (Suarez-Rivera et al., 2011).

The individual components of the RQI within Core Well 3 are displayed in Figure 5.2. The highest quality reservoir is highlighted in red, medium is in yellow and low is represented in gray. Where RQI is high, potential for fracture growth and minimum breakdown pressure is at a maximum. Based on these two factors, communication with the ideal reservoir is increased, as the environment for reaching far-wellbore fracture networks is optimized.

In Figure 5.3, the RQI results for Core Well 3 are compared to gamma ray (GR) and Young’s Modulus (E). GR aids in differentiating the lithologies based on clay content, while E identifies zones of brittle rock (where E is high). Geomechanical properties, such as E, derived from dipole sonic logs are not accounting for local stresses that may dramatically affect reservoir stimulation. The RQI is unique as it combines the information from the previously discussed logs, in addition to the stress state of the reservoir. This methodology quantifies where the best quality reservoir resides based on a multitude of driving factors, such as depositional, petrophysical and the hydraulic state of the reservoir rocks along the wellbore.

The results of the RQI in Core Well 3 are then compared to results from the core analysis, as seen in Figure 5.4. The B Chalk and the top of the B Marl display a higher RQI. The C Chalk exhibits consistently high RQI throughout the bench. The amount of bentonite beds at this particular vertical well in the C Chalk is fairly low, while the B Chalk is comprised of several bentonite clusters. Based on the core facies, the marl benches have much thicker packages of marl core facies, most likely contributing to the lower RQI in these units.
Figure 5.2: Log representation of the RQI components in Core Well 3. The normalized rock brittleness (left) is subtracted from the natural log of the normalized stress differential (middle) in order to obtain the RQI (right).

As for the work within the vertical wells, the RQI results displayed in Figure 5.3 clearly suggests that mainly targeting the chalk reservoir intervals is misleading. Units within the marl benches are also exhibiting higher RQI values. For example, the C Chalk should not be the only target. Within this particular well, the C Chalk and into the top of the C Marl display high reservoir quality and should potentially be considered an entire target zone.
Figure 5.3: Suite of logs in Core Well 3 displaying the uniqueness of the RQI. From left to right: GR, E, RQI. The RQI is plotted with the GR and E in order to reveal how the RQI combines multiple components that may better express where the ideal target reservoir is located along the wellbore.

5.2 RQI in Lateral Wells

I chose to apply the RQI to the lateral wells within the Wishbone section, in order to compare the results with the completion and seismic data. Ideally, the RQI should be built with sonic logs within the lateral wells for anisotropic stress profiling (Bammi et al., 2015). In this case, gamma ray (GR) and deep induction (ILD) resistivity logs were utilized in a neural
network to generate synthetic sonic logs. Unfortunately, only 5 out of the 11 lateral wells have GR and ILD logs, while the other 6 consist of only GR. Measuring the radioactivity of the minerals along the wellbore, GR is utilized by the drilling engineers as a means of navigation throughout the reservoir as the well is being drilled. The chucks and marls of the Niobrara Formation return a distinct gamma ray log signature. This signature will be further employed for lithology identification along the laterals through cluster analysis.
The GR logs for all of the lateral wells in the Wishbone section must be normalized to one another in order to remove any irregular borehole conditions. Additionally, only two of the eleven lateral wells have been normalized to the vertical wells surrounding the Wishbone section. These two laterals are 2N and 6N, highlighted in Figure 5.5. These two wells are significant because they exhibit FMI data, and are both located on opposite sides of the Wishbone section. Well 2N is located on the eastern portion with wider well spacing, while well 6N is more west exhibiting tight well spacing and more critically stressed faults (based on the previous work done by Tom Bratton in Chapter 2). The FMI logs available in both of the laterals have been previously interpreted by a fellow RCP student (Dudley, 2015). Utilizing the available logs in the lateral wells, cluster analysis will be applied to the rock composition portion of the equation, while a neural network will aid in determining synthetic sonic logs necessary for determination of the rock fabric and stress state.

Figure 5.5: Out of the 11 lateral wells in the Wishbone section, 2N and 6N have been highlighted by the red boxes. The color bar represents the different lithologies, in which the laterals are traversing through (based on the geosteering reports).
5.2.1 Cluster Analysis

Based on work done by Dudley (2015) on lateral wells 2N and 6N, the lithology was discriminated through GR cluster analysis. Originally this work involved a cluster analysis utilizing 5 vertical well logs: GR, bulk density, volumetric photoelectric factor, thermal neutron porosity and ILD. From the cluster analysis, 10 lithology clusters were determined throughout the Niobrara Formation within this particular well (Figure 5.6). From the clustering, the A through C chalk and marl benches exhibited similar alternating cluster classes throughout. Contrary, the D Chalk through the Codell did not have any cluster overlap or repeats. This illustrates how the properties and geology are differentiated between the A through C benches compared to the D bench, and should not be combined as previously discussed when calculating the RQI. The chalk and marls returned distinct gamma ray responses without the contribution of any of the other 4 vertical logs. This relationship is highlighted in the box and whisker plot, displayed in Figure 5.7. The chalk is represented by the light red clusters, a low GR marl represented by light blue, and a high GR marl represented by gray. The GR discrimination work clusters the lithologies as follows: a chalk is representative of API values less than 110, a low GR marl ranges from 110 to 141 API, and a high GR marl is representative of API values greater than 141.

This is a viable technique in determining the lithologies along the lateral wells due to the distinct GR signature of the varying chalks and marls, as seen in Figure 5.8. As previously mentioned, the lateral wells, 2N and 6N, are targeting the C Chalk. On the contrary, the laterals are rarely in one bench due to undulation and geologic structure within the Wishbone section. In Figure 5.8, 6N clearly illustrates how the well is only in the targeted chalk zone for only 20% of the time. In terms of geologic structural variation, all 11 lateral wells are intersecting a large graben trending NE-SW in the central portion of the Wishbone Section, as displayed in Figure 5.5. Within the graben, the C Chalk has been eroded away, thus the laterals are intersecting the B Chalk and Marl.
Figure 5.6: Zoomed-in vertical well cluster analysis utilizing 5 vertical well logs (Bratton, 2014).

