Integrated Geomechanical, Geophysical, and Geochemical Analysis of the Bakken Formation, Elm Coulee Field, Williston Basin, Montana

by

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ABSTRACT

Hydraulic fracturing is widely implemented in unconventional reservoirs. It requires comprehensive characterization of rock properties in order to determine accurate hydraulic fracture design and well placement. Core analysis has become a critical part of unconventional exploration and development. However, due to the exorbitant costs of core extraction, wireline acoustic logging tools have become the primary source of downhole measurements of geomechanical properties. This study is an integrated approach at defining the core derived geomechanical properties of the Bakken Formation and its relationship with wireline logs, facies characterization, and field scale structural features.

The Bakken Petroleum System at Elm Coulee Field is comprised of three formations of upper Devonian to lower Mississippian age: the upper Three Forks, Bakken, and lower Lodgepole (the Scallion Member and the False Bakken) formations. Elm Coulee Field is located in Richland County, Montana and covers 530 square miles on the southwestern margin of the Williston Basin. The Bakken Formation within this field contains three members: the Upper Shale, Middle Bakken silty dolostone, and Lower Shale, with total thicknesses ranging from 8 to 50 feet. Bulk mineralogy provided for this study describes a dolomite-rich interval in the Middle Bakken Member, which is where primary Bakken production occurs within Elm Coulee Field.

In order to assist in the upscaling of geomechanical properties to wireline logs, a lithofacies, bulk mineralogy (XRD), and elemental (XRF) analysis were performed using two supplied cores. This information provides insights onto the depositional environment and helps define why specific mechanical components occur in determined zones. Core mechanical analysis was conducted using a micro-rebound hammer, Proceq Bambino, to acquire the Leeb hardness value of the rock. Hardness refers to the measure of resistance to a permanent
deformation and can lead to the evaluation of fine-scaled heterogeneity and anisotropy of the rock. To confirm this data, TerraTek supplied core analysis work from TSI scratch testing and confirmed the converted Leeb hardness values with the Unconfined Compressive Strength (UCS) values. The UCS values show a direct correlation to the mechanical properties of the formation. The ductile nature of the Upper Bakken Shales represent lower UCS values and the dolomite rich upper Middle Bakken Member display brittle mechanical properties.

Log analysis was performed on 25 wells within the study area to create synthetic shear sonic logs by using an Artificial Neural Network (ANN) to train off one well that was supplied with a shear sonic log. Using this new log suite, dynamic geomechanical logs were calculated as well as cluster analysis tagging for all wells. Cross-sections transecting the study area were created to identify the geomechanical properties derived from the cluster analysis in relation to the dynamic logs. Geomechanically ideal reservoir conditions and the ductile nature of the UBS were identified with the cluster analysis and highlighted throughout the well-log cross-sections. The Flying Squirrel seismic survey was then used to interpret small scale structural features and compared the results to the cluster analysis cross-sections to highlight fracture prone zones within the Bakken Formation at Elm Coulee Field.
# TABLE OF CONTENTS

ABSTRACT......................................................................................................................... iii
LIST OF FIGURES.................................................................................................................. vii
LIST OF TABLES................................................................................................................... xiv
ACKNOWLEDGEMENTS........................................................................................................ xv

## CHAPTER 1 INTRODUCTION ......................................................................................... 1
1.1 Study Area..................................................................................................................... 3
1.2 Purpose and Methodology ............................................................................................ 3
1.3 Research Contributions ................................................................................................. 7
1.4 Previous Work ................................................................................................................ 7
   1.4.1 Sonnenberg and Pramudito, 2009 ........................................................................ 7
   1.4.2 Elaine Honsberger, 2013 .................................................................................... 8
   1.4.3 Henriette Eidsnes, 2014 ...................................................................................... 8

## CHAPTER 2 GEOLOGIC SETTING ............................................................................. 10
2.1 Structure ....................................................................................................................... 11
2.2 Stratigraphy .................................................................................................................. 14
   2.2.1 Lower Tippecanoe Sequence – Winnipeg Group .............................................. 18
   2.2.2 Kaskaskia Sequence ......................................................................................... 18
2.3 Bakken Petroleum System ............................................................................................ 20
2.4 Elm Coulee Field .......................................................................................................... 23

## CHAPTER 3 LITHOFACIES, MINERALOGICAL, AND ELEMENTAL ANALYSIS ... 27
3.1 Lithofacies ..................................................................................................................... 27
   3.1.1 Lower Bakken Member ..................................................................................... 27
   3.1.2 Middle Bakken Member ................................................................................... 28
   3.1.3 Upper Bakken Member .................................................................................... 33
3.2 Cores ............................................................................................................................. 36
   3.2.1 Larson 11-26 .................................................................................................... 36
   3.2.2 Coyote-Putnam ............................................................................................... 37
3.3 XRD ............................................................................................................................... 38
3.4 XRF ............................................................................................................................... 44
   3.4.1 Methodology .................................................................................................... 44
   3.4.2 Results ............................................................................................................. 45

## CHAPTER 4 GEOMECHANICS .................................................................................. 55
4.1 General Geomechanical Properties ............................................................................ 55
   4.1.1 Static vs Dynamic Properties ........................................................................... 56
LIST OF FIGURES

Figure 1.1 Location map of the Williston Basin, structure contour on base of Mississippian. The approximated extent of the Bakken deposition is identified by the dashed-black line. Green areas represent major Bakken producing fields (modified from Sonnenberg and Pramudito, 2009). ........................................ 2

Figure 1.2 Figure 1.2: Structure map of the top of the Bakken Formation with 50 foot contour interval. The dashed line indicates the field parameters for Elm Coulee Field. The structural high in the northwest section is the Poplar dome. The squares in this figure represent 36 mi² township and ranges. The red box towards the center of the figure indicates the field area for this study, with reference to the Montana state map in the bottom left corner (modified from Sonnenberg and Pramudito, 2011). .................................................. 4

Figure 1.3 Location of study area, Elm Coulee Field, Richland County, Montana. Red box identifies the study area limits, which includes: T24N R56E, T24N R57E, T24N R58E, T23N R56E, T23N R57E, and T23N R58E. The Flying Squirrel survey is outlined in grey. The centrally located red star highlights the Coyote-Putnam well location, and southern red star highlights the Larson 11-26 well. .................................................................................. 5

Figure 2.1 Figure 2.1: Upper Devonian paleogeography reconstruction showing the location of the Williston Basin (highlighted in blue circle). Transcontinental Arch, Antler Mountains and orogenic belt, and Canadian Shield locations shown during Bakken Deposition. Similarly productive shales from similar age are noted in black (modified from Blakey, 2005, and Sonnenberg, 2011). .................................................................................. 11

Figure 2.2 Williston Basin tectonic systems and their associated trends within the United States portion of the basin (modified from Gerhard et al., 1990). .......... 12

Figure 2.3 Williston Basin structural features displaying trends in the north-south and northwest-southeast orientation (from LeFever, 1992). ......................... 13

Figure 2.4 Stratigraphic column of Paleozoic producing units in the Williston Basin. Producing units are show with oil and gas symbols. Sedimentary sequences following Sloss (1963) and Gerhard et al. (1990) are displayed (modified from LeFever, 1991; Anna, 2010; Sonnenberg et al., 2011).............. 16

Figure 2.5 Two diagrams showing the marine connections and depocenters during both lower and upper Kaskaskia sequences (from Gerhard et al., 1990). .......... 17

Figure 2.6 Schematic diagram displaying the four processes in the formation of multi-stage collapse structures (modified from Oglesby, 1988, after Swenson, 1978).................................................................................. 19
Figure 2.7 Well log from Whiting Braaflat 11-11H through the interpreted interval displaying lithology of the Three Forks Formation, Lower Bakken Member, Middle Bakken Member and associated Facies A – Facies F, Upper Bakken Member, and the Lodgepole Formation’s Scallion Member and False Bakken. The Lower and Upper Bakken Member shales have very high Gamma Ray readings (>200 API). The Three Forks and Middle Bakken Member have low porosities (<10%). TOCDEN is the result of calculated TOC values from the density log (modified from Theloy, 2014)....

Figure 2.8 The geographical deposition extent of the Bakken Formation with accompanying schematic cross-section across the Williston Basin (modified from Meissner, 1978, and Sonnenberg, 2011).

Figure 3.1 Core photos of the Middle Bakken Member Facies A through Facies F. MBM-A: skeletal wackestone with brachiopod and crinoid fragments. MBM-B: Helminthopsis and Scalarituba burrows in argillaceous siltstone with high bioturbation. MBM-C: thinly interbedded silty sandstones and mudstones. MBM-D: cross-stratified limy sandstone. MBM-E: planar to wavy laminations lightly bioturbated dolomitic siltstones and mudstones. MBM-F: mottled skeletal dolomitic mudstone to siltstone with brachiopod fragments. Well locations: Braaflat 11-11H, Sec. 11, T 153N, R 91W, Mountrail County; Deadwood Canyon Ranch 43-28H, Sec. 28, T 154N, R 92W, Mountrail County; Gunnison State 44-36H, Sec. 36, T 161N, R 91W, Burke County; Long 1-01H, Sec. 1, T 152N, R 90W, Mountrail County; N&D 1-05H, Sec. 5, T 152N, R 90W, Mountrail County. Core photos are from the NDIC, Kowalski (2010), Simenson (2010), and Theloy (2014).

Figure 3.2 A & B are from the UBM and C & D are from the LBM. Small vertical fractures cemented by calcite and pyrite are visible in photo C. (Theloy, 2014).

Figure 3.3 Key for core description symbols for lithology, sedimentary structures, textures, and fossils. This legend refers to the cores interpretations.

Figure 3.4 Digitized core description of the Larson 11-26 well. See Figure 3.2 for core description legend.

Figure 3.5 Digitized core description of the Coyote-Putnam well. See Figure 3.2 for core description legend.

Figure 3.6 Coyote-Putnam bulk mineralogy through the Bakken Petroleum System section of the core. Respective weight percent of quartz, dolomite, calcite, k-feldspar, plagioclase feldspar, illite, chlorite, pyrite, and an unidentified mineralogy are represented by the chart. Facies boundaries are marked by
the blue lines and have been identified on the left portion of the chart. Sections with no sampled data display no readings.

Figure 3.7 Results from the Principal Component Analysis applied to the XRF elemental data of the Bakken Formation within the study area. The results highlight five distinct groupings.

Figure 3.8 Group 1 elemental data (Si, K, Al, and Ti) plotted as a function of core sampling depth. Coyote-Putnam core description also provided.

Figure 3.9 Group 2 elemental data (Cr) plotted as a function of core sampling depth. Coyote-Putnam core description also provided.

Figure 3.10 Group 3 elemental data (Cu, Fe, Mo, Ni, S, U, and V) plotted as a function of core sampling depth. Coyote-Putnam core description also provided for reference.

Figure 3.11 Group 4 elemental data (Ca, Mg, and Mn) plotted as a function of core sampling depth. Coyote-Putnam core description also provided for reference.

Figure 3.12 Group 5 elemental data (Zr) plotted as a function of core sampling depth. Coyote-Putnam core description also provided for reference.

Figure 3.13 Schematic representation of bacterial respiration versus water column depth in marine basins experiencing O2 depletion in the bottom water (Piper et al., 2009).

Figure 3.14 A) Cross-plot of XRF Si and Zr elemental data showing both positive and negative trend when plotting entire Bakken Formation indicating authigenic and biogenic silica. B) Cross-plot of XRF Si and Zr elemental data for just UBS with negative trend indicating only biogenic silica.

Figure 4.1 In order from left to right, examples of: isotropic, vertical transverse isotropy, horizontal transverse isotropy, orthotropic.

Figure 4.2 TerraTek TSI continuous unconfined compressional strength (UCS) test system. The depth of the scratch on the cores surface indicates rock strength and is represented by the red curve, which can be correlated to rock mechanical properties (TerraTek, 2007).

Figure 4.3 General trends of maximum horizontal stress as determined from GPS positioning data integrated to provide representative velocity vectors (247°) and a single data point from the World Stress Map (185°). Richland County, MT highlighted in orange. Elm Coulee Filed boundary highlighted in blue (modified from TerraTek, 2007).
Figure 4.4  The Proceq Equotip Bambino which was implemented in this study for measuring the Leeb hardness values. Bakken Formation hardness values ranged from 513 to 794 HL (hardness value) (Proceq, 2012)............66

Figure 4.5  Internal mechanism diagram for the Proceq Bambino which measures the rate of rebound within the impact device (Proceq, 2012).........................66

Figure 4.6  Cross-plot of HLD vs UCS values acquired from the Larson 11-26 core. Linear regression displaying an acceptable relationship value........................68

Figure 4.7  Larson 11-26 well log suite displaying TerraTek TSI derived UCS values in track 4 and converted UCS values derived from HLD values in track 5........68

Figure 5.1  All 25 wells used through the depth interval of 9,000 to 11,000 feet. A) Gamma ray histogram. Normalization of the gamma ray was not performed due to the lack of accuracy. B) Compressional slowness histogram displaying very consistent data, normalization not required. C) Shear slowness histogram displaying consistent data, normalization not required .............................................................71

Figure 5.2  Cross-plot displaying two separate principal components and its associated cluster cells and the associated cluster centroids (grey stars relatively centered within specific colored cluster cells). Cluster Analysis performed with eight clusters.................................72

Figure 5.3  Fall-off histogram and plot displaying the cumulative fall-off of statistical clustering dependent on the number of runs the simulation has performed. This dataset displays clustering events in the final 5%, therefore displaying unresolved behavior .................................................................73

Figure 5.4  Hill - 25083212870000 well track 1 containing gamma ray shaded yellow to represent the MBM facies and red for the UBM and LBM, track 2 deep resistivity, track 3 bulk density and neutron porosity, track 4 with synthetic shear slowness and compressional slowness, track 5 dynamic Young’s Modulus and dynamic Poisson’s Ratio, and track 6 bulk modulus. Bakken Formation units: UBM highlighted yellow, MBM highlighted light blue, and LBM highlighted orange.................................76

Figure 5.5  Fall-off plot for the Bakken Formation 10-cluster approach showing a good statistical representation of the data set, marked by the flat nature of the final 50% of the runs.................................................................79

Figure 5.6  Diagnostic cross-plot of 10-cluster approach displaying ideal separation of cluster centroids within the dataset.................................79
Figure 5.7 Larson 11-26 well log suite. Track 1: gamma ray with highlighted zonations for UBM, MBM, LBM. Track 2: bulk resistivity and neutron porosity. Track 3: compressional slowness and shear slowness sonic logs. Track 4: Young’s Modulus and Poisson’s Ratio values. Track 5: bulk modulus. Track 6: cluster unitless values.

Figure 5.8 Northwest-southeast cross-section of cluster analysis values. All wells within study area which contain DT logs are represented in the map. Cross-section corresponds to Figure 5.10.

Figure 5.9 Northeast-southwest cross-section of cluster analysis values. All wells within study area which contain DT logs are represented in the map. Cross-section corresponds to Figure 5.11.

Figure 5.10 Northwest (A) – southeast (A’) cross-section of cluster analysis values with datum on the contact between the UBM and the lower Lodgepole Formation. Track 1 contains gamma ray for easy identification of zonation. Color highlights within the logs represent: yellow for UBM, light blue for MBM, and orange for LBM. Wells used for cross-section are represented in Appendix B.

Figure 5.11 Northeast (B) – southwest (B’) cross-section of cluster analysis values with datum on the contact between the UBM and the lower Lodgepole Formation. Track 1 contains gamma ray for easy identification of zonation. Color highlights within the logs represent: yellow for UBM, light blue for MBM, and orange for LBM. Wells used for cross-section are represented in Appendix B.

Figure 6.1 Pre-plot design and filed area for Flying Squirrel survey parameters provided by Enerplus. Survey area approximately 48 square miles, located in Richland County, Montana.

Figure 6.2 Inline 136 from the Flying Squirrel 3D seismic survey highlighting the horizons of interest for this study. Ow: Winnipeg Formation; Or: Red River Formation; Dtf: Three Forks Formation; Mb: Bakken Formation; Mc: Charles Formation; Kg: Greenhorn Formation.

