FRACTURE ANALYSIS OF THE BAKKEN FORMATION, WILLISTON BASIN.
FIELD STUDIES IN THE LITTLE ROCKY MOUNTAINS AND BIG SNOWY
MOUNTAINS, MT, AND BEARTOOTH MOUNTAINS, WY,
AND 3D SEISMIC DATA, WILLISTON BASIN

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

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ABSTRACT

The Bakken Formation, of the Williston Basin, is well known for its substantial hydrocarbon recovery despite its low primary porosity and permeability. Fractures within the petroleum system have been discovered to play a key role in increasing local porosity and permeability of a well. Fractures not only aid hydrocarbon recovery, but also provide a tool in understanding structural development of a basin, such as internal and external stress development.

The Williston Basin is an intracratonic basin in North America that has consequently experienced minimal tectonic influence. However, the presence of subsurface fold structures and natural fractures provide evidence of stress transfer, which has occurred in a wrench tectonic style fashion. Fracturing associated with the wrench system is poorly understood; and, by applying fracture analysis, a better understanding of the wrench system and origin of fractures is possible.

Regional northeast and northwest fracture trends are identified throughout the Williston Basin using previous studies, attribute analysis of 3-D seismic data from the Billings Anticline area, and field studies located in north central Montana and northern Wyoming. A right lateral wrench fault model is applied to explain regional fracture and fold orientations.

Fracture measurements acquired in the field and from curvature attribute analysis of the 3-D seismic data show favored concentric and radial fracturing, associated with structural orientation. These structurally oriented fractures are compared to regional trends and show favored fracture patterns related to structural trend.

Mechanical stratigraphy properties are analyzed using an additional outcrop from the Bighorn Basin in the Beartooth Mountains, northern Wyoming, which is age and lithologically equivalent to the Bakken Formation. Results show concentrated fracturing within the coarse middle member of the Cottonwood Canyon Formation and extensive radial fractures that continually cut through the Cottonwood Canyon, Three Forks, and Lodgepole Formations.
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ACKNOWLEDGMENTS

I am forever grateful to my advisor Dr. Rick Sarg for not only his expert advice and wonderful guidance throughout this study, but also for allowing me to participate in other projects around the world, which has helped me in my own research and greatly broadened my geologic knowledge.

I would also like to thank my committee members Dr. Steve Sonnenberg and Dr. Bruce Trudgill. With Dr. Sonnenberg’s great knowledge of geology and application to petroleum systems, such as the Williston basin, he provided helpful ideas for study topics and key references to use. Dr. Trudgill’s outstanding teaching ability and great structural input has helped me tremendously not only in this study, but throughout graduate school.

Thanks to the students, professors, and members of the Colorado School of Mines Bakken Consortium for the valuable discussions and funding throughout the years.

I owe a huge thanks to my friend and field assistant, Johan Claringbould. His enthusiasm for geology, patience, and great ideas in the field has had a great influence on this work. I wish him the best of luck in his continuing studies.

Thanks to the “mapping software pro” Mike Doe, who sacrificed a lot of his time getting me started and making the 3-D modeling portion of this study possible.

I would also like to thank the Colorado School of Mines Geology and Geological Engineering Department. The faculty and staff in this department have provided me with exceptional educational and life experiences that will be carried with me forever. Special thanks to Marilyn Schwinger and Debbie Cockburn for making my life less stressful by handling all the administrative matter and endless paper work.

I’m especially grateful for the loving support of my parents who have supported and encouraged me to follow my interests no matter where they take me. I also dearly thank my friends, neighbors, and family members who have provided great support and essential mental escapes, which permitted the spark of several great ideas.

A special thanks goes to Jade Everett, who has relentlessly encouraged me throughout graduate school, and has kept my focus in the right direction. Her selfless support has carried me through the thick and thin of graduate school. Thank you so much!!
CHAPTER 1
INTRODUCTION

1.1 Importance

Fractures within sedimentary strata develop as a result of structural and stratigraphic stresses. Once produced, fractures often provide preferable fluid migration paths for basinal fluids, such as hydrocarbons. Understanding the character and properties of fracturing provides a tool to, not only understand fluid migrations, but to also understand internal and external stresses of a basin through time.

The Bakken petroleum system is a system within the Williston Basin which, as a result of low primary porosity and permeability, relies heavily on fracturing for hydrocarbon recovery. Today, Bakken reservoirs are commonly artificially fractured, significantly increasing local permeability of a well, and increasing the efficiency of an individual well. Surprisingly, few fracture studies have been performed that focus on the origin, generation, and characteristics of natural fracturing in the Bakken petroleum system. This has resulted in a poor understanding of natural fracture networks in the Bakken.

This study focuses on regional and localized fracturing within the Bakken petroleum system incorporating subsurface data and field data collected at related outcrop locations. Regional fractures are studied using outcrop fracture orientation data, subsurface fracture data from previous studies, and interpreted 3D seismic data. Localized fracturing along structures are studied using 3D modeling of the Big Snowy Mountains and relating strain maps to the basin. Mechanical stratigraphy properties of fractures in lithological and age equivalent strata to the Bakken Formation are also analyzed.

Conclusions reached in this study are focused towards both scientific and industry needs. Results of this study can be applied to enhance recovery of hydrocarbons from the Bakken system in the Williston basin. Understanding fracture development aids in ones understanding of reservoir characteristics and quality, particularly in an unconventional tight systems, such as the Bakken Petroleum system. Scientifically, this project will not
only assist with understanding stress development within the Williston Basin, but with fracture development within intracratonic basins and solitary structures, such as anticlines.

1.2 Objectives

The main objectives of this study include:

1) Measure fracture orientations at outcrop and relate trends to regional fracture trends within the Williston Basin.

2) Interpret subsurface fracture systems within the Williston Basin using attribute analysis on a 3D seismic grid.

3) Build a simple 3D model of the Devonian Jefferson Formation of the Big Snowy Mountains and structurally restore to understand localized fracturing along the anticline structure and relate this to similar structures within the basin.

4) Map fracture distribution in an outcrop in Clarks Fork Canyon, Beartooth Mountains, to understand mechanical stratigraphy properties of fracturing.
CHAPTER 2
BACKGROUND

2.1 Regional Setting

The Bakken petroleum system lies within the intracratonic Williston Basin located on the western edge of the North American craton, straddling Canada and the United States (Figure 2.1). The basin is bounded by subtle structural highs and forms a broad deep basin. The basin lies unconformably on a complex Precambrian basement, which has influenced depositional patterns, structure, and thermal properties throughout its development.

![Regional Map of the Williston Basin](image)

Figure 2.1 Regional Map of the Williston Basin.

2.1.1 Precambrian Basement

Structural and stratigraphic controls within the Williston Basin are ultimately governed by the complex Precambrian basement of North America (Carlson and Anderson, 1965; Gerhard et al., 1991; Fowler and Nisbet, 1985; Green et al., 1985).

The underlying Precambrian is composed of three main geologic provinces; the Churchill hinterland (CH), Trans-Hudson Orogen (TH), and Superior Province (SU)
The Trans-Hudson Orogenic belt is the result of the collision between the Superior and Churchill Provinces, occurring ~2.0 Ga, (Hoffman, 1991). The boundaries between these provinces trend in a north/south orientation. The more complex Trans-Hudson Orogen province comprises the dominant terrain beneath the Williston and is responsible for the structural and/or thermal subsidence of the Williston Basin, that was initiated ~530-440 Ma (Kaminski and Jaupart, 2000).