As the GR cluster analysis within the lateral wells was performed, the analysis was also applied to the vertical well, Core Well 3. This validation is required in order to confirm the cluster results in the lateral logs. For Core Well 3, the similar GR cluster classes were applied
to the vertical GR log, ranging from the A Marl to the C Marl. At each measured XRD depth, the assigned GR cluster class was averaged for each mineral that was called for within equation 4.7. A table displaying the difference in averages between calcite and total clay content based on the GR classes is displayed in Figure 5.9. Along with the determination of the average values for each GR cluster class, a standard deviation of less than 10% was returned.

From the table represented in Figure 5.9, the chalk GR cluster class exhibits higher calcite content and lower total clay content, while the high GR marl exhibits lower calcite and high total clay content (as expected). Once the relationships were confirmed from the original XRD data, the GR cluster classes were each assigned average mineral values required for the composition component of the RQI equation (equation 4.7). The cluster classes were then applied to the entire normalized GR log in Core Well 3, and from there the composition
Figure 5.9: Table displaying how the GR cluster analysis is supplemented for the available XRD data. The GR cluster classes were assigned to Core Well 3 XRD data, where the average mineralogy was determined for each cluster class. For example, the average calcite content exhibits a higher average in the chalk and lower in the high GR marl, vise versa for the average total clay content.

Brittleness was determined at each depth. Lastly, the RQI was recalculated for Core Well 3, replacing the original XRD data calculations with the new GR cluster class derived values (Figure 5.10). The difference between the original RQI and the modified RQI is negligible, thus this method may now be applied to the lateral wells.

The compositional brittleness component of the RQI equation has been applied to the lateral wells utilizing the same method applied to Core Well 3. The two lateral logs have normalized gamma ray logs, in order for the same range in API values to be assigned to each GR cluster class. The new mineral averages for the GR cluster classes have been successfully assigned to each lateral well, as they were in Core Well 3. Thus, the composition was successfully represented in the lateral wells through cluster analysis of the GR logs.

### 5.2.2 Synthetic Log Generation through Neural Network

Dipole sonic logs are among the missing information in applying the RQI to the lateral wells within the Wishbone section. These logs are necessary in calculating the rock fabric (equation 4.4) and stress state (equation 4.7). Synthetic sonic logs are generated through a feedforward backpropagation neural network (NN) model built in MATLAB computing software (Bray, personal communication). The feedforward component of the NN algorithm is referring to the multi-layer network where there are input layers, hidden layers, and individual output layers. The backpropagation component of the NN algorithm refers to the
Figure 5.10: The modified RQI was calculated using the GR cluster classes in Core Well 3. From left to right: GR, E, original RQI, modified RQI, and the difference between the two results.

The technique of assigning a weighted error by subtracting the trained data from the desired output through multi-layer steps in order to determine a certain error weight. These weights are then assigned to the initial inputs in order to reduce overall error of the outputs. The particular NN has been trained with 4 different dipole sonic logs from vertical wells surrounding the Wishbone section in order to determine $V_P$ and $V_S$ from just GR and ILD logs. In this
case, the NN only had two input neurons (GR and ILD), one hidden layer, four iterations to solve for the error weight, and one output ($V_P$ or $V_S$), as displayed in Figure 5.11.

![Feedforward Backpropagation NN Model](image)

**Figure 5.11**: A schematic diagram of the feedforward backpropagation NN process within MatLAB, modified from Leverington (2009). The components of the NN consists of input, hidden and output layers.

The 4 vertical wells that were incorporated into the training of the NN algorithm required a blind test well for validation (Figure 5.12). Once the training was completed, the blind well was then used to assess the accuracy of the new synthetic sonic logs generated from the 4 vertical wells. The accuracy for the synthetic sonic logs, utilizing only the GR and ILD logs, returned a value of 86% for the predicted $V_P$ and 89% for the predicted $V_S$. Once the accuracy of the blind well test was confirmed based on the high accuracy percentages in the vertical well, the NN was then applied to 2N and 6N, returning an accuracy of 87% for predicted $V_P$ and 91% for predicted $V_S$. As more well logs are included, such as density and neutron porosity, the predicted accuracy would ideally improve, although when dealing with the lateral wells, GR and ILD are the only available logs.

A consideration when utilizing ILD in calculating synthetic sonic logs is the possibility of polarization spikes within the lateral logs. When measuring resistivity in a vertical well, the measuring tool is parallel to the formations, assuming that it is relatively horizontal.
Figure 5.12: The blind well NN training results, with the original sonic log in red and the predicted sonic log in black. Correlation factor of 86%.

However, given that the horizontal well has a high angle of deviation, the measuring the tool intersects the varying formations at high angles (Schlumberger Oilfield Glossary). Where there is a formation boundary, specifically as these horizontal wells are crossing between the chalk and marl benches of the Niobrara Formation, there may be a large charge buildup depending on the apparent dip from the borehole to the bed boundary. The charge buildup is seen as a spike by the resistivity measuring tool, also known as a polarization horn. This
apparent spike in the log significantly increases as the angle between the measuring tool and the bedding planes grow. The polarization horn may also be beneficial in being a direct indicator of when the lateral well is crossing a bed boundary. Unfortunately, for this study purpose, generating synthetic logs from the available resistivity logs in the lateral wells may prove to be unreliable if there are any polarization horns present. Therefore, examining the lateral resistivity logs in fine detail is required in order to generate accurate synthetic logs utilizing the available gamma ray and resistivity logs in the lateral wells. In this case, 2N and 6N did not have any polarization spikes. This is most likely due to the fact that as the laterals are undulating between the chalks and marls, variations in mechanical properties are much lower than if the lateral were to cross a bedding boundary between the Fort Hays and the D Chalk, for example.

5.2.3 Stress State

The last step in determining the RQI along the laterals is solving for the stress state. Through personal communication with Tom Bratton, a general overburden stress ($\sigma_V$) assumption based on $TVD_{bgl}$ was determined within the Wishbone section, regardless of density. This assumption was made due to the relatively flat-lying Wishbone section located within the Front Range of the Rocky Mountains, as well as the small amount distance between the lateral wells. The equation for determining $\sigma_V$ was designed by fitting the curve to the overburden stress, which was originally calculated from density, as shown in Figure 4.4. This new equation that determines $\sigma_V$ from $TVD_{bgl}$ alone has been previously discussed in Chapter 4 (equation 4.9).

