RECENT SEISMICITY AND REGIONAL EXTENSION WITHIN
SOUTHWESTERN MONTANA, USA

by

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A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science
Geosciences
Western Michigan University
August 2015

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Southwestern Montana has experienced several large damaging earthquakes over the last 100 years, but many minor ones that unveil the nature of the intraplate seismicity. The region in this study is part of two distinct Late Cretaceous tectonic provinces, the Rocky Mountain Foreland Basement (RMFB) and the Cordilleran Fold and Thrust Belt (CFTB). Relationships between the two provinces and their faults show that the focal mechanisms are different. Deep focal mechanisms (between 8 and 10 km) within the RMFB can be placed on a specific fault, with many smaller events falling within the hanging wall. The hypocenters within the hanging wall are hypothesized to be related to the lowering of effective stress by the movement of hot spring water through fractured metamorphic bedrock.

T-axes within the northern CFTB cluster closely around N80°E/S80°W with few outliers. Extension in the southern RMFB generally trends roughly N10°E/S10°W. Subsidence of the Snake River Plain appears to influence the north-south extension. In the northern RMFB is a 125 km wide transition zone with T-axes oriented N45°E/S45°W. North of this transition zone, the Northern Rocky Mountain Province follows the same east-west extension as in the Basin and Range Province to the south of the Snake River Plain.
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ACKNOWLEDGEMENTS

What an experience this has been. I believe that through writing and researching my thesis, I have learned more about myself than I have about earthquakes in southwest Montana. I am sad and excited for this chapter of my life to end and the next to begin. But like most things in life, there’s no way I would be where I am now without several important people.

I first would like to thank my thesis advisor, Christopher Schmidt. Who knew that setting me loose on ‘I wonder how much seismicity there is in Montana’ could turn into this manuscript, and ignite a passion in both of us. Thank you Chris for always making sure I keep my sense of humor, for always believing in me, and for always taking the time to read one draft, after another draft, after another draft, after another draft. I look forward to working with you more and can only hope that soon you remember how to copy and paste a picture without supervision.

This entire manuscript would not have been possible without Michael Stickney of the Montana Bureau of Mines and Geology. Thank you for supplying data, software and insights into Montana seismicity. Thank you for getting me started with GMT and helping with all issues and problems that I had with the program. I appreciate every quick email response, every round of edits,
every encouraging word, and your patience and willingness to answer the same question several different times.

Thank you to Michelle Kominz and William Sauck for agreeing to be on my committee. I appreciate your edits and suggestions. Thank you Michelle for helping me figure out the math to put error bars on my cross sections. Thank you, Dr. Sauck, for pushing me in your classes to shape me into the geophysicist that I am today.

I would also like to thank Susan Vuke from the Montana Bureau of Mines. Susan was a pleasure to meet in Montana, and was always willing to answer any question that I had about faults, fault names, and fault locations.

Thank you to Tom Howe, the staff geologist at WMU. Tom has been so helpful in acquiring software, providing me with several opportunities, and has been a generally great friend. Thank you also to Kyle Chouinard for continuously answering my ArcMap questions, making sure I have the right ArcMap license, for always being willing to help fix one of my computers when I did something stupid.

Thank you to Western Michigan Universities Graduate College and the Geological Society of America for helping me fund my trip out to Montana in May 2013. Thank you to the Geosciences Department at Western Michigan University for multiple scholarships (the Randall Kerhin Graduate...
Acknowledgements - continued

Scholarship, the W. David Kuenzi Student Research Fund, and the Student Service Awards) for helping fund my way through graduate school.

I could never have finished this without the support of my friends who listened to my frustrations, distracted me when I needed a break, and gave me suggestions when I needed it. I want to apologize to my family for screening multiple phone calls in the last 3 years to avoid the “what are you doing with your life” question. I still don’t know, but I will still let you know when I do know.

Jessica Szkody
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CHAPTER I

INTRODUCTION

Purpose of Study

The M_w 7.3 Hebgen Lake earthquake on August 18, 1959 is the largest known earthquake in the Northern Rocky Mountain region (Figure 1). Since this catastrophic rupture, seismologists have studied the intraplate extensional nature of the earthquakes within the region. The seismic network in Montana has grown substantially since 1959, largely through the efforts of the Montana Bureau of Mines and Geology, increasing the database of quality data on earthquakes to allow progressively more detailed studies in the region.

The seismicity in southwestern Montana (Figure 2) consists of a complicated array of movements on long-lived active faults that have a great diversity of attitudes (Figures 3-7). Faults within the area are undergoing extensional strain that roughly parallels the trend of earlier Late Cretaceous- Early Tertiary (Laramide) shortening strain (West 1992). Many of the individual faults are close together (within a few hundred meters) and frequently intersect. This creates uncertainty in establishing the specific faults or fault zones that are responsible for many of the earthquakes.

The directions of compression and tension (P and T axes) responsible for the fault movements have not been exhaustively studied within the region. In addition, from the
Figure 1 Map of large historical earthquakes with their corresponding magnitudes.
Figure 2 Map of Montana with study area highlighted in insert (top left, yellow). Study area epicenters are represented as red dots.

Yellowstone/Snake River Plain region north to Helena, Montana, the P and T axes derived from first motion earthquake data rotate 90° from North-South to East-West but there have been few theories as to why this change occurs over such a relatively small distance (approximately 117km).

The purpose of this study is to: 1) determine the current state of extensional strain within southwestern Montana using first motion focal mechanism solutions. To do this I will compare earthquake T-axes in the area to those better known in the Yellowstone/Snake River Plain region, and explain the differences for changes in extensional patterns northward away from the Yellowstone Area; 2) investigate the nature of fault movement associated with recent seismicity in southwest Montana. I will
investigate how much control the orientation of the fault has on the focal mechanisms, how much control the tectonic setting has on the focal mechanism, and control of the T-axis orientation on focal mechanisms. I will examine five areas within three different tectonic settings, different dominant fault trends, and different T-axis orientation; and 3) relate concentrations of earthquakes to specific known faults within and around the Tobacco Root Mountains at locations where the hypocenters and geometry of the faults are well established. This will include a new hypothesis to explain earthquakes that cannot be located on specific faults but are likely to be related to these faults.

Structural Background

Within the Late Cretaceous and Paleogene Rocky Mountain Foreland, recurrent movement has been noted on four sets of faults that cut through old (Archean and Early Proterozoic) basement rocks (Figure 3 and 4). Prominent northwest striking, northeast-dipping faults (Figure 5) originated as early as the Middle Proterozoic and were active during Late Cretaceous shortening, with left reverse-oblique movement (Lopez and Schmidt, 1985; Schmidt and Garihan, 1986). The faults strike between N20W-N70W with most striking about N50W. These NW-trending faults are spaced between 6 and 10 km apart with the longest faults about 150 km long. The strike of the faults changes to more northerly and become 5-10° more gently dipping in the younger (Paleozoic) rocks above the basement rocks. Most of these northwest striking faults dip between 50-80°NE (Schmidt and Garihan, 1986).

Northeast striking, west-northwest dipping faults (Figure 6) may have originated during the Late Archean continental accretion and were also active during Late Cretaceous shortening (McBride et al., 1992). North striking, west dipping faults (Figure
7) formed during the Late Cretaceous (Kellogg et al., 1995). Finally, east striking, north
dipping faults (Figure 8), such as Centennial Fault, may be related to subsidence of the
Snake River Plain (Janecke, 2007). The faults discussed within this study are therefore
likely to be reactivated older faults with movements (slip direction) compatible with the
current extension directions.

The Late Cretaceous and Paleogene faulting within the Rocky Mountain Foreland
Basement rocks of southwestern Montana is overlapped by the Late Cretaceous and
Paleogene Cordilleran fold and thrust belt to the north (Kulik and Schmidt, 1988) (Figure
9). Neogene normal faults are common in both settings. The boundary between the two
tectonic settings is the southwest Montana transverse zone, with the main fault being a
long east-west trending fault-the Jefferson Canyon fault (Figure 8) (Whisner, et. al 2014).
This transverse zone also marks the southern border of the Helena Salient, a convex
curve in the thrust belt (Figure 9). Within the Helena Salient, faults splay off of the
Jefferson Canyon fault, and follow the salient north and then to the northwest. The
northern boundary of the salient is the Lewis and Clark Line, which formed as a result of
clockwise rotating thrust slabs, which controlled the trend of the northern Helena Salient
(Figure 9). The Lewis and Clark Line is a complex, 400 km long, N55°W to N80°W
trending structural discontinuity with long-lived sinistral shear and recurrent activity
(Reynolds, 1979; Stickney and Bartholemew, 1987; Wallace et. al. 1990, Sears and
Hendrix, 2004). This zone contains high angle strike-slip, oblique-slip and dip-slip faults
which are typically longer and very linear compared to the faults in Rocky Mountain
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Figure 4. Mapped faults within the study area.
Figure 5. Northwest striking faults within the study area.
Figure 6 Northeast striking faults within the study area.
Figure 7 North-South striking faults within the study area.
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Figure 9 Locations of the Lewis and Clark Line (LCL), the Helena Salient, the southwest Montana transverse zone (SWMT), the Snake River Plain (SRP), and the Yellowstone Hot Spot. Teethed line represented the front of the Cordilleran Fold and Thrust Belt within Montana.
Figure 10 The Yellowstone Hot Spot track, with the approximate age of the eruptive calderas and an outline of the Snake River Plain (dotted), based on Smith and Braile (1994).
Subsidence of the Snake River Plain

The Eastern Snake River Plain, located directly to the south of the study area, is a 700 km-long, aseismic region that contains igneous rocks that documents the movement of the North American Plate over a hotspot for the last 17 Ma (Anders and Sleep, 1992; Smith et. al., 2009; Smith and Sbar, 1974; Pierce and Morgan, 1990; Smith and Braile, 1994). The plain is composed of a bimodal suite of largely rhyolite tuffs and mafic volcanic flows from the various locations of the hot spot and is continuously undergoing subsidence by crustal flexure and thermal contraction (Anders and Sleep, 1992; Rodgers, et. al., 2002).

The Snake River Plain has a higher heat flow (approximately 150 mWm$^{-2}$) than surrounding areas (between 65-90 mWm$^{-2}$) most likely due to the previous locations of hot spot calderas. Thermal subsidence is most evident in the decrease in elevation with an approximate 2 km difference from its neighboring Basin and Range province (Figure 11 and 12) (Rodgers et al 2002). GPS measurements of the northern ridge of the plain in Idaho from 1995-2000 show southward motion, indicating axial contraction (Puksas et al. 2007). The Snake River Plain itself plunges to the southwest with approximately 1.5 km of relief between older rocks to the southwest and younger rocks to the northeast (Figure 11 and 12) (Rodgers et al 2002).

