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Paleomagnetism and rock magnetism of remagnetized carbonate rocks from the Helena salient, Southwest Montana

Benjamin F. (Benjamin Franklin) Baugh
Western Washington University

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MASTER’S THESIS

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Date: ______________________________________
PALEOMAGNETISM AND ROCK MAGNETISM OF REMAGNETIZED CARBONATE ROCKS
FROM THE HELENA SALIENT, SOUTHWEST MONTANA

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Ben Baugh
November, 2010
Abstract

The Helena salient is an arcuate curve in the southwest Montana fold and thrust belt, characterized by thin-skinned folding and thrusting. Ages from volcanic sills imply that deformation in the region began 77 million years ago during the Late Cretaceous (Harlan et al., 2008). This study investigates the nature of curvature associated with this salient using paleomagnetic techniques. Carbonate rocks of the Mississippian Madison Group were sampled from 24 sites across three folds: the Devil’s Fence anticline, the Three Forks anticline and the Turner anticline (near Townsend, MT). Results from 16 sites have well defined, but very weak, magnetizations. At 100% untilting, two components of magnetization are revealed: a Mississippian primary magnetization (M-group) from at least two sites, and a Late Cretaceous chemical remanent magnetization (CRM) for 13 sites (K-group). Fold tests for the K-group indicate that each fold acquired a magnetization at 90-100% untilting. A mean direction for the K-group, in geographic coordinates and $D = 35^\circ$, $I = 72.9^\circ$, $\alpha_{95} = 8.8^\circ$ is obtained for Devil’s Fence anticline, $D = 37.7^\circ$, $I = 70.1^\circ$, $\alpha_{95} = 23.9^\circ$ for Three forks anticline and $D = 224.6^\circ$, $I = 69.1^\circ$, $\alpha_{95} = 29.1^\circ$ for Turner anticline. Using a direction ($D = 335.8$, $I = 70.1$ and $\Delta D = 6.3^\circ$) for the locality calculated from a Late Cretaceous North American (NA) reference pole (McFadden and McElhinny, 1995), the K-group indicates large (~60° CW) vertical axis rotations from Devil’s Fence and Three Forks anticlines, as well as 111° counter-clockwise rotation from Turner anticline since the Late Cretaceous. Magnetic hysteresis data fall on the superparamagnetic + pseudo-single domain mixing lines, consistent with rock magnetic data from other studies sampling remagnetized carbonate units (e.g. Suk et al., 1993; Xu et al., 1998). When K-group directions are un-rotated on an equal-area plot to a Late Cretaceous NA reference pole, the M-group restores to a direction similar to a direction expected from a Mississippian NA reference pole ($D = 310$, $I = 8.2$ and $\Delta D = 4.7^\circ$) and indicates a clockwise rotation of the pre-deformational sedimentary basin of $22 \pm 18^\circ$ to $59 \pm 14^\circ$. Rotations reveal rigid block behavior of a clockwise rotating Elkhorn plate, while thrust sheets along the northern margin of the Helena salient experienced buttressing against the foreland margin resulting in counter-clockwise rotation.
Acknowledgements

There are a number of people who contributed to this project and for that I am forever thankful. First and foremost, thank you Bernie Housen for taking me on as a graduate student and assisting me in the development of the project. Bernie, on more than one occasion, went out of his way to see this project get completed in a timely and efficient manner.

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Russ Burmester helped with every part of the methods, analysis and interpretation of this project. Russ is an expert in the field of paleomagnetism, and specializes in the geology of western Montana. Without his help, this project may have never materialized.

Additional thanks to my field assistant Steve Shaw, and to all the graduate students who supported me throughout my graduate career. Funding for this project was granted by the GDL Foundation, a grant from Research and Sponsored Programs at Western Washington, and a grant from the Western Washington University Geology Department.
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Introduction

The North American Cordilleran fold and thrust belt trends approximately north-south along the east side of the Cordillera through British Columbia to southern Nevada. Throughout much of its extent, the trend of the fold and thrust belt is linear, but it deviates from this trend in southwest Montana, Idaho, and Wyoming where thrust traces bend to form large curves (Fig. 1). Such curves are called salients when thrust traces are convex toward the foreland (Miser, 1932). In contrast, “recess” describes the curve where thrust traces are convex towards the hinterland (Fig. 2). Using paleomagnetism, this study investigates the nature of curvature associated with the Helena salient in southwest Montana by quantifying vertical-axis rotation along the margin of the salient, as well as from the interior of the salient.

Figure 1. The Helena and Wyoming salients (modified from Harlan et al., 2008). A rectangle shows the location of the Helena salient thrust traces.
Sussman and Weil (2004) propose three broad categories for curved orogens: oroclines, primary arcs and progressive arcs. An orocline is defined as a curved orogen that originally had a linear grain, but acquired its curvature through a subsequent phase of deformation (Carey, 1955). Vertical axis rotation along a limb of an orocline should result in a 1:1 relationship between rotation and measured curvature of the arc. In contrast, a primary arc is defined as a curved orogen that acquired its curvature through its initial phase of deformation and should theoretically show no vertical-axis rotation along its limbs. A progressive arc either acquired curvature throughout the history of deformation or
inherited part of its curvature during the initial phase of deformation. Vertical-axis rotations within a progressive arc should be less than the amount of measured curvature of thrust traces (Sussman and Weil, 2004).

In the northern Rockies, paleomagnetic vertical-axis rotations have been observed in both the Wyoming and Helena salients of the North American Cordilleran fold and thrust belt. Grubbs and Van der Voo (1976) observed clockwise rotation along the southern margin and counter-clockwise rotation along the northern margin of the Wyoming salient. This pattern was attributed to buttressing effects of the fold and thrust belt against a pre-existing arcuate foreland margin. Schwartz and Van der Voo (1984) later sampled from the interior of the Wyoming salient and observed no significant rotation, supporting the hypothesis that rotations observed along the margin were not translated back to the interior of the salient. Eldredge and Van der Voo (1988) sampled Cretaceous red beds of the Kootenai Formation from a variety of locations along the southern margin of the Helena salient in southwest Montana and documented a similar pattern of rotations along the margins of the salient. This pattern was attributed to buttressing effects against a contemporaneously uplifted foreland margin (Eldredge and Van der Voo, 1988) and they concluded that thrust sheets did not rotate in a coherent manner, but broke apart and rotated where buttressing effects were greatest.