The pore pressure (PP) was successfully determined, as it is dependent on $\sigma_V$. This relationship has also been previously discussed in Chapter 4 in equation 4.12, where the only required inputs are $TVD_{bgl}$ and $\sigma_V$. The two lateral wells are located only 1800 feet away from one another, thus general assumptions for the stresses within the lateral wells are considered viable.
CHAPTER 6
RESULTS

Once the log calculations for each RQI component was accomplished, the results from the GR cluster analysis and NN were successful in their application to the lateral wells. The RQI results for lateral wells, 2N and 6N, have been plotted with lithology and GR cluster classes, separately, as seen in Figure 6.1. Generally, the RQI is higher in the chalk GR cluster classes than the high GR marls. As lithology is one of the main drivers of the RQI, the stress state is also influencing these results. Thus, GR is successful in discriminating lithologies, however, this log type alone will not suffice in targeting the best quality reservoir. Now that the RQI has been solved for within the two lateral wells, the production and completion data may now be compared for further validation of the RQI.

The overall goal of the RQI is to optimize completions by designing perforation clusters based on high rock quality and low stresses. Rock quality identifies where the rock will most likely fail, while the stress state identifies areas with lower stress that will improve fracture connectivity from the near to far wellbore. The ability to effectively hydraulically fracture a layered rock, such as the Niobrara reservoir, is dependent on two factors: 1.) shear strength of the rock and 2.) increase in minimum horizontal stress ($\sigma_h$) (Teufel and Clark, 1984). Targeting cluster perforations around areas of lower $\sigma_h$ will improve fracture growth and connectivity within the targeted reservoir.

Generally, perforation clusters along a lateral are geometrically spaced, neglecting the rock quality and stresses paralleling the wellbore. By neglecting geology and local stresses when stimulating the reservoir, a large amount of stages become ineffective. In theory, when zones of high stress and low reservoir quality are perforated, a small amount of surface area within the reservoir is accessed within these inhospitable environments. When production in certain stages is ineffective, resources are wasted and costs are increased.
Figure 6.1: RQI results for 2N and 6N compared to the lithology and GR cluster classes
In order to improve stimulation and efficiency, perforation clusters should be scientifically placed based on areas with high rock quality and low stress (Bammi et al., 2015; Cipolla et al., 2012; Suarez-Rivera et al., 2011).

The geometrically placed clusters were compared to selectively placed clusters based on rock quality and stresses. The geometrically placed perforation stages are displayed in Figure 6.2. The figure specifically shows stages 8 through 13, where rock quality (top of lateral) and stresses (bottom of lateral) are extremely heterogeneous within one stage. Within these particular stages, the hydraulic fractures are most likely inhibited where stress is too high. These zones will cause the fractures to only propagate where higher reservoir quality and lower stress is present, represented by the white arrows. Thus, designing the stages based on homogenous zones where rock quality is high and stresses are low throughout one stage will allow for completion and production optimization.

From Figure 6.3, the newly designed perforation clusters take into account rock quality (top of lateral) and the stress state (bottom of lateral). The black boxes represent areas along the wellbore with uniformly high rock quality, while outside of the boxes represents areas with uniformly low rock quality. The figure at the bottom conveys that the RQI, combining the rock quality and stress state, in a single well log is just as effective in designing homeogenous stages, whether high or low quality. Hydraulically fracturing these selections will improve the effectiveness of fracture connectivity between near and far-field fracture networks in relation to the wellbore (Suarez-Rivera et al., 2011). Within these selections, multiple perforation clusters and stages may be designed in order to increase rock-fluid interactions and surface area reached through increased fracture connectivity. If stages are placed where stresses are high (where RQI is low), then breakdown pressures will consequently be higher when pumping within these particular stages, thus higher pressure and fracture fluids are necessary to complete these lower quality stages.
Figure 6.2: The 32 geometrically spaced stages in 2N are separated by black lines along the wellbore. Behind the logs along the wellbore, blue represents the C Chalk bench, while gray represents the marls benches. The log on top of the wellbore represents the rock quality (fabric and composition from the RQI), while the bottom log represents the stress state from the RQI equation. A zoomed in section of stages 8-13 is shown in the bottom of the figure. Within these stages, the rock quality and stresses are heterogenous. The white arrows represent locations where hydraulic fracture fluid most likely penetrated, as the fluid generally follows the path of least resistance.

By understanding the conditions that exist along the wellbore and how they are affecting completions, communication with potential reservoir rock beyond the wellbore may be improved. The available completions and seismic data has been utilized to compare to the RQI results along lateral wells 2N and 6N. These relationships and comparisons will be further explained throughout the following chapter.
Figure 6.3: Zones of uniform rock quality are selected based on rock quality and stresses (top) and RQI (bottom). Black boxes represent zones with uniformly high rock quality, outside of the black boxes represent zones of uniformly low rock quality. Stages and perforation clusters may be designed based on the location of homogenous rock types, where similar completion parameters may be applied to the uniform zones.
By understanding the conditions that exist along the wellbore and how they are affecting completions, communication with potential reservoir rock beyond the wellbore may be improved (Suarez-Rivera et al., 2011). In order to determine the driving mechanisms for initial production along the wells, an investigation of available production and completion data is necessary. Comparisons to the RQI results between the completion data and seismic surveys will be discussed throughout the chapter. Many assumptions were made when calculating the RQI in the laterals, including the utilization of cluster analysis and neural networks (NN). With this in mind, there is more to the completion story than just the rock quality along the wellbore, including faults, fractures, bedding boundaries, and pressure compartmentalization.

7.1 Upscaling Core Work

In order to improve fracture propagation predictions, the driving mechanisms within the reservoir must be identified. The degree of laminations and bioturbation were noted throughout the core data in Core Well 3, as displayed in Figure 3.5. Core work has allowed for a better understanding of the heterogeneity within the Niobrara, and to upscale this work a Rock Quality Index (RQI) was developed from the well logs in concurrence with the core work. Additionally, applying the RQI to lateral wells has allowed for completion optimization by preferentially selecting stages based on homogenous zones of rock quality. Once the RQI has been applied to more wells with core, a relationship may be established between the core components that are affecting the anisotropy of the reservoir.

Ideally, the geologically scaled RQI is then applied to vertical wells without core that are utilized in the Turkey Shoot seismic survey. The 13 wells located throughout Turkey Shoot are applied to an engineering facies model designed by fellow RCP student, Yanrui Ning.
The facies model was designed in Petrel and was created in order to properly distribute the reservoir properties for simulation modeling. The RQI from each of these wells was then applied to the interpreted facies model, displayed in Figure 7.1. The benefit of these models is understanding production history, and how to improve methods for future drilling.