Cretaceous fold hinges within the ranges along the edges of the Snake River Plain plunge southward towards the plain and plunge more steeply the closer to the Snake River Plain the measurement was taken (McQuarrie and Rodgers, 1998). This structural tilting is interpreted as crustal flexure, attributed to the subsidence of the area. Based on a
Figure 11 Elevation cross section locations through the Snake River Plain with approximate caldera locations (outlined) and the approximate locations for the MQuarrie and Rodgers (1998) plunging fold hinges (dashed)
Figure 12 Elevation cross sections through the Snake River Plain from figure 11.
2002 study by Rodgers, et al., the Snake River Plain subsided 3.1 km since 8.5 Ma, and an additional subsidence (between 1.4 and 4.4 km) before 8.5 Ma. This indicates rapid subsidence before 8.5Ma (1.5km/Ma) and slow subsidence currently (0.2km/Ma) and continuing to the present.

Seismicity within Southwestern Montana

The study area is within the northern Intermountain Seismic Belt (ISB) (Figure 13), a seismically active zone trending N-S from Northern Arizona to northwestern Montana (Chang and Smith, 2002). The ISB is approximately 75 km wide with boundaries sharply defined by micro earthquake activity (Stickney and Bartholomew, 1987). The majority of earthquakes within the ISB are shallow, less than 15 km in depth, and they sometimes occur in swarms that are often related to geothermal hot springs and areas of high heat flow (Smith and Sbar, 1974). Minor parts of the study area lie within two other seismic seismically active areas that bound it on the north and south. The northern one contains the Lewis and Clark Line. The other is the Centennial Tectonic Belt (CTB), an east-west trending belt that is about 350 km long and 50-100 km wide from northwest Yellowstone into east central Idaho (Figure 13) (Stickney and Bartholomew, 1987).

A symmetric parabolic distribution of historically high seismicity surrounds the Snake River Plain (Figure 14). It has been suggested that this high seismicity is due to the northeastward migration of the hotspot. The inner parabola defines the border between the aseismic Snake River Plain and the end of high seismicity and Quaternary faulting. The outer parabola defines the transition between this region and the less active Basin and Range (Anders et. al., 1989).
Figure 13 Locations of the Lewis and Clark Zone, the Intermountain Seismic Belt (ISB) and the Centennial Tectonic Belt (CTB). Modified from Stickney and Bartholomew (1987).
Several larger (M>5.5) historical earthquakes have occurred within the ISB in the past 100 years, of which a few noteworthy ones occurred within, or just outside the study area (Figure 1); Hebgen Lake; Clarkston Valley, Helena and Borah Peak. The largest earthquake recorded in Montana occurred in 1959 at Hebgen Lake. The main shock’s focal mechanism reveals pure dip slip movement on a N12°W striking fault, dipping 64°S (Ryall, 1962; Doser, 1984, Smith and Sbar, 1974). Focal mechanisms of the aftershocks of the Hebgen Lake earthquake reveal normal, strike-slip and reverse solutions suggesting a local variation in the stress field or movement on faults with diverse orientations (Doser, 1984).

The Borah Peak, ID earthquake, with a moment magnitude of 6.9, occurred in 1983 on the Thousand Springs segment of the Lost River fault. The main focal mechanism revealed a normal movement with a small component of left-lateral strike-slip on a northwest striking, southwest dipping fault plane (Doser and Smith, 1985; Richins et. al., 1987). Near-surface net slip averaged a 0.17m left lateral movement with 1.0m of pure dip slip (Crone et al., 1987, Richins, et.al., 1987). Focal mechanism solutions show the average regional strain to be extensional with a NNE-SSW direction (Chang and Smith, 2002).

Figure 14 Location of the Tectonic Parabola, the current position of the Yellowstone Hot Spot (YHS) and the Snake River Plain. Seismicity is represented as red dots.
The Helena earthquake swarm included a magnitude 6.25 earthquake on October 18, 1935 and a magnitude 6.0 earthquake on October 31, which was followed by over 1800 earthquakes during the next seven months (Qamar and Stickney, 1983). Doser (1989) used teleseismic waveforms (data from an earthquake that occurred more than 1000 km from the measurement site) to determine the earthquake focal mechanisms that show right-lateral strike-slip faulting on an east-west striking fault plane or left-lateral slip on a north-south fault, with a poorly resolved near vertical dip.

Extension within the Northern Rocky Mountains

The Basin and Range has been undergoing extension since the mid-Miocene (Pierce and Morgan, 2009). Extension within the region is thought to be a combination of several causes, including back arc extension, weakening and heating of the lithosphere by the Yellowstone Hot Spot, and gravitational collapse following tectonic thickening during the late Cretaceous-Early Tertiary Laramide-Sevier orogeny (Dickinson and Snyder, 1978; Pierce and Morgan, 2009). Northeast-southwest to east-west extension leads to normal and strike-slip faulting, and is consistent with the dominantly active NW trending normal faults.

Smith and Sbar (1974) proposed two sub plates within the Northern Rocky Mountains. One (the Northern Rocky Mountain Sub plate) is bounded by the Intermountain Seismic Belt and the Centennial Tectonic Belt (Figure 15). However, they did not define a boundary to the north or to the west of this sub plate boundary. The second subplate, the Great Basin Subplate is bounded by the Intermountain Seismic Belt, and the Snake River Plain. Using focal mechanism data and this model of two sub plates,
Smith and Sbar attribute the 90° rotation of T-axes to the two sub plates moving away from each other in a North-South direction.

Friedline et. al. (1976) also recognized the rotation in the T-axes, and indicated that the rotation could be from a reorientation of the regional stress field relative to this Northern Rocky Mountain Province. Friedline’s study, conducted on the 1935 Helena swarm, suggests that if the rotation of T-axes is related to a sub plate boundary, that it is probably related to a zone of lithospheric weakness dominated by a north-south extension, that changes to an east-west extension to the north.

Zoback and Zoback’s (1980) map of contemporary stress of the United States shows a variety of stresses within this portion of the Basin and Range Province (Figure 16). T-, B- (the intermediate stress), and P-axes from previously published earthquake and in-situ measurements within southwestern Montana and southeastern Idaho were used to categorize the Hebgen Lake and Centennial Valley as N-S extension, consistent with Smith and Sbar’s (1974) previous observations. The Hebgen Lake Region is composed of a large part of middle Idaho and a small part of Montana. The southern boundary of the province is marked by a 90° rotation of the T-axis and the northern boundary is undefined (Figure 16).

Zoback and Zoback (1980) interpret the Snake River Plain as having its own strain regime, with NE-SW extension, running parallel to the axis of the Snake River Plain. North of the Hebgen Lake Province the Northern Rocky Mountain Province, has an east-west extension, similar to that of the Basin and Range province to the south of the Snake
River Plain (Figure 16). This corresponds to the Late Cretaceous and Paleogene (Laramide) maximum principal stress (West, 1992).

Figure 15 Locations of the subplate boundaries described by and modified from Smith and Sbar (1974) including the extension directions (arrows) discussed including the Yellowstone Hot Spot (YHS) and the boundary of the Intermountain Seismic Belt.
Figure 16 Regional Stress Map modified from Zoback and Zoback (1980). Small arrows represent minimum principal stress taken from the World Stress Map Project including insitu measurements and focal mechanisms. Large arrows indicate the generalized stress directions from Zoback and Zoback’s 1980 map of the conterminous United States. This area is broken up into 5 regions, Northern Rocky Mountain Province (NRM), Hebgen Lake (HL), Snake River Plain (SRP), the Northern Basin and Range Province (NBR) and the Colorado Plateau (CP). Dashed lines represent inferred boundaries.
CHAPTER II
DATA SELECTION, METHODOLOGY AND STATISTICS

Selection of Hypocenters

The Montana Bureau of Mines and Geology (MBMG) has provided the earthquake catalog from 1982-2013 for this study determined using data from their seismic network and surrounding seismic networks. Their seismic network has grown from 1 station to 35 stations since 1936, with the majority of the increase occurring during the mid-1990s. Stations within the Montana Bureau of Mines and Geology network all have a short period seismometers. As the number and aerial coverage of stations increased, more accurate hypocenter locations became possible. The MBMG used HYPO71 (Lee and Lahr, 1975) to determine hypocenter locations and magnitudes. For this study, hypocenters were filtered based on the following parameters, to eliminate events with less reliable hypocenter locations:

- At least eight phases used, including both P and S waves. This ensured that the hypocenter location was calculated using at least four stations,
- An azimuthal gap of less than 180˚, representing the greatest angle between stations,
- A depth of ≤ 25 km,
- A RMS (root mean square of travel time residuals) ≤ 0.30,
- Horizontal uncertainty ≤ 1.5 km,
- Vertical uncertainty ≤ 3.0 km.
Application of these constraints reduced the number of earthquakes from 38,458 to 12,610. Within the study area, earthquakes located east of Hebgen Lake to Yellowstone were also disregarded, assuming that these are all related to the high seismicity of the Yellowstone Hot Spot and geothermal features. At the end of the filtration process 8,722 well-located earthquake events from 1982-2013 were selected for study.

The selected earthquakes have a magnitude spread of 0.8 to 5.1 with the magnitude bin with the largest number of the events being between 1 and 1.2 (Figure 17). Hypocenter depths have a bimodal distribution with peaks at 11-9 km and 6-5 km (Figure 18).

Figure 17 Magnitude distribution of earthquakes within the study area.
Figure 18 Depth distribution of earthquakes within the study area.

Focal Mechanism Theory

A focal mechanism is a diagrammatic representation of movement on a fault. The diagram produces two nodal planes, one of which is called the auxiliary plane, and the other represents the fault plane. The attitude of the fault plane responsible for the movement is inferred from the P-wave first motions recorded by seismic stations. Each station records either a compression (upwards) or dilatation (downwards) motion. A fault plane solution (focal mechanism) divides P-wave first motions into four quadrants (two compressive quadrants and two dilatational quadrants) on a lower hemisphere stereoplot, known as the focal sphere. Each seismic station is represented as a closed point (compression) or an open point (dilation) and is plotted according to their azimuth from the event to the seismic station and their angle of incidence ($i_0$). This represents the take-off angle of the ray path (Figure 19). This angle is a function of the angular distance, $\Delta$,.
which therefore can be traced backward through the ray path parameter \((\delta T/\delta \Delta)\) to where
the station exists on a focal sphere, called the angle of departure \((i_h)\). This angle of
departure can be calculated (Equation 1) by using a seismic version of Snell’s Law,

\[
\frac{r \sin i_h}{v} = \frac{\partial T}{\partial \Delta},
\]

Equation 1

where \(r\) is the distance from the hypocenter to the center of the earth, \(v\) is the velocity at
the hypocenter and \(\delta T/\delta \Delta\) (often referred to as “slowness”) is the derivative of the travel
time curve (Kennett 1995). The two planes that create the four quadrants are the fault
plane and the auxiliary plane. Without geologic knowledge of the region, it would be
impossible to determine which plane is the fault plane.