**Geology of western Montana and the Helena salient**

In southwest Montana, thrust traces of the fold and thrust belt change from approximately northwest-southeast to northeast-southwest (Fig.3). This curve in thrust traces is referred to as the Helena salient. South of the Helena salient, beyond the smaller
McCarthy Mountain salient, thrust traces are overlain by Snake River Plain volcanics and reappear near the Idaho-Wyoming border forming another arcuate bend, the Wyoming salient (Fig.1).

Figure 3. Generalized map of the Helena salient and geology of southwest Montana (Eldredge and Van der Voo, 1988). I.B.: Idaho Batholith; B.B.: Boulder Batholith; P.B.: Pioneer Batholith. Shown in box is the sampling area for this study. Yellow star: approximate location of Townsend, MT. Black Stars: approximate locations of folds sampled in this study.
The fold and thrust belt in western Montana propagated west to east between 72 and 56 Ma, during the Late Cretaceous / Eocene (Hoffman et al., 1976). Within the nose of the Helena salient, thrusting is highly imbricated and east verging. Recent work has provided some detailed constraints on the age of folding in this area. Harlan et al. (2008) sampled diorite sills along the southern margin of the Helena salient, adjacent to the southwest Montana transverse zone (Fig. 3). Magnetic directions obtained from the sills pass the fold test at 100% unfolding, indicating emplacement prior to deformation. An $^{40}\text{Ar}/^{39}\text{Ar}$ date from the sills puts an upper limit on the age of deformation in the region at 77 Ma.

The Helena salient is bounded to the south by the southwest Montana Transverse Zone and to the north by the Lewis and Clark shear zone (Fig. 3). Faults within the southwest Montana transverse zone strike northeast and dip northwest. Motion along these faults is characterized by reverse faulting with a right-lateral shear component (Schmidt and O’Neill, 1983). The Lewis and Clark shear zone trends west-northwest and is characterized by reverse faulting and a left-lateral component of slip (e.g. Smith, 1965). Underlying the region of the Helena salient is the Helena embayment, a Precambrian reentrant along what was the continental margin where Belt-Purcell Supergroup accumulated to their greatest thickness within the Proterozoic Belt Basin (Harrison et al., 1974). The Lombard thrust fault is the principal thrust of the Helena salient and defines the eastern margin of the Elkhorn plate (Ruppel et al., 1981) (Fig. 3). Within the interior of the Elkhorn plate, the Boulder batholith intruded syn-thrusting, approximately 78 Ma to 68 Ma (Tilling et al., 1968). Because the Boulder Batholith comprises most of the interior of the Helena salient (Fig. 3),
paleomagnetic investigations have been prevented from testing whether or not rotations along the margins of the Helena salient occur within the interior.

**Methodology**

For this study, three sampling locations were chosen across the southern margin of the Helena salient in order to investigate variation in vertical-axis rotation between three folds spanning from the interior to the foreland of the salient (Fig.4). Two folds, the Three Forks and Turner anticlines, are along thrust traces that make up the salient and one fold, the Devil’s Fence anticline, is located within the interior of the Elkhorn plate. While sampling discrete locations along the salient provides a snapshot of the geology at each site, this localized transect provides a more robust understanding into variations of vertical-axis rotation and formation of the salient.
Figure 4. Merged DEM of the study area with a geologic overlay of the units sampled. Pink: Mission Canyon limestone exposures. Yellow: Lodgepole limestone exposures. Rectangles show locations of the three anticlines sampled in this study. In red are approximate thrust trace locations, which disappear beneath Quaternary alluvial deposits. The western trace is the Lombard thrust fault. (GIS data from Reynolds and Brandt, 2006).
Sampling

Samples were collected from 24 sites across three anticlines that together form an east-west transect across the Helena salient (Fig.4). Paleozoic carbonates, primarily from the Mission Canyon Limestone and underlying Lodgepole Limestone of the Mississippian Madison Group, were chosen for sampling. Cambrian to Devonian carbonates were sampled from a few sites for comparison of paleomagnetic characteristics with the Mississippian units. Originally, several folds were considered for sampling based on their geographic distribution across the salient. Sampling over a large region (20-30km) increases the likelihood of observing spatial trends in age of magnetization and variation of vertical-axis rotation across the salient, if present. From the folds considered, the three sampled were chosen based on land accessibility. Ten sites were collected from what will be referred to here as the Devil’s Fence anticline (Fig.5), with one site sampled from the middle Cambrian Meagher Limestone. Eight sites were sampled from the Three Forks anticline with two sites from the Devonian Jefferson Formation (Fig.6). Six sites were sampled from the Turner anticline, all of which are from the Mission Canyon and Lodgepole Limestone formations (Fig.7). The Three Forks and Turner anticlines are both overturned. Five to eight samples were taken from each site using a gas-powered drill and oriented using a magnetic compass. Six sites were collected as oriented block samples due to problems with the gas powered drill, and five of the six sites were later cored in the lab using a drill press. The rest of the cores were oriented, marked in the field and cut to standard lengths for paleomagnetic analysis in the lab (2.2cm). Overall, 149 samples were analyzed from 23 sites. Due to problems with the drill press, block samples for one site (site 6) have yet to be
cored and analyzed. The remaining 23 sites were further cut into to 255 possible specimens for analysis. During this process, rock fragments were saved from each site for magnetic hysteresis analysis.