![Turkey Shoot - RQI Facies Model](image)

Figure 7.1: Facies model built from the geologically scaled RQI that was applied to 13 lateral wells within the Turkey Shoot seismic survey. Represents the RQI throughout the Smoky Hill Member of the Niobrara Formation (work by Yanrui Ning).

### 7.2 FMI along the laterals

Along with the engineering data, the FMI logs for the 2N and 6N laterals have been interpreted by a fellow RCP student (Dudley, 2015). The following structural features have all been extensively identified throughout the FMI logs: faults (open, closed, induced), fractures, bedding planes and bentonite beds. The faults and fractures within the FMI logs were identified based on their distinct appearances, as displayed in Figure 7.2. The fractures (open and sealed), as well as the faults, are trending NW-SE in 2N and NE-SW in 6N. Faults and fractures along 2N are more prominent than structures identified throughout the FMI log in 6N. In Figure 7.3, the RQI is compared to the locations of faults, fractures and bentonite beds. The bentonite beds were generally paralleling the bedding planes, as
previously discussed and shown in Figure 3.3. From the core analysis in Chapter 3, the bentonite beds are present throughout the reservoir intervals (Figure 3.2).

Figure 7.2: FMI picks based on the appearance of certain structures. Identified from left to right: open fracture, sealed fracture and fault (Dudley, 2015).

While analyzing the available completion data, the FMI logs for 2N and 6N were correlated to these completion data, in conjunction with the RQI. The examination of this data will allow for a better understanding of communication that is occurring between the near-wellbore in-situ conditions and the reservoir. Communication is affected by the fractures, faults, rock quality, localized stresses, and pressure compartmentalization. As previously discussed the bentonite beds may act as fracture barriers and may subdivide the reservoir into different flow units within the chalk and marl units (Sonnenfeld et al., 2015). The centrally located graben that is intersected by all 11 lateral wells, also plays a critical role in production and communication along the lateral wells (Figure 5.5). Additionally, a large cluster of major faults and fractures picked within the FMI logs defines this highly stressed fault zone, characterized by a listric normal fault and antithetic faults (Figure 1.8). The affects that the FMI logs may have on the available completion data will be further discussed throughout this chapter.
Figure 7.3: The FMI picks along 2N and 6N are represented by the colored tick marks, overlaying the RQI results for each lateral well. The tick marks represent the picked faults (blue), fractures (green) and bentonite beds (orange).

7.3 Upscaling the RQI to Completion Data

The RQI has been validated through the analysis and comparisons with available completion data along the 2N and 6N lateral wells. The data specifically available for this study includes: net pressure trends from treatment plots, relative instantaneous shut-in pressure (ISIP), gas shows from mudlogs, and radioactive proppant tracer data.

7.3.1 Net Pressure Trend Comparisons

The net pressure trends are available in the treatments plots within the completion reports for each lateral well. The net pressure trend is identified by the slope of each stage, represented by the red lines in each individual pressure plots, displayed in Figure 7.4. The modes, ranging from I-IV, relate fracture propagation behavior to each net pressure trend (Nolte and Smith, 1981). A plot identified as Mode I, exhibits slightly increasing pressure, suggesting normal, lateral fracture growth. A plot identified as Mode II, exhibits constant
pressure over the stage time, suggesting stable, lateral growth with less propagation compared to Mode I. A plot identified as Mode III, exhibits a tremendous amount of increase in pressure over the course of the stage time, suggesting that fracture propagation has stopped and pressure is building up rapidly. At this point, the completion engineers must pay close attention in order to avoid a screenout, where an alarming rise in pump pressure occurs. Lastly, a plot identified as Mode IV, exhibits decreasing pressure, suggesting that fractures are rapidly growing in height, potentially out of zone (i.e. out of the C Chalk). All of the modes identified in Figure 7.4 were picked for each individual stage along the lateral wells by a fellow RCP student (Grazulis, 2016).

Figure 7.4: Representation of the four modes of the net pressure trend plots from the completion summary within 6N. The mode of each trend is illustrated by the slope of the red line on each plot.
By analyzing the net pressure trends within each stage of the 2N and 6N laterals, the control that RQI has on net pressure within each stage is observed. A box and whisker diagram establishes the relationship between the varying net pressure modes and the average RQI values per stage (Figure 7.5). From the diagram, Modes I and II are both favorable net pressure trends for stable, lateral fracture growth that is kept in zone. When compared to the RQI averages per stage, these modes exhibit the highest RQI values. On the other hand, Mode III is considered the most alarming net pressure trend, as the potential to screenout is high as pressures rapidly increase. When compared to the other mode relationships with RQI, mode III exhibits the lowest overall RQI values. It should also be noted that the error within the box and whisker plot is expected, as driving factors beyond RQI, such as large faults, may be affecting the varying modes of the net pressure trends. Additionally, as RQI is applied to more lateral wells, the net pressure trends may have stronger correlation and higher variations between the modes.

Figure 7.5: Box and whisker plot representing the net pressure trends per stage compared to the average RQI per stage in 2N and 6N. The box colors correspond to the different types of modes, identified in Figure 7.4.
7.3.2 Relative ISIP comparisons

Generally, the instantaneous shut-in pressure (ISIP) and closure stress may be used as indicators of minimum horizontal stress ($\sigma_h$). ISIP relates to the fracture gradient, and how the fracture network may be communicating with the reservoir away from the wellbore. For instance, when the ISIP is high, complex hydraulic fracture networks are assumed to have generated near the wellbore (Nelson et al., 2007). The difference in ISIP and closure stress is assumed to be the net pressure. The relationship between the ISIP and closure stress is a direct indicator for the predicted behavior of the hydraulic fracture, regarding the complexity and proximity to the wellbore. The values assigned to these completion results are indicative of the relative amount of stress that is necessary to close a hydraulic fracture, as conveyed in Figure 7.6.

Figure 7.6: Schematic diagram of the relationship between the perforation location, released proppant, hydraulic fracture, and stresses. The direction of the hydraulic fracture initiation is represented by the black dashed line, while the red dashed line represents the imposing principal stresses that are acting upon the hydraulic fracture (modified from Kraemer et al. (2014)).