P (maximum compressive) axis is located in the middle of the dilatation quadrant
while the T (minimum compressive) axis is located in the middle of the compression

Figure 19 Diagram describing the angle of incidence and angle of departure. Modified from Havskov and
Ottemeller, (2010)
quadrant. The B (null) -axis occurs at the intersection of the two nodal planes, orthogonal to the P and T axes (Zoback and Zoback, 2002). All three axes are mutually perpendicular. These axes are analogous to, but not exactly the same as the axes of principle stress. T-axes in particular imply extensional strain whereas the analogous minimum principle stress, \( \sigma_3 \) may be either positive (compressive) or negative (tensional).

Focal Mechanisms

Although it is possible to create first motion focal mechanisms by hand, it is more widely accepted to use a computer program to compute them. These programs are more consistent than human eyes and can easily determine error, saving time and allowing for a large quantity of data to be analyzed. Focal mechanisms for this study were derived using the program FPFIT program (Reasenberg and Oppenheimer, 1985). The program searches for a double-couple fault plane solution from first motion polarities as observed from earthquakes using a two-stage gridding search. The program will output more than one option for the fault plane solution if multiple solutions satisfy the first motion data. However for this study, the solution with least error was chosen by the program. I used a minimum of 10 P-wave first motions to calculate a focal mechanism. The resulting catalog contains 1,106 focal mechanisms within the study area. From the FPFIT output files, P-, T- and both nodal plane strikes and dips were calculated in MKTABLE, a FORTRAN program provided by the USGS.

Focal mechanisms viewed in profile can help determine which of the two nodal planes represent the fault plane. The lower hemisphere focal mechanisms shown in a map view illustrate the traditional normal, strike-slip, thrust, and oblique movements. When
the focal mechanisms are rotated 90° to a profile view, they are shown as a full circle and when using multiple focal mechanisms, similar trends for one of the two nodal planes will suggest the location and dip of the fault responsible for the earthquakes (Figure 20).

Figure 20 Diagrams of map view, 3-D view and cross section representations of focal mechanisms
Statistics

Ternary Diagrams

The plunge of the T-, P-, and B-axes on a fault plane solution are plotted on a ternary diagram to indicate what type of fault movement occurred. Ternary diagrams were produced to categorize the different types of focal mechanisms generated throughout the study area. The diagrams follow Frohlich’s (1992) theory of triangle diagrams, in which each of the axes (P, T, and B) are mutually perpendicular and the sine of each axis plunge follows the definition of a sphere,

\[ x^2 + y^2 + z^2 = 1 \]  
Equation 2

therefore,

\[ \sin^2 \delta_T + \sin^2 \delta_B + \sin^2 \delta_P = 1 \]  
Equation 3

where \( \delta_T \) = the plunge of the T-axis, \( \delta_B \) = the plunge of the B-axis, and \( \delta_P \) = the plunge of the P axis. (Frohlich, 1992)

P, T and B axis plunges from the focal mechanisms were categorized for ternary diagram based on the Triep and Sykes (1996, 1997) stress regime categorization. Triep and Sykes defined the Normal-Oblique and Thrust-Oblique as four separate categories; strike-slip thrust, thrust strike-slip, strike-slip normal, normal strike-slip. For this study, a more basic approach was used, and the four categories were condensed into two categories; thrust oblique, and normal-oblique. Thrust-oblique includes the thrust strike-slip and strike-slip thrust categories and normal-oblique includes the normal strike-slip and strike-slip normal categories (Table 1).
### Table 1

P, T and B plunges and their tectonic regime

<table>
<thead>
<tr>
<th>P axis plunge</th>
<th>B axis plunge</th>
<th>T axis plunge</th>
<th>Tectonic Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>pl ≥ 45°</td>
<td>pl &lt; 25°</td>
<td>pl ≤ 45°</td>
<td>Normal</td>
</tr>
<tr>
<td>25° &lt; pl &lt; 65°</td>
<td>pl ≤ P axis pl</td>
<td></td>
<td>Normal-oblique</td>
</tr>
<tr>
<td>pl &lt; 45°</td>
<td>pl ≥ 65°</td>
<td>pl ≤ 45°</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>pl ≤ 45°</td>
<td>25° &lt; pl &lt; 65°</td>
<td>pl &lt; P axis pl</td>
<td>Thrust-oblique</td>
</tr>
<tr>
<td>pl ≤ 45°</td>
<td>pl &lt; 25°</td>
<td>pl ≥ 45°</td>
<td>Thrust</td>
</tr>
</tbody>
</table>

The results of the categorization shows mostly normal movement to normal-oblique movement (63%), confirming that southwestern Montana is undergoing extension (Figure 21) which can be represented in a ternary diagram (Figure 22). Ternary Diagrams will be used throughout the rest of this thesis to determine the dominant focal mechanism throughout a given region.

![Pie Diagram representation of type of fault movement from focal mechanisms based on T, B, and P axes.](image)

Figure 22 Ternary representation with corresponding focal mechanisms.

Magnitude Completeness

The relationship between earthquake magnitude and frequency of earthquakes has been studied by seismologists since Gutenberg and Richter (1945). These two early seismologists determined that earthquakes with one magnitude occur ten times more frequently as earthquakes with a magnitude one interval larger (Gutenberg and Richter, 1945; Yeats, et al., 1996). This can be expressed as the linear relationship (Equation 4),

\[ \log_{10} N = a - bM \]  
Equation 4
where $N$ is the number of events with a magnitude of $M$ or larger; $a$ is the intercept and represents the seismic activity in the area within a given time and; $b$ describes the relative distribution of small and large earthquakes (Gutenberg and Richter, 1945). The smallest magnitude at which this equation fits the data is considered threshold of the magnitude completeness ($M_c$). The magnitude completeness is considered to be the magnitude above which all earthquakes within a given earthquake catalog are detected and reported.

Many seismologists have studied the $b$-value in depth to compare seismicity rates of different areas (Smith and Sbar, 1974; Woessner and Wiemer, 2005; Popandopoulos and Chatzioannou, 2014; Wiemer and Wyss, 1997). Typically, a $b$-value of 1.0 represents a seismically active region with an equal ratio of large earthquakes to small earthquakes. The higher a $b$-value, the more earthquake swarms are typically in the area. This $b$-value can also be used in determining earthquake hazard and recurrence intervals. Wiemer and Wyss (1997) proposed a time recurrence equation,

$$T_r = \frac{\Delta T}{10^{(a-bM_c)}} \quad \text{Equation 5}$$

where $T_r$ is the time recurrence, and $\Delta T$ is the total time in years of the study (Wiemer and Wyss, 1997). Small changes in a $b$-value will create large differences in hazard analysis (Felzer, 2006).

The $M_c$ was calculated using the all the earthquakes provided by the MBMG. A $M_c$ for this study was calculated using the maximum curvature technique. The maximum curvature technique simply defines the maximum curvature by computing the maximum value of the first derivative of the frequency-magnitude curve (Figure 23). In practice, this also corresponds to the largest number of events in a magnitude bin. For this study
the Mc is 1.0. A $b$-value was calculated using the maximum likelihood technique. Traditionally, the least squares method was used to determine the constants of $a$ and $b$ (Gutenberg and Richter, 1945). The least squares method uses a Gaussian error at each point, assuming equal error on each point and is disproportionately influenced by larger magnitude earthquakes. The maximum likelihood technique assumes a Poissonian error, and weighs each earthquake equally (Felzer, 2006). The maximum likelihood technique can be expressed as,

$$b = \frac{\log(e)}{\bar{m} - (Mc - \frac{M_{bin}}{2})}$$

Equation 6

where $\bar{m}$ is the average of magnitudes in the study above the Mc, Mc is the magnitude completeness previously determined, and $M_{bin}$ is the magnitude bin width (Aki, 1965; Woessner and Wiemer, 2005). For this study, a magnitude bin of 0.1 was used. The maximum likelihood technique gives a $b$-value of 1.17, an $a$-value of 5.48 with the $M_c=1.1$ (Figure 23), therefore (Equation 7),

$$\log_{10}N = 5.48 - 1.17M$$

Equation 7

This $b$-value indicates a higher proportion of smaller events to larger events.

Stickney (1987) reported a comparable $b$-value of 1.15 and 1.24 for southwestern and central-western Montana, using 734 events and 1371 events, respectively, indicating that the seismicity within southwest Montana has been consistent throughout the length of the two studies. In a larger comprehensive earthquake hazard analysis, Wong et. al. (2005) reports much lower $b$-values of $0.77 \pm 0.03$ and $0.94 \pm 0.1$ for the Northern Intermountain Seismic Belt and the Centennial Tectonic Belt respectively. The $b$-value of
the Centennial Tectonic Belt of 0.94±0.1 is closest to the $b$-value of this study. Wong’s values are slightly different than the values in this study because he used a declustered catalog of earthquakes to only analyze earthquakes with a magnitude greater than 3. The $M_c$ and $b$-value for this study suggests that the area is seismically active and contains earthquake swarms.

Figure 23 Magnitude Completeness graph with a $M_c$ of 1.1. Triangles represent the total number of events and squares represent the cumulative frequency of events.
CHAPTER III

EARTHQUAKE AND FAULT RELATIONSHIPS

Seismicity in southwestern Montana occurs in the Rocky Mountain Foreland basement terrane in the south, and the Cordilleran Thrust Belt in the north. In the Rocky Mountain Foreland, seismicity follows pre-existing thrust faults in basement rocks. In the Cordilleran Thrust Belt, the seismicity appears to be confined to the thrusted Proterozoic Belt sedimentary section and is less obviously controlled by the known thin skinned thrusts (Figure 9). Focal mechanisms, plotted on a ternary diagram show a dominance of normal, normal-oblique and strike-slip faulting, indicating that these thrust faults have been reactivated as normal faults (Figure 24). The majority of the seismicity falls within the seismic provinces previously described, with the northern limb of the tectonic parabola of the Yellowstone hotspot clearly defined. Seismicity occurs in the vicinity of the Centennial fault, along the southern boundary (Figure 25).

Figure 24 Ternary Diagram of focal mechanism data for the entire study area showing mostly normal movement.
Earthquakes tend to cluster in regions where either one or more fault sets of different orientations intersect, or there is no mapped fault in the vicinity to account for the seismicity, so it is unclear which fault could be responsible. Seven areas (Figure 26) have been selected to examine in cross section view to investigate relationships between
Figure 26 Locations of investigated areas for fault and earthquake relationships within the study area. 1- Sheridan; 2- Norris; 3- Central Tobacco Root Mountains; 4- Waterloo; 5- Northeast Norris; 6- Clarkston; 7- Townsend.
faults and seismicity. These regions have been selected based on the amount of seismicity, event magnitudes, and proximity to known faults.