Figure 6.3 Winnipeg Formation time-structure map. Note the east northeast dip direction and the northeast-southwest orientated structure highs located in the center of the image.

Figure 6.4 Bakken Formation time-structure map. Note the east northeast dip direction and the northeast-southwest orientated structure highs located in the center of the image.
Figure 6.5 Inline-142 from the Flying Squirrel seismic survey with enlarged view of a seismic peak (red horizon) identifying the Bakken Formation horizon (Mb), and a seismic trough (blue horizon) identifying the Three Forks Formation (Dtf). ................................................................. 90

Figure 6.6 Inline-142 at 5-times vertical exaggeration, confirming the accuracy of basement fault picks. Some faults propagate up through the Winnipeg Formation (highlighted in the pink horizon). ........................................................................... 92

Figure 6.7 Oblique view of seismic survey. A) 118 Precambrian basement faults identified within study area. B) Time-structure map of the Winnipeg formation which lies stratigraphically just above basement. C) Combination of both map and faults................................................................. 93

Figure 6.8 Oblique view of Flying Squirrel seismic with both inline and xline present. A) Winnipeg Formation time-structure map with all interpreted Precambrian basement faults. B) Addition of the Bakken Formation time-structure map, no faults propagate through Bakken Formation... ............ 94

Figure 6.9 Z-scale (time) view of: A) 118 Precambrian basement faults; B) Winnipeg Formation time-structure map with basement faults; C) Bakken Formation time-structure map stratigraphically above the Winnipeg; D) inferred trends of the basement faults superimposed onto the Bakken Formation time-structure map. .................................................................................. 95

Figure 6.10 Seismic volume attributes tested for this study to extract faults within the study area. Each image was obtained from the relative Bakken Formation time-slice at -2090ms. A) Dip attribute; B) Azimuth attribute; C) 3D Curvature; D) Variance attribute; E) Ant Tracking attribute................................. 97

Figure 6.11 Inline-136 Ant Tracking attribute analysis methodology: 1) original seismic volume, 2) smoothed volume, 3) Variance attribute, 4) Ant Tracking attribute........................................................................................................... 99

Figure 6.12 Final output of Ant Tracking attribute analysis on Inline-142. Horizons identified from basement up: Ow, Or, Dtf, Mb, Mc, and Kg................. 100

Figure 6.13 Inline-142: A) structurally smoothed and fault interpreted seismic volume, B) Ant Tracking attribute volume with superimposed fault interpretation displaying no correlation................................................................. 101

Figure 6.14 Z-scale (time) view of: A) 118 Precambrian basement faults; B) Winnipeg Formation time-structure map with basement faults; C) Ant Tracking attribute volume in z-scale (time) at the relative Winnipeg Formation depth. D) Superimposed basement fault orientations on top of the relative Winnipeg Formation depth of the Ant Tracking volume................................. 102
Figure 7.1 Cross-plots of converted UCS data against bulk mineralogical values. Correlations are found for both dolomite ($R^2 = 0.3466$) and illite ($R^2 = 0.7316$) cross-plots.

Figure 7.2 Log suite of the Larson 11-26 well. Cluster values represented in track 6, TerraTek TSI testing results in track 7, and Bambino derived and converted UCS values in track 8.

Figure 7.3 A) Winnipeg Formation dip/azimuth attribute time slice highlighting basement lineaments (Honsberger, 2013). B) Bakken Formation dip/azimuth attribute time slice highlighting basement lineaments with left-lateral system (Honsberger, 2013). C) Winnipeg Formation time-structure with interpreted small scale faulting from the basement. D) Bakken Formation time-structure map with no faults propagating through the formation at seismic scale.

Figure C.1 Red River Formation time-structure map. Horizon displays dip towards the east at a 5msec contour interval.

Figure C.2 Three Forks Formation time-structure map. Horizon displays dip towards the east at a 5msec contour interval.

Figure C.3 Charles Formation time-structure map. Horizon displays dip towards the east at a 5msec contour interval.

Figure C.4 Greenhorn Formation time-structure map. Horizon displays dip towards the east at a 5msec contour interval.
LIST OF TABLES

Table 3.1  Middle Bakken Member Facies A – Facies F description summary (modified from Gent, 2011) ................................................................. 35
Table 4.1  Description of samples test, depth sampled, and type of section .................. 59
Table 4.2  Summary of the in-situ stress measurements ............................................. 64
Table 6.1  Acquisition parameters for the Flying Squirrel seismic survey (Enerplus 2007) ......................................................................................... 85
Table A.1  Wells used for cluster analysis. Well names and API numbers ....................... 118
Table B.1  Northwest – southeast cross-section wells and API numbers ....................... 118
Table B.2  Northeast – southwest cross-section wells and API numbers ....................... 119
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CHAPTER 1 INTRODUCTION

The Upper Devonian-Lower Mississippian Bakken Formation is a highly economic play within the Williston Basin. It extends from Montana, South Dakota, and North Dakota into southern Saskatchewan, Canada (Figure 1.1). Based on the conodont biostratigraphy, deposition occurred from 375 to 350 million years ago during the Fammenian (latest Devonian deposition) and the Kinderhookian (earliest Mississippian deposition) (Karma, 1991). The Bakken Formation contains world-class source rocks and according to the most recent United States Geological Survey assessment, it contains an estimated mean technically recoverable oil resource of 3.65 billion barrels of oil (USGS, 2013). The first Bakken well was drilled in 1953 discovering the Antelope Field on the southeast flank of the Nesson Anticline. Production continued in the Williston Basin through the early 1980s, however it remained sporadic until the drilling boom of the 2000s. Increase in completion technologies and the advent of horizontal drilling have greatly improved recovery rates in this basin.

The largest field in the Williston Basin is Elm Coulee Field (discovered in 2000 by Lyco Energy). It is a highly productive field which produces from of the Middle Bakken dolomite-rich siltstone reservoir facies. New technologies are continuously being applied to better understand the reservoir at Elm Coulee Field and aid in developing an understanding of why it has become such a prolific reservoir. This study will incorporate geochemical and geomechanical data coupled with high resolution seismic data to greatly improve our understanding of the Bakken Formation at Elm Coulee Field.
Figure 1.1: Location map of the Williston Basin, structure contour on base of Mississippian. The approximated extent of the Bakken deposition is identified by the dashed-black line. Green areas represent major Bakken producing fields (modified from Sonnenberg and Pramudito, 2009).
1.1 Study Area

Elm Coulee Field is located at the southwest margin of the Williston Basin within Richland County, Montana (Figure 1.2). The field extends over 530 square miles and trends northwest-southeast. The well-log suite and Flying Squirrel seismic dataset constrains the boundary of this study which is in the center of Elm Coulee Field. This study area is approximately 72 square miles and stretches between six township and ranges: T24N R56E, T24N R57E, T24N R58E, T23N R56E, T23N R57E, and T23N R58E (Figure 1.3). Two Bakken cores were described within the study area: the Larson 11-26 (Sec. 26-T23N-R57E) which lies two miles south of the Flying Squirrel survey and the Coyote-Putnam (Sec. 9-T57N-R57E) which lies within the survey parameters in the township and range of T23N R57E. Sufficient well data is available within this field area which was provided through the Bakken Research Consortium at Colorado School of Mines.

1.2 Purpose and Methodology

The purpose of this project is to characterize the Bakken Formation and its reservoir facies within the parameters of the study area at Elm Coulee Field. Integrating geochemical, geomechanical, and geophysical data to aide in the interpretations will provide valuable insight as to what is driving hydrocarbon accumulations specific certain zones of interest. Detailed methodology for this study will be outlined in greater detail at the beginning of each chapter due to the broad spectrum of data incorporated, however the general workflow is as follows:

- Determine reservoir quality at Elm Coulee Field within the study area by integrating core plug analysis, geochemical, and geomechanical data to identify the relationship between core interpretations and well log data. To address this integrated approach, this study used the following workflow:
Figure 1.2: Structure map of the top of the Bakken Formation with 50 foot contour interval. The dashed line indicates the field parameters for Elm Coulee Field. The structural high in the northwest section is the Poplar dome. The squares in this figure represent 36 mi² township and ranges. The red box towards the center of the figure indicates the field area for this study, with reference to the Montana state map in the bottom left corner (modified from Sonnenberg and Pramudito, 2011).
Figure 1.3: Location of study area, Elm Coulee Field, Richland County, Montana. Red box identifies the study area limits, which includes: T24N R56E, T24N R57E, T24N R58E, T23N R56E, T23N R57E, and T23N R58E. The Flying Squirrel survey is outlined in grey. The centrally located red star highlights the Coyote-Putnam well location, and southern red star highlights the Larson 11-26 well.
1. Performed routine core interpretation and determined reservoir quality from the core analysis reports on the two cores provided for this study: the SM Energy Larson 11-26 (Sec. 26-T23N-R57E), and the Enerplus Coyote-Putnam (Sec. 9-T57N-R57E). The Colorado School of Mines Bakken Consortium nomenclature was also assigned for these cores, which aided in identifying the vertical and lateral facies variations.

2. Analyzed core and well-log data with rock properties to determine the controlling factors which create the ideal reservoir in the Middle Bakken Member facies.

3. Used bulk chemical and mineralogical values to analyze what contributing factors are aiding in enhanced reservoir performance.

- Identify zones of ideal geomechanical properties and assign a neural network algorithm to project to corresponding wells within the study area.

1. Assigned Unconfined Compressive Strength (UCS), Poisson’s Ratio, and Young’s Modulus values to the lithofacies and well-logs of to both the Larson 11-26 and Coyote-Putnam wells.

2. A neural network was then assigned to the sonic log characteristics, Unconfined Compressive Strength, Poisson’s Ratio, and Young’s Modulus values. Once values were acquired they were then projected to corresponding wells within the study area.

3. Mapping of these values was then performed which highlighted ideal geomechanical properties for the Bakken reservoir facies.

- Determine what factors are contributing to areas higher hydrocarbon production at Elm Coulee Field.
1. Performed a structural and stratigraphic analysis on the Flying Squirrel seismic dataset provided by Enerplus, while also incorporating geophysical attribute analysis interpretations.

2. Correlations between the seismic data and neural network cluster analysis were performed, rendering potentially higher fracture zones with ideal geomechanical characteristics.

1.3 Research Contributions

Upon completion of this study, the results will have both industry and scientific impacts. The conclusions will advance the understanding of reservoir properties at Elm Coulee Field and will also aid in the process of enhanced hydrocarbon recovery of the Bakken Petroleum System within Williston Basin. With the implementation of geomechanical and structural interpretations at the seismic scale, this study assists in the analysis of fractured zones and their relationship to field scale structural trends.

1.4 Previous Work

There has been a vast amount of published work on the Williston Basin and specifically the Bakken Petroleum System throughout the past decade. Some of the previous work performed that will be useful in relationship to this study are as follows:

1.4.1 Sonnenberg and Pramudito, 2009: Petroleum Geology of the Giant Elm Coulee Field, Williston Basin

This publication acts as a great introduction to the Bakken Formation at Elm Coulee Field in particular its stratigraphy, structures, and petroleum system. The authors point out that the thickness anomaly associated with Elm Coulee Field, which trends northwest-southeast, is
possibly related to Prairie salt dissolution occurring and creating accommodation space which was then infilled by subsequent strata. Becoming familiar with the field and its general trends was a vital component to this publication.

1.4.2 Elaine Honsberger, 2013: Geophysical Insights into the Bakken: Secrets from a Sleeping Giant Elm Coulee Bakken Field (Sleeping Giant), Montana USA

Honsberger’s study was conducted on the same seismic dataset that was provided by Enerplus for this study, the Flying Squirrel dataset. The purpose of her work was to investigate the data by gathering better insight as to how the Bakken fracture networks could show any indications of better well performance. She used the 48 square mile dataset to choose two horizons, Bakken and Winnipeg, which best represented the structural history within its parameters. She was able to delineate faults described at the Winnipeg level into faults at the Bakken level, both sets of which being related to a basement-driven, regional strike-slip fault system. These faults trend with a primary 45˚NE and secondary trend of approximately 60˚NW. Honsberger concluded that the faults may act as baffled barriers and fracture propagation barriers between compartmented zones.

1.4.3 Henriette Eidsnes, 2014: Structural and Stratigraphic Factors Influencing Hydrocarbon Accumulations in the Bakken Petroleum System at Elm Coulee Field, Williston Basin, Montana

Eidsnes performed a robust study within Elm Coulee Field using three seismic surveys that overlapped one another, the Vaux (19.66 mi²), Intake II (9.69 mi²), and South Fork (21.77 mi²), and performed core work on six Elm Coulee wells. The purpose of her study was geared to find correlations similar to that of Honsberger’s work, but with the implementation of core work to find smaller scale conclusions as well. The main interpretation tool she used was a program
within Schlumberger’s Petrel called Ant Tracking. Ant Tracking is used to automatically extract faults from pre-processed seismic volume resulting in an attribute volume that displays fault zones in detail. The tool showed northwest-southeast trending fracture networks within the low resolution seismic which coincide with literature of the Williston Basin. However, after comparing the data with previously published EUR maps of Elm Coulee Field it was inconclusive if the fractures supported a higher hydrocarbon accumulation network that could be found.
CHAPTER 2 GEOLOGIC SETTING

The Williston Basin is an intracratonic basin which is located on the western edge of the North American craton. The elliptical structurally depressed basin is bounded by slight structural highs and extends approximately 133,000 square miles and has a sedimentary fill of approximately 16,000 feet (Gerhard et al., 1990). The basin extends through northwest South Dakota, central and western North Dakota, and northeastern Montana in the United States, and southern Saskatchewan and southwest Manitoba in Canada (Figure 2.1). The Williston Basin unconformably lies on fault-bounded Precambrian terranes, which have heavily influenced the depositional environment, sedimentation, structural features, and hydrocarbon potential during the basin evolution (Gerhard et al., 1990).

The Canadian Shield and the Transcontinental Arch create the stable core for the North America Paleozoic craton. During Early to Middle Paleozoic the Transcontinental Arch separated the North American craton into a western and eastern marine shelf system (Peterson and MacCary, 1987). The Cordilleran Shelf formed on the northwestern flank of the Transcontinental Arch and southwest part of the Canadian Shield. The Cordilleran Shelf accommodated shallow marine cyclic sedimentation through most of the Paleozoic and Mesozoic periods that consist of carbonates, shales, and sandstones. The Antler orogenic belt was located directly west of the shelf and began active growth during the Middle Devonian creating thick accumulations of deep water shales, submarine volcanic deposits, fine-grained limestone, and coarse clastics during Paleozoic time (Peterson and MacCary, 1987). The eastern side of the Cordilleran shelf was adjacent to the Transcontinental Arch and comprises the current Northern Great Plains region. This region is home to many paleostructural elements, most important being the Williston Basin which began subsiding during Ordovician time (Peterson
and MacCary, 1987). During the deformation of the Cordilleran orogeny and ensuing crustal additions to the western continental margin, the Williston Basin moved from a craton-margin or continental shelf basin into the current intracratonic basin (Gerhard et al. 1990).

Figure 2.1: Upper Devonian paleogeography reconstruction showing the location of the Williston Basin (highlighted in blue circle). Transcontinental Arch, Antler Mountains and orogenic belt, and Canadian Shield locations shown during Bakken Deposition. Similarly productive shales from similar age are noted in black (modified from Blakey, 2005, and Sonnenberg, 2011).

2.1 Structure

The Precambrian basement underlying the Williston Basin is composed of several provinces: the Wyoming craton, the Trans-Hudson orogenic belt, and the Archean Superior craton (Pitman et al., 2001). Although considered to be relatively tectonically quiescent, the basin gains its architecture due to structural deformation and basement rooted faulting, as well as
deformation related to the Trans-Hudson orogenic belt (Gerhard et al., 1990). The Trans-Hudson belt connected the Archean Superior craton to the Wyoming craton creating a north-south trending strike-slip fault and shear belt and subsequently a basin center (Burrett and Berry, 2000). The Trans-Hudson orogeny also included the northeast-trending fault and lineament zones: Transcontinental Arch, Brockton-Froid fault zone, Great Falls Tectonic Zone, Poplar fault, and Hindsdale fault (Gerhard et al., 1987; LeFever, 1992) (Figure 2.2). Possible wrench movement on these Precambrian structures reactivated during the Neoproterozoic which created new structural features trending north-south and northwest-southeast. These structural features led to the formation of: the Nesson, Cedar Creek, Little Knife, and Billings anticlines, and a number of structural features in the Williston Basin (Gerhard et al., 1982) (Figure 2.3).