Unfortunately, only 1 out of the 11 lateral wells was shut-in during completions, therefore, the ISIP could not be properly calculated for the other 10 lateral wells (including 2N and 6N). On the other hand, the relative ISIP was determined by a fellow RCP student, Travis Pitcher, by taking note of the general ISIP trend for each of the stages within the laterals. Throughout the 10 lateral wells, a low pump rate was employed when moving from stage to stage in order to save time during the hydraulic fracture job. Thus, the ISIP consistently
reads higher within the treatment reports compared to instances where each stage is usually shut-in (Pitcher, 2015). Consequently, the relative ISIP values for 2N and 6N were cross plotted with the average RQI values per stage. For all stages within the two lateral wells, the ISIP relationships vary greatly, as seen in Figure 7.7. The 2N lateral conveys that as ISIP decreases, RQI increases. On the other hand, 6N conveys the exact opposite relationship. Ideally, the ISIP should decrease as the overall rock quality increases and stress state decreases.

Figure 7.7: Cross plots of the average RQI values per stage versus the relative ISIP values per stage in 2N and 6N. The plots on top include all 32 stages, while the plots on the bottom represent the stages that are not intersecting major faults. 2N is represented by the orange data points, while 6N is represented by the blue data points. A linear trendline for each relationship is represented by the black line.

The next step in analyzing the completion data required removing the large faults that intersect the lateral wells with the aid of the coherency map in Figure 2.3. By identifying the stages where large faults may be greatly influencing completion data, the driving mechanisms
in terms of rock quality and geomechanical properties may be determined. In terms of the RQI averages plotted against ISIP per stage after stages within major faults were removed, the general trends still hold true for 2N and 6N, although the overall trend has improved, as displayed in the lower portion of Figure 7.7.

For 2N, the linear relationship between ISIP and RQI is the most ideal, as the ISIP decreases, the RQI increases. Thus, as rock quality increases, the environment for hydraulic fracturing along the wellbore has improved. On the contrary, 6N establishes a linear trend with ISIP that exhibits the complete opposite relationship. This trend suggests that the environment for hydraulic fracturing within 6N is becoming more hostile as RQI is increasing. Suggesting that there are larger driving mechanisms that may explain the high production rates along the 6N well, located within the tighter spaced, western portion of Wishbone. This relationship will be further discussed throughout the chapter.

7.3.3 Gas Shows from Mud Logs

Gas shows have been determined through the analysis of the mud log data. During drilling, mud is brought to the surface along with any internal hydrocarbons. As the gas shows are recorded within the mud log, the exact depth of the original location is relatively unknown, due to the lag time between the drill bit (where the gas was collected) and the surface (where the gas was measured) (Ablard et al., 2012). The gas bubble that originally enters into the wellbore has expanded by the time it reaches the surface, due to mixing with the mud and a significant drop in pressure.

For this particular study, the available mud logs are limited to 6N. When overlaying the approximate locations of these gas shows over the coherency map of the Niobrara C Chalk (extracted from the P-wave seismic data), the gas shows are often aligned with major fault locations Figure 7.8. In some instances, the gas shows appear in areas where faults may be under vertical resolution of the seismic coherency attribute, or rock quality variations may exist along the wellbore. Unfortunately, this analysis is not suitable for the comparison to the precise locations of the RQI along 6N.
7.3.4 Radioactive Proppant Tracer Data Comparisons

As previously illustrated in Figure 1.8, tracers are injected into the wellbore in order to track the path of the fluid as it migrates through the targeted reservoir. In this study, the tracers are radioactive, in which they are mixed within proppant material prior to being injected within the wellbore (Dang, 2016). The radioactive tracers are tracked by gamma ray log measuring tools that are placed downhole. The gamma log responses explicitly show the varying radioactive tracers as they are injected into the reservoir near the wellbore (RCP, 2015).

Another useful technique for validating the RQI is comparing the radioactive proppant tracer data along the lateral wellbores. The radioactive proppant tracer data is available in 11 lateral wells within the Wishbone section. These data consists of three proppant tracer types, including scandium, iridium, and antimony. For the purpose of this study, the outflow portion of the tracer data is analyzed (rather than the inflow). By comparing the outflow of proppant to the RQI along specific points along the wellbore, controlling factors between

Figure 7.8: Significant gas shows from mud logs within the Niobrara C lateral wells, overlaying the coherency attribute displaying the Niobrara C faults (RCP, 2015).
the rock quality and faults may be differentiated (Figure 7.9). Where the propagation of tracer data increases, this may be associated with zones of higher rock quality (comparing to RQI) or major fault and fracture zones (comparing to Dudley’s FMI observations). Within this study, the radioactive proppant tracer data was not traced in stages 1 through 3 within 6N. Additionally, 2N does not include tracer data for the following stages: 1, 2, 4, 5, and 6. Both of the lateral wells each have a total of 32 stages.

When applying the total proppant tracer data to the RQI along the wellbore, a cutoff of 5000 API was applied. This will differentiate the proppant spikes from the background noise of proppant as it is being continuously pumped within each stage. Thus, identifying where significant proppant has been pumped from the wellbore is what is being compared to the RQI. The linear trend between significant proppant totals and RQI for 2N and 6N are displayed in Figure 7.10. The relationship determined from the significant tracer data and the two lateral wells is that as the RQI increases, the amount of radioactive proppant tracers released into the reservoir also generally increases. This relationship is variable due to the inability to separate perforation clusters that intersect major faults when compared to proppant.

When comparing the radioactive proppant tracer data to the RQI, FMI and perforation locations along the wellbore, dependent variables come to light. For both 2N and 6N, the surge in tracers released into the reservoir is not consistent with the locations of faults, including the centrally located graben (based on FMI logs). Generally, the significant increase in proppant injections into the reservoir involves higher RQI, or nearly perpendicular fractures. For 6N, a minority of the significant proppant injections are located along bed boundaries between the C Chalk and Marl, nonetheless these particular injections are also aligning with higher RQI. When the proppant tracer data is cross plotted against the RQI, a linear trend is established between the two variables. By targeting areas with higher rock quality along the wellbore, the maximum surface area reached by the proppant will increase as communication between the near and far-field fracture networks increases.
Figure 7.9: Total radioactive proppant tracer data along the 2N and 6N lateral wells. RQI is displayed on top, with FMI and perforation locations for hydraulic fracturing in the center, and total proppant tracer data on the bottom. Perforations represent the packer locations along the lateral. Perforation clusters are located between each white dot.
Figure 7.10: Significant total proppant tracer API values are plotted against the RQI for 2N and 6N. A linear trendline is represented by the black line.