The first five study areas are located within uplifted Rocky Mountain Foreland basement terrane. The last two are located within the Cordilleran Fold and Thrust Belt. A secondary objective for this part of the study is to analyze any differences in focal mechanisms and fault movements between the crystalline basement and fold and thrust belt.

**Sheridan (Figure 26, location 1)**

A magnitude 4.6 earthquake with a focal depth of 13.5 km occurred 7 km southeast of Sheridan, Montana on May 8, 2007 followed by 75 aftershocks (Figure 27). Smaller earthquake sequences have occurred within this area since this large event, totaling 114 hypocenters with a maximum magnitude of 1.7. The majority of these earthquakes occurred between 5 and 15 km in depth.

Focal mechanisms reveal predominantly normal faulting with a small component of right lateral movement. The main shock focal mechanism indicates a north-northwest-trending normal fault, dipping northeast. Stickney (2007) suggested that the 2007 Sheridan earthquake resulted from normal slip at depth along the Ruby Range northern border fault because of the northeast dipping fault projects to the surface near the trace of the Ruby Range northern border fault. The cross section (Figure 28) indicates that the majority of the earthquake hypocenters in this sequence occurred in the hanging wall block, above the fault plane. Focal mechanisms deeper than 10 km are consistent with normal slip on this fault but become more diverse at shallower depths. These focal mechanisms are not depicted as lying on a specific fault and likely represent reactivation
of minor faults in the hanging wall block following the main shock. All focal mechanisms have relatively similar T-axes, but the orientations of the actual nodal planes are diverse. The possible relationship of these focal mechanisms to the main fault is discussed in a later section.

Figure 27 Map of the Sheridan earthquake cluster and location of cross section A-A’ (Figure 28)
A swarm including more than 700 locatable earthquakes occurred near the town of Norris, Montana from late May through October 1987. This study includes 204
earthquakes, of which 34 have focal mechanisms. Stickney (1988) deployed a portable seismograph network early enough during the swarm to record the largest earthquake (M 4.1) and many subsequent events, providing detailed information about this swarm. A few earthquakes have occurred within the area since, and are included in this study. The epicenters outline a northwest trending zone extending approximately 6km southeast of the town of Norris (Figure 29).

The Charmichael fault is part of the set of northwest striking, northeast dipping faults in the Tobacco Root Mountains, striking approximately N56°W and dipping steeply to the northeast. It is projected from known locations west of Norris and is inferred to pass about 4 km to the southwest of the town of Norris (Figure 29). Several small, unnamed normal faults of varying orientations are also located within the area, including an approximately east-west striking fault (herein called the Norris fault) just to the southeast of Norris in the vicinity of the Norris Hot Springs (Kellogg et. al, 2007). The dip direction and movement on this fault is unknown.

The largest magnitude earthquake (Figure 29) shows a west-northwest striking, southwest dipping right lateral oblique slip nodal plane. This nodal plane is favored to represent the fault plane due to its steeper dip. The majority of the other focal mechanisms have a normal component and nodal planes strike northwest. Focal mechanisms that do not follow the trend of the largest magnitude earthquake (shown in blue on figure 29) and have either east-west striking or north striking nodal planes and occur at a more shallow depths.
Figure 29 Map of the Norris earthquake swarm and location of the cross section A-A’ (Figure 30), C-C’ (Figure 31) and B-B’ (Figure 32). Blue focal mechanisms do not follow the trend of the largest magnitude earthquake of the Norris swarm.

Stickney (2007) suggested that two conjugate faults are responsible for the earthquake swarm, in which a set of southwest and northeast dipping faults intersect. This may be the reason that the earthquake swarm is shallower than 10km in depth. Cross section A-A’ (Figure 30) suggests that the Norris fault may dip approximately 70° to the southwest and that it intersects with the Charmichael fault (dipping 65° to the northeast). The suggested dips of the conjugate faults on cross section A-A’ indicates an intersection at about 6km. Most of the focal mechanisms that do not fit with the Charmichael fault
appear to fit well with the Norris fault. Focal mechanisms that do not fit with either fault trend will be addressed in a future section. A stereoplot of the faults with the chosen dips reveal an intersection oriented 50°, 68°SE (Figure 31 inset). Using this orientation, a second cross section (Figure 31 C-C”) was created through the Norris swarm, parallel to the trend of the intersection, to determine a possible relationship between the two intersecting faults and their hypocenters. Hypocenters along the 68°SE trend of C-C”, through the Norris swarm tend to follow the 50° plunge of the intersection fairly well, with equal numbers of hypocenters falling above and below the intersection.

Figure 30 Cross section A-A’ from figure 29 showing the intersection relationship between the Charmichael fault and the Norris fault.
Figure 31: Cross section C-C’ from figure 29. This cross section runs parallel to the trend of the intersection of the Charmichael fault and the Norris fault. The inset is a stereoplot representation of the intersection, with the intersection represented as a triangle at 50, 68SE.

A second cluster of 172 earthquakes occurred to the northwest of Norris, and are aligned in a similar northwest trend as the Norris swarm (Figure 28). These earthquakes range in magnitude from 0.4 to 2.95. Although there are few focal mechanisms within this cluster, they consistently show a northwest striking, northeast or southwest dipping normal mechanism. In cross section view, the focal mechanisms are best placed on the Carmichael fault at a depth of 8-10 km, with many hypocenters (without focal mechanisms) occurring within the hanging wall block at a shallower (6-7 km) depth.
(Figure 31). Hypocenters within the hanging wall block will be discussed in a later section.

Figure 32 Cross section B-B’ from figure 29 showing the inferred location of the Charmichael fault dipping the same direction and amount as in cross section A-A’ (figure 30).

Central Tobacco Root Mountains (Figure 26, location 3)

Epicenters of three earthquake clusters lie in a northwest linear trend through the Tobacco Root Mountains (Figure 33). The area contains three main northwest striking, northeast dipping faults: the Mammoth, the Hollowtop and the Bismark faults. All three
faults strike approximately N40W. Left lateral reverse movement occurred on these faults during the Late Cretaceous (Schmidt and Garihan, 1986) and they are currently mapped as left lateral strike-slip faults (Vuke et al., 2014).

Figure 33 Map through the Tobacco Root Mountains, showing the Bismark, Hollowtop, Mammoth and Charmichael faults, the locations of cross section A-A' (Figure 34), the cross section B-B' (Figure 35) and the hypocenters that are part of those cross sections. Fault movement indicators are for known or presumed Cenozoic movement.

The southernmost cluster (#1 on figure 33) contains 125 events and occurred approximately 5-6 km southwest of the small town of Pony between June and September of 2006. The largest earthquake had a magnitude of 4, with smaller events continuing to the present day. Focal mechanisms from this swarm reveal mostly normal faulting with a small component of right-lateral-normal oblique motion. A cross section created through
the area reveals that the earthquakes most likely occurred along the Bismark fault, with a dip of approximately 60° to the northeast, with several smaller magnitude earthquakes located in the hanging wall of the fault with similar focal mechanisms (Figure 34). The focal mechanisms from earthquakes suggest reactivation of the fault in a normal sense with a small component of right lateral motion.

![Cross section A-A’ from figure 33 showing the deepest earthquakes falling on the Bismark fault.](image)

Another cluster is located between the Carmichael fault and the Mammoth fault, approximately 4km southwest of Pony (#2 on figure 33). This area has been active since
1989, with the majority of the events occurring in a 2005 sequence from October through January 2006 with a maximum magnitude of 2.65. Smaller sequences have continued within this area through the present. Focal mechanisms in this area reveal mostly normal faults along a fault plane striking roughly N20W°. A cross section through this cluster (B-B’) suggests the most likely fault responsible for the earthquakes is the Hollowtop fault, dipping approximately 50 degrees to the northeast (Figure 35). Several of the smaller magnitude focal mechanisms have similar focal mechanism solutions in the hanging wall block of the fault. This phenomenon will be discussed in a future section.

![Figure 35 Cross section B-B’ from figure 33 showing the deepest earthquakes are consistent with slip on the Hollowtop fault.](image)

Several small sequences have occurred farther north (#3 on figure 33), due west of Pony. The highest magnitude was a 2.65, which occurred on November 20, 1989. This
area experienced a sequence of 15 earthquakes in 2006 which may be related to the 2006 earthquake swarm that occurred in the southernmost cluster in this region (#1 on figure 33). Only four focal mechanisms are available for this area and reveal two strike-slip movements, with varying strikes, and two normal movements with varying strikes. With the inconsistent nodal planes, these focal mechanisms could not be successfully placed on a known fault. Based on epicenter location, I hypothesize that these earthquakes are related to the Tobacco Root fault and Bismark fault intersection. More quality focal mechanisms in this area may constrain what fault is responsible for the events in this area.

Waterloo (Figure 26, location 4)

A magnitude 4.1 earthquake occurred approximately 4 km southeast of the small town of Waterloo, Montana on October 28, 1998 (Figure 36). Waterloo is located within the Jefferson Valley, just to the east of the Tobacco Root Mountains. Eight aftershocks from this event have magnitudes ranging from 0.9 to 2.45, with only one focal mechanism. Since the M4.1 earthquake occurred, over 175 earthquakes have occurred within its vicinity with the largest magnitude being 3.6 on February 2, 2002.

Waterloo lies approximately 4 km west of the Tobacco Root fault, a north-south striking, west dipping range-bounding normal fault that cuts a Late Cretaceous thrust of the same strike. In the Waterloo area, the Tobacco Root fault intersects several other Late Cretaceous faults, including the Bismark fault, which is interpreted to continue to the northwest of the Tobacco Root fault (dotted line, figure 36), below the Jefferson River valley. Hanneman and Wideman (1991) inferred another northwest trending fault below the Jefferson River valley in this area named it the Waterloo fault (Hanneman and
Wideman, 1991). The Hollowtop fault, which runs parallel to the Bismark and the Mammoth faults, has been mapped in the Precambrian metamorphic rock but terminates before reaching the Paleozoic cover (Vitaliano, 1979; McDonald et. al., 2012) (Figure 36).

The focal mechanism from the October 28, 1998 earthquake reveals a right lateral normal-oblique motion, with the fault plane striking N33°W, dipping 76°SW. Several earthquakes with focal mechanisms mimic this motion (Figure 36, #1). These earthquakes have been interpreted to occur in the footwall block of the Tobacco Root Fault (Stickney, 2007). Hypocenter distribution suggests that the dip of the Tobacco Root fault is steeper than 80°, which would allow the fault to be responsible for this large earthquake (Figure 36).

A second cluster (Figure 36, #2) of earthquakes occurred 2-3 km to the northeast of the cluster #1. The focal mechanisms in this cluster have mostly a normal motion, with some left lateral normal-oblique an a few left lateral strike-slip movements. Although these focal mechanisms show a mostly normal movement-like those of cluster #1- the oblique component in cluster #1 is right lateral, and in cluster #2 it is left lateral. The geographical difference between the two clusters and different lateral movements suggest that these clusters are related to different faults.