Figure 2.2: Williston Basin tectonic systems and their associated trends within the United States portion of the basin (modified from Gerhard et al., 1990).
The Nesson and Cedar Creek anticlines are the most prominent features in the United States portions of the basin. These structural features have been targeted as early petroleum exploration locations within Williston Basin and remain productive to date (LeFever et al., 1987). The north-south trending Nesson anticline has two major faults, the first runs along the western edge of the anticline and the other along the Antelope anticline bifurcation (Gerhard et al., 1987). The near vertical basement fault began movement during Precambrian time but experienced the largest amount of movement during the Bakken Petroleum System’s deposition during the Devonian and early Mississippian (LeFever et al., 1987). A reversal in direction was experienced during the Laramide orogeny which resulted in a stress regime change. This resulted in the asymmetric geometry of the anticline and its respective deep dip along the western flank (Gerhard et al., 1990).
The Brockton-Froid lineament system and the Transcontinental Arch are the two most prominent left-lateral fault zones which control the orientation of many of the other structural features found in the Williston Basin (Gerhard et al., 1990). The orientations of wrench-fault movement along these zones are consistent with that of the other basin features. Vertical uplift is the most dominant movement associated to variations in stress field orientation over time for the majority of structure related faults. These types of faults are important to the basin as they provide reservoir traps and significantly impact the fracture patterns within many of the petroleum reservoirs in the Williston Basin (Gerhard et al., 1990).

2.2 Stratigraphy

Approximately 16,000 feet of sediment was deposited during the Phanerozoic in the Williston Basin (Gerhard et al., 1990) (Figure 2.4). Both Sloss (1963) and Gerhard et al. (1990) delineate several unconformity bounded sequences and their associated formations in the stratigraphic column in Figure 2.4. The Sauk sequence is the first major sequence of the group and consists of the Upper Cambrian Deadwood Formation. Sedimentation began over the low-relief and variable Precambrian surface due to the transgression of the Sauk Sea. At the termination of the Sauk sequence, the Williston Basin began to subside as a result of the strike-slip movement on the northeast-southwest trending basement propagating faults which triggered the onset of the Taconic orogeny.

The Tippecanoe unconformably overlies the Sauk sequence and is composed of Ordovician and Silurian sediments. During this time depositional patterns suggest the subsidence at the present-day Williston Basin center which displays a connection to the Cordilleran Sea to the southwest (Gerhard et al., 1990). The initial transgression deposited the Winnipeg Group which is composed of lower Ordovician shallow marine sandstone and shale, and Middle
Ordovician through Silurian carbonates. The Tippecanoe sedimentation terminates due to a regression at the end of the Silurian which lead to erosion of previously deposited units.

The Kaskaskia sequence forms following uplift of the Transcontinental Arch that shifted the basin center towards the northwest into the Canadian Shield resulting in a marine connection to the northwestern Elk-point. Gerhard et al. (1990) divides the Kaskaskia sequence into two regional sea level transgressions, the lower Kaskaskia and the upper Kaskaskia sequences (Figure 2.5). These sequences are divided at the Acadian unconformity, which occurs between the Three Forks and Bakken formations and marks the beginning of uplift of the Transcontinental Arch and exposure prior to Bakken deposition. With the onset of the upper Kaskaskia sequence, the uplift also coincides with the a major change in basin configuration from a circular basin in northwestern North Dakota with a marine connection to the Cordilleran Sea, into the present-day depocenter and northwest-southeast trending Williston Basin.

The Absoraka sequence begins during the Early Pennsylvanian where North American tectonism was widespread creating erosion of the Ancestral Rocky Mountains, Hartville uplift, Sioux arch, and the Canadian Shield leading to deposition of clastic Pennsylvanian to Triassic strata. The Zuni sequence represents the Jurassic and Cretaceous deposits in the Williston Basin and shares a similar package of rocks as the Absaroka sequence with successions of clastic and minor carbonate and salts. Subsidence of the Williston Basin as a structural depression halted during the Zuni sequence, along with the basin subsidence. The last sequence described by Sloss (1963) and Gerhard et al. (1990) is the Tejas sequences, which continued sedimentary input from mid-Paleocene through Quaternary and consisted of mostly clastic input with some low grade coal.
Figure 2.4: Stratigraphic column of Paleozoic producing units in the Williston Basin. Producing units are show with oil and gas symbols. Sedimentary sequences following Sloss (1963) and Gerhard et al. (1990) are displayed (modified from LeFever, 1991; Anna, 2010; Sonnenberg et al., 2011).
Figure 2.5: Two diagrams showing the marine connections and depocenters during both lower and upper Kaskaskia sequences (from Gerhard et al., 1990).
2.2.1 Lower Tippecanoe Sequence – Winnipeg Group

The Winnipeg Group is composed of three formations: the Black Island, Winnipeg Shale or Icebox, and Roughlock (Bitney, 1983). These formations represent a series of transgressive events that were deposited unconformably on the Deadwood Formation and conformably overlain by the Red River Formation (LeFever, 1996). The Winnipeg Shale is a greenish-gray calcareous shale that changes into a sandstone when approaching the northwestern part of North Dakota and ranges in thickness from 90 to 200 feet thick (Bitney, 1983). Due to its proximity to the Precambrian basement, mapping the basement faulting events in the Flying Squirrel dataset are best seen in the high amplitude Winnipeg Shale horizon and thus makes the Winnipeg Group vital for this study.

2.2.2 Kaskaskia Sequence

In terms of structural features, it is important to acknowledge the lower Kaskaskia middle Devonian Prairie Formation. The Prairie Evaporites stratigraphically underlie the Bakken Petroleum System by approximately 800 – 1100 feet and are subject to dissolution. The dissolution of these salts has led to collapsing of overlying strata; coupled with sedimentation this process has created thickness anomalies in the overlying strata (LeFever and LeFever, 2005) (Figure 2.6). The Prairie Formation includes deposits of anhydrite, halite, and potassium salts, and occasional dolomite and shale strata (Parker, 1967; Rogers et al., 1985). The thickness of salts range from a few feet to approximately 600 feet thick. This is due to post-depositional dissolution events caused by migrating waters from underlying aquifers removing the salts.
Figure 2.6: Schematic diagram displaying the four processes in the formation of multi-stage collapse structures (modified from Oglesby, 1988, after Swenson, 1978).
The middle Kaskaskia sequence marks the deposition of the Bakken Petroleum System, which consists of the Upper Devonian Three Forks Formation, Upper Devonian – Lower Mississippian Bakken Formation, and the overlying Lower Mississippian Lodgepole Formation. The Three Forks Formation averages 150 feet in thickness and is composed of green and tan to pink interbedded shales, and grey and to yellowish siltstones, carbonates, and evaporates (Meissner, 1978; Gerhard et al., 1990; Heck et al., 2007). Sedimentary structures found within the Three Forks Formation include locally brecciated laminations and ripple laminations (LeFever, 2005). The Bakken Formation unconformably overlies the Three Forks Formation and is composed of three members: an upper and lower organic-rich shale member and a dolomitic-rich middle siltstone, a result of a transgressive-regressive deposition (Webster, 1984). Conformably overlying the Bakken Formation is the Lodgepole Formation, which consists of argillaceous carbonates, Waulsortian bioherms, and shale beds all deposited in a normal marine to restricted shelf environment. These three formations compose the Bakken Petroleum System and will be discussed further in the next section.

2.3 Bakken Petroleum System

The Bakken Petroleum System is classified as a continuous unconventional tight-oil accumulation with pervasive hydrocarbon saturations over a large areal extent. The system has characteristics of being abnormally pressured in many locations within the basin, has low porosity and permeability, and contains areas of stress induced fracturing and partings which aide in hydrocarbon accumulation. The reservoir characteristics display low recovery rates with low water production, lithology controlled high EUR “sweet spots” and a close proximity to mature source rocks (Sonnenberg, 2010). The Bakken Petroleum System, as discussed in the previous section, is composed of the upper 50 feet of the Three Forks Formation, the Bakken
Formation, and the lower 50 feet of the lower Lodgepole Formation (Meissner, 1978; Price and LeFever, 1992) (Figure 2.7).

The contact between the Three Forks Formation and overlying Bakken Formation in the basin center is conformable and transitions into an unconformable contact at the basin margins. According to Webster (1984), the unconformable contact displays evidence of subaerial exposure which has well developed diagenetic porosity. The Three Forks Formation has produced oil since the 1950s due to the formation being sourced by the lower Bakken Shale (Murray, 1968; LeFever and Nordbeng, 2008). Production originally occurred from the Sanish sandstone (now called Pronghorn) and other portions of the upper Three Forks Formation out of fields like Antelope Field in North Dakota. Production has significantly increased into other parts of the Three Forks Formation as technology has progressed.

The Bakken Formation averages 140 feet thick in the central part of the basin. Each unit of the Bakken progressively overlaps each older member of the Bakken (Figure 2.8). The Lower Bakken Shale is composed of dark gray to black non-calcareous, fissile, organic-rich shale that contain conchoidal to smooth horizontal fractures (Meissner, 1978; Hayes, 1985). The Upper Bakken Shale is similar in lithology and appearance to the lower member; however, the upper member is more fossiliferous containing fish teeth, scales, and bones, woody fragments, brachiopods, conodonts, and lag deposits (Webster, 1984). Both members are considered “world class” mature source rocks with the lower member averaging a total organic content (TOC) of 11.5 weight percent (wt. %) and the upper having an average TOC of 12.2 weight percent (Schmoker and Hester, 1983). Based on hydrogen and oxygen index characteristics the kerogen found in the Bakken Petroleum System is mainly type I and II (sapropelic), however type III kerogens are present along the shallow eastern flank of the basin (Sonnenberg, 2011). The
depositional environment of both shales has been interpreted as a shallow offshore marine setting in a temperate climate during a period of steady and relatively slow sea level rise. The Upper Bakken Shale is interpreted to have been deposited over a large flat area due to its relatively uniform thickness throughout the basin, while the Lower Bakken Shale displays localized thickness anomalies due to the Prairie salt dissolution that occurred prior to Bakken deposition (Webster, 1984). Due to this factor, lower member thicknesses can reach a maximum of 50 feet while the upper has a maximum thickness of only 23 feet (LeFever, 1991).

The Middle Bakken Member is a complex and highly variable unit across the basin. It is a 20-30 foot thick unit that overlies the Lower Bakken Shale. Separating the two members is a sequence boundary that appears sharp to irregular in some places and as a gradational contact in others (Pitman et al., 2001). Where the sharp to irregular contact exists there is typically a thin lag deposit composed of pyrite nodules, pyritized shell fragments, and black mudstone intraclasts associated with it (LeFever et al., 1991; Smith and Bustin, 1996). In a general description, the middle member lithology is a light gray to darker gray interbedded calcareous siltstone or siliciclastic dolostone with distributed amounts of shale, silt, sand, ooids, and bioclastic materials (Hayes, 1985; LeFever, 1991, Pitman et al., 2001). The lithofacies within the middle member range from massive to coarsely bedded to planar bedded to trough cross-bedding structures, soft sediment deformation features, and abundant bioturbation (LeFever, 1991). The bioclastic materials found in the middle member include brachiopods, conodonts, bryozoans, gastropods, and ostracods. Common within the middle member is pyrite replacement of the bioclastic materials, presence of pyrite nodules, as well as calcite cement throughout the lithofacies. In general, the depositional environment has been interpreted to have occurred under oxic marine
conditions in a shallow marine to a nearshore, shoreface setting (Webster, 1984; Smith and Bustin, 1996).

Conformably overlying the Bakken Formation is the oldest unit within the Madison Group, the Lodgepole Formation. It is composed of argillaceous, shaley, silty, and cherty thin to medium bedded limestone (Peterson, 1984). Thicknesses of the Lodgepole can reach up to 1000 feet in certain parts of the Montana trough. The lowermost member of the Lodgepole Formation is the Scallion member, which directly overlies the Bakken Formation and is a dense medium gray limestone containing abundant pelmatozoan material (Webster, 1984). Stratigraphically above the Scallion member is the False Bakken which is composed of black shales or marl and clay-rich limestones and a thickness range of zero to 250 feet thick. The depositional environment for the lower Lodgepole members has been interpreted to be shallow marine environment on the slope and basin margin (Webster, 1984). The lower Lodgepole members are important to the Bakken Petroleum System due to the members being the seal for the system.

2.4 Elm Coulee Field

Elm Coulee Field, located in Richland County, Montana, was officially discovered in 2000 by Lyco Energy (Walker et al., 2006). There has been a substantial amount of publications mentioning that the Middle Bakken reservoir at Elm Coulee Field has had tremendous oil shows over the last 50 years (Nordquist, 1953; Webster, 1984; Hansen and Long, 1991; Sperr, 1991; Sonnenberg and Promudito, 2009); however, it was not exploitable until the onset of horizontal drilling. Now the field is projected to produce approximately 250 million barrels of oil and with wells testing an average of 500 BOPD (Brown, 2006; LeFever and Helms, 2006).
Figure 2.7: Well log from Whiting Braaflat 11-11H through the interpreted interval displaying lithology of the Three Forks Formation, Lower Bakken Member, Middle Bakken Member and associated Facies A – Facies F, Upper Bakken Member, and the Lodgepole Formation’s Scallion Member and False Bakken. The Lower and Upper Bakken Member shales have very high Gamma Ray readings (>200 API). The Three Forks and Middle Bakken Member have low porosities (<10%). TOCDEN is the result of calculated TOC values from the density log (modified from Theloy, 2014).
Figure 2.8: The geographical deposition extent of the Bakken Formation with accompanying schematic cross-section across the Williston Basin (modified from Meissner, 1978, and Sonnenberg, 2011).
The target reservoir within the Bakken Petroleum System at Elm Coulee Field typically focuses on the 8-15 foot middle Bakken, bioturbated, dolomite-rich, siltstone facies, containing 8-12% porosity (Walker et al., 2006). Due to a low natural fracture occurrence, production relies on the diagenetic and depositional properties of the strata with a large emphasis on matrix and secondary porosities at Elm Coulee Field (Brown, 2006; Sonnenberg and Pramudito, 2009).
CHAPTER 3 LITHOFACIES, MINERALOGICAL, AND ELEMENTAL ANALYSIS

This chapter will define the stratigraphy found within the Bakken Petroleum System and its juxtaposed relationships to its mineralogy and elemental analysis specific to Elm Coulee Field, Richland County, Montana.

3.1 Lithofacies

In this section the Lower Bakken Shale, Middle Bakken Member Facies A through Facies F, and the Upper Bakken Shale have all been defined with the Colorado School of Mines Bakken Consortium nomenclature (Sonnenberg, 2010). All of these facies are present in Elm Coulee Field. The Lower Bakken Shale occurs towards the northeast portions of the field and begins to pinch out towards the southwest. This is observed by the two available cores where the Coyote-Putnam core has the Lower Bakken Member present, whereas the Larson 11-26 does not.