Figure 5. Map showing sampling locations for Devil's Fence anticline (dots, with site numbers shown). Pink: Mission Canyon limestone. Yellow: Lodgepole limestone. Green: Middle Cambrian Meagher limestone sampled at Site 7. (Digital data from Reynolds and Brandt, 2006)
Figure 6. Map showing sampling locations along Three Forks anticline (dots, with site numbers shown). Pink: Mission Canyon limestone. Yellow: Lodgepole limestone. Light and dark green: Devonian Jefferson Formation. Pink and orange: Upper Cambrian Pilgrim Formation. A gap exists in the GIS data between Townsend (north) and Bozeman (south) quadrangles. (Digital data from Vuke et al., 2002; Reynolds and Brandt, 2006)
Figure 7: Map showing sampling locations for Turner anticline (dots, with site numbers shown). Pink: Mission Canyon limestone. Yellow: Lodgepole limestone. (Digital data from Reynolds and Brandt, 2006)
Analysis

In order to acquire a characteristic remanent magnetization, samples were subjected to thermal and alternating field demagnetization. In a magnetically shielded room, 144 specimens were thermally demagnetized using an ASC TD-48 thermal demagnetizer. Natural Remanent Magnetizations (NRM) were measured using a 2-G 755 DC-SQUID magnetometer. Specimens were subjected to thermal demagnetization in eight to ten temperature steps for 30 minutes per step between 100° and 520°C. Selected thermal steps varied slightly depending on the nature of demagnetization per site, but the representative procedure was as follows (°C): NRM, 100, 200, 275, 350, 400, 440, 480, 520. Most specimens fully demagnetized or became unstable at approximately 510°C. Samples were chosen for Alternating Field (AF) demagnetization when thermal demagnetization yielded noisy or unusable results. Thus, AF demagnetization was carried out on 20 specimens increasing over 10-12 steps from 5mT to 200mT. To investigate the possibility of a viscous remanent magnetization (VRM) is interfering with the characteristic remanent magnetization (ChRM), representative samples were subjected to low-temperature demagnetization (Dunlop and Argyle, 1991) using liquid nitrogen. Samples were cooled to 77 Kelvin and subsequently allowed to reach room temperature in a magnetically shielded encasing. The NRM was measured before and after this experiment in order to test the possible interference of a VRM. This experiment found little or no NRM loss following low-temperature demagnetization, thus these samples have not been affected by a VRM. After demagnetization measurements, remanent directions were interpreted using principal
component analysis (Kirschvink, 1980) in CTanalysis software, and site mean directions were determined using Fisher (1953) statistics.

The data obtained from demagnetization procedures were plotted on stereoplots using Super-IAPD 99 software. Samples with a 95% cone of confidence ($\alpha_{95}$) of less than 20° were used to determine site means within Devil’s Fence and Turner anticlines. A cut-off criterion using $\alpha_{95} < 25°$ was applied to Three Forks anticline due a higher average $\alpha_{95}$ for directions obtained from this fold. On occasion, a sample was determined an outlier and removed from a site. If the outlier within an individual site was at least one cone of confidence removed from the site mean calculated for the rest of the cluster, it was removed from analysis. Such outliers can be attributed to error during sampling or measurement. Site means were then subjected to a McElhinny (1964) fold test for each fold in order to attain a percentage of unfolding at which optimal clustering for each fold occurs. Fold plunge was calculated to be <10° for all three folds. Because of low plunge angles and variation in fold hinge orientations, plunge is not corrected for.

Hysteresis curves were acquired for 11 specimens using a vibrating sample magnetometer (VSM) in order to characterize grain size of ferrimagnetic particles within the samples. Magnetic hysteresis curves provide a visual representation of saturation magnetization (Ms), saturation remanence (Mrs), and magnetic coercivity (Hc). Diamagnetic material (feldspar, quartz, calcite) will result in a curve with a negative slope, while paramagnetic material (higher concentrations of magnetite, hematite) will result in a curve with a positive slope. Reducing Mrs to zero in the presence of a backfield gives coercivity of remanence (Hcr), measuring magnitude of the backfield field necessary to reduce Mrs to
zero. Plotting the ratios of Mrs/Ms to Hcr/Hc on a Day-plot (Day et al., 1977) characterizes magnetic grain size of particles within the sample. Characterizing magnetic grain size can test whether the results are characteristic of remagnetized or unremagnetized carbonate rocks by plotting along different mixing lines (e.g., Channell and McCabe, 1994). Samples on the VSM were subjected to a maximum applied field of 2000 Oersteds (Oe) at 50 Oe increments with a 1.0 second averaging time over 15-40 total averages.

**Paleomagnetism Results**

In order to generate site means, a minimum of three samples with well-defined magnetizations are generally needed. Examples of vector plots illustrating well-defined magnetizations from this study are shown in Figure 10. Given this criterion, 16 out of 23 sites analyzed resulted in enough specimens with stable magnetizations to generate a site mean (Table 1).

Samples from Devil’s Fence anticline yielded six sites with well-defined magnetizations. Each site includes a minimum of four samples (n≥4) and a minimum precision parameter of thirteen (k≥13). At 100% untilting, there are at least two apparent components of magnetization from rocks sampled at Devil’s Fence anticline (Fig.9). Sites 4, 7, 8 and 9 cluster with northeasterly declinations and steep inclinations, plotting in the lower hemisphere of the equal-area plot. Sites 3 and 10 both yield westerly declinations, and shallow inclinations plotting in the upper hemisphere. These two sets of directions are not antipodal to each other, and are considered to represent two separate characteristic directions for these groups of sites. Site means for the lower hemisphere group pass the fold test at 90% unfolding (Fig.10). A grand mean direction was calculated for the lower
hemisphere group for 90% unfolding as $D = 35^\circ$, $I = 72.9^\circ$, $\alpha_{95} = 8.8^\circ$ and $k = 110$ (Fig. 10, Table 2). The upper hemisphere group clusters best at 100% untilting. Due to the small number of sites that carry this component, a fold test is not statistically feasible; however, a mean direction is calculated for site 3 at $D = 252^\circ$, $I = -18.8^\circ$, $\alpha_{95} = 14.2^\circ$. Site 10 is excluded from analysis because it shares directional characteristics with site 3 and magnetic properties with the rest of the sites and is thus treated as its own group.
Figure 8. Representative vector diagrams showing directional characteristics of samples from thermal and alternating field demagnetization. B, C and E are representative of the lower hemisphere components in geographic coordinates. A and D are representative of the shallow, upper hemisphere components in geographic coordinates. F shows a poorly defined magnetization. Blue: horizontal component. Red: projection of vertical component. Temperatures of demagnetization steps (degrees C) are labeled for A, B, C, E and F, alternating field steps (in mT) are labeled for D.
Table 1. Site-mean Data in Geographic Coordinates