The Bismark fault (dipping steeply to the northeast) obliquely intersects the Tobacco Root fault (steeply dipping to the west) at a depth of about 2km (Figure 37). The majority of the earthquakes fall within the mutual footwall of the fault blocks. Focal mechanisms follow nodal planes that represent either the Tobacco Root fault or the
Bismark fault within the mutual footwall blocks of each fault. Cenozoic movement on the Bismark fault has been determined to be right lateral normal-oblique as discussed through focal mechanisms in a previous section.

Figure 36 Map of Waterloo earthquake clusters. Red focal mechanisms are represented in cross section A-A' (Figure 37), green focal mechanisms are represented in cross section B-B' (Figure 38), brown focal mechanisms that are not represented in a cross section and cross section C-C' (Figure 39 showing a possible intersection relationship. Fault movement indicators are known or presumed Cenozoic movement.
It is also probable that the focal mechanism for the large magnitude earthquake is consistent with a 76°W dip, but on a parallel, secondary, fault of the Tobacco Root fault in the subsurface that may not reach the surface. Parallel secondary faults are common within range bounding faults and fit the hypocenter distribution related to the Tobacco Root fault.

Strike-slip movement may be related to a northeast-southwest striking minor fault located between the Mammoth and Bismark faults (Figure 36). This fault has previously been mapped as a normal fault (Vuke et.al., 2014). Although the two strike-slip focal mechanisms cannot be confidently placed on this fault, if it is responsible for movement, then the fault is now a right lateral strike-slip fault.

The northern focal mechanisms (Figure 36, #3) reveal several consistent normal movements with some component of oblique movement. The focal mechanisms strike ± 10° of North, dipping west or east. A cross section suggests the focal mechanisms are related to the Bismark fault, with the majority of the hypocenters falling within the hanging wall. (Figure 36, #3 and Figure 38).

The Tobacco Root fault and the Bismark fault intersect at 50°, 15°NW (Figure 39, inset). In cross section view, the majority of the seismicity falls below the intersection line (Figure 39). Based on the hypocenter locations earthquakes in this region are probably not related to the intersection of the two faults.

To the northeast of the main Waterloo event, is another sequence of earthquakes with diverse strike-slip, normal and normal-oblique focal mechanisms. Although the focal mechanisms appear to have either a north-south or east-west fault plane, they could
not be successfully placed on a specific fault. However, these earthquakes are probably related to the intersection of the Bismark fault and the Tobacco Root fault. More seismicity in the region will allow for a more accurate cross section. (Figure 35, #4)

Figure 37 Cross section A-A’ from figure 36 (red focal mechanisms, clusters 1 and 2).
Figure 38 Cross section B-B' from figure 36 (green focal mechanisms, cluster 3).
Figure 39 Cross section C-C' from figure 36, running parallel to the trend of the intersection of the Bismark and Tobacco Root faults. Inset is the corresponding stereoplot with faults intersecting at 50, 15NW (triangle).
Northeast of Norris (Figure 26, location 5)

An area approximately 12 km to the northeast of the town of Norris, Montana has experienced intermittent seismicity since May 2003 when a magnitude 2.4 earthquake occurred. Since this earthquake, 72 more earthquakes occurred with a maximum magnitude of 3.13. Of these earthquakes, 16 produced focal mechanism data. Epicenters are surrounded on three sides by known faults; the Elk Creek fault to the north, striking northwest and dipping to the northeast; the Cherry Creek fault to the south, striking northwest and dipping to the northeast; and a small northeast striking fault (herein called the Gallatin River fault) of unknown dip. Based on the dips of the majority of the other Neogene northeast striking faults I am assuming this fault also dips to the northwest. (Figure 40).

Figure 40 Map of the Northeast Norris cluster of earthquakes and the locations of cross section A-A’ (Figure 41), B-B’ (Figure 42), and C-C’ (Figure 43). Fault movement indicators are for known or presumed Cenozoic movement.
Figure 41 Cross section A-A’ from figure 40 showing the relationship of the Cherry Creek fault with the cluster of earthquakes.

The largest magnitude earthquake along with five others show pure strike-slip movement (Figure 40, blue focal mechanisms). The rest of the focal mechanisms show almost completely normal movements (Figure 40, red focal mechanisms). In cross section view, the earthquakes poorly follow the Cherry Creek fault with only a few focal mechanisms following a 70° northeast dip (Figure 41). With the Gallatin River fault dipping to the northwest, the intersection of the two faults was determined based on the
surface intersection and the location of the majority of the earthquake cluster. A cross section was created parallel to this trend (N2°W) to determine the plunge of the two intersecting faults (Figure 42). The plunge appears to be approximately 60° to the north. Using this information, a dip of 77° was determined for the Gallatin River fault. Focal
mechanisms do not seem to follow this dip, however the many of the earthquakes are strike-slip, and will not be able to be placed on a specific fault (Figure 43). The majority of the earthquakes appear to occur within the footwall of both faults.

Figure 43 Cross section B-b' from figure 40 showing the relationship of the Gallatin River fault with the earthquake cluster.

Clarkston (Figure 26, location 6)

The magnitude 6.6, 1925 Clarkston earthquake is the first earthquake to be recorded instrumentally in Montana (Doser, 1989). Relocation of this earthquake
suggests that it occurred somewhere within the Clarkston Valley at a depth of 9 ± 1 km. However considering the horizontal error of the location, the epicenter could lie anywhere within the valley (Doser, 1989). Dewey et. al (1973) suggest that the earthquake occurred along a north-south striking near vertical fault. Doser’s (1989) focal mechanism indicates a normal-oblique motion with a north-trending fault plane dipping steeply to the east. Since the time of this large earthquake, consistent seismicity has occurred within the valley and has a maximum magnitude of 3.2. The earthquake catalog for this study includes 544 earthquakes, 40 with focal mechanism data. Focal mechanisms are consistent with the 1925 Clarkston Valley earthquake movement showing mostly normal/normal-oblique motion with a few strike-slip mechanisms, however there are notable differences. The favored fault plane of the 1925 earthquake dips to the east, and the major active faults within the region are known to dip to the west and the T-axis orientation of the 1925 earthquake trends to the northwest, while the rest of the T-axes trend east-west. (Figure 44)

The tectonic setting of the Clarkston Valley area earthquakes differs somewhat from the areas previously described because it is within the Late Cretaceous and Paleogene fold and thrust belt. The areas previously described are in the basement uplifts of the Rocky Mountain Foreland. To the west of the Clarkston valley is the Lombard thrust fault, which, in this region, trends north-northeast, and dips gently to the northwest. A group of unnamed north-northeast to north-south striking, west-dipping Neogene faults approximately 2 km apart are located between the Lombard thrust and the Neogene Clarkston Valley fault. (Figure 44)
Following Burton et al. (1996) and Ballard et al. (1993), Schmidt et al (1990) reinterpreted a seismic reflection profile through the Lombard thrust sheet and related faults to be folded above thrust culminations (Devils Fence Anticline) and having a basal detachment above basement (Figure 45). The cross section ends just to the east of the Lombard Thrust, showing the Poison Hollow thrust splaying off of the basal detachment at a depth of approximately 15 km. Focal depths for the Clarkston Valley earthquakes are all above but near the inferred basal detachment.
Cross section A-A’ runs perpendicular to the Clarkston Valley fault. From this cross section, it appears that the Clarkston Valley fault, at this orientation, cannot be responsible for the earthquakes within the area.

A second cross section, B-B’ is oblique to the general trend of the faults in the region, but is perpendicular to the nodal plane that most likely represents the fault plane of the larger magnitude focal mechanisms. In this cross section, two packages of seismicity are identified (Figure 47). From 0 km to 8 km in depth, focal mechanisms show dominantly oblique normal movement and are located primarily in the southern-most part of the study area (Figure 44, grey dots and red focal mechanisms). The other focal mechanisms from this package are located further north and reveal some normal-oblique movement and some vertical movements (Figure 44, black dots and blue focal mechanisms). In cross section, these appear to be related to a normal fault, dipping approximately 65°SW, directly to the east of Clarkston, herein called fault A (Figure 44 and 47, fault A). Fault A is a concealed west dipping normal fault under Quaternary cover that runs along the west side of Miocene and Oligocene sedimentary deposits mapped by Reynolds and Brandt (2006). I hypothesize that fault A changes its strike slightly under the Quaternary cover and connects with a north-south trending inferred fault directly to the north of Clarkston (Figure 44 and 47, fault A).
Figure 45 Map location and seismic reflection controlled cross-section through the Lombard Thrust, used to interpret focal mechanisms through the Clarkston Valley (Modified from Schmidt et al., 1990).
The majority of the earthquakes in the Clarkston area are located in and around the town of Clarkston (Figure 44, black dots and blue focal mechanisms). These earthquakes occur at approximately 9 km to 20 km in depth. Focal mechanisms reveal mostly normal to normal-oblique motion (Figure 44), however the strike of these are more variable than the first package. In cross section, these earthquakes appear to have occurred on the Clarkston Valley fault and perhaps another fault (Fault B) approximately 1.75 km to the west of it (Figure 44 and 47). Both of these faults change orientation to the northwest near the northeast end of the cross section, accounting for the more northerly striking focal mechanisms. If the earthquakes occur along both faults, the dip of both faults is similar (approximately 45°WSW). Focal mechanisms that are not consistent with
a north-northwest striking fault plane can be best explained by fault B to the west of the Clarkston Valley fault. The strike of this fault changes significantly from one location to another (Figure 44 and 47).

Figure 47 Cross section B-B' from figure 44 showing the relationships of the Clarkston Valley fault, Faults A and B and the Basal Detachment with seismicity in the Clarkston Valley.
Earthquake swarms have occurred in the northern part of the study area, northeast of the town of Townsend, Montana throughout the timeframe of this study. The largest magnitude was 4.2, which occurred during a 2000 sequence. A total of 477 earthquakes have been recorded in this area. However, because of poor hypocenter location constraint, only 17 are well located, with the largest being a magnitude 2.45, which occurred during a 2011 swarm (Figure 48 and 49). Thirty-one focal mechanisms are included in this study. Two cross sections were created, one including all 477 hypocenters (Figure 50 and 51), and one including only the well-constrained data (Figure 50). Error bars are not placed on the cross section that includes all of the hypocenters.

Figure 48 Map of Townsend cluster, showing only focal mechanisms and well constrained hypocenter location epicenters and the location of cross section A-A' (Figure 50).
because the size of the error did not allow for a definitive interpretation (Figure 51).