3.1.1 Lower Bakken Member

The Lower Bakken Shale is composed of organic-rich shales ranging in color from dark gray to brownish-black to black in color and occur as either massive or fissile. The maximum thickness for this interval is 55 feet located in the depocenter east of the Nesson Anticline within the Williston Basin. The homogenous nature of these shales are remarkably consistent throughout the basin and are composed of high silica contents (~40% – 70%) in the form of silt-sized quartz grains, sponge spicules, and radiolarian which translates to the shales exhibiting brittleness. The remaining mineralogical components include illite and smectite clays, and minor amounts of feldspar, dolomite, calcite, and pyrite. The pyrite can occur readily distributed throughout the shales and also in lenses and laminations in its concentrated form. Multiple types of fractures are observed in both core and in petrographic thin section, which include: horizontal,
vertical, blocky, conchidal, and ptygmatic. The amorphous sapropelic organic matter found in
the Lower Bakken Shale is evenly distributed throughout the matrix and is not confined within
laminations or lenses (Meissner, 1978; Webster, 1984; LeFever, 1992; Sonnenberg et al, 2011;

3.1.2 Middle Bakken Member

The Middle Bakken Member (MBM) has been divided into six different facies by the
Colorado School of Mines Bakken Research Consortium classification scheme (Sonnenberg,
2011) (Figure 3.1). Geologically starting from the bottom: MBM – Facies A, a skeletal lime
wackestone; MBM – Facies B, bioturbated argillaceous siltstone; MBM – Facies C, laminated
sandstone-siltstone; MBM – Facies D, calcareous sandstone-grainstone; MBM – Facies E,
laminated dolomitic siltstone; and MBM – Facies F, massive fossiliferous wackestone (Table
3.1).

3.1.2.1 MBM – Facies A

The light to medium grey skeletal lime wackestone is the basal unit of the Middle Bakken
Member and is separated from the Lower Bakken Shale with a sharp contact. This facies consists
of fine-grained silty limestone with a mixture of silt-sized quartz, clays, and dolomite. It was
deposited in an offshore marine to distal shelf environment below wave base. The calcite content
averages 42% and the quartz percent content averages about 36%. Fossils found in the interval
are mainly brachiopod and crinoid allochems; however, bryozoans and gastropods have also
been identified. The thickness is relatively thin for this facies and averages of 2-3 total feet
(Gent, 2011).
Figure 3.1: Core photos of the Middle Bakken Member Facies A through Facies F. MBM-A: skeletal wackestone with brachiopod and crinoid fragments. MBM-B: Helminthopsis and Scalarituba burrows in argillaceous siltstone with high bioturbation. MBM-C: thinly interbedded silty sanstones and mudstones. MBM-D: cross-stratified limy sandstone. MBM-E: planar to wavy laminations lightly bioturbated dolomitic siltstones and mudstones. MBM-F: mottled skeletal dolomitic mudstone to siltstone with brachiopod fragments. Well locations: Braaflat 11-11H, Sec. 11, T 153N, R 91W, Mountrail County; Deadwood Canyon Ranch 43-28H, Sec. 28, T 154N, R 92W, Mountrail County; Gunnison State 44-36H, Sec. 36, T 161N, R 91W, Burke County; Long 1-01H, Sec. 1, T 152N, R 90W, Mountrail County; N&D 1-05H, Sec. 5, T 152N, R 90W, Mountrail County. Core photos are from the NDIC, Kowalski (2010), Simenson (2010), and Theloy (2014).
3.1.2.2 MBM – Facies B

The contact between MBM - Facies A and MBM - Facies B is gradational and is marked by the initial decrease in fossils and an increase in bioturbation. The main characteristic in identifying this facies is the extensive amount of Helminthopsis and Scalarituba burrows which increases in abundance up-section. The lithology of this unit is a light grey to tan argillaceous, calcareous siltstone with randomly distributed and infrequent brachiopod and crinoid fragments. Original sedimentary structures are not preserved due to the increase in bioturbation. Two types of carbonate cement are common: calcite cement producing a light grey color and dolomite-cemented areas producing a more tan color. The mineralogy is widely variable with quartz ranging from 17-51%, calcite 5-70%, dolomite 6-29%, and clay 2-11%, and thicknesses of this facies ranges from 3 to 34 feet. The depositional environment has been interpreted as being a subtidal environment. Although not typically the target reservoir throughout the basin, this facies is the primary reservoir in Elm Coulee Field (Simenson, 2010).

3.1.2.3 MBM – Facies C

The MBM – Facies C is composed of thin alternating layers of light grey, very fine-grained silty sandstones and dark-grey argillaceous siltstones. Sedimentary structures include the prominent planar laminations which vary in thickness from 0.1 – 0.2cm, and less frequent ripple laminations with double mud drapes, soft sediment deformation (in thicker units), and fluid escape structures. This facies has the highest amounts of silica in comparison to the rest of the Middle Bakken Member facies, with quartz contents up to 47%. The depositional environment has been interpreted as an intertidal setting do to the rhythmic cyclicity of laminations. Adding to this interpretation is the lack of fossils or bioturbation which implies a stressed environment and possibly shallower water levels with potentially dysoxic conditions. Thicknesses of this facies...
ranges from 2-14 feet and is the target reservoir throughout most of the basin interior (Gent, 2011).

### 3.1.2.4 MBM – Facies D

Facies D is unique in comparison to the others present in the Middle Bakken Member due to it having the highest energy depositional environment resulting in the coarsest-grained material. The coarsest grains appear in the northern portion of the basin and fine to the south away from the clastic sediment source, which produced grain sizes ranging from fine sand to medium-grained sand in some local areas. The Canadian part of the Williston Basin has improved reservoir properties and the facies is a conventional reservoir. However, in the United States there are significant lateral variations ranging from carbonate bioclastic-dominated lithologies to calcite cemented tight sandstones. In certain areas the facies is composed of ooid-rich grainstones with abundant fossil fragments. With the decrease of detrital input from the north, the south area shows higher yields of in-situ carbonate production. Pervasive calcite cementation has diminished porosity and permeability in this facies, despite it having the coarsest grain size and in fact acts as a barrier to fluid flow. A variety of sedimentary structures can be present: massive, ripple laminations, cross-stratification, rhythmic centimeter scale laminations, micro-faults and slumps, or soft sediment deformation. The color ranges from light grey to dark grey and ranges in thickness from a few inches to 22 feet. The facies is interpreted as being a lowstand-deposit in an intertidal setting (LeFever et al., 1991; Gent, 2011).

### 3.1.2.5 MBM– Facies E

Facies E is composed of thinly planar laminated, bedded, to contorted very fine-grained light grey dolomitic sandstones interbedded with darker grey argillaceous siltstones. Other common sedimentary structures found in this facies are wavy laminations, ripples, and localized
moderate bioturbation. Microbial laminations occur in this interval. Predominant mineralogy is quartz and dolomite, with minor amounts of calcite and some pyrite. Microfractures are present with both horizontal and vertical orientations. Facies E represents the initiation of an overall deepening and fining-upwards trend in the basin and has been interpreted to have a depositional environment of an intertidal to subtidal setting. Overall thickness of this unit ranges from 6-11 feet (Kowalski, 2010).

3.1.2.6 MBM – Facies F

The calcareous fossiliferous silty wackestone Facies F is massive to bioturbated and has been deposited in a similar environment as Facies A, within or just below storm wave base. The fossils deposited within this unit include brachiopod fragments, bryozoans, echinoderm spines, and occasional shell lags may have been produced during storm events. The contact between the Middle Bakken Member Facies F and Upper Bakken Shale is sharp and frequently has pyrite nodules that form in close proximity. Pyrite also occurs in smaller nodules throughout the facies and can occur disseminated throughout the unit. The thickness for this facies ranges between 1-3 feet (Gent, 2011).

3.1.3 Upper Bakken Member

The Upper Bakken Shales are similar in lithology to that of the Lower Bakken Shales. This unit ranges in color from dark grey to brownish-black to black and occurs as either fissile or massive with some planar laminations. High silica contents of approximately 40-70% occur in this interval with the remaining mineralogy including illite and smectite clays, and minor amounts of feldspar, dolomite, calcite, and pyrite. Fractures do occur and include horizontal, vertical, blocky, conchoidal, and ptygmatic variations. The dissimilarities between the Upper Bakken Shales and the Lower Bakken Shales are the higher Total Organic Carbon (TOC) values,
greater abundance of fossils, and thinner maximum thickness of approximately 28 feet (Figure 3.2) (Gent, 2011).

Figure 3.2: A & B are from the UBS and C & D are from the LBS. Small vertical fractures cemented by calcite and pyrite are visible in photo C. (Theloy, 2014).
Table 3.1: Middle Bakken Member Facies A – Facies F description summary (modified from Gent, 2011).

<table>
<thead>
<tr>
<th>Facies Unit</th>
<th>Lithology</th>
<th>Sedimentary Structures</th>
<th>Biogenic features</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies A - Crinoid, brachiopod, lime Wackestone</td>
<td>Light gray, fine grained limestone with crinoid and brachiopod fragments. Bioclastic material has significant pyrite replacement.</td>
<td>Massive</td>
<td>Crinoids, brachiopod shells and fragments, bryozoans.</td>
<td>Shallow marine below storm wave base.</td>
</tr>
<tr>
<td>Facies B - Bioturbated, argillaceous, calcareous silstone/sandstone</td>
<td>Dark gray to tan, very fine grained, bioturbated, argillaceous, calcareous sandstone. Pyrite and calcite replacement of several bioclastic</td>
<td>Bioturbated, sediments obscured</td>
<td>Crinoid, brachiopod shells and fragments, helminthopsis, scalarinub.</td>
<td>Shallow marine subtidal.</td>
</tr>
<tr>
<td>Facies C - Laminated, argillaceous, calcareous silstone/sandstone</td>
<td>Very fine grained, light gray to tan, laminated, argillaceous, calcareous silstone and sandstone. Pyrite nodules or frambooids scattered throughout unit.</td>
<td>Very fine planar parallel laminations with occasional storm event</td>
<td>None</td>
<td>Shallow marine subtidal to intertidal.</td>
</tr>
<tr>
<td>Facies D - Calcite grainstone/sandstone with planar to low angle silstone lamination</td>
<td>Very light gray, sandy calcite grainstone and very fine grained sandstone. Dark gray very fine argillaceous silstones in laminations. Abundant pyritic frambooids just below upper facies boundary</td>
<td>Structureless interbedded with planar to low angle undulating laminations, cross-strata, ripple laminations and trough cross-beding</td>
<td>Echinoid spines, fossil fragments, ooids</td>
<td>Shallow marine carbonate shoal intertidal.</td>
</tr>
<tr>
<td>Facies E - Laminated, bioturbated, fossiliferous, dolomitic mudstone/siltstone</td>
<td>Light gray, bioturbated dolomitic mudstone and light gray very fine grained silstone. Pyrite and calcite replacement of fractures and bioclasts. Pyrite nodules scattered throughout unit.</td>
<td>Massive to planar laminations, wavy to ripple laminations, bioturbated</td>
<td>Planolites, helminthopsis, scalarinub, brachiopods</td>
<td>Shallow marine subtidal to intertidal.</td>
</tr>
<tr>
<td>Facies F - Bioturbated, fossiliferous, calcareous Wackestone/siltstone</td>
<td>Light gray, very fine grained, bioturbated, fossiliferous, calcareous wackestone to silstone. Pyrite replacement of bioclasts.</td>
<td>Structureless with several bioclastic lags.</td>
<td>Brachiopod shells and fragments, echinoid spines, bryozoans</td>
<td>Offshore within storm wave base.</td>
</tr>
</tbody>
</table>
3.2 Cores

The foundation of this thesis is to develop a firm understanding of reservoir lithology of the Bakken Petroleum System. A total of two cores were supplied from wells within Elm Coulee Field for this study: the Larson 11-26 (Sec. 26-T23N-R57E), and the Coyote-Putnam (Sec. 9-T57N-R57E). Enerplus supplied the Coyote-Putnam core which was previously described by Eidsnes (2014) and the Larson 11-26 is a new core that has been supplied by SM Energy. Each core description includes lithology and facies identification, identification of sedimentary structures, and bioturbation index (Figure 3.3).

3.2.1 Larson 11-26

The Larson 11-26 core is located in T23N R57E Section 26, which lies within the south-central part of Elm Coulee Field, Richland County, Montana. The core was extracted on December 6th, 2003, between 10350 feet to 10434 feet, making the core a total length of 84 continuous feet (Figure 3.4). The interval, from the lowermost portion, begins in the Devonian Three Forks Formation and continues upward into the Middle Bakken Member, the Upper Bakken Shale, and ends with the Mississippian Lodgepole Formation. This core is located on the southwestern flank of the Bakken depositional basin and has no Lower Bakken Member present. The Three Forks Formation is separated from the Middle Bakken Member by an unconformity indicated by a basal conglomerate. The Middle Bakken Member begins deposition with a 2 foot thick Facies A interval. The gradational change into Facies B is marked by the last observed brachiopod fragment and initiation of increased bioturbation. The 19 foot thick B facies shows an increase in bioturbation up-section. The uppermost portions serve as the primary target within this field area. Facies C and Facies D are absent do to these facies stratigraphically pinching out before reaching this point in the field. Facies E is composed of dolomitic sandstone with wavy to
parallel laminations and is overlain by the half foot dolomitic siltstone Facies F, which contains brachiopod fragments. Sharply overlying the Middle Bakken Member is the organic-rich, 7 foot thick Upper Bakken Shale. These shales are very dark brownish-grey to black, and contain some brachiopods and some fractures occurring sub-vertical to horizontal. These shales are overlain by a thick limestone and crinoid-rich Lodgepole Formation that encompass the rest of the core.

3.2.2 Coyote-Putnam

The location of the Coyote-Putnam core is located in T23N R57E Section 9, and falls within the central part of Elm Coulee Field, Richland County, Montana. The core was taken from 10335 feet to 10395.3 feet on October 16th, 2008, resulting in a total length of 60.3 feet (Figure 3.5). The core begins in the lowermost part in the Devonian Three Forks Formation and continues upwards into the Lower Bakken Shale Member, the Middle Bakken Member, the Upper Bakken Shale Member, and ends in the Scallion Member of the Mississippian Lodgepole Formation. Separating the Three Forks Formation from the Lower Bakken Shale Member is an unconformity marked by a half inch pyritized fossil lag surrounded by black mudstone. The Lower Bakken Shale Member is a 2.5 foot thick grey dolomitic siltstone that has fractures and occasional bioturbation. The abrupt contact separates the Lower Bakken Shale Member from the initial Middle Bakken Facies A Member. This 3 foot interval is a dark grey dolomitic siltstone with occasional brachiopod and crinoid fragments and little bioturbation. The contact between Facies A and Facies B is gradational and is marked by the last observed crinoid and the initial increase in bioturbation. Facies B is a 19.5 foot unit that is composed of dolomitic siltstone bioturbated by Helminthopsis and Scalarituba. Facies C or Facies D are absent in this core due to non-deposition or erosion. Facies B is sharply overlain by the 3 foot Facies E, which is a dolomitic sandstone unit with wavy and parallel laminations. Overlying the previous unit is
Facies F consisting of 1.5 foot thick dolomitic siltstone interval that is mottled and contains brachiopods. A sharp contact separates the Middle Bakken Member from the Upper Bakken Shale Member which is 7 feet thick and is composed of an organic-rich shale with fractures and silty laminations. Another sharp contact separates the Upper Bakken Member from the Lower Lodgepole Scallion Member. The Scallion Member is a limestone containing crinoids and stylolites.