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<td>5.6</td>
<td>344</td>
<td>110</td>
<td>8</td>
<td>100</td>
<td>5110286</td>
</tr>
<tr>
<td></td>
<td>09mm18</td>
<td>323.3</td>
<td>55.4</td>
<td>18.5</td>
<td>346</td>
<td>132</td>
<td>4</td>
<td>26</td>
<td>5111635</td>
</tr>
<tr>
<td></td>
<td>09mm21</td>
<td>53.3</td>
<td>59.5</td>
<td>10.2</td>
<td>163</td>
<td>50</td>
<td>3</td>
<td>146</td>
<td>5116834</td>
</tr>
</tbody>
</table>

Dec: declination; Inc: inclination; α95: cone of confidence about the mean; n: number of samples used to determine site mean; k: Fisher (1953) precision parameter. Dip values above 90° are overturned. Location values are UTM coordinates in meters, NAD-83, Zone-12.
Table 2. Grand-mean directions in Stratigraphic Coordinates

<table>
<thead>
<tr>
<th>Fold Name</th>
<th>Dec.</th>
<th>Inc.</th>
<th>α_{95}</th>
<th>N</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Devil's Fence</td>
<td>35</td>
<td>72.9</td>
<td>8.8</td>
<td>4</td>
<td>110</td>
</tr>
<tr>
<td>Three Forks</td>
<td>37.7</td>
<td>70.1</td>
<td>23.9</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Turner</td>
<td>224.6</td>
<td>69.1</td>
<td>29.1</td>
<td>4</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fold Name</th>
<th>Dec.</th>
<th>Inc.</th>
<th>α_{95}</th>
<th>n</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Devil's Fence</td>
<td>252</td>
<td>-19</td>
<td>14</td>
<td>4</td>
<td>43</td>
</tr>
<tr>
<td>Turner</td>
<td>41</td>
<td>-23</td>
<td>18.5</td>
<td>4</td>
<td>26</td>
</tr>
</tbody>
</table>

Dec: declination; Inc: inclination; \( \alpha_{95} \): cone of confidence about the mean; N: number of sites used to determine grand mean; k: Fisher (1953) precision parameter

Figure 9. Characteristic directions for samples from the Devil’s Fence anticline comparing In-situ (9-a) and 100% untilting (9-b) coordinates. Filled symbols are plotted in the lower hemisphere. Open symbols are plotted in the upper hemisphere. Samples with no visible error circles have an \( \alpha_{95} \) smaller than the plotted symbol.
Figure 10. Fold test for lower hemisphere site means from Devil’s Fence anticline. Symbols plot in the lower hemisphere. K is the fisher (1953) precision parameter, CR is the critical value, at 95% confidence, for change in k(unfold)/k(prefold) calculated for this fold test (McElhinny, 1964).

The Three Forks anticline yielded six usable sites with well-defined magnetizations, n ≥ 4 and k > 9. Due to two apparent components of magnetization within Site 23, the site mean has a high cone of confidence and a low precision parameter. Thus, a site mean was generated for each apparent component separately (23-A and 23-B, Table 1) and both were used for the fold test. Due to a low number of samples within component 23-B (n=2), its site mean has a high cone of confidence, but is still eligible for analysis with a high precision parameter of k = 22.5. Removal or retention of this component has no significant effect on the analysis of characteristic directions from the Three Forks anticline. At 100% untilting,
four sites have lower hemisphere inclinations and two have upper hemisphere inclinations (Fig 11). These two sites, Site 22 and Site 24, were subjected to a reversals test (McFadden and McElhinny, 1990) to determine whether their antipodal directions are similar to the sites with lower hemisphere inclinations. After reversing these directions, the upper hemisphere sites are not discernibly different from the rest of the sites, and their lower hemisphere directions were used for the fold test. Applied to a fold test, site means cluster best at 90% unfolding, but this result is not statistically different than 100% unfolding (Fig.11). The calculated grand mean for Three Forks anticline at 100% untilting is $D = 37.7^\circ$, $I = 70.1^\circ$, $\alpha_{95} = 23.9^\circ$ and $k = 7.36$, a similar direction to the calculated grand mean from Devil’s Fence anticline. No shallow inclinations, as found for sites 3 and 10 at Devil’s Fence anticline, are observed within Three Forks Anticline in this study.