Focal mechanisms reveal mostly strike-slip movement, with either a north-south striking fault plane or an east-west striking fault plane. Normal movement tends to occur in larger magnitude earthquakes with a northwest striking, northeast dipping nodal plane or a northwest striking, southwest dipping nodal plane, and have a larger hypocenter error than the strike-slip movements. (Figure 48 and 49)

Four major faults within the region are hypothesized to be responsible for the Townsend cluster. The faults locally strike north-northwest, dipping to the southwest; the Townsend Fault Zone; the Deep Creek fault; the Upper Sixmile Creek fault; and the Canyon Ferry fault.
The cross section through the Townsend cluster reveals earthquakes on three of the four faults, the Deep Canyon fault, the Upper Sixmile fault and the Canyon Ferry fault. Although strike-slip faulting is prominent in the Townsend area, the few normal focal mechanisms and their larger error bars allows for the possibility that any, or all three, faults are currently experiencing seismic activity. Normal fault mechanisms suggest that fault dips tend to become steeper to the east. If the unfiltered hypocenters

Figure 50 Cross section A-A' from figure 48 with well constrained hypocenter locations.
had a smaller error, I believe they would be located at a more shallow depth and further to the west (westward and upward, closer to the well constrained hypocenters with focal mechanisms) (Figure 47, 48, 49 and 50).

The northeast area of the fold and thrust belt in southwestern Montana is replete with seismicity. For a better understanding of the seismicity in the area, at least one
seismic station needs to be placed to the northeast of the area. This will allow for better hypocenter location to allow more interpretation of the seismicity in the area.

Discussion

In all of the regions discussed above one or more hypocenters with focal mechanism data can be located directly on a known fault, mostly those at deeper depths (>5 km). However, the majority of the hypocenters fall within the hanging walls of the faults. Of these, some agree with the main focal mechanism for the fault, but some of them do not follow the same trend and cannot be placed on individual faults. The purpose of the following discussion is to evaluate the possibility that these inconsistent mechanisms are related to hot spring activity.

A known hot spring is located within an average of 13 km from each earthquake within the study area (Figure 52) (Metesh, 2000). With a combination of high heat flow, dense fault population, the nearby Yellowstone hot spot, and tall mountain ranges, southwestern Montana is an ideal place for artesian hot springs. There are 110 known hot springs within the study area. These hot springs are typically found in valleys with a neighboring mountain range. The recharged water is heated at depth and then travels up larger faults to the surface (Figure 52 B). Of the faults previously described, hot springs lie directly on three of the faults, and the other four have nearby hot springs. Each previously described earthquake cluster is within 26 km from a known hot spring, with an average distance of 9 km. These earthquakes do not typically cluster around known hot springs—with the one exception of the Norris area.
As discussed in Chapter 1, the Late Cretaceous (Laramide) movement on the principal northwest trending and northeast trending faults is associated with the “brittle folding” of basement rocks below anticlinal folds in the Paleozoic section. The basement rock was everywhere highly fractured below the Laramide anticlines (Schmidt et al., 1993) (Figure 54). This fracturing includes secondary faults of various orientations that were probably large enough to have produced earthquakes at the time of their initial movement. If the major fault, with renewed contemporary movement, remains in the subsurface, or if fluid is otherwise blocked from venting to the surface, the fluid may rise from the fault into the fractured hanging wall basement and become pressurized. As fluid pressure builds up, minor faults and fault intersections become pathways by which heated water reduces the normal stress across fault surfaces. With reduced effective stress, faults which are now under tensional stress, may slip causing small earthquakes within the hanging wall of the main fault (Figure 53 A).

This hypothesis may explain the different orientations of focal mechanisms on the hanging wall of faults within Waterloo, the Tobacco Root Mountains, Clarkston, Townsend, and northeast Norris. However, there is not a known hot springs along the northern Ruby Range bounding fault to explain the Sheridan earthquake cluster. There are two hot springs in the northeastern region of the Ruby Range (Figure 27 and 52). Recharge water from within the Ruby Range is hypothesized to travel through the highly faulted area, including the northern Ruby Range bounding fault. Heated water travels both to the current exposed hot springs, along with traveling through the main bounding faults. The water then behaves in a manner similar to that in figure 53 A, with water traveling through a deformed hanging wall, creating minor earthquakes.
Figure 52 Epicenter locations with locations of known hot springs within and near the 7 locations previously discussed.
Figure 53 Basic diagram of interaction between recharge water, the hot springs of southwestern Montana and the many faults, fractures and minor faults.
Figure 54 Sequential diagram of movement on northwest-trending faults and resulting hanging wall fracturing in Precambrian basement. Initial geometry based on the London Hills fault and associated anticline (Schmidt et al., 1993).

a. Late Cretaceous left hand thrust faulting (along earlier Proterozoic normal fault with associated folding of Paleozoic and Mesozoic cover and deformation of basement).

b. Continued Late Cretaceous fault movement.

c. Post Late Cretaceous erosion of hanging wall rocks.

d. Late Cenozoic right hand normal faulting related to contemporary seismicity. Fracture basement, though diagrammatic, generally represented the major antithetic faults associated with both Late Cretaceous and Cenozoic deformation and possible pathways for fluids.
Conclusions

Strike-slip faulting becomes more prominent north of Clarkston (Figure 26, location 6), and south of Sheridan (Figure 26, location 1). Beyond these limits, determining which faults are responsible for which earthquakes become more difficult to establish due to vertical fault planes on the focal mechanisms. This does not necessarily suggest vertical faults, only that pure strike-slip movement is occurring on the faults. Although most faults studied experience a normal-oblique motion, the oblique motion changes from south to north. Within and to the south of the Tobacco Root Mountain, the oblique component is dominantly right-lateral. To the north of the Tobacco Root Mountains, the oblique component is dominantly left-lateral if the fault plane trends north-south/northeast or right lateral if the fault plane trends northwest. This phenomenon may be more closely related to the Lewis and Clark line, the northern boundary of the study area. The Lewis and Clark line, as previously discussed in Chapter 1 has Neogene movement that is right lateral (Figure 9). The Lewis and Clark line lies just to the north of the observed left lateral strike-slip faulting in Townsend, suggesting that there faults may be secondary structures related to recent movement on the Lewis and Clark Line.

Intersections of faults were investigated within three areas; Waterloo, northeast Norris and Norris. Earthquakes that cluster in areas of fault intersection typically occur in the mutual footwall of the faults. Earthquakes tend to follow the intersection of faults except for in the Waterloo region where epicenters generally are located to the east of the intersection.

The orientations of the faults within the fold and thrust belt are more variable than those in the basement rocks. Focal mechanisms are more easily placed on known faults
within the crystalline basement rocks. Focal mechanisms do not fall on the dominant trend of the faults (such as the Clarkston fault), and more closely follow the trend of the changes in fault orientation.
CHAPTER IV
REGIONAL EXTENSION AS INFERRED FROM FOCAL MECHANISMS

The purpose of this chapter is to 1) examine the degree of regional consistency of T-axis orientations and types of fault movement derived from focal mechanisms for the 1606 earthquake focal mechanisms within the study area; and 2) to evaluate the change in T-axis orientation from south to north and to attempt to explain the change.

Incremental extensional strain derived from earthquake focal mechanisms is represented as the “tension” (T-axis) compatible with the fault slip pattern (Scholz, D.H. 1990). From the focal mechanism catalog in this study, an average extension direction throughout southwestern Montana is oriented N30°E-S30°W (Figure 55a). The general pattern of fault types from all the focal mechanisms may be represented on a ternary diagram with dip-slip normal, dip-slip thrust, and strike-slip end members (Figure 55b) (Frolich, 1992).

Figure 55 Stereoplot showing all T-axes from focal mechanisms (A) contoured in a 1% net area trending N30°E/S30°W and ternary plot (B) representing focal mechanisms of mostly normal to normal-oblique slip.
T-axis and Tectonic Setting

As described in Chapter 1, the earthquakes in southwestern Montana occur across two distinct Late Cretaceous tectonic provinces: the Rocky Mountain Foreland Basement (RMFB) and the Cordilleran Fold and Thrust Belt (CFTB) (Figure 9). The style of deformation in each of the provinces is distinct. The RMFB province has faults and folds that involve Archean and Lower Proterozoic metamorphic rocks, whereas the CFTB is essentially “thin skinned” with faults and folds in Middle Proterozoic (Belt Supergroup) and Phanerozoic sedimentary rocks. In many places the CFTB impinges on the RMFB province and in others (as along the southwest Montana Transverse Zone (Figure 9)), thin skinned thrusts are folded by movement on basement faults (Schmidt et al., 1988). Because Cenozoic faulting is clearly influenced and/or controlled by the earlier structures, differences in focal mechanisms should be expected in the two provinces. In this regard, because the two provinces overlap, it is important to determine which earthquakes in the CFTB occur in basement below the thrusts and which occur in the thrusted sedimentary section.

By inspection, the region was divided into five sections based on the similarities in fault trend and type and T-axis orientation (Figure 56). Section 1 is a region of overlap, where the CFTB impinges the RMFB. It is bounded on the south by the Snake River Plain. Section 2 is entirely within the RMFB. It is also bounded by the Snake River Plain to the south and is located near the northwestern edge of the Yellowstone Hot Spot. Section 3 is principally within the RMFB but is overlapped on the west by the CFTB. Section 4 also lies principally within the RMFB province but is overlapped on the
extreme northwest by the CFTB. Section 5 is entirely within the Helena Salient of the CFTB.

Figure 56 Sections 1-5 separated by similar fault trend and movement and T-axis orientation. Section 1, 3, and 4 represent earthquakes within the Rocky Mountain Foreland (RMFB) and the Cordilleran Fold and Thrust Belt (CFTB). Section 2 is solely in the RMFB and section 5 is solely in the CFTB. The red line marks the approximate boundary between the CFTB and the RMFB provinces.
Cross sections through section 1 by Perry et al. (1988) and Skipp (1988) reveal the CFTB and the RMFB basement occurs at a maximum depth of 5 km. 82% of hypocenter depths for section 1 are deeper than 5 km and can therefore be assumed that most hypocenters occur within basement rocks (RMFB). Faults within section 1 trend northwest with major range bounding faults trending northeast and northwest (Figure 57). Focal mechanisms within this area are mostly normal with some strike-slip movements (Figure 58 A). T-axes cluster around N5°E/S5°W however, there are several outliers (Figure 58 B).

Figure 57 Section 1 from figure 56 showing focal mechanisms and T-axes (represented as black triangles).
Faults within section 2 trend mostly northwest. However there are many faults that have various orientations. Major range-bounding faults within this section trend north-south (the Madison fault, running parallel to the Madison River) (Figure 59). Focal mechanisms are variable, however are mostly normal (Figure 60 A). T-axes average N15°E/S15°W and are not well clustered (Figure 60 B). A large trend of seismicity follows a concave north pattern through section 1 and section 2 revealing right lateral strike-slip and normal faulting, assuming a northeast trending nodal planes which run parallel to the seismicity trend, without a nearby fault that follows the trend. This phenomenon will be discussed in a later section.