3.3 XRD

X-Ray Diffraction (XRD) data, derived from core plug analysis, was supplied for one core for this study, the Coyote-Putnam core. XRD analysis provides a semi-quantitative analysis of the mineralogical data present within a unit of rock. This process allows for mineral identification based on the unique spacing of the mineral structure of each individual mineral. Figure 3.6 displays the XRD mineral abundances and distribution through the entire cored interval of the Bakken Petroleum System. The Bakken Formation is composed of quartz, dolomite, calcite, k-feldspar, plagioclase feldspar, illite, chlorite, and pyrite. This analysis provides information on the degree of dolomitization within the Middle Bakken Member and can further be interpreted in relation to the corresponding reservoir properties. Each grouping of the Bakken facies have been labeled and analyzed independently of each other due to their individual mineralogical fractions, which include: the Middle Bakken Member Facies A, B, E, and F, and the Upper Bakken Shale Member. The Lower Bakken Member was not sampled in this dataset.
Figure 3.3: Key for core description symbols for lithology, sedimentary structures, textures, and fossils. This legend refers to the cores.
Figure 3.4: Digitized core description of the Larson 11-26 well. See Figure 3.2 for core description legend.
Figure 3.5: Digitized core description of the Coyote-Putnam well. See Figure 3.2 for core description legend.
Figure 3.6: Coyote-Putnam bulk mineralogy through the Bakken Petroleum System section of the core. Respective weight percent of quartz, dolomite, calcite, k-feldspar, plagioclase feldspar, illite, chlorite, pyrite, and an unidentified mineralogy are represented by the chart. Facies boundaries are marked by the blue lines and have been identified on the left portion of the chart. Sections with no sampled data display no readings.
Coyote-Putnam - Bulk Mineralogy in Weight %

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>UBM</th>
<th>Facies F</th>
<th>Facies E</th>
<th>Facies B</th>
<th>Facies A</th>
<th>LBM</th>
</tr>
</thead>
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<td>10352.4</td>
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<td>10350.3</td>
<td>10354.1</td>
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<tr>
<td></td>
<td>10346.6</td>
<td></td>
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</tr>
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<td>10346.6</td>
<td></td>
<td></td>
<td></td>
<td>10370.2</td>
<td></td>
</tr>
</tbody>
</table>

- **Quartz/Silica**
- **Dolomite**
- **Calcite**
- **K-Feldspar**
- **Plag Feldspar**
- **Illite**
- **Chlorite**
- **Pyrite**
- **Unidentified**
Dolomitization is abundant through the Middle Bakken Member. This is the process in which dolomite forms as a result of magnesium-rich ions replacing calcium ions in calcite. The stoichiometric equation that represents this reaction is displayed in Equation 3.1:

\[
2\text{CaCO}_3(\text{limestone}) + \text{Mg}^{2+} \leftrightarrow \text{CaMg(CO}_3)_2(\text{dolomite}) + \text{Ca}^{2+}
\]  

(3.1)

Due to the replacement of calcite, we do not see any calcite in the uppermost section of Middle Bakken Member Facies B and all of Facies E, and only small percentages through the rest of the facies. There is an anomalous increase in calcite however at the base of Facies A, which is more likely due to the sample containing higher amounts of brachiopod and crinoid fragments within the facies. This relationship indicates that dolomitization of the Bakken Formation is not uniform and has experienced further magnesium ion replacement in the upper section of the Middle Bakken Member. This process decreases the solid rock volume which creates secondary porosity and is quite noticeable in Facies B, the target reservoir at Elm Coulee Field (Sonnenberg and Pramudito, 2011; Alamanza, 2011).

3.4 XRF

X-Ray Fluorescence (XRF) data was collected from both the Larson 11-26 and the Coyote-Putnam core butts. This data aids in the interpretation of organic richness, paleo-productivity in the Bakken Shale Members, and provenance of the Middle Bakken Member.

3.4.1 Methodology

The data was obtained using a handheld Thermo Fisher Scientific Niton X-Ray Fluorescence Analyzer (Niton XL3t GOLDD+) and was obtained from both cores. This tool is capable of acquiring simultaneous data up to 40 elements ranging in atomic weight from magnesium (element 12) through uranium (element 92) and is a cost effective method. There are
three modes in which the Niton XL3t can operate: Soils, Mining, and TestAll Geo (Thermo Scientific, 2010). This study implemented the TestAll Geo mode to sample both cores at a maximum of 180 seconds for each sample at every six inch interval.

Before each sample reading is conducted, a systems check was performed to calibrate the detector which verifies that the operations are fully functional. This systems check was performed before and after each sample set was conducted with success on all readings. The sampling was performed on rinsed and wiped down samples. A station was set aside so that each core sampling interval would be taken to and examined for a debris free and salt free surface before engaging the instrument. The Niton XL3t was then applied to a flat surface away from the core box and a sample analysis was executed. A more detailed account on the XRF elemental data gathering using the Niton XL3t can be found in Nakamura (2015).

### 3.4.2 Results

The relationships between major and trace elements obtained by the XRF analysis must be identified and analyzed. Principal Component Analysis (PCA) is a widely accepted and applied tool (Cliff, 2014). When applying the PCA it will identify relationships within a data set that will highlight similarities and also the data’s differences while plotting the relationships in groups. Principal Component Analysis was performed on the Bakken Formation in both cores to identify these relationships and it paired the elements into five groupings (Figure 3.7).

Each group is indicative of a specific elemental signature and thus creates the relationships within the grouping. The elements Al, K, Ti, and Si in Group 1 are all associated to terrigenous minerals including quartz, feldspars, and clay minerals (Figure 3.7 and 3.8). The Cr in Group 2 relates to organic matter, redox conditions, and a marker for suboxic environments.
(Figure 3.7 and 3.9). For anoxic indicators Group 3 is identified by Fe, Cu, Mo, U, V, Ni, and S elements (Figure 3.7 and 3.10). Group 4 is associated to the carbonate and dolomite faction of elements: Ca, Mg, and Mn (Figure 3.7 and 3.11). Plotting as an outlier is the Zr element, which represents Group 5 (Figure 3.7 and 3.12) (Tribovillard et al., 2006; Piper et al., 2009).

There are four identified redox classes that have been interpreted by Tyson and Pearson (1991) when identifying zonations within a water column: oxic, suboxic, anoxic, and euxinic. The defining factors in differentiating anoxic and euxinic is that anoxic environments do not contain free H$_2$S in the water column and euxinic environments do. Previous work performed on the Bakken shales has interpreted the depositional setting to be an offshore marine anoxic or oxygen-restricted environment during periods of transgression (Webster, 1984; LeFever et al., 1991; Sonnenberg, 2011). In their work anoxic conditions are attributed to the occurrence of a stratified water column with the upper water zone being identified as well oxygenated and nutrient rich with high amounts of organic production overlying a lower stagnant zone. Confined zones in the water column that lead to stagnant water conditions with insufficient circulation will prevent O$_2$ renewal, thus creating anoxic conditions. Although there are other mechanisms for creating anoxia, Sonnenberg (2011) argues that the lack of benthic fauna and burrowing, coupled with high Total Organic Carbon (TOC) values translate to anoxic conditions during the time of Bakken Shale deposition. The data acquired from this study supports the anoxic conditions with the elements plotting in both Group 2 and Group 3. These groups are related to redox conditions which is why they are plotting in relatively similar regions on the PCA diagram. Piper et al. (2009) provides a detailed account of the conditions in which elements will precipitate out of a stratified water column (Figure 3.13). Transitioning from a suboxic to an anoxic environment
\( \text{Cu}^{2+} \) is the first to reduce and precipitate. However, in complete anoxic conditions, \( \text{FeS}, \text{CdS}, \text{ZnS}, \text{MoS}_2 \), and \( \text{NiS} \) will precipitate from redox reactions (Piper et al., 2009).

Silicon can be associated with quartz, clays, feldspar, and authigenic and biogenic silica. Differentiating abundances of Si from XRF data can be difficult due to the quantitative approach of the sampling. When dealing with clay-rich intervals, identifying the Si input between biogenic or detrital is needed. The results from the Si elemental data, cross plotted against elements such as Zr, can lead to the identification of biogenic or detrital input. The presence of detrital Si will show a positive trend in the cross plots with Zr, and a negative trend will represent biogenic Si input. In doing these cross plots both Group 1 and Group 5 data can be represented for the Bakken Formation, where Group 5 contains the outlier Zr, which should typically plot with Group 1 elements depending on their relationship. Figure 3.14 displays both a positive trend and a negative trend, which translates to both detrital and biogenic input for the entire Bakken Formation; however, Figure 3.14b displays Si cross-plotted against Zr specific to the Upper Bakken Shale and a negative trend is found. The negative trend translates to the UBS containing biogenic Si. Kocman (2014) describes this relationship of high biogenic input as being a result of radiolarian in the system. From these findings, the positive trend indicates detrital input for the Middle Bakken Member.

Group 4 elements, \( \text{Mg}, \text{Mn}, \) and \( \text{Ca} \) are associated to carbonate and dolomite content and are attributed to the Middle Bakken Member. Figure 3.11 shows a large increase in all three elements throughout the Middle Bakken with drastic decreases in both the Lower Bakken Member and the Upper Bakken Member. The increase of Mg through the upper part of the MBM can be associated to the increase of dolomite observed in the XRF data. An increase in dolomite trending upwards would translate to a slight decrease in Ca trending upwards as represented by
Equation 3.1, and observed in Figure 3.11. Similar to Group 1, these elements are more linked to changes in carbonate sediment supply, rather than paleo-oxygen water column conditions.

Figure 3.7: Results from the Principal Component Analysis applied to the XRF elemental data of the Bakken Formation within the study area. The results highlight five distinct groupings.
Figure 3.8: Group 1 elemental data (Si, K, Al, and Ti) plotted as a function of core sampling depth. Coyote-Putnam core description also provided.
Figure 3.9: Group 2 elemental data (Cr) plotted as a function of core sampling depth. Coyote-Putnam core description also provided.
Figure 3.10: Group 3 elemental data (Cu, Fe, Mo, Ni, S, U, and V) plotted as a function of core sampling depth. Coyote-Putnam core description also provided for reference.
Figure 3.11: Group 4 elemental data (Ca, Mg, and Mn) plotted as a function of core sampling depth. Coyote-Putnam core description also provided for reference.
Figure 3.12: Group 5 elemental data (Zr) plotted as a function of core sampling depth. Coyote-Putnam core description also provided for reference.
Figure 3.13: Schematic representation of bacterial respiration versus water column depth in marine basins experiencing O₂ depletion in the bottom water (Piper et al., 2009).

Figure 3.14: A) Cross-plot of XRF Si and Zr elemental data showing both positive and negative trend when plotting entire Bakken Formation indicating authigenic and biogenic silica. B) Cross-plot of XRF Si and Zr elemental data for just UBS with negative trend indicating only biogenic silica.
CHAPTER 4 GEOMECHANICS

Assessing geomechanical properties within an unconventional reservoir is vitally important for determining the economic production of a formation. Data will aid in determining where hydraulic fractures should be initiated and whether or not they will be successfully executed (Grieser and Bray, 2007).

4.1 General Geomechanical Properties

There are many properties when determining geomechanical behavior of rocks (Fjaer et al., 2009). This section will serve as an overview to the relevant properties pertaining to this study.

First and arguably the most important geomechanical property is the compressive strength of a material. It is measured by the capacity of which the material can withstand axially directed compressive forces. Uniaxial compressive strength, often referred to as Unconfined Compressive Strength (UCS), is the most common measurement to derive UCS values and is defined by the ultimate stress of rock material. Its application spans through defining hydrofracture design to analysis and modeling of material. Compressive strength can be obtained with lateral pressures by means of triaxial measurements; however for the purpose of this study UCS values are sufficient.

Young’s Modulus, $E$, is the ability of a material to resist yielding due to stress applied in a single direction and represents the stiffness of a material, provided it is not stretched beyond the limit of proportionality. It is defined as the ratio of the rate of change of stress with strain which can be experimentally derived from the slope of a stress-strain curve during testing of compressional and tensile tests conducted on a material.
\[ E = \frac{\sigma_{axial}}{\varepsilon_{axial}} \]  

(4.1)

Poisson’s ratio, \( \nu \), measures the ratio of lateral strain to the axial strain, at the linearly-elastic region. This is represented by the later stage of loading beyond the linearly-elastic region where lateral strain increases faster than the axial strain which then leads to a higher ratio.

\[ \nu = -\frac{\varepsilon_{radial}}{\varepsilon_{axial}} \]  

(4.2)

Shear strength is used to describe the strength of rock materials by resisting deformation due to shear stress. This is measured by the differentiation of two internal mechanisms: cohesion and friction. Cohesion is a measure of internal bonding of rock materials, whereas internal friction is caused due to the contact between particles. The shear modulus, \( G \), of a material governs its resistance to being sheared.

\[ G = \frac{\tau}{\gamma_s} \]  

(4.3)

The bulk modulus, \( K \), of a material measures the materials resistance to volumetric compression under hydrostatic loading. It is defined as the ratio of the decrease in volume and the resulting increase of pressure that the material experiences due to the decrease.

\[ K = \frac{P}{\varepsilon_{volumetric}} \]  

(4.4)

### 4.1.1 Static vs Dynamic Properties

There are two specific techniques in measuring geomechanical properties, static and dynamic. A sample of rock material can be tested directly by applying force and recording the resulting stress and strain. From the measured outcome of the test, the above mentioned moduli
are calculated using proper relationships of stress and of strain. This type of measurement process is referred to as static because the measurement usually takes place at very low frequencies of an applied force, or at “static” conditions. Another method of acquiring geomechanical properties is by measuring the same properties by means of recording wave propagation travel times from both shear and compressional sources then calculating the moduli, which is referred to as dynamic properties. The frequency at which dynamic force is applied is much greater than the static, which allows the material to generally react differently, especially when dealing with porous material containing fluids while in-situ. When dealing with lithologies, heterogeneity, pore space, and fluids will all affect the rock differently depending on the strain rate of the applied forces (Fjaer et al., 2009; Mavko et al., 2003).

4.1.2 Elastic Properties

Elasticity deals with two properties: isotropic and anisotropic. In an isotropic material the velocities measured in any direction will be equal and, therefore, there are only two independent elastic constants required when describing the elasticity of the material. In anisotropic materials, velocities will differ depending on the direction of propagation. Heterogeneous material consists of dissimilar or diverse constituents and as a result leads to anisotropy. Anisotropy is defined as the variation of property with the direction in which it is measured. There are several common forms of anisotropy found in rocks: vertical transverse isotropy (VTI), horizontal transverse isotropy (HTI), and orthotropic anisotropy (Figure 4.1). A transversely isotropic material, referred to as a TI media, exhibits the same properties in the plane of isotropy and different properties in the transverse plane. An orthotropic material deals with different properties in all directions. Horizontal laminations are an example of vertical transverse isotropy (VTI) in a rock (Fjaer et al., 2009; Mavko et al., 2003).
There are a wide range of geomechanical properties that are dependent on the orientation of the measurement, such as orders of magnitude difference in adjacent cores for Young’s modulus values, therefore knowing the orientation is vital in accurate measurements (Barree et al., 2009).

4.2 Core Testing

Core from the Larson 11-26 well was analyzed for geomechanical properties. This is essential for calibrating the log-based mechanical analysis and determining the formations intrinsic isotropic and anisotropic properties. TerraTek performed the analysis on behalf of Enerplus by conducting: Anelastic Strain Recovery (ASR), Differential Strain Analysis (DSA), and Continuous Mechanical Property Profiling by means of scratch testing to obtain Unconfined Compressive Strength (UCS).

4.2.1 TerraTek Mechanical Analysis

The mechanical analysis testing in relation to depth and sample number is shown in Table 4.1. This section will define the testing methods for ASR, DSA, and Continuous Mechanical Property Profiling.
Table 4.1: Description of samples test, depth sampled, and type of section.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample Depth (ft)</th>
<th>Sample Length (in)</th>
<th>Sample Diameter (in)</th>
<th>Type of Test</th>
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<tbody>
<tr>
<td>ASR-1</td>
<td>10407.8 – 10408.35</td>
<td>Whole Core</td>
<td>Whole Core Section</td>
<td>ASR</td>
</tr>
<tr>
<td>ASR-2</td>
<td>10408.35 – 10409.05</td>
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<td>Whole Core Section</td>
<td>ASR</td>
</tr>
<tr>
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<td>10413.50 – 10414.20</td>
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<td>Whole Core Section</td>
<td>ASR</td>
</tr>
<tr>
<td>ASR-4</td>
<td>10414.20 – 10414.90</td>
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<td>Whole Core Section</td>
<td>ASR</td>
</tr>
<tr>
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<td>1.5-inch Cubes</td>
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</tr>
<tr>
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<td>1.5-inch Cubes</td>
<td>DSA</td>
</tr>
<tr>
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<td>DSA</td>
</tr>
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<td>Half Moon Sections</td>
<td>TSI</td>
</tr>
</tbody>
</table>

4.2.1.1 ASR

Anelastic Strain Recovery (ASR) is a core-based technique for determining the magnitudes and directions of the in-situ principal rock strains. This method can also infer the magnitudes and directions of the in-situ principal stresses. This approach relies on monitoring time dependent strain relaxation of newly acquired and freshly cut core at the wellsite. Differential relaxation occurs immediately upon extraction and is measured and related to the directions and magnitudes of the in-situ stresses using elastic or viscoelastic relationships. The total measured strain involves two derived components: an instantaneous elastic component, and an anelastic component. Of the two, the anelastic is time dependent and can require 10 to more than a hundred hours of record time to obtain a full measurement. This is of course strictly dependent upon the types of strain and stressors within the in-situ formation. The resolution of this testing method is $0.5\mu$ strains and is a completely three-dimensional measurement.
4.2.1.2 DSA

Differential Strain Analysis (DSA) is a testing method performed in a laboratory setting and conducted with whole core samples. The objective of DSA is to determine the principal strain directions and to infer the orientation and magnitude of the in-situ principal stress.