Four sites yielded well-defined magnetizations from Turner anticline with $n \geq 4$, with the exception of Site 21 with $n = 3$, instead of $n = 4$. Samples from site 21 have well-defined magnetizations and generate a site mean with an exceptionally high precision parameter of $k = 146$ (Table 1). Site 16 reveals two apparent components of magnetization internally and was treated with the same method applied to Site 23 from Three Forks anticline. With this as an exception, site means from Turner anticline have an $\alpha_{95} < 20^\circ$ and $k > 25$. Similar to Devil’s Fence anticline, two apparent magnetization components are observed when sites are tilt-corrected (Fig. 12). Sites 16, 17 and 21 form a cluster at 100% untilting with steep inclinations plotting in the lower hemisphere. Site 18 yields shallow inclinations plotting in the upper hemisphere and has a site mean of $D = 41.3^\circ$, $I = -22.8^\circ$ and $\alpha_{95} = 18.5^\circ$. The lower hemisphere cluster passes the McElhinny (1964) fold test at 100% unfolding (Fig.12). A
grand mean direction for the tilt-corrected lower hemisphere component was calculated to be $D = 224.6^\circ$, $I = 69.1^\circ$ and $\alpha_{95} = 29.1^\circ$. A Tauxe and Watson (1994) fold test was also applied to Turner anticline because of the possibility that site 17 may be anti-podal to the rest of the sites, rather than being an inverted lower-hemisphere direction. The Tauxe and Watson (1994) fold test treats directions as eigenvectors, ignoring polarity and determining the orientation of bedding at which directions reach maximum tightening. If site 17 were antipodal to the others, this would imply optimum clustering in in-situ coordinates. This possibility is illustrated in figure 13; two spikes in the fold test show there is a favorable tightening in both pre-tilting and post-tilting coordinates. Site 17 is not considered to be antipodal to the other sites, but is interpreted as an inverted normal direction on the overturned limb of Turner anticline and yields a pre-tilting magnetization age (Fig. 12).
Figure 11. Fold test for Three Forks anticline. In geographic coordinates, reverse directions (dashed $\alpha_{95}$) from Sites 22 and 24 have been inverted to normal directions. Closed symbols plot in the lower hemisphere. Open symbol plot in the upper hemisphere. $k$ is the Fisher (1953) precision parameter. CR is the critical value, at 95% confidence, for change in $k$(unfold)/$k$(prefold) calculated for this fold test (McElhinny, 1964).
Figure 12. Fold test for Turner anticline. Closed symbols plot in the lower hemisphere. Open symbol plot in the upper hemisphere. $k$ is the Fisher (1953) precision parameter. CR is the critical value. Site 18 is not included in this fold test, but is shown to illustrate its behavior during tilt-correction.
Figure 13. Tauxe and Watson fold test (1994) for Turner anticline. The two peaks show that when directions are treated as matrix elements, there is good clustering in both geographic and stratigraphic coordinates. Site 18 is not included in the fold test. Refer to Figure 14 for its behavior during unfolding.
Interpretation

Paleopoles and Expected Directions

To evaluate vertical-axis rotations of thrust sheets across the Helena salient, expected paleomagnetic directions were calculated for this part of North American for both the Mississippian and Late Cretaceous based on paleopoles for North America derived by McFadden and McElhinny (1995). Previous paleomagnetic studies in western Montana have tended to use different published paleopoles for the Late Cretaceous when evaluating vertical-axis rotation in the region, creating a need for consistency. Several have used the Adel Mountain volcanics reference direction (Jolly and Sheriff, 1992; Harlan et al., 2008) obtained from a volcanic field adjacent to the northern margin of the Helena salient. This study combines these published data with new data obtained for this study, and evaluates rotation in the region relative to an expected direction derived using paleopoles averaged by McFadden and McElhinny (1995). From the geographic location of the study area, combined with relative pole location, an expected direction for this part of western Montana was calculated for each pole by first determining the angular distance ($p$) between the lat/long of the study area and the lat/long of the paleopole:

$$p = \cos^{-1} [(\sin x p \sin y s + \cos x p \cos y s \cos(\phi p - \phi s))]$$

With the angular distance ($p$) known, declination ($D_x$) and inclination ($I_x$) are solved using:

$$I_x = \tan^{-1}(2\cot p)$$

and;

$$D_x = \cos^{-1}(\sin x p - \sin y s \cos p / \cos y s \sin p)$$.
where $\lambda_p = \text{paleopole latitude}, \lambda_s = \text{site latitude}, \phi_p = \text{paleopole longitude},$ and $\phi_s = \text{site longitude}$. Expected directions calculated for this study are shown in red (Cretaceous) and blue (Mississippian) in figure 14. The paleopoles, and resulting expected directional data for this study are listed in Table 3.

**Groups and Age of Magnetization**

At 100% untilting, two separate ages of magnetization are revealed. The grand mean inclinations for the lower hemisphere components, the “K-group”, in stratigraphic coordinates ($I = 72.9^\circ, 70.1^\circ, 69.1^\circ$) are essentially identical to the calculated expected inclination of 70.1° for the Late Cretaceous in this part of North America. Sites containing the upper hemisphere component, the “M-group”, have shallow inclinations and are closer to the inclination of the magnetic field for this part of North America during the Mississippian, when North America was closer to the equator. McFadden and McElhinny (1995) devised a method to average published paleomagnetic poles, assigning a weighted value to each pole based on the number of sites used in each study. Using these poles, changes in paleolatitude for North America are compared with paleolatitudes for the location of the study area, derived from tilt-corrected inclinations of the two magnetization components revealed from this study (Fig. 14).
Figure 14. Graph showing paleolatitudes derived from tilt-corrected inclinations from the two components of magnetization observed in this study. Paleolatitudes are plotted along with a paleolatitude path for North America (at the study location) derived from average reference poles calculated by McFadden and McElhinny (1995)

The K-group is interpreted as a secondary chemical remanent magnetization (CRM), having been remagnetized during the Late Cretaceous. Fold tests reveal the age of magnetization for the K-group is pre-folding, making the age of acquisition at least 77 Ma (Harlan et al., 2008). CRMs are a common characteristic observed in Paleozoic carbonates within fold and thrust belts (e.g. Enkin et al., 2000). O’Brien et al. (2007) sampled the Castle Reef Dolomite and Allan Mountain Limestone members of the Madison Formation in the Sawtooth Range, north of the Helena salient. Using strontium isotopes, they concluded that the characteristic remanent magnetization observed in the Sawtooth Range is a CRM attributed to hydrocarbon or radiogenic fluid migration. Units sampled in the Sawtooth Range are equivalent to those sampled in this study, only under different assigned lithologic names (Knechtel, 1959; Mudge et al., 1962).
The M-group is shown to have acquired a magnetization between the Pennsylvanian and Early Permian (Fig. 14). This component is represented by only two sites with a high \( \alpha_{95} \). Due to a lack of geologic evidence that remagnetization might have occurred during the Pennsylvanian – Early Permian, the component is interpreted as a primary detrital magnetization and Mississippian in age; however the possibility that site 18 was remagnetized by the Early Permian cannot be completely ruled out. If an expected direction were to be used for the Early Permian, differences in the analysis of vertical-axis rotation would be negligible because of a relatively small change in paleopole location for this part of North America between the Mississippian and Early Permian.