7.4 Geophysical Survey Comparisons

The RQI is upscaled to the available microseismic and seismic surveys, including multicomponent time-lapse seismic over the Wishbone section.

7.4.1 Microseismic Comparisons

Originally when plotted in depth, the surface microseismic data depicted that the reservoir was being stimulated distances greater than 200 ft above the reservoir. This study was conducted as the microseismic was being reprocessed, thus, the data were never displayed accurately in depth. Despite the reprocessing issues of the microseismic data, the number of events was calculated per stage in all 11 lateral wells (White, personal communication). Even though the exact location of where the reservoir is being stimulated based on microseismic is unknown, the controlling factors at the wellbore, such as RQI, faults and fractures, and stratigraphic architecture are explored.

From the microseismic crossplot against the average RQI per stage, shown in Figure 7.11, the relationship between percentage of total events per stage and RQI is established. The initial linear trend is relatively poor when compared to all of the RQI stages (as seen in top crossplots of Figure 7.11). Once the stages that are intersected by major faults was
removed, the linear trends become exceedingly more convincing, as conveyed by the lower crossplots. Therefore, the relationship between the two variables conveys that as the average RQI increases, the percent number of events increases for each measured stage that is not within a major fault zone. Communication between the reservoir and the hydraulic fracture begins along the interface with the wellbore. If rock quality is low and stresses are high, then hydraulic fracture propagation may be constrained by the poor overall RQI exhibited at the wellbore.

Figure 7.11: The percent of microseismic events per stage is compared to the average RQI per stage. 2N is represented by the orange dots, while 6N is represented by the blue dots. The black line represents the linear trendline fit to the data points. The two plots on the top consist of all 32 stages along the well, while the bottom two plots have removed major stages intersecting major faults.
7.4.2 Time-lapse Seismic Surveys

The stimulated seismic volumes consist of the time-lapse P-wave and shear wave splitting inversions. These two seismic volumes incorporate the baseline survey, acquired before stimulation of the reservoir, and the monitor survey, acquired after stimulation of the reservoir. The objective in computing the difference between the two surveys aids in identifying where the hydraulic fractures are communicating within the reservoirs beyond the wellbore. For further explanation on these processes, refer to Butler (2016) and Mueller (2016).

The baseline shear data would ideally provide information on pre-existing fracture networks prior to stimulation. The baseline seismic survey was collected prior to reservoir stimulation within the Wishbone section. This particular survey contains mixed modes within the fast (S1S1) and slow (S2S2) shear volumes. Motamedi (2015) discovered a presence of positive and negative anomalies between the fast and slow shear baseline survey, thus the fast shear energy was not correctly separated from the slow shear energy. When analyzing the difference between the fast (S1S1) and slow (S2S2) shear volumes in the baseline survey, the difference is relatively homogenous (as shown in Figure 7.12). Thus, individual anomalies that would ideally identify locations of fracture networks around the 11 lateral wells is not detected within this particular seismic survey (Mueller, 2016).

The purpose of comparing the RQI and the seismic time-lapse data is to identify where the predicted highest quality reservoir is located along the wellbore, and how it relates to where the reservoir was stimulated and produced through the stimulated reservoir volume (SRV). In order to compare the RQI results along the laterals, the values were upscaled by averaging the RQI every 40 ft. The RQI was measured along the wellbore every half foot, therefore, in order to compare the RQI results to seismic the resolution of both inputs should be similar. Usually, the seismic surveys have poor vertical resolution, however, through incorporation of well log data and inversion of the seismic data the vertical resolution can be increased. The seismic volumes were compared to the RQI once a depth conversion was performed utilizing a P-wave and S-wave sonic velocity model. Figure 7.13 displays the shear wave splitting
Figure 7.12: Difference between the fast (S1S1) and slow (S2S2) shear volumes in the baseline survey. The higher the difference in shear-impedance, the greater the difference between S1S1 and S2S2. The 11 lateral wells are identified by the black (Niobrara wells) and yellow (Codell) wells. The underlying coherency map of the Middle Niobrara seismic horizon shows fault locations (Mueller, 2016).

time-lapse volume overlain by the upscaled RQI.

As for the shear wave splitting time-lapse anomalies, Mueller (2016) interpreted that the positive anomalies are indicative of fracture networks being generated within the reservoir, while the negative anomalies are indicative of fractures closing or unstimulated reservoir. Analyzing the seismic anomalies along 2N and 6N, the majority of the negative percent differences are located where RQI is low. The central graben exhibits a positive percent increase in 2N, while there is a negative percent difference in 6N. This may be associated with the strike of the faults and fractures along the wellbore, where in 2N these structures are
Figure 7.13: The largest percent difference in the shear wave splitting time-lapse data are displayed by the red anomalies with the Top Niobrara and Codell horizons displayed as well. The upscaled RQI for 2N and 6N is overlaying the microseismic data.

striking in the direction of $\sigma_H$, NW-SE, while in 6N the structures are striking in direction of $\sigma_h$, NE-SW. Generally, microseismic fractures propagate in the direction of $\sigma_H$ and open in the direction of $\sigma_h$. Therefore, when fractures are propagating against $\sigma_H$, then the fracture network is less likely to communicate with far-field fractures in relation to the wellbore.
7.5 Integration across Multiple Disciplines

Production within the 2N and 6N wells are strikingly similar, as seen in Figure 7.14. Although, when the production per well was normalized based on the number of stages, 2N exhibited slightly higher production than 6N. The spacing of the wells, as seen in Figure 2.3, shows the spatial separation between laterals within the Wishbone. The spatial distribution varies greatly across the 11 lateral wells, as the well spacing in the western portion of Wishbone is much tighter than the spacing between wells in the east. Therefore, the drainage networks between 2N and 6N varies greatly based on the localized structural geology, stratigraphy, and natural fracture networks. Through development of the RQI along the two lateral wells, high RQI exists within both the chalk and marl benches. Therefore, even when RQI is high along the wellbore, there may be greater controls over production, such as natural fracture networks and communication away from the wellbore. Production per stage along the wellbore is unknown, thus, this potentially useful information is inapplicable to this study.