Section 3 includes the Sheridan, MT earthquake cluster (discussed in Chapter 3) along with the July 2005 M_w 5.6 Dillon, MT earthquake sequence. This swarm included over 1150 aftershocks. The main shock showed normal slip with a small component of right hand oblique slip along a north-northwest striking fault (Stickney, 2007). 95% of
Figure 59 Section 1 from figure 56 showing focal mechanisms and T-axes (represented as black triangles).

Figure 60 Ternary diagram (A) showing very diverse fault movements and a stereoplot contoured at 1% net area (B) showing T-axes for the section 2 from figure 56 and 59.
the hypocenters within section 3 are deeper than 5 km, and therefore can also be assumed to all occur within the basement rocks (RMFB). Faults in this section trend northwest (Figure 61). Focal mechanisms within this section are normal with a few strike-slip movements (Figure 62 A). T-axes are well clustered around N45°E/S45°W (Figure 62 B).

Figure 61 Section 3 from figure 56, showing focal mechanisms of the southern basement rocks of the study area and T-axes (represented as black triangles).
Section 4 includes the Waterloo, Norris and northeast Norris regions discussed in Chapter 3 (Figure 63). This area includes a small region of the CFTB rocks, through the Waterloo clusters. However, based on the cross sections in Chapter 3, we can assume that these earthquakes also occur within the basement rocks. Northwest faults also dominate this area, with notable exceptions such as the Tobacco Root north-south range bounding fault (Figure 63). Focal mechanisms in this area show a dominant normal movement (Figure 64 A). T-axes trends cluster consistently around an average N70°E/S70°W (Figure 64 B).

Section 5 is entirely within the CTFB and includes the Clarkston and Townsend regions discussed in Chapter 3 (Figure 65). Seismicity within section 5 is completely within the fold and thrust belt because the CFTB is thicker in this region than in the previously overlapped regions due to stacking of thrust sheets within the Helena embayment (Burton et. al., 1996; Ballard et. al., 1993; Schmidt et. al., 1990). Fault trends in this area are dominantly either east-west or north-south, following those of the thrust
belt structures (Figure 9 and 56). Focal mechanisms reveal strike-slip faulting with some normal movements (Figure 66 A). T axes cluster east-west, averaging N80°E/S80°W (Figure 66B).

Figure 63 Section 4 from figure 56, showing focal mechanisms and T-axes (black triangles) from the northern basement rocks.

Figure 64 Ternary diagram (A) showing mostly normal movement from section 4 from figure 56 and a stereoplot contoured at 1% net area (B) showing T-axes consistent with an east-northeast/west-southwest extension.
Figure 65 Section 5 from figure 56 showing focal mechanisms and T-axes (black triangles) of the fold and thrust belt.

Figure 66 Ternary diagram (A) showing mostly normal to strike-slip movement on faults within the fold and thrust belt (section 5 from figure 56) and stereoplot contoured at 1% net area (B) showing T-axes trending west-southwest/east-northeast.
T-axis Rotation

From the previous discussion, it is clear that T-axes change orientation depends on geographical location within the study area (Figure 67). In order to examine the geographical change/rotation of the T-axes, half rose diagrams were created for each 30 by 30 minute section from latitude 44.5°N to 46.5°N and longitude 111°W to 113°W (Figure 68). The north-south change in T-axis orientation is represented by combined half rose and stereoplots for the four latitude segments from 44.5°N to 46.5°N. Results show a range of T-axis orientations, with a general North-South trend from latitude 44.5°N to 45°N with a mean of N10°E (Figure 69a). T-axes begin to show a northeast-southwest trend from latitude 45°N to 45.5°N with mean of N35°E (Figure 69b). From latitude 45.5°N to 46°N the trend becomes more northeasterly with a mean of N70°E (Figure 69c). Finally, from latitude 46°N to 46.5°N, the T axis trend is almost entirely east-west with a mean of N80°E (Figure 69d).

Ternary diagrams for each latitude segment illustrate the general change in slip sense from south to north (Figure 70). The southernmost region (from latitude 44.5°-45°N) shows the most diverse range of fault slip types, consistent with the large variability of T-axes as well as diverse fault attitudes (Figure 70a). Normal to normal-oblique faults are dominant, but there is a significant number of strike-slip faults, and some oblique-thrust to thrust faults. From latitude 45°-45.5°N, the general senses of fault movement is more consistent with dominantly normal faults with fewer strike-slip faults and still fewer thrust-faults (Figure 70b). From latitude 45.5°-46°N, normal faults continue to be dominant with an increase of strike-slip faults (Figure 70c). From latitude
46°-46.5°, the fault movement is dominantly strike-slip with fewer normal faults (Figure 70d).

Figure 67 All T-axes from the focal mechanism catalog. T-axes become dense and hard to see based on population, which inspired the half rose diagrams in figure 68.
Figure 68 Half Rose Diagrams of T-axes.
Figure 69: Half Rose Diagrams of T-axes with 1% area contours where: A) Latitude 44.5-45 degrees; B) Latitude 45-45.5 degrees; C) Latitude 45.5-46 degrees; and D) Latitude 46-46.5 degrees.
Figure 70: Ternary Diagrams showing: A, from 44.5-45 degrees; B, from 45-45.5 degrees; C, from 45.5-46 degrees; and D, from 46-46.5 degrees.
Although the trend of the T-axes is variable in each section (1-5) and each latitude segment, it is clear that there is a significant change/rotation from south to north. This rotation appears to occur somewhere within the region bounded by 111.25°W to 112.5°W and 45.25°N to 45.74°N. These four sections were subdivided into smaller 15 minute sections within them to determine where the most significant T-axis change occurs (Figure 71). T-axes show a general north-south trend throughout latitude 45° to 45°15’N, but begin to rotate slightly to a more northeasterly trend in the next northerly 15’ section. The half rose plots in the 15’ sections just north of Ennis Lake are consistent with the sections containing the lake. Maximum change appears to occur along and east-west line at latitude 45°15’N to longitude 112°W then jogs south to 45°N and then continues west (Figure 71).

Regional Stress Provinces

Zoback and Zoback (1980) created a stress map using focal mechanisms, in situ data, and previously published data (Figure 16). The map shows several distinct zones north of the Basin and Range Province, which have east-west extension; the Northern Rocky Mountain Province, with an overall northeast-southwest extension; Hebgen Lake-Centennial Valley, with a mostly north-south extension; the Snake River Plain, with a northeast extension. There were few data points used for this interpretation. In 1987, Stickney and Bartholomew reinterpreted this map (Figure 72), limiting the extent of the region with dominant north-south extension of to just the Hebgen Lake area, interpreting the remainder of western Montana as having an overall northeast-southwest extension and indicating the eastern extent of the Montana-Idaho Basin and Range Province to be approximately coincident with the front of the Cordilleran thrust belt.
Figure 71 Half Rose Diagrams including the 15 by 15 minute section used for further investigation. Red line represents the major change in T-axes shown by the half rose diagrams.
Figure 72 Extension, modified from Stickney and Bartholomew (1987) showing the overall Montana-Idaho Basin and Range, the extent of that extension (dashed line). The dotted line represents the most western edge of the Yellowstone Hot Spot (YHS) influence on extension.
Figure 73 Locations of the Northern Rocky Mountain, Transition and Centennial Provinces with T-axes azimuths.
Considering the south to north change in T-axis orientation described above, three provinces are proposed herein (Figure 73). The province boundaries described are all tentative, and should be continued to be re-evaluated and further constrained as more seismic data is available.

The lower-most province (Centennial Zone) has the highest seismicity. This province includes Hebgen Lake but ends abruptly at the border of Montana and Wyoming for the purpose of this study. The Centennial Zone contains mostly northeast, northwest and east-west trending seismically active faults, including the slightly active to inactive (within the last 30 years) Snowcrest, Madison and Centennial normal faults. T-axes trends within the Centennial Zone (Figure 74) have a mean of 5°N, with an average plunge of 20.2°. Fault movements within this zone are typically normal, normal-oblique and strike-slip and contains the greatest number of thrust faults in the study area.

Figure 74 Stereoplot contoured at 1% net area (A) and ternary diagram showing diverse fault movements for the Centennial Zone.
The Transition Zone (Figure 75) is the province where the T-axis trend begins to rotate from north-south to east-west. This zone has the least seismicity within the study area. It includes the Ruby Range and the Ruby Range front normal fault (also known as the Sage Creek fault of Perry et al (1988)), the northern most part of the Snowcrest normal fault, and the most of the Madison range front normal fault. The Transition Zone T-axes have a mean of 45°, with more closely constrained plunges averaging 15.5°. Ternary plots of this area reveal dominantly normal to normal-oblique faults with several strike-slip faults and a few thrust faults.

![Figure 75 Stereoplot contoured to 1% net area (A) and ternary diagram (B) for the transition zone showing Northeast-Southwest extension on normal to strike-slip faults.](image)

To the north of the Transition Zone is the northern Rocky Mountain Province (Figure 76). Extension in the Rocky Mountain Province is roughly east-west with an azimuth of 80° and average plunge of 14.6° (Figure 76). Ternary diagrams show this region contains dominantly normal faults and strike-slip faults.
Influence of the Yellowstone Hot Spot and Snake River Plain

A change/rotation of T-axes from south to north is confirmed by the detailed examination of focal mechanism T-axes of southwestern Montana. The Centennial Zone to the south represents roughly North-South extension, dominated by normal slip. The diversity of fault trends in the area explains the diversity of T-axes. This entire zone may be under the influence of the Yellowstone Hot Spot and the Snake River Plain.

Previous studies attribute subsidence of the Snake River Plain to crustal flexure and thermal contraction (Rodgers et al. 2002; Brott et al., 1981; Pierce and Morgan, 1992). As the upper and middle crust continue to cool, thermal contraction occurs. This thermal contraction produced a regional topographic low or downward crustal flexure at the edges of the Snake River Plain. Rodgers et al. (2002) showed that the Cretaceous fold hinges up to 30 km from the edge of the Snake River Plain that plunge southerly, towards the plain, and attributed to this crustal flexure. The Snake River Plain plunges very gently to the southwest. Presumably as the Snake
River Plain’s crust cools, the northeast portion of the plain will match the topographic low of the southwest portion.

The Heise volcanic field and Island Park volcanic field (Figure 77) are between 35 and 45 km to the south of the study area, similar to the distance between the volcanic fields and fold hinges studied by Rodgers et al. (2002) in Idaho. The southern portion of the study area does not contain large folds, so similar data could not be analyzed. However, T-axes to the north of the Snake River Plain are parallel to the fold hinges studied in Idaho, perpendicular to the Snake River Plain.