Table 3. Calculated Expected Directions and Paleopoles

<table>
<thead>
<tr>
<th>Geologic Period</th>
<th>Paleopole</th>
<th>Expected Dec.</th>
<th>Expected Inc.</th>
<th>( \Delta D_x )</th>
<th>( \Delta I_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Cretaceous</td>
<td>72.3°N/194.8°E</td>
<td>335.8°</td>
<td>70.1°</td>
<td>6.3°</td>
<td>3.6°</td>
</tr>
<tr>
<td>Mississippian</td>
<td>29.9°N/130.1°E</td>
<td>310°</td>
<td>8.2°</td>
<td>4.7°</td>
<td>2°</td>
</tr>
</tbody>
</table>

Dec: declination; Inc: inclination \( \Delta D_x \): declination error; \( \Delta I_x \): inclination error. Paleopoles are from McFadden and McElhinny (1995)

Vertical-axis rotation

Evaluation of vertical-axis rotation can be accomplished using these two sets of ancient directions, but there are a variety of permutations to this problem. While the K-group passes the fold test, passing the fold test merely indicates the rocks were planar (not folded) when remagnetized, and so some component of pre or post magnetization tilt is geometrically permissible. The “M-group” directions have less uncertainty, in that bedding
can serve as paleohorizontal, but the directions obtained here have a large error due to the small population of this set of data. With these comments in mind, a simple rotation scenario that corrects for differences between the observed and expected Cretaceous and Mississippian aged magnetization directions is presented below.

K-group directions from Devil’s Fence anticline reveal a clockwise rotation of 59° ± 25° from the Late Cretaceous expected direction (Fig. 15-a). Similarly, the K-group from Three Forks anticline shows a clockwise rotation of 62° ± >60° (Fig. 15-b). The grand mean direction for Turner anticline; however, reveals a counter-clockwise rotation of 111° ± >60° (Fig. 15-c).

Rotation errors are derived from Demarest (1983) where steeper inclinations result in more uncertainty in rotation. As inclination approaches vertical, the error of rotation of the declination component approaches infinity. This steep inclination, combined with a high α⁹⁵, contributes to the high errors with these rotations and is a fundamental problem when dealing with rocks that acquire magnetizations at higher latitudes. For example, if the K-group from Three Forks anticline were to have an inclination of 15°, vertical-axis rotation would be 62° ± 20°. Therefore, a high error does not rule out an actual vertical-axis rotation.

If the vertical-axis rotation determined via this comparison between Cretaceous directions were the only rotation that has occurred, the M-group should also closely match the expected Mississippian direction for North America. When grand mean directions for the K-group are restored, M-group directions are closely antipodal to their Mississippian expected direction. The M-group, however, remains offset slightly clockwise from their expected direction (Figures 15-d and 15-e). The high cone of confidence for the K-group
from Turner anticline may also yield an interpretation of negligible rotation, in which case the in-situ direction of the M-group from Turner anticline would need to be re-evaluated. However, under the assumption that the grand means of the K-group represent the true paleomagnetic direction, this offset implies that before remagnetization, the geologic setting in which these rocks existed may have experienced a clockwise vertical axis rotation. Site 18 indicates a rotation of $22 \pm 18^\circ$ and Site 3 indicates a rotation of $59 \pm 14^\circ$. The timing of this older rotation is difficult to constrain, but could be a consequence of Sevier or early stages of Laramide deformation in the region. Because the M-group is composed of only two sites, further sampling from the region is needed to reveal additional shallow inclination directions in order to better constrain the possibility of this older stage of deformation.
Figure 15. Equal-area plots showing vertical-axis rotation of the K-group and M-group. A-C show grand mean directions for the K-group and M-group in each fold. D-E show where the M-group plots when the K-group is rotated to its expected direction.

Vertical-axis rotations revealed from this study are significantly greater than those found from other studies along or near the Helena salient, assuming grand mean directions for Three Forks and Turner anticlines represent their true paleomagnetic direction. It is important to note that due to a high $\alpha_{95}$, grand mean directions for Three Forks and Turner anticlines could be interpreted as little to no rotation. However, the default interpretation for this study is that these grand means reflect a significant sense of rotation. If indeed Turner anticline reflects $\sim 111^\circ$ of counter-clockwise rotation, this magnitude is significantly greater than apparent rotation of the fold-axis, assuming an initial north-south orientation.
Sandbox models have shown that rotation within thrust sheets along the margins of salients can result from shear strain, in which material within thrust sheets may reflect a higher magnitude of rotation than what might be expected by the orientation of thrust traces (Macedo and Marshak, 1999).

Using an expected reference direction similar to that used in this study, Eldredge and Van der Voo (1988) sampled Cretaceous redbeds and showed 54° clockwise rotation near the southern margin and 23° clockwise rotation within the Montana transverse zone. Near the sampling area for this study, within the nose of the salient, 35° clockwise and 30° counter-clockwise rotations were observed (Fig. 16). Harlan et al. (2008) sampled diorite sills where thrust traces of the Helena salient converge into the southwest Montana transverse zone, which showed little to no rotation relative to an Adel Mountain volcanics reference direction (D=351.5°, I=69.3°) (Gunderson and Sherriff, 1991). However, when compared to the reference direction derived from paleopoles established by McFadden and McElhinny (1995), these results suggest 11° ± 18.7° clockwise rotation. Although this is a small magnitude of rotation, results are in agreement with the sense of rotation observed in the southwest Montana transverse zone by Eldredge and Van der Voo (1988).
Figure 16. Map of the Helena salient plotting site mean declinations (arrows) from Eldredge and Van der Voo (1988) with approximate sense of rotation (fans) of the three folds sampled in this study. Black arrows show declination of reference directions. Red indicates clockwise rotation, blue indicates counter-clockwise rotation. Stippled areas show locations of Cretaceous intrusives. (modified from Eldredge and Van der Voo, 1988)

Jolly and Sheriff (1992) sampled from the Late Cretaceous Two-Medicine Formation within the fold and thrust belt just north of the Helena salient and revealed a counter-clockwise rotation of $25^\circ \pm 6^\circ$. Relative to the calculated expected direction for this study, these results show a counter-clockwise rotation of $8.7^\circ \pm 12^\circ$ which can be concluded as little to no rotation (Fig. 17). Results from Mississippian carbonates sampled from the
Sawtooth Range (O’Brien et al., 2007) were averaged for this study from three locations retaining pre-tilting magnetizations generating a grand mean direction antipodal to the Late Cretaceous expected direction calculated, showing little to no rotation in the Sawtooth Range (Fig. 17).