![BOE Normalized by # of Stages](image)

Figure 7.14: 2N has slightly higher production than 6N when the production was normalized based on the number of stages (RCP, 2015).
The microseismic trends vary a considerable amount between 2N and 6N. The coherency attribute from the P-wave seismic data identifies the fault locations as they intersect the middle Niobrara seismic horizon (where the C Chalk is located). The combination of the coherency map and the microseismic data is displayed in Figure 7.15. Well 2N mainly exhibits clustered microseismic events. Clusters of microseismic near the wellbore are indicative of more fracture networks near the wellbore being accessed, meaning that more surface area within the reservoir has been reached. Alternatively, 6N exhibits many long, linear microseismic trends extending over many closely spaced, nearby lateral wells to the west, exhibiting far less activity on the eastern side of the wellbore. These trends parallel the direction of $\sigma_H$, influenced by intersecting, large scale faults and possible pre-existing natural fracture networks from prior stimulation in eastern Wishbone wells. Once adjacent wells have been stimulated following the calculation of RQI, the in-situ stresses that have been accounted for within the equation have changed, in terms of stress and nearby fracture networks.

These results are combined with the shear wave splitting (SWS) time-lapse work within the seismic volumes (Mueller, 2016). From the SWS time-lapse differences, the anomalies identify areas where the reservoir is being stimulated by hydraulic fracturing, conveyed in Figure 7.16. The SWS seismic volume requires that the differences between S1 (fast shear waves) and S2 (slow shear waves) be taken in order to determine the shear velocity changes within rock, before and after the reservoir is stimulated. Essentially, the SWS is calculated from the baseline (before stimulation) and monitor (after stimulation) inverted surveys, and then subtracted in order to acquire the SWS time-lapse survey. Where percent difference is higher, the anomalies identify locations where the reservoir is being stimulated, and complex fracture networks are generated. The lower anomalies may indicate where fractures are being closed or unstimulated, as these anomalies were larger in the baseline survey compared to the monitor survey prior to stimulation.
Figure 7.15: Coherency map of the Middle Niobrara seismic horizon overlain with microseismic events from 2N and 6N. The microseismic events are colored by stage, and the magnitude of each event is represented by the size of each dot. Clusters in 2N are highlighted in orange, while the linear trends in 6N are highlighted in blue.

Based on Figure 7.7, ISIP was determined to be high regardless of RQI within well 6N. From the SWS time-lapse seismic results, 6N overlaps negative SWS differences, indicating fractures closing or areas that were not stimulated within the middle Niobrara seismic horizon. Therefore, based on 6N having high production, the well is draining hydrocarbons from elsewhere. When the SWS time-lapse seismic results are analyzed within the Codell Formation, positive anomalies have considerably increased throughout the Wishbone, indicating that more reservoir is being stimulated within this formation (Figure 7.17). A large degree of stimulation is occurring on the western portion of Wishbone, where the laterals are closely spaced compared to the eastern portion. Although the location at which the highest amount of production is occurring along the wellbore is unknown, a safe assumption can be made regarding that 6N is draining from further reservoirs in areas where ISIP may be lower.
Figure 7.16: The figure includes the coherency map for the Middle Niobrara seismic horizon and the SWS time-lapse percent differences, all of which is overlain by the location of the lateral wells in the Wishbone section. The high percentage anomalies, highlighted by the red box, identify areas where the rock is being stimulated, while the negative anomalies identify locations fractures are closing, highlighted by the gray box. The resolution of the seismic survey includes a time slice of 40 ms (150 feet), extending from the B Chalk to the C Marl (modified from Mueller (2016)).

and fracture networks may have higher communication. As the wells were completed from east to west, the nearby reservoir and stresses may have already changed before 6N was even completed.

Based on previous work done by Tom Bratton, the faults in the western portion of the Wishbone section are unstable and critically stressed, as they are aligned with maximum horizontal stress ($\sigma_H$). Combining this information with the SWS, the production within the western portion of the Wishbone is driven by critically stressed faults that are acting as conduits between the Niobrara and Codell within the central graben. In areas with fewer critically stressed faults and greater well spacing, fracture networks are accessed near the
Figure 7.17: The figure includes the coherency map for the Codell seismic horizon and the SWS time-lapse percent differences, all of which is overlain by the location of the lateral wells in the Wishbone section. The high percentage anomalies identify areas where the rock is being stimulated, while the negative anomalies identify locations fractures are closing (modified from Mueller (2016)).

wellbore, driven by the presence of higher rock quality. The RQI has proven useful when identifying locations prior to stimulating the reservoir, consequently the dynamic reservoir is changing due to tighter well spacing affecting nearby unstimulated wells. Accessing the RQI and locations of critically stressed faults intersecting the lateral wells is key to increasing production in complex, tight shale reservoirs.
CHAPTER 8
CONCLUSIONS

Overall production within unconventional reservoirs may be improved by stimulating better quality rock within each stage of the lateral well. In order to maximize the effectiveness of completions, the reservoir along the wellbore needs to be characterized based on the rock properties and stress state of the reservoir interval. By developing the RQI in the lateral wells, I was able to compare the results with the location and orientation of natural fractures with the available completions data. Beginning with the small-scale heterogeneity of the reservoir and ending with large-scale completion effectiveness, has aided in determining the driving factors within the Niobrara Formation at Wattenberg Field.

The following conclusions have been drawn from this study within Wishbone:

- Based on core analysis, bioturbation has a larger affect on anisotropy within the reservoir than laminations or facies changes between chalks and marls.

- Converted confined compressive strength (CCS) from the Bambino measurements are directly proportional to dynamic geomechanical properties, such as Young’s Modulus. Relationships gathered from the core, such as driving mechanisms for geomechanical properties, are applicable to wells without core, and should be used as calibration points within the dynamic well logs.

- The Rock Quality Index (RQI) combines rock quality and the stress state. From this index, higher RQI was identified in both chalk and marl benches. Thus, future drilling in the Niobrara should target both of these lithology types, rather than the chalks alone.

- Developing the RQI within the laterals, utilizing GR cluster analysis and NN for synthetic sonic generation, proved successful in applying useful information to horizontal
wells where logs are limited.