I propose the following hypothesis: extension within southwest Montana is the same as the east-west, Basin and Range extension that is present to the south of the Snake River Plain. The North-South extension of the Centennial Zone is a regional effect due to the subsidence of the Snake River Plain. The Transition Zone represents a transition between the two stress regimes. This transition zone is not present to the south of the Snake River Plain and its absence may be due to the northeast path of the hot spot.

Conclusions

Tectonic setting and the stress provinces previously discussed appear to be directly related. Sections 1 and 2 (Figures 57 and 59) are within the Centennial stress province. This province is directly influenced by the subsidence of the Snake River Plain and the Yellowstone Hot Spot. T-axes are variable, but predominantly trend north-south with variable fault movements.
Figure 77 Heise and Island Park Volcanic Fields and their relationship to T-axes of southwestern Montana.
Sections 3 and 4 are within the Transition Zone, with consistent northeast/southwest trending T-axes. Faults within the area trend northwest, and focal mechanisms reveal normal and normal-oblique movement.

Section 5 is within the Northern Rocky Mountain Province with consistent east-west extension. Faults follow the north-south or east-west trends of the Cordilleran Fold and Thrust belt with dominant strike-slip movements.
CHAPTER V

CONCLUSIONS

Seismicity

Seismicity within southwestern Montana occurs within two different Late Cretaceous tectonic provinces, the Rocky Mountain Foreland Basement (RMFB) and the Cordilleran Fold and Thrust Belt (CFTB). Earthquake foci prefer long lived active faults at depths between 8 and 10 km within the Rocky Mountain Foreland Basement. The dips on these faults are steeper than those of the CFTB, and therefore more easily accommodate extensional reactivation. Focal mechanisms observed in this region are predominantly normal/normal-oblique movements. For example, the prominent set of northwest trending, northeast dipping normal faults show right hand oblique movement (hanging wall down and right (southeast) with respect to the footwall). This is the most recent movement of a protracted history on this fault set with normal movement in the middle Proterozoic and left hand reverse slip in the Late Cretaceous (Schmidt and Garihan, 1986). The large diversity of fault orientations also allows for some strike-slip and thrust faulting. Within the Cordilleran Fold and Thrust Belt earthquake foci cannot be readily assigned to specific faults. There are several likely reasons for the lack of correspondence of foci to specific faults in the CFTB (when compared to the RMFB). First, both the depths and epicenter locations are less well constrained in this region. Second, the foci all lie within the Middle Proterozoic sedimentary section that was shortened by thrust faulting in the Late Cretaceous and did not have subsequent reactivation, like the faults of the RMFB.

Many of the foci within the Rocky Mountain Foreland Basement fall within the hanging walls of associated faults. These earthquakes may be explained by movement on fractures and secondary faults influenced by subsurface water related to hot springs in which heated water
migrates through the highly fractured hanging walls of the Late Cretaceous (Laramide) thrust faults. By reducing effective stress due to fluid pressure, the minor faults undergo renewed slip, causing earthquakes within the hanging walls of the major faults.

**Extension**

Extension within southwestern Montana is described as generally northeast-southwest, which is consistent with normal and normal-oblique faulting on dominantly northwest striking faults. However, the extension direction changes throughout the study area from north-south in the southern most regions to east-west in the northern most regions. The extension direction may be divided into three distinct provinces: the Centennial Province, the Transition Zone, and the Northern Rocky Mountain Province.

Extension within the Centennial Province trends north-south and can be explained by the subsidence of the Snake River Plain on predominantly north-northwest and east-west fault trends. The Transition Zone is represented by northeast-southwest extension on northwest striking faults. Within the Transition Zone, extension becomes less influenced by the Snake River Plain, and is more influenced by east-west extension found in the Northern Rocky Mountain Province. The extension in the Northern Rocky Mountain Province is consistent with the east-west extension of the Basin and Range to the south of the Snake River Plain.

**Future Work**

Although this study covered several aspects of seismicity and extension throughout southwestern Montana, there are several unanswered questions. The areas discussed within Chapter 3 need to be continuously observed for any differences in focal mechanisms that could be applied to the cross sections. Field data would be helpful to have a better control on fault
Figure 78 Seismicity and fault map of southwestern Montana showing locations of future interest discussed within the text.
orientation, dip direction and dip angle. These goals could be accomplished by searching for fault scarps, using near-surface geophysical measurements (such as seismic reflection studies and electrical resistivity), or trenching across faults.

The faults described throughout Chapter 3 are represented as flat planes however many of the faults throughout southwestern Montana behave in a listric fashion (Schmidt and Garihan, 1986; McBride et. al., 1992). The listric nature of the faults has not been exhaustively studied, and therefore the amount of curve and dip of curve is unknown for the region. Field data along faults with clear rollover (such as the Sage Creek fault within the Snowcrest Range (Perry et al., 1988)) could help constrain the earthquake cross sections in this study.

Along with the seven areas discussed, there are several areas that could still be examined for fault movements including: Dillon, Dell, earthquake clusters around the northern Tobacco Root Mountains (Figure 78). However, the fault population within the Dell, MT area is extremely dense and the mapping may not represent the actual number of faults in the area. Updated maps of the quadrangle containing the Beaverhead Range would allow for this area to be confidently examined.

There is some seismicity between Boulder and Townsend (from the unfiltered hypocenter list) but very few mapped faults in the area can account for the earthquakes (Figure 78). There are several focal mechanisms, but few well located hypocenters. This is most likely due to the lack of a northeastern seismic station to constrain the hypocenter locations. The geologic maps of the area are out of date, and needs to be updated.

Many major Cenozoic faults appear to be inactive in recent times. These include, the western Ruby Range front, the Snowcrest fault (also known as the Sage Creek fault (Perry et. al.,
the Jefferson Canyon fault, the Madison Range fault and the Eastern Centennial fault (Figure 78). The Madison fault is a roughly north-south trending, west dipping fault composed of 3 fault segments that change directions, similar to the Wasatch fault of Utah (Bruhn et al., 2005). Earthquakes do not occur within the Madison Valley, to the west of the Madison fault, but they do occur within the Gravelly Range farther west (Figure 78). Based on a cross section by Schmidt et. al. (1993), the Madison fault is projected to be approximately 7 km below the Gravelly Range. Earthquakes within the Gravelly Range average 8.87 km in depth, suggesting the seismicity may be related to the Madison fault. A focal mechanism revealing normal movement at 44.8725°N, -111.741667°W is approximately 25 km away from the Madison fault. The focal mechanism suggests a 25° westward dip, which accounts for the 11.25 km depth of the earthquake. The dip and location of the earthquake agrees with Schmidt et. al. (1993) cross section through the region. There may only be a few earthquakes occurring on the Gravelly Range faults due to the north-south T-axis influence from the Snake River Plain. More cross-sections and a detailed analysis may confirm this hypothesis.

The Centennial Tectonic Belt has high seismicity; however with dominant strike-slip focal mechanisms make it difficult to place these earthquakes on specific faults. The earthquakes within the eastern region follow a concave south pattern with consistent northeast trending nodal planes, interpreted as the fault planes. There are no faults mapped within the area that follow this trend, suggesting a blind fault with a curved strike east of the mapped portion of the Centennial fault and the seismicity (Figure 78). An alternative hypothesis is that the seismicity does fall on the Centennial fault, but the eastern portion (at depth) has become annealed by the Yellowstone Hot Spot. The trend of the curve is roughly parallel to the trend of the Snake River Plain. Cross sections and field work may confirm one of these hypotheses.
Although T-axes were examined throughout this study, the actual principal stress directions were not addressed. Focal mechanism inversion throughout the areas discussed would allow for constrained strain directions. After inversion, the averaged T-axis directions that were used in this study could be compared to actual principal stress directions.

A final topic for additional research is to try to determine the factors that control the boundaries of seismicity within the Northern Rocky Mountain Province in Montana and Idaho. As described in this study, most of the seismicity can be ascribed to renewed movement on faults that were active during the Late Cretaceous thrusting in the CFTB and faulting in the RMFB. This evidence is especially strong in the RMFB and somewhat less so in the CFTB.

In Montana, north of approximately 46°N, the eastern boundary of major seismicity coincides roughly with the eastern boundary of the CFTB, although scattered minor seismicity continues nearly 150 km east of the boundary and major zones of seismicity, such as the Clarkston and Townsend areas, occur west of the boundary in the central part of the Helena Salient (Figure 79). Major zones of seismicity also occur along this boundary south of 46° N, but here long faults in the RMFB are seismically active far to the east of the boundary to at least 111°W. Major seismicity does end however at about 111°W however, whereas the great faults and ranges of the northern RMFB continue to the east for hundreds of kilometers. It is probable that tensional stress simply decreases rapidly eastward of 111°W. However the presence of the large field of Eocene Volcanics (the Gallatin volcanic field, Chadwick, 1969) might have had an annealing effect on the basement fault zones east of 111°W (Figure 79).

The southern boundary of major seismicity is clearly a product of the annealing effect of volcanism on Cretaceous fault zones, effectively destroying any previous Cretaceous thrust belt
anisotropy. Westward of about 113°W, major seismicity effectively ends south of 44°N (Figure 79). Here the distance from the edge of major seismicity to the Snake River Plain increases somewhat as the plain bends from northeast to northwest at about 115°W, perhaps related to other igneous bodies like the southern part of the Late Cretaceous Idaho batholith and Eocene Challis Volcanic fields (Figure 79).

The reason for the position of the western boundary of major seismicity is also a topic for future research. From 47°N southward to 43°N, the only zone of major seismicity occurs in the Sawtooth range, east of the Idaho batholith. The 1983, M6.9 Borah Peak earthquake occurred in the southern part of this region. Minor earthquake sequences occur on the western margin of the batholith at about 116°W. When compared to adjacent areas, those occupied by the Idaho, Phillipsburg, Boulder and Pioneer batholiths and the Challis Volcanics have minimal seismicity. Perhaps this igneous activity was responsible for annealing the faults within the CFTB to the extent of making brittle failure on pre-existing faults unlikely (Figure 79).

Despite the correlation between the batholiths and the earthquake clusters, it is important to remember the little amount of data within the area. If the Borah Peak, Idaho earthquake had not occurred, then the seismicity map within the Northern Rocky Mountains would not include much data in Idaho. I would suspect that if we had substantially more data, the seismicity map would look extremely different from today.
Figure 78 Seismicity and batholith relationship within Idaho and southwestern Montana along with locations of the Rocky Mountain Foreland Basement (RMFB) and the front of the thrust Belt. PB is the Pioneer Batholith (Late Cretaceous); BB is the Boulder Batholith (Late Cretaceous); PhB is the Phillipsburg Batholith (Late Cretaceous); CV is the Challis Volcanics (Eocene); GV is the Gallatin Volcanics (Eocene); and the Snake River Plain contains Neogene Volcanics.
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