Although it is poorly understood what initiates subsidence of intracratonic basins, studies have shown that subsidence of the Williston Basin is controlled by the nature of the Precambrian basement pertaining mostly to the complex Trans-Hudson Orogenic province (Gerhard et al., 1991; Ahern and Mrkvicka, 1984; Fowler and Nisbet, 1985; Baird et al., 1995).

Fowler and Nisbet (1985), building from the Ahern and Mrkvicka (1984) thermal model, make a case that subsidence initiated and is driven by thermal cooling and density contrasts within the Precambrian. A underlying gabbroic intrusion is believed to have been emplaced during the Trans-Hudson Orogeny, and subsequently metamorphosed into a denser eclogite facies, shown in Figure 2.3, and has pulled down the crust.
Within the Precambrian, a left-lateral wrench fault system exists, and is held responsible for deformation of the region (Gerhard et al., 1982; Brill and Nuttli, 1983; Brown and Brown, 1987). Lineament zones have been studied (Figure 2.4), and act as stress conduits, transferring stress produced from the western North American plate boundary, into the Williston Basin region (Warner, 1975).

2.1.2 Structure

The Williston Basin is an intracratonic basin, which lies a great distance from the western mountain front, and has therefore experienced minimal tectonic stresses during its evolution. However, several important structural features exist within the basin, and share parental roots with similar structures to the west.

Structures within the basin are dominantly anticlinal, formed as anticlines over blind faults (Figure 2.1). Structures such as the Red Wing Creek and Newport Structures are identified as impact structures and are unassociated with the tectonic development of the region (Gerhard et al., 1982).

Common structural trends are displayed in structural features such as the Nesson Anticline, Little Knife Anticline, and Billings Anticline, which share a common north/south trend (Figure 2.1). Others, such as the Antelope structure, Cedar Creek Anticline and Poplar Dome share a northwest/southeast trend.
Analogous to the structures studied by Nelson (1992) in central Montana, structures in the Williston formed as a result of reactivated faults within the Precambrian (Gerhard et al., 1982). Remnants of the Trans-Hudson orogenic event and late-Proterozoic rifting are argued to be the originating deformational event that produced the faults and control structural orientation (Nelson, 1992).

Several episodes of deformation have been identified in the Williston, although not all faults display deformation in each stage. Table 2.1 below summarizes the age and style of deformational events identified by Nelson (1992).

As shown in Table 2.1, the Laramide is the youngest structural event to have influenced Williston basin structures. The majority of Williston structures experienced thick-skinned style of deformation during the Laramide (Nelson, 1992; Gerhard et al., 1982).

Figure 2.4 Map of major lineaments in the western U.S. displaying major lineament zones. These are the major stress transfer conduits controlling structure within the Williston Basin, forming a left lateral wrench fault system (modified from Gerhard et al., 1982 and O’Neill and Lopez, 1985).
2.1.3 Stratigraphy

The Williston basin is a wide asymmetric basin that has a thick stratigraphic section. Subsidence initiated in the Late Cambrian and formed a depositional basin thru the Holocene. Few structural highs affected deposition throughout subsidence, allowing flat lying stratigraphy to be deposited across the basin.

The Devonian/Mississippian aged strata, focused upon in this study, form onlap/transgressive geometry along the edge of the basin (Figure 2.5). The general lithology of the Williston Basin Paleozoic and Bakken Petroleum system is shown in Figure 2.6.

The Devonian Three Forks Formation is a dolomitized fine-grained chloritic illitic mudstone to siltstone, commonly heavily bioturbated in the upper part. It sits unconformably below the Bakken Formation and can act as a fractured reservoir to the petroleum system. The Sanish pool member of the upper Three Forks is a discontinuous fine sandstone that also provides poor reservoir properties.

The Bakken Formation is composed of three members. The Upper and Lower Bakken shale are composed of black organic-rich siliceous shales. A large gamma-ray spike allows these shales to be easily recognized on logs. “Micro-cracks”, resulting from differential pressure, characterize the shales and aid to reservoir properties (Vernik, 1994).

The middle Bakken member is generally a dolomitized siltstone ranging to a silty fine crystalline dolomite. Several facies types have been identified. These are shown and described in Figure 2.6.

<table>
<thead>
<tr>
<th>Age</th>
<th>Style of Deformation</th>
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<td>Proterozoic</td>
<td>Normal</td>
</tr>
<tr>
<td>Cambrian/Early Ordovician</td>
<td>Reverse</td>
</tr>
<tr>
<td>Devonian/Mississippian</td>
<td>Reverse</td>
</tr>
<tr>
<td>Post-Pennsylvanian/pre-Middle Jurassic</td>
<td>Normal</td>
</tr>
<tr>
<td>Late Cretaceous/Early Tertiary (Laramide)</td>
<td>Left-Lateral Reverse</td>
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Table 2.1 List of deformational events affecting the Williston Region (Nelson, 1992).
The Mississippian Lodgepole Formation overlies the Bakken. It is most commonly composed of a medium to light gray, lime mudstone to wackestone with shale partings. It sits conformably over the Bakken Formation, and is widespread throughout the region.

![Diagram of Williston Basin cross-section](image)

Figure 2.5 General cross-section through the Williston Basin from west (left) to east (right). Modified from Meissner, 1978.

### 2.1.4 The Bakken Petroleum System

The Williston Basin contains several conventional and unconventional hydrocarbon plays (Peterson, 2006). Examples of conventional include the; Madison (Mississippian) Play, Red River (Ordovician) Play, Pre-Prairie Middle Devonian and Silurian Play, Post-Madison to Triassic Clastics Play. Example of unconventional include the Bakken Fairway Play. The most prolific of these is the Bakken. Estimated by the USGS to have over 3.65 billion barrels of oil in place, the Bakken Petroleum system is an important natural resource to North America.

Production of the Bakken system initiated in the late 1950s and has continued ever since. The Antelope field was the first to be discovered, and so far several other fields have subsequently been discovered. The application of horizontal drilling and artificial fracturing has allowed fields such as Elm Coulee and Parshall to be extremely large producers.
Figure 2.6 Overview of the Paleozoic strata of the Williston Basin. Red lines define the Bakken petroleum system. Facies description of the Middle Bakken member.
The Bakken is a mixed carbonate/clastic system that has low porosity and permeability. Permeability ranges from 0.1mD to 0.57mD, and porosity averages ~1% (Meissner, 1978). It is the large amounts of kerogen, the presence of fractures, and elevated pressures that make the system work. The upper and lower shales provide a rich hydrocarbon source, and can act as a reservoir where “micro-cracks” are present (Vernick, 1994). The middle member of the Bakken is the main targeted reservoir and has variable porosity/permeability between facies. With the aid of natural and artificial fracturing, the upper Three-Forks and lower Lodgepole have also been shown to contribute as reservoirs.

2.2 Outcrop Locations

Three outcrop locations have been used for this thesis, shown in Figure 2.7: 1) The Little Rocky Mountains; 2) The Big Snowy Mountains; 3) Clarks Fork Canyon, in the Beartooth Mountains. The purpose of each location is described in detail in Chapter 3. The following section summarizes the general geology and geological significance of each.