- Geometrically spaced perforation clusters along the lateral wells combines areas of high and low reservoir and completion quality, inhibiting effectiveness of hydraulically fracturing the reservoir. Thus, designing stages based on homogenous zones where the rock quality is high and the stresses are low throughout one stage will allow for completion and production optimization.

- In the presence of fractures perpendicular to the wellbore, propagation of microseismic is extensive regardless of rock quality.

- Geologic architecture, from the micro to macro scale, is a major driving factor for production within the study area.

- Effectiveness of hydraulically fracturing the reservoir is dependent on spacing of lateral wells. In instances where the laterals are further apart, rock quality has a linear relationship with completions. When laterals are closely spaced, factors beyond rock quality are affecting production, such as pre-existing fracture networks of adjacent nearby stimulated wells

- Microseismic clustering in the near wellbore is ideal for drainage through natural fracture networks where higher rock quality exists.

8.1 Recommendations for Future Work

This study was conducted utilizing a wide variety of data, including geologic (core work), geomechanical (well log analysis, cluster analysis of logs), engineering (production, completion, and pressure data), and geophysical (seismic-3D and 4D, microseismic). In order to further investigate the controlling factors on production in the Niobrara and Codell Formations in Wattenberg Field, the following should be considered:

- In-depth investigation of the Codell Formation, including interpreting the available FMI logs, applying the RQI and comparisons to the engineering and seismic results.
• Applying the RQI to normalized lateral wells within the Wishbone section in order to improve relationships between the index, completion and seismic data.

• Understanding the nature of energy dissipation by plotting reprocessed microseismic in depth, and comparing these locations with structural and stratigraphic architecture of the Niobrara.
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APPENDIX - CORE-SCALE MACRO FACIES AND DIGITIZED DESCRIPTIONS

As previously discussed in Chapter 3, the core-scale macro facies are identified in Table A.1 and Table A.2. The digitized core descriptions for Core Well 1 through 3 are represented in the following figures. Core Well 1 descriptions displayed in Figure A.1 and Figure A.2. Core Well 2 descriptions displayed in Figure A.3 and Figure A.4. Core Well 3 descriptions displayed in Figure A.5, Figure A.6, Figure A.7 and Figure A.8.
Table A.1: Smoky Hill Member Core-Scale Macro Facies

<table>
<thead>
<tr>
<th>Facies</th>
<th>Name</th>
<th>Description</th>
<th>Core Example</th>
</tr>
</thead>
</table>
| 1      | Laminated Chalk               | • Light to medium gray/tan with marl laminations  
• Shell fragments and forams present  
• Ripple and planar laminations  
  – 3mm to 1cm spacing                                                   | ![Image](image1) |
| 2      | Bioturbated Chalk             | • Light medium gray/tan  
• Heavy bioturbation  
• Trace fossils abundant  
• Foram presence low                                              | ![Image](image2) |
| 3      | Laminated Bioturbated Chalk   | • Light to medium gray/tan with marls interbedded  
• Light to medium bioturbation  
• Forams and shell fragments presence medium  
• Cocoolith-rich fecal pellets presence medium  
• Ripple and planar laminations  
  – 3mm to 1cm spacing                                                   | ![Image](image3) |
| 4      | Laminated Marl                | • Dark gray to black  
• Very prominent, distinct planar laminations  
  – 1mm to 3mm spacing  
• Often affiliated with abundant forams  
• Clusters of shell fragments (storm events)  
  – oysters and inoceramus  
• Pyrite presence medium to high                                      | ![Image](image4) |
| 5      | Bioturbated Marl              | • Medium to dark gray  
• Light gray burrows  
• Laminations destroyed by bioturbation  
• Forams and shell fragments presence medium  
• Cocoolith-rich fecal pellets presence high  
• Pyrite presence high                                                  | ![Image](image5) |
<table>
<thead>
<tr>
<th>Facies</th>
<th>Name</th>
<th>Description</th>
<th>Core Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Laminated Bioturbated Marl</td>
<td>- Medium to dark gray&lt;br&gt;- Laminations present with fuzzy appearance&lt;br&gt;   - 3mm to 1cm spacing&lt;br&gt;- Forams and shell fragments presence medium&lt;br&gt;- Pyrite presence high</td>
<td><img src="image1" alt="Image" /></td>
</tr>
<tr>
<td>7</td>
<td>Laminated Bioturbated Sandstone</td>
<td>- Light tan, well sorted&lt;br&gt;- Fine to medium size quartz grains&lt;br&gt;- Hummocky cross stratification, laminations&lt;br&gt;   - 1mm to 2mm spacing&lt;br&gt;- Bioturbation present</td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>8</td>
<td>Biourbated Sandstone</td>
<td>- Medium tan to brown&lt;br&gt;   - organic matter interbedded&lt;br&gt;- Well sorted, medium-size quartz grains&lt;br&gt;- Bioturbation extremely high&lt;br&gt;   - numerous trace fossils&lt;br&gt;- Carbonate clasts and burrows</td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td>9</td>
<td>Bioturbated Limestone</td>
<td>- Very light gray&lt;br&gt;- Bioturbation medium to high&lt;br&gt;- Skeletal debris - mainly oyster shells&lt;br&gt;- Thin interbedded dark marls</td>
<td><img src="image4" alt="Image" /></td>
</tr>
</tbody>
</table>
Figure A.1: Core descriptions of Core Well 1, including formation, lithology, facies, lithology outline, laminations, bioturbation, and in-depth descriptions.
Figure A.2: Core descriptions of Core Well 1, including formation, lithology, facies, lithology outline, laminations, bioturbation, and in-depth descriptions.
Figure A.3: Core descriptions of Core Well 2, including formation, lithology, facies, lithology outline, laminations, bioturbation, and in-depth descriptions.
Figure A.4: Core descriptions of Core Well 2, including formation, lithology, facies, lithology outline, laminations, bioturbation, and in-depth descriptions.
Figure A.5: Core descriptions of Core Well 3, including formation, lithology, facies, lithology outline, laminations, bioturbation, and in-depth descriptions.
Figure A.6: Core descriptions of Core Well 3, including formation, lithology, facies, lithology outline, laminations, bioturbation, and in-depth descriptions.
Figure A.7: Core descriptions of Core Well 3, including formation, lithology, facies, lithology outline, laminations, bioturbation, and in-depth descriptions.
Figure A.8: Core descriptions of Core Well 3, including formation, lithology, facies, lithology outline, laminations, bioturbation, and in-depth descriptions.