Comparing these results shows that, relative to a calculated expected direction derived from paleopoles of McFadden and McElhinny (1995) for the Late Cretaceous, rotation within and along the Helena salient suggests a complex history of vertical-axis rotation associated with the Elkhorn plate and the Helena salient, while thrust sheets along the fold and thrust belt north of the salient, and south in the Montana Transverse zone, have experienced little to no vertical-axis rotation.
Figure 17. (A) Equal-area plot showing grand mean directions from published studies conducted in the western Montana fold and thrust belt and CRM grand mean directions from this study. Closed squares plot in the lower hemisphere, open square plots in the upper hemisphere. The Late Cretaceous expected direction for this study is shown in red. DF: The Devil’s Fence anticline. TF: The Three Forks anticline. Tu: The Turner anticline. (B) Basemap showing approximate sampling locations (Eldredge and Van der Voo, 1988). SR (yellow): Mississippian carbonates from the Sawtooth Range (O’Brien et al., 2007). TM: Late Cretaceous Two-Medicine Formation (Jolly and Sheriff, 1992). TZ: Diorite sills in the Montana Transverse Zone (Harlan et al., 2008). Open box: this study.
**Rock Magnetism**

The M-group has lower magnetic susceptibilities than the K-group (Fig. 18). This difference implies that the mechanism responsible for remagnetizing rocks may not have affected areas where primary magnetizations are observed. During fluid migration, authigenic magnetite precipitates in carbonates recording a new magnetic direction. This process is interpreted to be the likely mechanism for remagnetization of carbonates (e.g., McCabe and Elmore, 1989). Remagnetized carbonates generally contain more magnetite than unremagnetized carbonates, demonstrating the relationship between magnetite authigenesis and chemical remagnetizations (McCabe and Elmore, 1989). Relative to other sites that yielded stable magnetizations, Site 3 and Site 18 have the lowest magnetic susceptibilities (Fig.18). There is also a decreasing west-to-east trend in magnetic susceptibility, implying that the remagnetization mechanism responsible for the K-group affected rocks toward the hinterland more intensely than towards the foreland.

![Magnetic Susceptibility](image)

**Figure 18.** Magnetic susceptibilities of samples used in this study. Blue bars are the M-group, sites 3 and 18, interpreted to retain primary magnetizations. The rest shown here are of the K-group.
Magnetic hysteresis results show curves with negative slopes consistent with diamagnetic behavior resulting from very low amounts of ferromagnetic material in the carbonates sampled. Plotting Mrs/Ms against Hcr/Hc for both the M-group and the K-group shows a narrow range (0.1-0.3) of Mrs/Ms ratios and a wide range (2-15) of Hcr/Hc ratios (Fig. 19). Five specimens plot between the 10nm and 15nm SP+SD mixing lines, and six specimens plot along SP+PSD mixing curves (Fig. 19), both consistent with remagnetized carbonate data of Suk et al. (1993) and Xu et al. (1998) (Fig. 20). Two of the sites tested more than once, sites 10 and 3, illustrate that the difference between the two groups cannot be explained by differences in lithology, but by variation of magnetic grain sizes within a specimen (Fig. 18). Un-remagnetized carbonate rocks have been shown to plot along SD (single-domain) + MD (multi-domain) mixing lines with higher Hcr/Hc ranges and narrower Mrs/Ms ranges (Channell and McCabe, 1994). Unremagnetized sites from this study, the M-group, plot with the K-group along the SP+PSD mixing line, and not the SD+MD admixture line, opening the possibility that they may have been remagnetized prior to deformation in western Montana, but remain to record shallow inclinations.
Figure 19. Day et al. (1977) plot showing magnetic hysteresis parameters for representative samples. SD (single domain), PSD (pseudo-single domain) and MD (multi domain) regions are shown. In red are site numbers. Specimens plot along SP+PSD and SP+SD mixing lines. Figure modified from Dunlop (2002), after Day et al. (1977)
Figure 20: Remagnetized carbonate data from Suk et al. (1993) and Xu et al. (1998), as compiled and plotted by Dunlop (2002). The Onandaga and Trenton limestones plot between SP+SD mixing curves. The Leadville dolomite and limestone plot along SP+PSD mixing curves.

Discussion

Regional Deformation

It is feasible that rotation of the Elkhorn plate and rotations found along the Helena salient could be the result of two independent kinematic events: clockwise rigid-block rotation of the Elkhorn plate in conjunction with sinistral shear of the Lewis and Clark Shear Zone, and buttressing effects against an uplifted foreland margin along the Helena salient.

The Helena salient has previously been attributed to rigid block rotation associated with the Lewis and Clark line adjacent to the northern edge of the Elkhorn plate (Sears and
Sears and Hendrix (2004) interpret the Lewis and Clark line as a sinistral shear zone experiencing counter-clockwise rotation, in association with clockwise rotation of the Lewis-Eldorado-Hoadley slab to the north and the Elkhorn plate to the south. This kinematic relationship is similar to the rotation of three spinning gears stacked atop one another. According to this hypothesis, clockwise vertical-axis rotation should be apparent within the Elkhorn plate, as well as within the Lewis-Eldorado-Hoadley slab north of the Lewis and Clark line. Devil’s Fence anticline is located within the interior of the Elkhorn plate and reflects ~60° of clockwise rotation. This rotation may be kinematically related to the ~60° clockwise rotation observed from Three Forks anticline, implying the Elkhorn plate has rotated as a rigid block. Assuming rigid block rotation of the Elkhorn plate, the counter-clockwise rotation observed from Turner anticline must result from buttressing against the foreland margin, which would otherwise display clockwise rotation similar to the Devil’s Fence and Three Forks anticlines. Clockwise rotation observed from Three Forks anticline may also result from buttressing against the foreland as thrust sheets propagated into the underlying Helena embayment along lateral foreland ramps, resulting in clockwise rotation along the southern margin and counter-clockwise rotation along the northern margin of the Helena salient.