![Regional Map highlighting outcrop locations with yellow stars.](image)

Figure 2.7 Regional Map highlighting outcrop locations with yellow stars.
2.2.1 Little Rocky Mountains

The Little Rocky Mountains are located in north central Montana near the western edge of the Williston Basin (Figure 2.7). Initially studied and explored for gold (Hayden, 1868), the Little Rockies provide exposure of Devonian/Mississippian strata within close proximity to the Williston basin. Figure 2.8 summarizes the general geology of the Little Rocky Mountains.

Marking the northeastern extent of the Great Falls Tectonic Zone (GFTZ), the Little Rocky Mountains expose Precambrian gneisses through Cretaceous strata in a domal structure cored by an alkalic intrusion (O’Neill and Lopez, 1985). The location of the intrusion was structurally controlled during the creation of the GFTZ by deep-seated preexisting faults within the Precambrian (Thom, 1923; O’Neill and Lopez, 1985; Wilson and Kyser, 1988).

The growth of the Little Rocky Mountain dome, described by Wilson and Kyser (1988), is complex due to multiple phases of uplift during the intrusion. The first phase of uplift occurred during initial emplacement of a Tertiary alkalic intrusive body. A continuous faulted contact between the igneous and sedimentary rocks and a lack of contact metamorphism within the adjacent Cambrian strata indicates a secondary uplift event, which is interpreted to be the consequence of further igneous activity within the laccolith (Wilson and Kyser, 1988).

2.2.2 Big Snowy Mountains

The Big Snowy Mountains are located ~144 km south southwest of the Little Rocky Mountains, Figure 2.7. Figure 2.9 summarizes the geology of the Big Snowy Mountains. The double plunging anticlinal structure trends to the northwest at ~270°. It is asymmetric in nature with the steeper limb of the anticline dipping to the south at ~40-60° while the gentler northern limb dips at approximately 3-10° (Figure 2.9).
Figure 2.8 Summary of the Little Rocky Mountains. Geologic map of the Little Rocky Mountains (top) from Knechtel, 1959. General north/south cross-section (lower) from Klauk (2007). Stratigraphic column of outcropping formations (right). Colors of stratigraphic column relate to colors on map.
Structurally, the Big Snowy Mountains are similar to structures in the Williston Basin. The mountains sit over a northeast dipping basement fault formed during Proterozoic rifting (Nelson, 1992). This fault marks the southern boundary of a east/west trending rift valley, while the Cat Creek fault, to the north, marks the northern valley boundary.

The underlying fault of the Big Snowy Mountains was later reactivated during other deformational events described above. The most recent deformational event was the thick-skinned Laramide (Nelson, 1992).

2.2.3 Clarks Fork Canyon (Beartooth Mountains)

Clarks Fork Canyon is located on the southeastern corner of the Beartooth Mountains, Figure 2.7. At this location, strata of the western Big Horn Basin is uplifted and exposed in the footwall of the Beartooth reverse fault, Figure 2.10. According to Hughes (1933), throw on the Beartooth fault decreases southward and eventually terminates in Clarks Fork Canyon where it becomes a blind thrust fold. This canyon marks the southern extent of the Beartooth Mountains and the northern extent of the Absaroka Mountains.

Age equivalent strata of the Bakken Formation are exposed in the Beartooth Mountains, and comprise the Cottonwood Canyon Formation. The Cottonwood Canyon Formation is described by Sandberg (1967) as having an upper and lower shale member and a middle sandstone member similar to the Bakken Formation in the Williston Basin. The Three Forks Formation is also described by Sandberg (1967) to underlie the Cottonwood Canyon and the Lodgepole Formation overlying.
Figure 2.9 Geological Map of the Big Snowy Mountains (top) from Porter et al., 1996. Top of the map is north. Cross-section through the Big Snowy Mountains (below) modified from Reeves, 1931. General stratigraphic column of outcropping formations (right). Zone of interest is the Devonian Jefferson Formation (Dj).
Figure 2.10 Cross-section through Clarks Fork Canyon of the Beartooth Mountains (from Hughes 1933). Cottonwood Canyon Formation is upper Devonian (D).
3.1 Fracture Studies

As explained earlier, three studies were conducted for this thesis: 1) a regional fracture study 2) a localized fracture study 3) and a mechanical stratigraphy study. The conclusions of each study will then be compared to each other to better understand the behavior of Bakken fractures on small and larger scales. The methodology of each study is described below.

3.1.1 Regional Fractures

The purpose of the regional fracture study is to test regional trends within the Williston Basin and outcrop sites against tectonic fracture models that apply to the Williston region. The goal is to find a model(s) that fits the fracture trends in order to understand what tectonic stresses are responsible for the observed trends. To achieve this, the following steps were taken:

1) Populate basin fracture data with previous studies.
2) Interpret 3D seismic data from the Bicentennial field and use seismic attribute processing to highlight fracture trends within seismic area.
3) Normalize fracture orientation data from field sites to horizontal stratigraphy and plot on regional map.
4) Compare basin trends to trends within outcrop.
5) Compare regional trends to tectonic models.

3.1.2 Localized Fractures

The purpose of the localized fracture study is to observe fracture patterns on outcrop and basin structures and compare to fracture models. Strain and curvature analysis will be performed on a 3D model of the Big Snowy Mountain structure to understand fracture patterns. To achieve this, the following steps were performed:
1) Obtain fracture orientation data from basin and outcrop locations within Devonian/Mississippian strata.

2) Produce a 3D surface model of the top of the Devonian Jefferson Formation in Midland Valley’s 3D Move, using the geologic map from Porter et al. (1996) and cross-sections from Reeves (1931).

3) Structurally restore the surface to horizontal, forward model to current shape, and produce both a strain analysis and dip-curvature analysis.

4) Compare results to similar structures in the basin such as the Antelope Structure, and also compare to the regional fracture study.

3.1.3 Mechanical Stratigraphy

The mechanical stratigraphy study was conducted to understand local and regional fracture distribution within Bakken equivalent strata. Fracture data collected from Clarks Fork Canyon, Beartooth Mountains, were analyzed for fracture orientation and lithostratigraphic distribution.

Clarks Fork Canyon was chosen for this study because of its excellent exposure of the Cottonwood Canyon Formation, of the Big Horn Basin, which is age and lithologically similar to the Bakken Formation. The following steps were applied for this study:

1) Produce a detailed stratigraphic column of the Cottonwood Canyon Formation.

2) Obtain fracture orientation data from outcrop including descriptions describing the stratigraphic extent of each fracture.

3) Plot fracture orientation against stratigraphy and compared to regional and localized fracturing.

3.2 Field Work

One field season was conducted July-August, 2009 at several locations in central Montana and northern Wyoming. Structural and lithological measurements were acquired where possible along suitable outcrop sites. The Little Rocky Mountains, Big Snowy Mountains, and Clarks Fork Canyon in the Beartooth Mountains were each
targeted for the specific studies described above. The purpose of each location and details of outcrop localities are described in the sections below.

At each site, fractures were measured within Devonian and/or Mississippian age strata. Each fracture measurement included orientation data (using the right-hand rule method) and fracture descriptions (using the number system described in the example below, Table 3.1). Although not all of the information was used in this study, this system allowed for numerous fractures to be measured in detail in a timely manner.