The basis of this measurement is the occurrence of core deformation once the core is extracted from the in-situ environment due to the stress relief. The stress relief leads to the opening of microfractures within the core that are then recorded for density and orientation which represent the spatially varying magnitudes of the in-situ stress field. As a result, the microfracture population created during the coring process is a reflection of the in-situ stress, as is the directionality derived from the orientation of the microfracturing.

During the testing phase of this method, the core sample undergoes a hydrostatic reloading to beyond the in-situ stress conditions. The sample is strain gauged during testing to derive the directional deformation in three-dimensional properties. As reloading occurs, microfractures induced by the stress relief close first, while continued loading causes deformation of the intrinsic mechanical properties of the rock. By discriminating between intrinsic behaviors at higher hydrostatic pressures than that which occur in-situ and the induced behavior by the presence of open microfractures, the directional contribution due to the microfractures can be determined. The direction of the maximum in-situ principal strain corresponds to the maximum microfracture density orientation. However, if the material properties are isotropic, a one-to-one ratio will occur for the principal strain and the principal stress directions.
4.2.1.3 Continuous Mechanical Property Profiling

Continuous Unconfined Compressional Strength (UCS) measurements were conducted on the entire core through means of scratch testing using the TerraTek TSI scratch test system (Figure 4.2). This test system is constructed with a moving station with an attached sample holder and loading fixture that performs “scratching” of the specimen. A load-cell is attached to the moving station and measures in the range of 10N to 4000N of both the horizontal force, in the cutting direction, and the vertical force, normal to the cutting surface, all within the range of 1N. Computer aided controls allow the variable speed of the machine, automated data acquisition, and real-time data analysis. The core was tested at post-slab dimensions of four inches wide and three feet in length. The rock surface is then scratched at a constant depth of cut at 0.2mm to 0.5mm. The data collected represents the normal and tangential forces on the cutting mechanism which are then computed into rock strength (UCS) values. Many reports have concluded the accuracy of this technique and its implementation in industry practices (Schei et al., 2000). Outside of acquiring high-resolution UCS values, continuous UCS measurements on core are practical for log correlation in order for scaling up laboratory static measurements into dynamic log-derived measurements of geomechanical properties.

4.2.2 Core Property Results

In-situ stress was evaluated based on the obtained measurements of Anelastic Strain Recovery (ASR) and Differential Strain Analysis (DSA), regional scale calculations of plate tectonic motion, comparisons derived from available data on the World Stress Map, continuous unconfined compressional strength calculations, and comparisons with fracture orientations on core. Continental-scale evaluations on motion were obtained using GPS positioning data and
have been integrated into the interpretation to assess velocity vectors from any desired location, which represent the averaged directions of maximum horizontal stress.

Figure 4.3 shows a maximum horizontal stress on a regional averaged direction to be 247°. Regional calculations from bore-hole breakouts assess the horizontal stress orientation to fall within approximately 185°, thus concluding that the maximum horizontal stress should fall within the range of 185° to 247°. Core induced microcracking and anelastic deformation lacked adequate resolution for interpretation of maximum horizontal stress values derived from ASR and DSA testing. The layered nature of the core specimens resulted in considerably higher microfracture density and anelastic deformation along the vertical direction and a correspondingly low microfracture density and low anelastic deformation in the perpendicular direction. Results from both the ASR and the DSA testing show that the orientations of the minimum and maximum horizontal stress often become switched with one another. However, implementing the regionally derived stress orientations and confining the data acquired within the 185° to 247° range, stress orientation emerges. Table 4.2 shows a summary of the in-situ stress magnitudes and orientations.

Results from the scratch test were obtained at 20 measurements consecutively per foot, considerably high resolution. This was then digitized and added into the Bakken Consortium IHS Petra project data base and correlated to the Larson 11-26 Gamma Ray log to acquire appropriate depth shifting. After calibration was confirmed, Unconfined Compressive Strength (UCS) geomechanical properties are represented for further use in upscaling of wireline log data.
Figure 4.2: TerraTek TSI continuous unconfined compressional strength (UCS) test system. The depth of the scratch on the cores surface indicates rock strength and is represented by the red curve, which can be correlated to rock mechanical properties (TerraTek, 2007).

Figure 4.3: General trends of maximum horizontal stress as determined from GPS positioning data integrated to provide representative velocity vectors (247°) and a single data point from the World Stress Map (185°). Richland County, MT highlighted in orange. Elm Coulee Filed boundary highlighted in blue (modified from TerraTek, 2007).
Table 4.2: Summary of the in-situ stress measurements.

<table>
<thead>
<tr>
<th>DSA Sampled ID</th>
<th>Magnitudes (psi/ft)</th>
<th>Orientation (Dip and Dip direction in deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Stress ($\sigma_v$)</td>
<td>1.18</td>
<td>(67±20, 0±15)</td>
</tr>
<tr>
<td>Maximum Horizontal Stress ($\sigma_h$)</td>
<td>0.79</td>
<td>(8±8, 247±12)</td>
</tr>
<tr>
<td>Minimum Horizontal Stress ($\sigma_h$)</td>
<td>0.72</td>
<td>(14±14, 158±12)</td>
</tr>
<tr>
<td>Pore Pressure</td>
<td>0.5</td>
<td>N/D</td>
</tr>
<tr>
<td>Effective Vertical Stress ($\sigma'_v$)</td>
<td>0.68</td>
<td>(67±20, 0±15)</td>
</tr>
<tr>
<td>Effective Maximum Horizontal Stress ($\sigma'_h$)</td>
<td>0.29</td>
<td>(8±8, 247±12)</td>
</tr>
<tr>
<td>Effective Minimum Horizontal Stress ($\sigma'_h$)</td>
<td>0.22</td>
<td>(14±14, 158±12)</td>
</tr>
<tr>
<td>Effective Mean Stress ($\sigma'_m$)</td>
<td>0.397</td>
<td>N/D</td>
</tr>
<tr>
<td>Averaged K_o = ($\sigma'_h$/$\sigma'_v$)</td>
<td>0.37</td>
<td>N/D</td>
</tr>
</tbody>
</table>

4.3 Micro-Schmidt Hammer

A low-energy non-destructive rebound hammer was implemented to further characterize rock strength (Unconfined Compressive Strength (UCS)) in the Bakken Formation cores. Leeb hardness values (HLD) were obtained from the rebound hammer and later converted to UCS values. This process was achieved by using cross-plots with HLD data sampled at the same sample interval as the TerraTek TSI scratch test sampling, then applying the derived slope-intercept equation to the entire data set.

4.3.1 Previous Work

The Schmidt hammer was originally designed and used as a means to measure material strength, or rebound hardness, in metals and concrete for industrial-civil engineering purposes. The technology was then applied in measuring the rock strength properties of intact rocks, followed by the application to rock outcrops with successful results (Poole and Farmer, 1980; Underwood et al., 2003; Morris et al., 2009). However, core samples were ruled out for testing due to the destructive nature of the high-energy impact with the rock (Taylor and Appleby,
The Proceq Equotip Bambino, a micro-rebound hammer, was developed due to the inability of testing with a larger device (Figure 4.4). This tool has been successfully implemented in multiple studies which validate its accuracy in measuring the Leeb hardness values of slabbed core and, by extension, Unconfined Compressive Strength (UCS) values (Khaksar et al., 2008; Ritz et al., 2014).

### 4.3.2 Methodology

The methodology applied to measuring the Leeb hardness values while using the micro-rebound hammer from the Bakken core samples will follow a similar approach taken by Ritz et al. (2014). Both the Larson 11-26 and Coyote-Putnam cores were slabbed upon extraction; however, testing was executed on the cut surface of the core butts. Sample intervals were performed at 3in for the entirety of the Bakken Formation (approximately 31 feet for the Larson 11-26, approximately 35 feet for the Coyote-Putnam) to obtain high-resolution measurements. Areas chosen for measurement location best represented the average lithology for the 3in interval and where an average of 10 samples could be obtained without overlapping of measurements. Missing core or heavily fractured intervals were bypassed averages were assigned between the surround measurements for those zones.

To take a single measurement, the core remained in the supplied core box as the thickness of the core sample would not impede accurate geomechanical readings attributed to core positioning (Ritz et al., 2014). The Proceq Bambino requires a vertical (perpendicular to the testing surface) placement while executing measurements so that the internal spring-loaded mechanism can rebound naturally within the extraction zone. The recorded height of the internal mechanisms rebound after impact is then measured by the onboard computer which generates a Leeb hardness value in HLD units (Figure 4.5). In total, 124 measurements were collected from
the Larson 11-26 core and 142 were collected from the Coyote-Putnam core. Approximately 10 initial readings are recorded across the measured section and an average is assigned to represent that interval. During post-processing, the five to eight most representative readings for each sample interval were selected and averaged into one measurement so that the standard deviation would achieve a 90% or higher accuracy.

Once Leeb hardness values (HLD) have been assessed from the core intervals, they are then converted to Unconfined Compressive Strength (UCS) values by cross plotting available data with derived data.

Figure 4.4: The Proceq Equotip Bambino which was implemented in this study for measuring the Leeb hardness values. Bakken Formation hardness values ranged from 513 to 794 HL (hardness value) (Proceq, 2012).

Figure 4.5: Internal mechanism diagram for the Proceq Bambino which measures the rate of rebound within the impact device (Proceq, 2012).
4.3.3 Micro-Schmidt Hammer Results

The Unconfined Compressive Strength (UCS) values obtained from TerraTek’s TSI scratch testing and the Proceq Bambino’s Leeb hardness values (HLD) were compared in Figure 4.6 cross-plot. The sampling interval was taken at the same depth resolution which allowed the data to be cross-plotted against each other to derive a relationship value through the linear regression trend. The linear regression value is well within the means to be considered an acceptable relationship ($R^2 = 0.7799$), therefore the linear equation was used to convert the HLD values into UCS. Figure 4.7 shows the TerraTek TSI scratch test derived UCS values plotted alongside the converted UCS values obtained from the HLD values. The lower UCS values (approximately 1 to 15 Kpsi for the TSI derived values, approximately 5 to 20 Kpsi for the converted values) correspond to the Upper Bakken Shales. The Middle Bakken Member has average UCS values of 25 to 30 Kpsi with an increase in the upper Middle Bakken to approximately 35 Kpsi. The increase corresponds to the enhanced mechanical brittleness experienced in the upper Middle Bakken.

The correlation from the UCS (TSI derived) and converted UCS (Proceq Bambino derived) values mimic each other in the UBM, MBM, and LBM, except for two anomalous troughs which occur at 10,418 and 10,420 depths. These troughs in the original UCS values can be attributed to either tool malfunction or to relatively ductile thin laminations. Given the nature of the UBM averaging higher values than these two troughs, it is inferred that tool error occurred. Due to the strong correlation in the Larson 11-26, the HLD values obtained from the Coyote-Putnam core were converted to UCS using the same linear equation.
Figure 4.6: Cross-plot of HLD vs UCS values acquired from the Larson 11-26 core. Linear regression displaying an acceptable relationship value.

\[
y = 5.4552x + 552.95 \\
R^2 = 0.7799
\]

Figure 4.7: Larson 11-26 well log suite displaying TerraTek TSI derived UCS values in track 4 and converted UCS values derived from HLD values in track 5.
CHAPTER 5 LOG ANALYSIS, CLUSTER ANALYSIS, & CROSS-SECTIONS

Of the well data provided for this study, 25 open-hole well logs were used to conduct a cluster analysis and create two cross-sections through the study area (Appendix A). These wells were selected due to their similar log suites and through the entirety of the Bakken Petroleum System.

5.1 Log Analysis

Scaling-up of laboratory geomechanical measurements from sample-scale to reservoir-scale is essential when evaluating unconventional reservoirs. These reservoirs are comprised of complex mineralogy, thin beds, and are typically very heterogeneous due to diagenetic effects and multiple depositional cycles. Historically, scaling-up from core scale to reservoir scale has been dependent on accurate calibration of well-log based models to wells that have little, to any, geomechanical property measurements further than core-plug scale. Such a sample size would inadequately characterize the range of heterogeneities in the reservoir, which would result in inaccurate modeling. Conventional log analysis requires a large number of log inputs, due to the amount unknown variables, which result in the cost of logging to be substantial for operators. To alleviate this burden, cluster analysis has been applied to this study to group specific geomechanical properties by their specific log responses, which in turn saves both time and money when adapted. The cluster analysis approach, aided by core-interpretation, represents the mechanical variables which occur in the reservoir facies on a field scale when upscaling to cross-sections.

5.1.1 Log Quality Control – Normalization

Before the cluster analysis was performed, all wells were prepared and selected for similar well suites. Of the 65 available wells that contained DT logs within the study area, only 25 had...
the appropriate well log suite needed for cluster analysis through the interval depth of 9,000 to 11,000 feet. The logs needed for this study and supplied by the 25 acceptable logs are: gamma ray (GR), neutron porosity (NPOR), bulk resistivity (RHOB), deep resistivity (LLD), and compressional sonic (DTC). Quality control of this dataset was performed through normalization of the three main inputs for cluster analysis, which were the GR RHOB, DT, and the computed Synthetic DTSM which included the log suite for calculating the value (discussed later in chapter). The normalization module is used to normalize a set of logs using statistical analysis. This method compensates log measurements for more than one condition: inaccurate tool calibration, drift in the measuring device, different types of tools built to derive the same logs but from different manufacturer calibrations, differences in rock and fluid properties, and anisotropy (Techlog, 2013). Normalization results in Figure 5.1 show strong correlations in both the compressional slowness (Figure 5.1B) and the shear slowness histograms (Figure 5.1C) most likely due to the relationship of the high density/fast velocity intervals in the formation. Normalization was not performed on the slowness data due to the possibility of destroying potential real variation recorded through the tools and the consistent nature does not require it. However, a discontinuous trend is found for the gamma ray histogram (Figure 5.1A). This is attributed to the heterogeneity of the lithology derived from the gamma ray logs and quite possibly due to the many different vendor tools used in this study area. The correlations, being very accurate within the DTC and DTSM logs, allow the use of bulk density in place of gamma ray for the dataset, which will maintain the geomechanical properties for the clustering analysis.
Figure 5.1: All 25 wells used through the depth interval of 9,000 to 11,000 feet. A) Gamma ray histogram. Normalization of the gamma ray was not performed due to the lack of accuracy. B) Compressional slowness histogram displaying very consistent data, normalization not required. C) Shear slowness histogram displaying consistent data, normalization not required.
5.2 Cluster Analysis

When using cluster analysis there are multiple methods to achieve slightly different outputs, this study will focus on the K-means approach. K-means methodology is a means for determining clusters by taking the input well-log data and translating them into \( n \)-principal components in \( n \)-dimensional space. For example, if two logs are chosen for clustering then they will be transformed into two principal components. This means of delineation is performed in such a manner to maximize the variability in one principal component relative to another principal component. K-means differs from other methods due to its cluster centroids, which are assigned based on the input principal components and their cumulative “distance” between all of the other varying cluster cells and assigned cluster centroids (Figure 5.2). The centroids are then positioned to the mean of a new cluster cell and the procedure is repeated for a specified number of runs until a minimum cumulative distance is reached for the total cluster cells for the dataset.

![Cross-plot displaying two separate principal components and its associated cluster cells and the associated cluster centroids (grey stars relatively centered within specific colored cluster cells). Cluster Analysis performed with eight clusters.](image)

Figure 5.2: Cross-plot displaying two separate principal components and its associated cluster cells and the associated cluster centroids (grey stars relatively centered within specific colored cluster cells). Cluster Analysis performed with eight clusters.