Table 3.1 Table displaying fracture measurements and descriptions.
Example showing the number system.

<table>
<thead>
<tr>
<th>Strike</th>
<th>Dip</th>
<th>Length</th>
<th>Type</th>
<th>Relationship</th>
<th>Displacement</th>
<th>Measurement Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Hand Rule</td>
<td>1 = &lt;1</td>
<td>1 = Concentric</td>
<td>1 = Solitary</td>
<td>1 = 0</td>
<td>1 = Confident</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 = 1-3</td>
<td>2 = Radial</td>
<td>2 = Solitary</td>
<td>2 = &lt;10cm</td>
<td>2 = Unsure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 = &gt;3</td>
<td>3 = Bedding</td>
<td>3 = Swarm</td>
<td>3 = &gt;10cm</td>
<td>3 = Poor</td>
<td></td>
</tr>
<tr>
<td>183</td>
<td>80</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

3.2.1 Little Rocky Mountains

The Little Rocky Mountains provide outcrop of Devonian/Mississippian strata within close proximity to the Williston Basin. Because of its proximity, the Little Rocky Mountains are expected to be in the same tectonic regime as the Williston Basin and share similar fracture trends. Three canyons on the north, south and west side of the dome structure provided cliff-side outcrops, commonly of the Lodgepole Formation, shown in Figure 3.1. These canyons were picked because they provided to have the best exposure of Devonian/Mississippian strata. Because of the heavy biological cover in the mountains, measurements were mostly taken within the lower Lodgepole Formation.

3.2.2 Big Snowy Mountains

The Big Snowy Mountains were targeted for this study because of its exposure of Mississippian/Devonian strata that are within close proximity to the Williston Basin. The Big Snowy Mountains also provide an excellent analog to other structures within the
Williston Basin. It is a basement controlled feature and has similar timing of growth as Williston Basin structures (Nelson, 1992).

This location was used for both the localized and regional fracture study. Fracture measurements were obtained on both, steep and gentle, limbs of the asymmetric anticline structure (Figure 2.8). Outcrop locations are shown in Figure 3.2.

### 3.2.3 Clarks Fork Canyon (Beartooth Mountains)

Located on the western edge of the Bighorn Basin, Clarks Fork Canyon provides excellent exposure of the Cottonwood Canyon Formation (Figure 3.3). As stated earlier, the Cottonwood Canyon Formation is age and lithologically equivalent to the Bakken Formation, and because of this, this site was used to collect mechanical stratigraphy data as well as regional and local fracture data.

Fracture measurements were acquired in the same process as the previous sites, but with more focus on the lithological distribution of fractures. A detailed stratigraphic column of the upper Three Forks Formation up to the lower Lodgepole Formation was produced along with facies delineation of the Cottonwood Canyon Formation. The stratigraphic extent of each fracture through these formations was recorded.
Because of the outcrops limited size and hazardous conditions, fractures were measured within a narrow window of the Cottonwood Canyon Formation, focused along the lower shale and lower part of the middle sandstone.

Figure 3.2 Aerial view of the Big Snowy Mountains. Outcrop locations are shown with orange circles. Yellow dashed line defines approximate location of the anticline axis with the steep limb to the south and gentle limb to the north.

Figure 3.3 Aerial view of the southeastern Beartooth Mountains (Clarks Fork Canyon). Outcrop site is located with orange circle.
3.3 Seismic Data

The 3D seismic data used in this study were provided by Savant Resources, Inc. Located in western North Dakota, just northwest of the Billings Nose structure, the 3D seismic survey covers approximately 117 square kilometers of the Bicentennial Oil Field (Figure 3.4). Data below 2.3 seconds are proprietary and will not be displayed.

Kingdom suite software was used for interpretation and analysis of the 3D seismic. Seven wells within the surveyed area were used to produce well ties. Synthetics were produced on six of the seven wells using sonic logs, acquired from the North Dakota Industrial Commission website (NDIC). Figure 3.5 displays inline 291 showing an example of a synthetic overlay with formation top data acquired from the NDIC.

The 3D Hunt function deemed to be the best method to initially pick the seismic horizons. Manual picking was initially attempted, and discovered to be inconsistent on a very small scale, producing interpretation artifacts (“grid” pattern). This resulted in east/west and north/south “grids” on the curvature attribute maps. The 3D Hunt auto pick produced a more continuous plane, and a more accurate horizon. This is likely due to the low amplitudes of the seismic data and the gentle subsurface topography.

After the Bakken horizon was automatically picked by the 3D Hunt function, it was then manually edited in an east/west and north/south fashion where seismic data were noisy and the 3D Hunt function produced unrealistic features. Manual editing was performed to the author’s best ability, but resulted in a “grid” pattern in some areas. These areas will be highlighted in the maps with grey and not included in fracture interpretation.

The Bakken horizon was picked on the trough at approximately 2.2 seconds (Figure 3.5). The top of the Lodgepole and Prairie Salt horizons were also picked in a similar fashion, but with less accuracy. These horizons were only picked to provide scale and stratigraphic orientation. The Prairie Salt falls below the 2.3 seconds cut off.
Figure 3.4 Close up of the Williston Basin Map (Figure 2.1). Seismic location represented by the red box.

Figure 3.5 Inline 291 (east/west) of the 3D Bicentennial seismic. Two way travel time shown on vertical scale on the left. Example of well tie and synthetic shown. Green line is the interpreted Bakken horizon sitting at ~2.2 sec and the blue is the top of the Lodgepole at ~2.1 sec.
3.3.1 Attribute Processing

Curvature attributes have been found to be very useful in predicting fracture distribution and orientations (Roberts, 2001; Hakami et al. 2004). Chopra et al. (2006) define curvature as the reciprocal of the radius of a circle that is tangent to the given curve at a point. Straight lines produce zero curvature and bent lines produce higher degrees of curvature, and from these previous studies, fractures have been found to produce high curvature, thus allowing curvature analysis to highlight fractures.

Based on the successful fracture studies with curvature analysis, several curvature maps were produced using the Kingdom Advanced the *extended math calculator* curvature functions. Calculated attributes included:

1) Dip Curvature: Measure of the rate of change of dip in the maximum dip direction.
2) Minimum curvature: Measure of the curve perpendicular to the maximum curvature.
3) Maximum curvature: Measures the largest absolute curvature.
4) Strike curvature: Measures curvature in a direction that is at right angles to the dip curvature.
5) Negative Curvature: Measures magnitude of negative curvature (concave shape).
6) Positive Curvature: Measures magnitude of positive curvature (convex shape).
7) Gaussian Curve: The product of the maximum and minimum curvatures.

Additional attributes were calculated using *Rock Solid Attributes* of Kingdom Core. The following *Rock Solid Attributes* included:

1) Dominant Frequency: Measures the most common frequency in geophysical data.
2) Instantaneous Frequency: Measures the rate of change of phase over time.
3) Instantaneous Frequency Envelope Weighted: Multiplies the value of instantaneous frequency by the normalized value of the instantaneous envelope and average over a short time window.
4) Instantaneous Lateral Continuity: Measures the instantaneous curvature of seismic reflectors.

5) Similarity: Measures lateral continuity.

6) Similarity Variance: Measures the difference between smoothed similarity and its local value, which is equivalent to the high-pass filtered similarity.

7) Dip Variance: Measures the difference between the smoothed dip of maximum similarity and the local value of the dip of maximum similarity.

Because of the very subtle nature of the seismic, the two categories of attributes were used to test consistency in fracture orientation. Each category of attributes also performs its calculations on different scales. The Rock Solid Attribute toolbar is limited to running algorithms only on specified time slice focusing on the geophysical data, while the extended math calculator curvature functions run algorithms on specified interpreted horizons, such as the Bakken horizon.

3.4 Big Snowy Geomodeling

A 3-D model of the Jefferson Formation (Figure 3.6), of the Big Snowy Mountains, was constructed using Midland Valley 3D Move software. Geologic maps from Porter et al. (1996) and cross-sections from Reeves (1931) were used in concert with a 10-meter Digital Elevation Model to construct the 3-D model. Because other surfaces had a greater amount of formation contact lines on the geologic map (data control points), other surfaces were constructed prior to the construction of the Jefferson surface. These other surfaces were then used along with formation thickness data from Porter et al. (1996) to construct the Jefferson surface. This process allowed for a more accurate shape and position.

Initially, geologic formation contacts of Cambrian thru Late Mississippian age strata were digitized, using the map of Porter et al. (1996). Digitized cross-sections from Reeves (1931) were then added to calibrate the anticline structure. Using the Midland Valley 3D Move surface creator, the top of the Jefferson Formation surface was then constructed (Figure 3.6a).
The Jefferson Formation surface was edited to a more accurate shape by inserting additional cross-sections through the surface where it lacked control points. The additional cross-sections were constructed and modified in 2D Move. Sections were produced perpendicular to the fold axis to produce a more accurate model.

The constructed model is general and lacks detail. But for the purpose of this model, which is to produce strain and curvature maps, it serves a general analog to Williston Basin structures.

Once constructed, a curvature and strain analysis was performed on the Jefferson surface. The curvature map was produced on the Jefferson Formation with the intention of highlighting regions of high curvature where fracturing is likely to occur.

Strain analysis was performed using Midland Valley 3D Move strain analysis tools. To perform this analysis, the Jefferson Formation surface was flattened to horizontal and then structurally restored to its current shape using Midland Valley 3D Move tools. The strain analysis was run simultaneously during restoration measuring the distortion each cell of the surface experienced, as the model changed shape from flat to curved. Areas of high strain are expected to be regions of high fracturing.
Figure 3.6 a) Screen shot from Midland valley 3D Move showing initial digitized contacts and cross-sections used to produce the Jefferson surface. b) The Jefferson surface used for strain and curvature analysis. Model is approximately 17 miles in length (E/W) and 10 miles wide (N/S)
4.1 Regional Fracture Maps

The regional fracture map produced for this study is composed of a collection of data types including: previous studies within the Williston basin, prior core analysis, collected outcrop data, and seismic attribute interpretation. A summary of these data is shown in Figure 4.1. Overall, dominant northeast (NE) and northwest (NW) trends are recognized and are consistent throughout each data type. Figure 4.1 shows consistent NE and NW trends within the basin, while outcrop locations show more variation in fracture orientation.

![Figure 4.1 Regional map of the Williston Basin and outcrop locations. Fracture plots showing regional and local trends.](image-url)
4.1.1 Previous Studies

Of the few existing Williston basin fracture studies, NE and NW trends are commonly recognized among the studies. Previous studies focus on both structural features and within undeformed strata.

The Narr and Burrus (1987) study focuses on fracturing on the northern end of the Little Knife Structure (Figure 4.1). Natural vertical fractures are observed in the Mission Canyon Formation (above the Lodgepole Fm.), and are interpreted as extensional fractures. The combined rose plot of all fractures measured in this study show a dominant east/west trend.

The fracture study of Strum and Gomez (2009) reveals two fracture trends within the Bakken Formation. Formation Micro Image (FMI) logs of three wells were used to measure fracture orientation in “off structure” stratigraphy. Natural open fractures were measured resulting in dominant northwest orientations, while induced fractures were found to form in northeast orientations.

Murray’s (1968) quantitative fracture study concludes that a fracture system runs parallel to the strike of the Antelope structure. The open fracture system is interpreted to be a product of tensional stress occurring along regions of high curvature. This fracture system is responsible for the high hydrocarbon production rates of wells within the Sanish Pool member of the Three Forks. The map in Figure 4.2 shows the high producing wells paralleling the trend of the Antelope fold axis located at the crest of the anticline. The crest and trough of the anticline are where high curvature was calculated.

4.1.2 Core Analyses

Two core analyses from the Williston Basin were used to assist in populating basin data. Both were completed by Western Atlas International Core Laboratories in locations away from structures. The Anhel Grassy Butte analysis included measurements of several fracture types including: mineralized, non-mineralized, tectonic fractures, and induced. Although unexplained how each fracture type was identified, the results revealed a dominant NE and NW trend of natural fractures.
The Rauch Shapiro Fee 13-3 fracture analysis measured orientation of “petal fractures,” which are induced fractures produced during artificial fracturing. These fractures display current principle stress directions. This analysis revealed a dominant NE fracture trend in the “petal fractures.”

Figure 4.2 Murray (1968) structure contour map of the Bakken Formation on the Antelope Structure. Each square is equal to 1 mile and well locations plotted as black circles. Large producing wells are located on crest of structure, paralleling the strike of the structure.

4.1.3 Little Rocky Mountains

Fracture orientation and bedding strike data from each outcrop location in the Little Rocky Mountains are shown in Figure 4.3. Fracture populations vary between each outcrop location, but are weighted evenly amongst each location. Fracture orientations
are displayed as solid black and bedding strike orientations are displayed as the mesh patterns. At WP 7 in Mission Canyon, bedding strike data were not acquired.

Dominant fracture sets are recognized at each site which frequently share a near perpendicular and/or parallel relationship to bedding strike and as a result these two trends occur nearly perpendicular to each other.

Figure 4.4 plots all fracture measurements in the Little Rocky Mountains. High fracture populations and gaps within fracture orientations separate four observed fracture sets. Each set is highlighted in yellow in Figure 4.4. Set 1 trends to the northwest/southeast ranging from ~305-340°. Set 2 trends to the north ranging from ~350-250°. Set 3 trends to the northeast/southwest ranging from 30-55°. Set 4 trends to east/west ranging from 80-110°.

4.1.4 Big Snowy Mountains

Figure 4.5 plots fracture orientations and bedding strike of each outcrop location in the Big Snowy Mountains. Similar to the Little Rocky Mountains, each location displays dominant fracture trends that share a relationship to the strike of the bedding and structural trend.

Figure 4.6 plots all Big Snowy Mountain fracture measurements weighted as a whole (same as Figure 4.4). Three sets of fracture orientations are observed: set 1) a northeast (~358-25°); set 2) northwest (~300-325°); set 3) west-northwest (~270-285°). The anticline fold axis is plotted as yellow.