This method requires the user to establish the number of clusters for which should be entered into the model. It requires multiple “runs” of the data to determine the best the proper
amount of reasonable clusters that the model needs to run to achieve the greatest accuracy. Clustering should also be ran through a large enough well-log interval so that variability can be found and identified with different cluster centroid assemblages. The variability of the cluster centroids should be present based on observations of the cross-plot assemblages; however this can be determined by the fall-off chart. The most diagnostic tool for determining the accuracy of a cluster analysis is the fall-off chart. It displays the number of runs the analysis used and plots it against the statistical significance of the clustering event. If the numbers of cluster inputs are sufficiently variable, then the chart will display a relatively flat “fall-off” in the later runs in the clustering analysis (figure 5.3). It displays the unique centroid distribution was achieved if the final 10-15% of runs show little to no clustering. Figure 5.2 shows insufficient fall-off since there are clustering events still occurring in the final 5% of the runs in the clustering analysis, therefore reassigning total cluster input would be needed for this example data set.

Figure 5.3: Fall-off histogram and plot displaying the cumulative fall-off of statistical clustering dependent on the number of runs the simulation has performed. This dataset displays clustering events in the final 5%, therefore displaying unresolved behavior.
5.2.1 Synthetic Logs

Cluster analysis can also provide a means of creating synthetic well-logs. This is performed by tagging wells that are in need of specific well-logs, however were not supplied with them. This approach is performed using the Heterogeneous Rock Analysis (HRA) Tagging module. The HRA Tagging method uses a singular well from which a dataset can “learn” from and works by applying the learned cluster values to other wells that have similar log-suites which lack a specific log that the original well can “teach” it. The tagging module within the HRA method uses Linear Discriminant Analysis (LDA) to rotate the input well-log data onto axes that maximizes the difference between cluster cells. The LDA then pools that information and assigns the prediction data to the appropriate class of cluster cells which will highlight specific outputs depending on the specific inputs. This method works in conjunction with the Principal Component Analysis and is applied during the tagging process in order to maximize the separation of the tagging of cluster centroids.

This HRA Tagging method was performed on one well, the Larson 11-26, to train the GR, DTCO, NPOR RHOZ, and DTS of its own log suite to obtain the synthetic shear slowness logs for the remaining 25 wells in this study area to be tagged. The tagging was possible due to the 25 wells having all the necessary logs (GR, NPOR, RHOB, LLD, and DT) for the Larson 11-26 tagging results to mimic from in order to create the DTSM. The DTSM was created through the entire depth interval between 9,000 to 11,000 feet. Creating the shear slowness logs for the entire dataset made calculating Dynamic Young’s Modulus, Dynamic Poisson’s Ratio, and Dynamic Bulk Modulus logs possible through equations (5.1) through (5.5).
\[ CMM_{DYN} = 13474.45 \times \left( \frac{RHOZ}{DTCO+DTCO} \right) \]  

(5.1)

\[ SMG_{DYN} = 13474.45 \times \left( \frac{RHOZ}{DTSM+DTSM} \right) \]  

(5.2)

\[ BMK_{DYN} = CMM_{DYN} - \frac{4.0 \times SMG_{DYN}}{3.0} \]  

(5.3)

\[ PR_{DYN} = \frac{(3.0 \times BMK_{DYN}) - (2.0 \times SMG_{DYN})}{(6.0 \times BMK_{DYN}) + (2.0 \times SMG_{DYN})} \]  

(5.4)

\[ YME_{DYN} = \frac{(9.0 \times SMG_{DYN}) - (2.0 \times SMG_{DYN})}{(SMG_{DYN} + (3.0 \times BMK_{DYN}))} \]  

(5.5)

Figure 5.4 displays the log suite from an arbitrarily selected well, Hill, from the 25 computed wells. Each well displays rather exceptional correlations between the compressional and shear slowness logs in relation to the ductile nature of the higher Poisson Ratio and lower Young’s modulus values derived from the computations for the UBM. This dynamic geomechanical data derived from these calculations will aid in confirming the cluster analysis values calculated from the geomechanically inclined log suite selected for data input. They will not however be included into the cluster analysis due to these logs being used in order to calculate these geomechanical values and would render them redundant when clustering.
Figure 5.4: Hill - 25083212870000 well track 1 containing gamma ray shaded yellow to represent the MBM facies and red for the UBM and LBM, track 2 deep resistivity, track 3 bulk density and neutron porosity, track 4 with synthetic shear slowness and compressional slowness, track 5 dynamic Young’s Modulus and dynamic Poisson’s Ratio, and track 6 bulk modulus. Bakken Formation units: UBM highlighted yellow, MBM highlighted light blue, and LBM highlighted orange.
5.2.2 Cluster Analysis Results

Many sets of clusters were run in the HRA Clustering module using different log inputs to achieve the best representation of the geomechanical properties. This was performed by selecting a specific log suite from a determined interval depth or zone, selecting the number of clusters then run the clustering module. Once complete, cross checking the fall-off chart along with the diagnostic cross-plots and determining if there were too many clusters or not enough to sufficiently represent the dataset is performed. This method was repeated until an appropriate number of clusters were reached. Once the quality control was complete, this strategy would represent the largest number of clusters which would also still achieve sufficient diagnostic plot readings. Clustering of bulk density, compressional slowness, and shear slowness created the best diagnostic plot readings with a 10 cluster approach. Figure 5.5 shows the fall-off for the 10 cluster approach. Adequate fall-off for the statistical analysis is represented with little to no clustering occurring after 50% of runs. Additionally, diagnostic plots for the cross-plots show a similarly successful distribution of statistical variability for the 10 cluster approach (Figure 5.6). The cluster analysis was performed through the entire Bakken Formation, with zoned intervals through the UBM, MBM, and LBM in each of the 25 wells.

The well suite in Figure 5.7, the Larson 11-26 well, was used to calibrate the clustering in comparison to provided core work performed in Chapter 3. The logs correspond to the clusters by accurately differentiating the geomechanical variables. In the fourth track, the Young’s Modulus and Poisson’s Ratio values display ductile response values for the UBM which correspond to the dark purple cluster value at its most ductile portion and black and red cluster values for the transitional phases into more brittle indicating properties. Not seen in the Larson 11-26 cluster analysis are the orange, dark yellowish-green, and dark red clusters which are
associated to the UPM as well, depending on the geomechanical properties derived from the analysis. The orange cluster values are a strong indicator of high ductile geomechanical properties which is indicated by the statistical plot in Figure 5.6. The MBM the clusters are assigned light green, dark blue, and light blue and occasionally yellow. The YME_DYN and PR_DYN logs indicates that the upper portion of the MBM has the greatest indicators of brittleness due to high YME_DYN and low PR_DYN values and observed crossover of logs. This ideal fracture zone is highlighted by the light green cluster value and can be traced throughout the upper portions of the MBM. Due to the isotropic nature of the MBM facies, the dark and light blue cluster values represent higher than normal brittleness indications.

Cross-sections displaying cluster analysis values were created within the study area (Figures 5.8 through Figure 5.11). The orientation was selected for these cross-sections to be in the strike (NW-SE, Figure 5.8 and Figure 5.10) and the dip (NE-SW, Figure 5.9 and Figure 5.11) of Elm Coulee Field to represent the field center and the lateral variability of geomechanical properties experienced in the study area. The wells selected for each of the cross-sections are represented in Appendix B.

The lateral variability seen throughout the study area for the MBM indicates that the dark and light blue cluster values can predict ideal geomechanical properties; however the light green cluster values highlight the highest quality of brittleness derived from the dynamic mechanical properties. The yellow cluster value is typically associated with the MBM Facies A and is possibly due to the higher calcite content found in the fossil fragments associated to the facies. This can be confirmed due to the yellow cluster values also, occasionally, occurring where the MBM Facies F occurs in the log data, which is commonly associated to MBM Facies F due to similarly facies and high calcite values. There is less to infer when observing the LBM.
Figure 5.5: Fall-off plot for the Bakken Formation 10-cluster approach showing a good statistical representation of the data set, marked by the flat nature of the final 50% of the runs.

Figure 5.6: Diagnostic cross-plot of 10-cluster approach displaying ideal separation of cluster centroids within the dataset.
Figure 5.7: Larson 11-26 well log suite. Track 1: gamma ray with highlighted zonations for UBM, MBM, LBM. Track 2: bulk resistivity and neutron porosity. Track 3: compressional slowness and shear slowness sonic logs. Track 4: Young’s Modulus and Poisson’s Ratio values. Track 5: bulk modulus. Track 6: cluster unitless values.
Figure 5.8: Northwest-southeast cross-section of cluster analysis values. All wells within study area which contain DT logs are represented in the map. Cross-section corresponds to Figure 5.10.

Figure 5.9: Northeast-southwest cross-section of cluster analysis values. All wells within study area which contain DT logs are represented in the map. Cross-section corresponds to Figure 5.11.
Figure 5.10: Northwest (A) – southeast (A’) cross-section of cluster analysis values with datum on the contact between the UBM and the lower Lodgepole Formation. Track 1 contains gamma ray for easy identification of zonation. Color highlights within the logs represent: yellow for UBM, light blue for MBM, and orange for LBM. Wells used for cross-section are represented in Appendix B.

Figure 5.11: Northeast (B) – southwest (B’) cross-section of cluster analysis values with datum on the contact between the UBM and the lower Lodgepole Formation. Track 1 contains gamma ray for easy identification of zonation. Color highlights within the logs represent: yellow for UBM, light blue for MBM, and orange for LBM. Wells used for cross-section are represented in Appendix B.
This is due to the lack of statistically representative mechanical properties observed in the member, which can be attributed to Elm Coulee Field resting on the basin margin of Bakken Formation deposition where the LBM eventually pinches out entirely (observed in the Larson 11-26 core). The UBM is less consistent than the other zonations. The occurrence of such a variety of clustering is represented from the transitional zone the mechanical logs experience when recording from the MBM’s dolomitic siltstone facies into the UBM’s organic rich shale. The values obtained from the geomechanical logs when entering this zonation is also significantly larger than that of the MBM, therefore allowing for greater detail in the variability of the values.
CHAPTER 6 SEISMIC

A 3D seismic survey was provided for this study, the Flying Squirrel data set, to characterize the structural features within the study area. The survey is approximately 48 square miles in area and located in Richland County, Montana (Figure 6.1). The survey was conducted in January, 2007, by Conquest Seismic Services a Division of Norex Exploration Services Incorporated on behalf of Enerplus, and was supplied for this study on their behalf.

Figure 6.1: Pre-plot design and filed area for Flying Squirrel survey parameters provided by Enerplus. Survey area approximately 48 square miles, located in Richland County, Montana.

6.1 Provided Data

The Flying Squirrel was acquired using Vibroseis and brick layout and was originally intended for exploration of the deeper Red River Formations structural highs. The survey was reprocessed with the goal of enhancing the Bakken interval in 2010, resulting in an optimized seismic image for the entire dataset. The outcome of the seismic survey is a high resolution interval through the Bakken Petroleum System. The 3D survey was migrated to pre-stack and was not depth converted due to the lack of horizons with variable velocities or any complex
structural features above the Bakken Formation. A detailed report on data acquisition is presented in Table 6.1.

Table 6.1: Acquisition parameters for the Flying Squirrel seismic survey (Enerplus 2007).

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area</strong></td>
<td>Approximately 48 square miles</td>
</tr>
<tr>
<td><strong>Number of Sweeps/VP</strong></td>
<td>12</td>
</tr>
<tr>
<td><strong>Sweep Length</strong></td>
<td>12 seconds</td>
</tr>
<tr>
<td><strong>Sweep Frequency</strong></td>
<td>8-120 Hrz 6db/oct boost (0.2 start taper / 0.2 end taper)</td>
</tr>
<tr>
<td><strong>Listen Time</strong></td>
<td>3 Seconds</td>
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<tr>
<td><strong>Anti-Alias Filter</strong></td>
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<td><strong>Sample Rate</strong></td>
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<td><strong>Recording Patch</strong></td>
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<td><strong>Source Line Spacing</strong></td>
<td>1320 feet (diagonal)</td>
</tr>
<tr>
<td><strong>Source Line Orientation</strong></td>
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<td><strong>Source Interval</strong></td>
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</tr>
<tr>
<td><strong>Total Receivers</strong></td>
<td>7195</td>
</tr>
</tbody>
</table>

### 6.2 Interpretation

Interpretation of the Flying Squirrel seismic survey began with identifying the key horizons derived from well top data within the seismic study area in Schlumberger Petrel 2013 (Figure 6.2). This was performed to confirm the relationship between time and depth data. Following horizon interpretation a stratigraphic analysis was performed for the Bakken Formation to resolve the resolution limits of the formation. The structural interpretation is the main focus of this section with results focusing on basement faulting.
Figure 6.2: Inline 136 from the Flying Squirrel 3D seismic survey highlighting the horizons of interest for this study. Ow: Winnipeg Formation; Or: Red River Formation; Dtf: Three Forks Formation; Mb: Bakken Formation; Mc: Charles Formation; Kg: Greenhorn Formation.

### 6.2.1 Horizons

The six horizons selected and picked within the seismic survey for this study are: the Ordovician Winnipeg Formation (Ow), Ordovician Red River Formation (Or), Devonian Three Forks Formation (Dtf), upper Devonian lower Mississippian Bakken Formation (Mb), Mississippian Charles Formation (Mc), and the Cretaceous Greenhorn Formation (Kg). Surfaces were then created using these initial Inline – 136 horizon picks at a 2-Planestep (every other seismic line) interval for all inlines and all crosslines within the survey. This was conducted to achieve maximum confidence of horizon surfaces before running the Petrel guided 3D autotracking. Autotracking is a Petrel function which assigns points to previously identified signals and tracks them outwards from the initial seedpoint in all directions until the surface has
been fully identified. It is a powerful tool that works exceptionally well in a structurally quiescent survey. These identified horizons stack vertically, although not directly on one another, from the basement through to the Greenhorn Formation. The Winnipeg Formation and Bakken Formation time-structure maps are key in this seismic interpretation. Both the Winnipeg and the Bakken time-structure maps are displayed within this chapter (Figure 6.3 and 6.4) and the four time-structure maps remaining can be found in Appendix C Figure C-1 through Figure C-4.

The general trend of these time-structure maps indicates structural highs to the west with a gradual dip to the east northeast. This is in direct correlation to where the seismic is located in relation to the Williston Basin which is on the southwestern margin of the intracratonic basin. Subtle structural highs are observable at each time-structure in the centermost portion of the survey and trend in a northeast-southwest direction which is in relation to the regional maximum stress direction. Complex infill is observed by the time structure contour interval lines throughout all the measured horizons except for the Greenhorn Formation time-structure map which has relatively uniform dip. Gaussian smoothing was performed on each time-structure with four iterations and two filter widths. Trial an error led to the specific Gaussian smoothing numbers that would not impede actual data when displaying contour intervals.

6.2.2 Stratigraphy

Stratigraphy within seismic surveys can represent significant data if resolution is not an issue and extraction of rock properties through means of inversion are capable. The stratigraphy of the Bakken Formation, in terms of seismic, covers approximately 7msec at 20-80Hz. This is less than the thickness of one seismic peak within the survey for the entire Bakken Formation (UBM, MBM, and LBM) (Figure 6.5). Inversion of the dataset is not possible at this resolution due to a high risk of contamination, despite the high resolution post-processing performed.
Figure 6.3: Winnipeg Formation time-structure map. Note the east northeast dip direction and the northeast-southwest oriented structure highs located in the center of the image.
Figure 6.4: Bakken Formation time-structure map. Note the east northeast dip direction and the northeast-southwest orientated structure highs located in the center of the image.
Due to this a stratigraphic interpretation was not conducted for the Flying Squirrel survey and instead the focus will remain on a structural interpretation.

Figure 6.5: Inline-142 from the Flying Squirrel seismic survey with enlarged view of a seismic peak (red horizon) identifying the Bakken Formation horizon (Mb), and a seismic trough (blue horizon) identifying the Three Forks Formation (Dtf).