4.1.5 Clarks Fork Canyon (Beartooth Mountains)

The rose plot in Figure 4.7 plots all fractures measured in Clarks Fork Canyon (WP 31). Four sets of fracture orientations are recognized: set 1) north-northeast (350-30°); set 2) northwest (~295-320°); set 3) northeast (~40-65°), and Set 4) east/west (80-115°). These sets also share a similar relationship to the strike of the fold axis. Sets 3 and 4 show a near perpendicular relationship, while set 1 is nearly parallel to the fold axis.
Figure 4.3: Map of Little Rocky Mountain outcrop locations displaying fracture orientations of each location.
4.2  **Seismic Data**

Figure 4.8 is a contour map of the interpreted Bakken horizon. A northwest/southeast structural trend is revealed in a folded anticline structure, plunging to the northeast. This structure is interpreted to translate down, into the basement. Inline 291 (Figure 3.5) displays the fold structures in cross-section view near the right (west) side of the section.

4.2.1  **Attribute Processing**

The Similarity Variance attribute was found to be the most useful of the *Rock Solid Attributes* in the Kingdom seismic interpretation system. Figure 4.9a displays an example of inline 60 showing a linear trend of high amplitude events occurring at 2.1 seconds and below. This linear trend occurs on the fold structure within the seismic (Figure 4.9a), and when traced through the seismic, it trends parallel to the fold axis (Figure 4.9b). Because of its relationship with the structure and nature of the similarity variance attribute, this trend is interpreted as a zone of deformation, composed of either fractures or small faults, and/or a zone of differential compaction resulting from the underlying basement fault.
Figure 4.5: Map of Big Snowy Mountain outcrop locations displaying fracture orientations of each location.
Figure 4.6 Rose plot of all fractures measured in the Big Snowy Mountains. Interpreted fracture sets are highlighted in yellow.

Figure 4.7 Rose plot of fracture measurements collected at Clarks Fork Canyon. Interpreted fracture sets are highlighted in yellow.
Of all curvature functions processed in this study, the minimum curvature function provided the most consistent to the regional trends, and displayed the clearest results. Figure 4.10 displays the minimum curvature map processed on the Bakken horizon. Dominant NE and NW trends are observed in the minimum curvature map and are displayed in the rose plot (Figure 4.10).

Other curvature attributes that provided useful data are shown in Figure 4.11 and 4.12. The maximum curvature (Figure 4.11) and dip curvature (Figure 4.12) attributes both display consistent NE and NW trends. Although not as clear as the minimum curvature maps, these two curvature maps verify NE and NW fracture trends.

4.4 Big Snowy Geomodeling

Figure 4.13 displays the results of the strain and curvature analysis performed on 3D model of the Big Snowy Mountain structure. The surface used is the top of the Jefferson Formation (Devonian). The strain analysis (Figure 4.13a) displays a region of high strain located on the steep limb of the anticline (Figure 4.13b). This region of high strain is located where the strike of the fold axis changes strike.

The curvature analysis (Figure 4.13c) displays two trends of high curvature shown in Figure 4.13d. Two continuous linear trends, highlighted by white ovals in Figure 4.13d, of high curvature trends WNW-ESE near the crest of fold and near the trough of the fold. These trends parallel the strike of the anticline fold axis and display the highest amount of curvature. Shorter and less continuous trends, represented by purple ovals in Figure 4.13d, of high strain occur in the steep limb of the anticline structure. This set is also perpendicular to the previous.

4.5 Clarks Fork Canyon Mechanical Stratigraphy

Figure 4.14a is a photo of the Devonian/Mississippian strata that crops out in Clarks Fork Canyon of the Beartooth Mountains. The Cottonwood Canyon Formation, here on the edge of the Big Horn Basin, appears identical to the Bakken Formation of the
Figure 4.8 Screen shot of a contour map of the Bakken horizon. Color bar is in two-way time. Plot shows an anticlinal structure trending northwest. Structure shows a plunge to the northwest. Referenced inline sections run east/west and cross-lines run north/south. Seismic sections shown in Figures 3.5 and 4.9 are plotted with red lines.
Figure 4.9 a) Original and interpreted example of the Similarity Variance attribute of inline 60 (Figure 4.8). Linear zone is highlighted with red. b) Interpreted zone through 3D seismic (yellow) with Bakken contour map showing a paralleling trend to the anticline axis.
Figure 4.10 Minimum curvature map of the Bakken horizon (scale 1: 50,000). Interpreted fractures are displayed on the map to the right. Fracture colors show differing fracture orientations. Rose plot shows dominate northeast trend of interpreted fractures.
Figure 4.11 Maximum curvature map of the Bakken horizon (scale 1: 50,000). Interpreted fractures are displayed on the map to the right. Fracture colors show differing fracture orientations. Rose plot shows dominate northeast trend of interpreted fractures.
Figure 4.12 Dip curvature map of the Bakken horizon (scale 1: 50,000). Interpreted fractures are displayed on the map to the right. Fracture colors show differing fracture orientations. Rose plot shows dominate northeast trend of interpreted fractures.
subsurface. Figure 4.14 displays the measured column of the Cottonwood Canyon with facies delineation. Descriptions of each facies are described in Table 4.1.

The upper Three Forks is composed of a silty dolomitic mudstone (facies a). It forms a sharp upper contact with the lower Cottonwood Canyon Fm. The Cottonwood Canyon Formation is broken into three packages, upper and lower shaley members and a middle sandstone member. The lower member is composed of a silt-rich fissile shale (facies c) with occasional interbedded lenticular siltstone beds (facies b). These become more frequent in the upper part of the lower shale member and eventually grade into a thin to medium bedded, dolomitized, fine to medium grained sandstone (Facies d) that forms the middle member. The upper shale member is a silt-rich fissile shale (facies c) with interbedded tongues of fine dolomitic sandstone (facies d). The overlying Lodgepole Fm. has a sharp basal contact with the Cottonwood Canyon, and is composed of a bedded nodular lime mudstone (facies L).

Figure 4.14b highlights the fractures measured on the outcrop and displays the fracture distribution of the outcrop. Fracture distribution is also shown on the stratigraphic column in Figure 4.14. Most fractures are contained within the middle sandstone member of the Cottonwood Canyon Fm. Large vertical fractures are observed, occurring ~10 meters apart, that cut through the entire measured section. These through going fractures also have similar orientations.
Figure 4.13 a) Product of strain analysis with approximate location of fold axis. b) Strain analysis with regions of high strain outlined in white. c) Product of curvature analysis. d) Regions of high curvature outlined in white (parallel to fold axis) and purple (perpendicular to fold axis).
Figure 4.14 a) Devonian/Mississippian outcrop in Clarks Fork Canyon. b) Showing the measured fractures on the outcrop. Blue lines and planes represent concentric fractures and Purple lines and planes are radial fractures.
Figure 4.15 Stratigraphic column of the Three Forks, Cottonwood Canyon, and lower Lodgepole Formations. Radial (purple) and Concentric (blue) fracture distribution plotted. Light yellow box indicated measuring window.
Table 4.1 Facies descriptions of upper Three Forks, Cottonwood Canyon, and lower Lodgepole Formations in Clarks Fork Canyon.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Facies</th>
<th>Facies Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Three Forks</td>
<td>a</td>
<td>Dolomitic siltstone/mudstone, common calcite filled vugs.</td>
</tr>
</tbody>
</table>
| Cottonwood Canyon  | b      | Silt rich shale (more siltstone) very thinly bedding-
                              |       | laminated                                                |
|                    | c      | Silty shale (more shaley) black to dark grey. Very thinly
                              |       | laminated                                                |
|                    | d      | Heavily bioturbated vf-silty sandstone, organic rich
                              |       | laminated                                                |
|                    | *      | Organic Poor                                              |
| Cottonwood Canyon  | e      | fn-vf sandstone thin bedded, bioturbated                  |
| Lower Lodgepole    | L      | mud-wackestone with calcite filled vugs                   |


5.1 Regional Fractures

Regional fracture systems are commonly found in large areas of low deformation and horizontal stratigraphy (Lorenz et al., 1991; Pollard and Aydin, 1988), such as the Williston Basin. Regional fractures commonly form normal to bedding plane and are oriented with relation to the principle stress ($\sigma_1$). However preexisting planes of weakness are often followed (Lorenz et al., 1991). These types of fracture systems can also occur at great depths due to high pore pressures and differential horizontal stresses forming both open and closed fracture systems.

The regional fracture map in Figure 4.1 displays a consistent regional northeast and northwest trend of fracture orientations of all the data within the Williston basin. The Narr and Burrus (1987) study is the only anomaly and is discussed in the localized fracture discussion below.

Although there is insufficient data to constrain the extent of this regional fracture system, the scatter of data locations in the basin support a dominant northeast and northwest fracture system within the basin.

5.1.1 Outcrop Fractures

The fracture trends observed within the outcrops do not share common fracture patterns, leading to the conclusion that measured fractures are likely structurally controlled rather than regionally. Structurally controlled fractures are discussed in section 5.2 below.

Figures 4.6 and 4.7 of the Big Snowy Mountains and Clarks Fork Canyon fractures display well define fracture sets that have consistent relationships to fold axis orientation. However, sets 1 and 2 in the Big Snowy Mountains (Figure 4.6) do parallel the regional northeast and northwest regional trends found within the basin. This is also true for sets 1, 2, and 3 in Clarks Fork Canyon (Figure 4.7). These sets described in both outcrop locations are defined in section 5.2 as structurally controlled radial and
concentric fractures, but because of the similar northeast and northwest trends, these sets probably have a preexisting regional origin.

The Little Rocky Mountains however, do show a strong northwest set and a lesser northeast set, shown in Figure 4.4. These sets also probably follow the regional trend observed within the basin and are overprinted by the uplift of the dome structure.

5.1.2 Wrench Faulting

Because of the extensive nature of regional fracture systems, large scale tectonic models are applied to understand the stress regime responsible for the northeast and northwest regional fracture systems. As discussed in Chapter 2, the most acknowledged tectonic model for the Williston Basin is left-lateral wrench faulting, built within the Precambrian basement.

Wilcox et al. (1983) present a right-lateral strain ellipse model of a wrench fault system, predicting fracture and fold orientations (Figure 5.1). Table 5.1 summarizes the predicted fractures (shown in red) and fold orientations (shown in orange) displayed in the strain ellipse model (Figure 5.1).

![Figure 5.1 Right lateral strain ellipse models (Modified from Wilcox et al., 1983. Red lines indicate predicted fracture orientations. Orange indicates predicted fold axis.)](image-url)
When the Wilcox et al. (1983) wrench fault strain ellipse model is applied to the Williston Basin, and the strike of a right lateral wrench fault system (X-X') is oriented to the strike of the primary northeast trending lineaments, many similarities are shared with regional fracture trends and fold axis’s (Figure 5.2). The observed relationships are summarized in the right column of Table 5.1.

Axis’s X-X’ and C-C’ represent northeast regional fracture trends in the strain ellipse model. Northwest regional fracture trends follow the D-D’ axis. North/South trending folds in the basin such as the Nesson anticline, Billings anticline, and the Little Knife Anticline correspond to axis A-A’.

The right-lateral wrench fault model fits the data very well, however northwest trending structures such as the Cedar Creek Anticline, Poplar Dome, the Antelope Anticline do not fit the predicted fold axis (A-A’) in the model. These structures are likely the result of preexisting faults. Paleogeographic maps from Blakey (2005) show a strong northwest trend during the orogenic event of the Ancestral Rocky Mountains (Figure 5.3). This event occurred during the mid to later Pennsylvanian (Kluth and Coney, 1981). The northwest trend of the orogenic event could likely be the parental roots of northwest trending structures in the Williston region.

Table 5.1 Descriptions of strain ellipse axis’s and basin structural analogs.

<table>
<thead>
<tr>
<th>Strikes</th>
<th>Description</th>
<th>Williston Basin Analog</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-X’</td>
<td>Strike of Primary Wrench Fault</td>
<td>NE fracture trends</td>
</tr>
<tr>
<td>C-C’</td>
<td>Low Angle Conjugate Set</td>
<td>NE fracture trends</td>
</tr>
<tr>
<td></td>
<td>En Echelon conjugate sets (shear stress)</td>
<td></td>
</tr>
<tr>
<td>D-D’</td>
<td>High Angle Conjugate Set</td>
<td>NW fracture trends</td>
</tr>
<tr>
<td>B-B’</td>
<td>Bisecting conjugate set (tension stress)</td>
<td>none</td>
</tr>
<tr>
<td>A-A’</td>
<td>Long ellipse axis (parallel to fold axis)</td>
<td>North/South trending anticlines (Nesson, Billings, and Little Knife Anticlines)</td>
</tr>
</tbody>
</table>
Figure 5.2 Williston regional fracture map with Wilcox et al. (1987) strain ellipse model.
Localized Fractures

Fracture patterns produced in folded structures, such as anticlines and dome structures, form in conjugate sets, and each is 30° to the principle stress (σ1). Two types of patterns (Stearns and Friedman, 1972; van Golf-Racht, 1996) occur in these structures. Pattern 1, of Stearns and Friedman (1972), forms in conjugate sets as traversal fractures, oriented ~30° off parallel to bedding and/or structural strike. Pattern 2 forms conjugate sets similar to pattern 1, but oriented perpendicular to pattern 1. Although pattern 1 often precedes pattern 2, both patterns can be produced in the same bed (van Golf-Racht, 1996). Similar fracture patterns also occur in magmatic intrusion domes, however these are referred to as concentric and radial fractures (Koide and Bhattacharji, 1975).

Because this study involves both magmatic domes and folded anticline structures, pattern 1 will be referred to as concentric fractures (parallel to bedding/structural strike), and pattern 2 will be referred to as radial fractures (perpendicular to bedding and/or structural strike). Figure 5.4 displays the concentric and radial fractures on an anticline structure.
To display concentric and radial fracture patterns on rose diagrams, two perpendicular polygon sets, each extending $60^\circ$ (representing conjugate sets), are overlaid on top of the rose plot. Concentric patterns (blue) are oriented parallel to bedding strike or to the fold axis. The radial (purple) patterns are oriented perpendicular to the strike of bedding and the fold axis. Fractures or fracture sets that lie within the polygons are considered either concentric or radial.

5.2.1 Antelope Structure (Murray, 1968)

The extensional fractures observed in Murray’s (1968) study can be explained with the Sterns and Friedman (1972) model. The structure paralleling fractures observed by Murray (1968) are concentric fractures. As shown in Figure 4.2, high producing wells, resulting from an open fracture system that runs parallel to the fold axis, occur near the crest of the anticline, in the region of high curvature.
The high producing wells paralleling the strike of the Antelope structure and show the presence of concentric fractures. The existence of radial fractures is not documented in Murray’s (1968) study. This could likely be; 1) the characteristic of concentric and radial fractures, where concentric usually occur before radial 2) radial fractures may be present and are filled 3) they may not have developed in this gentle structure.