6.2.3 Structure

Deriving the history of the Precambrian basement of the Williston Basin is critical when attempting to understand the basin’s evolution, structural configuration, and depositional patterns. An initial unaided structural interpretation was performed within the survey which was then confirmed by implementing attribute analysis techniques to the final dataset. The goal to the structural interpretation of basement faulting in Elm Coulee Field is to discover whether or not these basement faults propagate through to the Bakken Formation. If these structural features are present through the Bakken Petroleum System, they can act as conduits of hydrocarbons to
source other formations and can enhance fracturing within geomechanical identified brittle zones.

6.2.3.1 Fault Interpretations

Fault interpretation is difficult in the Williston Basin due to the relative structural quiescence. The Winnipeg Formation time-structure map overlies the Precambrian basement and will be implemented in to the interpretation for scale of basement faulting, along with the formation of interest, the Bakken Formation time-structure map. Time to depth conversion was not necessary for fault interpretation for the Flying Squirrel survey due to the lack of robust structural features.

Basement fault interpretation required a large vertical exaggeration to identify discontinuities associated to faulting features, sometimes as high as 20-times vertical scale, and then quality checked at 5-times vertical exaggeration for accuracy (Figure 6.6). Fault analysis was conducted on every inline and every crossline within the survey. This approach was to maximize the fault resolution and helped in differentiating the fault families. 118 individual fault features were identified throughout the entire 48 square mile dataset which was achievable due to the high resolution of fault interpretation at one-timeslice distances (Figure 6.7). Figure 6.7a shows the robust volume of faults analyzed in an oblique view, followed by an oblique view of the Winnipeg time-structure map (Figure 6.7b) and finally both fault and Winnipeg time-structure map combined (Figure 6.7c). Figure 6.8 shows the same map and fault combination as before while also incorporating the Bakken Formation time-structure map. From this view, the Precambrian basement faults can easily be identified as propagating through the Winnipeg and Red River Formations but do not intersect the Bakken Formation. Observing the basement faults in the Z-scale (time) shows that although these faults are not intersecting the Bakken, they are
controlling the time-structure map to mimic the trends in contouring to the Winnipeg time-
structure map (represented by the red lines) (Figure 6.9).

Figure 6.6: Inline-142 at 5-times vertical exaggeration, confirming the accuracy of basement
fault picks. Some faults propagate up through the Winnipeg Formation (highlighted in the pink
horizon).
Figure 6.7: Oblique view of seismic survey. A) 118 Precambrian basement faults identified within study area. B) Time-structure map of the Winnipeg Formation which lies stratigraphically just above basement. C) Combination of both map and faults.
Figure 6.8: Oblique view of Flying Squirrel seismic with both inline and xline present. 
A) Winnipeg Formation time-structure map with all interpreted Precambrian basement faults. 
B) Addition of the Bakken Formation time-structure map, faults do not propagate through Bakken Formation at seismic scale.
Figure 6.9: Z-scale (time) view of: A) 118 Precambrian basement faults; B) Winnipeg Formation time-structure map with basement faults; C) Bakken Formation time-structure map stratigraphically above the Winnipeg; D) inferred trends of the basement faults superimposed onto the Bakken Formation time-structure map.
6.2.3.2 Attribute Analysis

A number of attribute analyses were conducted on the seismic survey for this study in order to confirm the structural interpretations and to maximize the use of the dataset. Of these methods: 3D Curvature, Azimuth, Variance, Dip deviation, and Ant Tracking were all implemented (Figure 6.10). The 3D Curvature method uses a particular point on a curved volume by defining it as the rate of change of direction from that particular curve. This method often implements the second derivative of the curve in order to obtain its direct measurement, except in the special case of zero dip. The Chaos method for computing attributes is a measurement of the lack of organization within the seismic survey in relation to the dip and azimuth estimations. Chaos method is used to illuminate faults and discontinuities and for seismic classification of chaotic textures. Variance method is a similar approach to the Chaos method; however they differ due to the variance method using estimations of local variance in the signal and provides greater ability of input variations such as structural smoothing. Variance is an ideal method in identifying edge detection in faults and discontinuities, and is typically used for objectives (structural features) in the 32 – 64 millisecond range (Petrel, 2011). Dip deviation method uses the difference in dip trend and the instantaneous dip to derive values for interpretation. This method tracks rapid changes in the orientation of the field which is useful for identifying truncations and edges of structural features, also when trying to identify low-angle faults. Ant Tracking is a multi-component method which comprises multiple attribute inputs. It is used to extract faults from pre-processed seismic volume. Of the multitude of attribute analysis options, Ant Tracking was chosen due to the approach of combining multiple inputs of attributes and having the best correlation to discontinuities.
Figure 6.10: Seismic volume attributes tested for this study to extract faults within the study area. Each image was obtained from the relative Bakken Formation time-slice at -2090ms. A) Dip attribute; B) Azimuth attribute; C) 3D Curvature; D) Variance attribute; E) Ant Tracking attribute.
Using Ant Tracking to extract faults and discontinuities requires multiple steps to reach the final output. The first step is to perform seismic conditioning, which can be achieved by structural smoothing of a realized seismic dataset. Smoothing of an input signal which is guided by the local structural features increases the continuity of the seismic survey. This is performed by computing the principle component dip and azimuth to determine the local structure and then is followed by Gaussian smoothing parallel to the orientation of found structures. Once structural smoothing is complete, the second step is to enhance the spatial discontinuities in the seismic data by implementing an edge detection attribute to generate faults and edge detection. This can be achieved using three different attributes: Chaos, Variance, or Dip Deviation. This study will focus on the Variance approach due to its ability for more user input as described previously in this section. The next step in the process is the first phase of implementing the Ant Tracking attribute volume. Edge enhancement is required at this phase and acts as an amplifier for enhancing the fault attributes by suppressing noise and remains of non-faulting events. This is how Ant Tracking acquired its name, because of the process emulating the behavior of ant colonies in nature and how they implement their pheromones to mark their paths in order to optimize gathering food. Unlike real ants however, Ant Tracking uses algorithms to create synthetic “ants” that can track specific patterns in the seismic discontinuity volume which can identify fault zones and as a result these fault zones display an attribute volume that has great detail. For the last step in this process, user input is implemented to fine tune the results until an appropriate volume has been achieved. Figure 6.11 displays these steps in detail, and Figure 6.12 represents the final output from the Ant Tracking attribute analysis.
Figure 6.11: Inline-136 Ant Tracking attribute analysis methodology: 1) original seismic volume, 2) smoothed volume, 3) Variance attribute, 4) Ant Tracking attribute.
6.3 Summary

The Precambrian basement faults were interpreted with a high amount of confidence. The series of small-scale deformations are observed and interpreted as small scale faults in the basement level. Fault analysis was performed at every singular inline and xline, this high resolution approach leads to the interpretation confidence. The orientation of these faults generally trend in the northeast-southwest, with a select number of faults trending east-west.

Although the Ant Tracking method has been implemented successfully in other studies (O’Brien et al., 2011; Angster, 2012; Eidsnes, 2014), it was relatively unsuccessful in
complementing the structural features derived in the user identified faults. When comparing inline-142 from the fault interpreted structurally smoothed volume to the inline-142 of the Ant Tracking volume, the interpretation is not represented in the Ant Tracking volume (Figure 6.13). When applying a similar approach to identify lateral continuity between the basement faults, Figure 6.14 displays the Z-scale (time) of the relative Winnipeg depth with only the northeastern-most portion displaying any correlations.

Figure 6.13: Inline-142: A) structurally smoothed and fault interpreted seismic volume, B) Ant Tracking attribute volume with superimposed fault interpretation displaying no correlation.
Figure 6.14: Z-scale (time) view of: A) 118 Precambrian basement faults; B) Winnipeg Formation time-structure map with basement faults; C) Ant Tracking attribute volume in z-scale (time) at the relative Winnipeg Formation depth. D) Superimposed basement fault orientations on top of the relative Winnipeg Formation depth of the Ant Tracking volume.
CHAPTER 7 DISCUSSION

The intention for this chapter is to identify the relationships within the presented data and draw conclusions from them.

The geomechanical properties identified through the TerraTek TSI testing and later confirmed with Proceq Bambino HLD converted UCS values, share strong correlations to bulk mineralogy in the Coyote-Putnam XRD data. The cross-plot in Figure 7.1 represents the Converted UCS value cross-plotted against quartz/silica, dolomite, calcite, and illite weight percent. The linear regression shows a strong correlation for both illite ($R^2 = 0.7316$) and dolomite ($R^2 = 0.3466$) cross-plots. If clay content is increased, low UCS values are observed. This is due to the ductile nature of clays which is apparent in the Upper Bakken Shales and Lower Bakken Shales where weight percent of clays reached 18-24%. Dolomite rich intervals increase towards the upper Middle Bakken Member and correspond to higher UCS values. This relationship is noted in track 7 and 8 in Figure 7.2, notably by the increase in UCS in the brittle zone indicated by the Young’s Modulus and Poisson’s Ratio crossover in the upper Middle Bakken. Correlations could not be derived from the cross-plots of quartz or calcite weight percent versus UCS values. This displays the limits of the Bambino in relation to bulk mineralogical conclusions; however, it is an accurate tool for acquiring geomechanical properties.

The mechanical cluster analysis shows promise for projecting cluster values to wells with similar log suites. Trial-and-error went into this method until the best fit approach of upscaling was accomplished. The final result found reasonable trends which were identified within the Larson 11-26 well-log suite and UCS values, Young’s Modulus, and Poisson’s Ratio values
The converted UCS value mimics the clustering values where the more brittle MBM facies are highlighted light green. The converted UCS value has an increase in value and counter to that trend the Upper Bakken Shale has a distinct decrease in UCS value. The calculation of Young’s Modulus and Poisson’s Ratio show cross-over in the reservoir facies within the MBM and the same increasing trend is identified for the converted UCS. This confirms that the Bambino derived data corresponds well with low Poisson’s Ration and high Young’s Modulus vales, and vice-versa, and accuracy in the cluster analysis.

The Flying Squirrel seismic survey was interpreted at a high resolution by expanding the vertical scale which exaggerates the discontinuities and increases the confidence in interpreting specific fault features. This same seismic survey was interpreted previously by Honsberger (2013) with a geophysics approach in the interpretation. Honsberger used a combination of dip and azimuth attribute analysis to interpret a left-lateral strike slip system (Figure 7.3). This interpretation differs from that of this study due this study identifying a series of small scale faulting events as opposed to singular large scale lineaments from the Honsberger study. The most significant difference in interpretation is that Honsberger insists that the lineaments propagate through the Bakken Formation time-structure map; however, when looking at the seismic in vertical scale it does not show evidence of this occurring at the seismic resolution of the Flying Squirrel survey. The orientation of the major lineaments do agree with this study and from the TerraTek core derived maximum horizontal stress as trending in the northeast-southwest direction. The tools used to aid in the interpretation in this study were different than in the 2013 study, possibly adding to the difference in interpretation. Identifying faults using every single inline and crossline increased the interpretations confidence. The interpretations for this study remains that there is no evidence of Precambrain basement faults propagating through the
Bakken Formation at a seismic resolution. The lack of evidence may also be attributed to the ductile nature of the Upper and Lower Bakken Shales which could lead to fault “healing”.

Figure 7.1: Cross-plots of converted UCS data against bulk mineralogical values. Correlations are found for both dolomite ($R^2 = 0.3466$) and illite ($R^2 = 0.7316$) cross-plots.
Figure 7.2: Log suite of the Larson 11-26 well. Cluster values represented in track 6, TerraTek TSI testing results in track 7, and Bambino derived and converted UCS values in track 8.
Figure 7.3: A) Winnipeg Formation dip/azimuth attribute time slice highlighting basement lineaments (Honsberger, 2013). B) Bakken Formation dip/azimuth attribute time slice highlighting basement lineaments with left-lateral system (Honsberger, 2013). C) Winnipeg Formation time-structure with interpreted small scale faulting from the basement. D) Bakken Formation time-structure map with no faults propagating through the formation at seismic scale.
8.1 Conclusion

The main objective of this study was to characterize the geomechanical properties of the Bakken Formation at Elm Coulee Field. The geomechanical properties were integrated with lithofacies descriptions, bulk mineralogy data, and cluster analysis to upscale the data set to field proportions. Seismic interpretation was then conducted to highlight structural features within the field that in conjunction with brittle geomechanical properties can highlight ideal reservoir conditions.

- Bulk mineralogy (XRD) was assessed in the Coyote-Putnam well which displays dolomite increasing significantly in the upper-MBM, typical of the upper portion of the MBM Facies B, the reservoir facies at Elm Coulee Field.

- Elemental data was sampled from both cores at an interval of every 6 inches, through the entire Bakken Formation. Principle Component Analysis was performed on the data which helped organize the dataset into five groups: terrigenous minerals, organic matter and redox conditions, anoxic indicator, carbonate and dolomite, and zircon.

- Geomechanical properties derived from TerraTek sampling on the Larson 11-26 core were cross referenced with Proceq Bambino HLD values to derive the computed UCS values. Once confirmed acceptable, Bamino HLD values were conducted on the Coyote-Putnam core and converted to UCS values using the linear equation developed from the Larson 11-26 core properties.
Coyote-Putnam XRD data was cross-plotted against the HLD values and identified a strong correlation with the HLD vs illite plots, translating to the accuracy of geomechanical properties in conjunction to bulk mineralogy.

Synthetic shear slowness logs were developed in 25 wells from the field area using HRA Tagging methodology. Dynamic Poisson’s Ratio, dynamic Young’s Modulus, and dynamic Shear Modulus were then calculated using the log suite of all 25 wells.

To further assess the geomechanical properties of the 25 wells selected for synthetic shear slowness logs, HRA cluster analysis was performed using the Bulk Density, DTC, and synthetic DTSM as inputs with a 10 cluster approach.

Cluster tagged wells were then projected into cross-sections to further identify the trends of heterogeneity of the geomechanical properties for the study area.

Seismic interpretation was performed to identify basement structural features within Elm Coulee Field.

Small discontinuities in the seismic were interpreted at a high resolution to identify the faulting occurring from the basement through the Winnipeg Formation. The faults do not reach the Bakken Formation at seismic resolution.

The random nature of small scale faults is clear throughout the seismic survey, however two structural trends were identified: the major being northeast-southwest trending and the less frequent east-west trend.

The seismic interpretations in relation to the upscaling of cluster analysis data can highlight fracture prone zones which can lead to higher producing reservoir targets.
8.2 Recommendations for Future Work

- Expand study area to entire Elm Coulee Field and apply the same methodology this study presents. Even without seismic information, mechanical stratigraphy along with elemental and bulk mineral analysis can aide in well planning operations for optimization.

- Acquiring a core with a thicker Bakken interval (possibly from the center of Elm Coulee Field) and performing a Uniaxial Geomechanical assessment would strengthen the UCS correlation with the Larson 11-26 well, thus aiding in the projection process to wells with the entire Bakken interval.

- Creating synthetic shear slowness logs for all wells within Elm Coulee Field that contain DTC logs and the appropriate log suite to perform HRA clustering of geomechanical values.

- Investigate small-scale faulting which occurs below seismic scale by interpretation through lateral log data and mapping the results in conjunction with geomechanical properties to highlight fracture networks.
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Honsberger, 2013, Geophysical Insights into the Bakken: Secrets from a Sleeping Giant, Elm Coulee Bakken Field (Sleeping Giant), Montana USA: Search and Discovery Article #20187, p. 7.


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APPENDICIES

Table A.1: Wells used for cluster analysis. Well names and API numbers.

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Table B.1: Northwest-southeast cross-section wells and API numbers.

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Table B.2: Northeast-southwest cross-section wells and API numbers.

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Figure C.1: Red River Formation time-structure map. Horizon displays dip towards the east at a 5msec contour interval.
Figure C.2: Three Forks Formation time-structure map. Horizon displays dip towards the east at a 5msec contour interval.
Figure C.3: Charles Formation time-structure map. Horizon displays dip towards the east at a 5msec contour interval.
Figure C.4: Greenhorn Formation time-structure map. Horizon displays dip towards the east at a 5msec contour interval.