5.2.2 Little Knife Structure (Narr and Burrus, 1987)

The Williston fracture map in Figure 4.1 displays the rose plot of the Narr and Burrus (1987) study of Madison Formation fractures over the Little Knife Structure. A dominant east/west trend is shown and does not follow the northeast and northwest regional trends. When concentric and radial fracturing is applied to these fractures (Figure 5.5), a strong radial fracture trend is revealed and explains the east/west trending fractures.

Figure 5.5 Rose plot of Narr and Burrus (1987) fracture study of the Little Knife Anticline. Concentric (blue) and radial (purple) fracture patterns plotted on top.
5.2.3 Field Studies

When this method is applied to fractures within the Big Snowy Mountains, Figure 5.5a, concentric and radial fractures can easily be identified. Sets 2 and 3 fall within the concentric pattern and sets 1 and 4 fall within the radial pattern. Few or no other fracture sets lie outside of the two patterns, and so these fractures are very likely to have been formed during structural growth.

Figure 5.5b of Clarks Fork Canyon displays a similar relationship. Sets 3 and 4 lay within a radial fracture pattern. Set 1 lies within the concentric pattern and only part of Set 2 lies in the concentric pattern. Set 2 could likely be a conjugate set of fractures occurring on the more western fractures of Set 1, and because fractures do not always form in perfect conjugate sets, Set 2 is interpreted as concentric.

Because the Little Rocky Mountains is a dome structure, concentric and radial fractures cannot be identified on the combined fracture plot. Figure 5.7 displays radial and concentric patterns within each outcrop location in the Little Rocky Mountains. Most outcrop locations display dominate fracture patterns that lie within the concentric and radial patterns. These include waypoints 6, 2, 5, 12, 3 and 11.

5.2.4 Seismic Data

Attribute processing of the Bicentennial 3D seismic data revealed a dominant northeast trending fracture system and a lesser northwest trending set, Figures 4.10, 4.11, and 4.12. When these fracture trends are compared to the strike of the northwest trending anticline structure in the 3-D seismic, radial and concentric patterns can be identified. Figure 5.8 highlights this and shows the strong northeast trend as radial fractures and the northwest fractures as concentric fractures. These are probably superimposed on the regional fracture trends.
Figure 5.6 a) Fracture plot of the Big Snowy Mountains showing concentric and radial fracture patterns. b) Fracture plot of Clarks Fork Canyon showing radial and concentric fracture patterns.
Figure 5.7 Fracture plots of outcrop locations in the Little Rocky Mountains. Concentric and radial fracture patterns plotted.
5.3 Mechanical Stratigraphy (Clarks Fork Canyon)

In general, when compared to the Bakken Formation, the Cottonwood Canyon Formation is similar in appearance and sequences, including an upper and lower shale member that bound a middle dolomitized sandstone member. The lower member of the Cottonwood Canyon is thicker than the upper and has less interbedded sandstones within the shale. However, the Cottonwood Canyon has a coarser character in all members compared to the Bakken.

Fracture distribution within the measured section (Figure 4.14) shows that most fracturing occurs in the middle coarser dolomitized member of the Cottonwood Canyon Fm. Few fractures extend into the upper and lower shales.

5.4 Local Fracturing vs. Mechanical Stratigraphy

When Clarks Fork Canyon fractures are plotted as concentric and radial fractures against stratigraphy (Figure 4.14), extensive radial fractures can be seen, cutting through the entire Cottonwood Canyon Formation, upper Three Forks, and lower Lodgepole. These extensive radial fractures have a spacing of ~4-5 meters.
This observation may be biased, due to the nature of the outcrop in Clarks Fork Canyon. The outcrop face trends parallel to bedding strike increasing the probability of intersecting radial fractures. Concentric fractures could exits, however the appearance of them would be rare because of their bed paralleling nature.

Figure 4.14 also shows other measured radial and concentric fractures that are dominantly contained within the middle sandy member of the Cottonwood Canyon Fm. Few to no fractures extend or are within the upper and lower shale members. This is likely due to the ductile nature of shale.

5.5 Regional vs. Local Fractures

The regional fracture study shows dominant northeast and northwest fracture sets (Figure 5.9). This trend was observed in previous studies, the 3D Bicentennial seismic, and possibly in the Little Rocky Mountains. These fracture trends are consistent with the Wilcox (1983) right-lateral wrench fault model when applied to this regional tectonic setting (Figure 5.2).

The localized fracture study demonstrated that concentric and radial fracture patterns are present on the studied folded structures such as; The Big Snowy Mountains, Clarks Fork Canyon, Little Knife structure (Narr and Burrus, 1987), and on the 3D seismic structure.

The northeast and northwest fracture trends in the seismic share both the regional and localized patterns. The overlap in regional and localized fracture patterns is a result of the strike of the northwest trending folded structure. Radial patterns trend perpendicular to the structure in a northeast orientation and overlap with northeast regional trends. This also applies to concentric patterns, where northwest concentric fractures trend parallel to the regional northwest set.

Overlap in both regional and localized fractures produces constructive interference. However the strong east/west fracture trend in the Narr and Burrus (1987) study does not share the regional trend and has a strong radial trend produced by the Little Knife Structure. This demonstrates that fracture patterns occurring on structures will be heavily influenced by the structure rather than the regional trend.
Figure 5.9 Summary fracture map showing regional and localized fracture patterns.
CHAPTER 6
CONCLUSIONS

6.1 Conclusions

The main conclusions of this study are:

1) Regional fractures in the Williston Basin trend to northwest and northeast. These trends are observed consistently throughout the basin and possibly in the Little Rocky Mountains.

2) Regional fracture orientations can be explained with the Wilcox et al. (1973) wrench fault strain ellipse model. A right lateral wrench fault explains regional fracture trends and North/South fold orientations.

3) Fold structures trending to the northwest, such as the Cedar Creek Anticline, Antelope Structure, and Poplar Dome do not agree with the Wilcox (1973) wrench fault strain ellipse model. These northwest-folded structures are likely controlled by preexisting structures within the Precambrian, and expressed in structural trends of the Ancestral Rocky Mountains.

4) Curvature attributes work well in areas of low to little subsurface topography in highlighting fracture sets. In this study, Minimum Curvature proved to be the most useful followed by Maximum Curvature, and then Dip Curvature.

5) Fractures located on the studied outcrop structures and the Bicentennial 3-D seismic are oriented with relation to the structure, forming in radial and concentric patterns.

6) Both local and regional trends are present within the Bicentennial 3D seismic data and the Antelope structure.
7) Strong east/west fracture patterns on the Little Knife Structure (Narr and Burrus, 1987) display radial patterns showing a preference towards structural trend.

8) Constructive fracture interference occurs between regional fracture and structural fractures. Concentric fracturing occurring on both north/south and northwest trending structures overprints northwest regional trends, while radial fracturing overprints northeast regional trends.

9) Mechanical Stratigraphy analysis of the Cottonwood Canyon Formation (Bakken equivalent in the Big Horn basin) shows concentrated fracturing within the middle member of the Cottonwood Canyon Fm. Extensive radial fractures extend through the Three Forks, Cottonwood Canyon, and Lodgepole Formations and possibly concentric fractures.