Paleomagnetic studies from the fold and thrust belt north of the Helena salient appear to show little to no vertical-axis rotation since deformation during the Late Cretaceous, relative to our calculated expected direction (Fig. 17). Therefore, rotations associated with the Helena salient may require a more localized model than the regional
rotational-shear model of Sears and Hendrix (2004) in order to better understand deformation in the region.

**Remagnetization Trends**

Previous work in fold and thrust belts has revealed the presence of remagnetization trends associated with uplift and deformation in sedimentary rocks (e.g. Stamatakos et al., 1996; Enkin et al., 2000). Enkin et al. (2000) observed normal polarity in the front ranges of the Canadian Rockies and reverse polarity in the inner foothills. Both studies attribute such patterns to remagnetization trends resulting in an association between uplift and a subsequent diagenetic front, remagnetizing rocks over a period of time sufficient enough to record different polarities (Enkin et al., 2000).

From this study, the age of magnetization for the K-group is pre-tilting within each of the three folds sampled. In stratigraphic coordinates, the K-group preserves a normal polarity in each fold and the M-group preserves a reverse polarity in two folds. This relationship does not suggest a trend in remagnetization age relative to the age of folding but the preservation of a primary Mississippian direction in the M-group. O’Brien et al. (2007) suggest that extending their study area further west may reveal the presence of remagnetization trends. For the present study, extending the study area further into the foreland may reveal a trend in the age of magnetization relative to deformation. Variation in the age of magnetization along strike of the fold and thrust belt is possible when comparing these results to the observations from carbonates in the Sawtooth Range. Reverse polarities were observed in the Sawtooth Range by O’Brien et al. (2007) from the
same lithologies sampled by this study across the Helena salient. The combination of reverse polarities observed in the Sawtooth Range, and normal polarities observed along the southern margin of the Helena salient makes it possible that carbonates in both regions were remagnetized by similar diagenetic fronts, but at different periods of time. Nonetheless, both regions experienced remagnetization associated with deformation between the Late Jurassic and early Tertiary (O’Brien et al., 2007). Investigating remagnetization trends along strike may be useful to combine with across strike variations in order to better understand the complex, potentially heterogeneous diagenetic front responsible for partially erasing older magnetic directions and replacing them with younger ones.

Results from Turner anticline suggest the possibility of optimum clustering in in-situ coordinates, as shown by the Tauxe (1994) fold test (Fig. 13). Interpreting this as a post-deformational remagnetization would reveal a remagnetization trend with pre-tilting magnetization towards the hinterland and a post-tilting magnetization towards the foreland. Stamatakos et al., (1996) observed the opposite: a remagnetization trend across the central Appalachians where the fold and thrust belt has pre-tilting magnetizations in the foreland, post-tilting magnetizations in the hinterland and syn-tilting magnetizations in the central region. These authors interpreted this trend to mean that folding toward the hinterland occurred before remagnetization and folding toward the foreland occurred after remagnetization, representing a short-lived remagnetization event capturing a snapshot of the fold and thrust belt at a time when folding had already occurred toward the hinterland and had not yet occurred toward the foreland. Interpreting Turner anticline as a post-
folding magnetization, a trend results that is opposite to that observed in the central Appalachians. This trend would require that deformation propagated from the foreland to the hinterland in this part of the Helena salient, under the assumption that remagnetization events are short lived relative to fold and thrust belt propagation. Because thrusting advanced west to east (Hoffman et al., 1976), the unlikelihood of this style of deformation is the contributing factor for interpreting the age of magnetization from Turner anticline to be pre-tilting.

**Conclusions**

Fold tests show the age of magnetization to be prefolding for the K-group (Cretaceous age CRM), which acquired a CRM prior to the 77 Ma maximum age of deformation of these rocks. Inclinations are steep, similar to that of the Late Cretaceous expected direction rather than what would be expected from a Mississippian, sub-horizontal direction. During thermal demagnetization, all samples lost their natural remanent magnetization before the 585°C Curie temperature for magnetite. Therefore, the age of magnetization from Mississippian carbonates across the southern margin of the Helena salient, for most samples, appears to be a Late Cretaceous CRM residing in magnetite.

Comparison of the K-group to the Late Cretaceous expected direction reveals the presence of significant vertical-axis rotation spanning from within the interior, to the eastern edge of the Elkhorn plate (Fig. 16). From the interior of the Elkhorn plate, Devil's Fence anticline reveals $59° \pm 25°$ clockwise rotation. Adjacent to the principal thrust of the Helena salient, the Lombard thrust, $62° \pm >60°$ clockwise rotation is revealed from Three
Forks anticline. Counter-clockwise rotation of 111° ± >60° is revealed from Turner anticline along the northern margin, and further east, towards the foreland.

A unique finding of this study involves the interpretation of primary detrital magnetizations in carbonates within a region that is mostly remagnetized. The M-group shows shallow inclinations that imply they are Mississippian to Early Permian in age. One characteristic of the M-group is that it has the lowest magnetic susceptibilities of all the samples that yielded usable results, showing that the remagnetization mechanism responsible for the CRM did not affect these two areas. Site 10 is a possible candidate for the M-group due to its similar directional characteristics, but is not included as its magnetic properties are more similar to the K-group.

When the K-group from Devil’s Fence and Turner anticlines is rotated back to its expected direction, the M-group shows that the predeformational basin in which these rocks existed may have experienced a clockwise vertical-axis rotation prior to deformation and remagnetization, introducing the possibility of detecting multiple deformation events when a combination of remagnetized and unremagnetized carbonates is present. Because only two sites make up the M-group, further sampling is needed to better constrain a pre-remagnetization vertical-axis rotation event.

Data from Three Forks and Turner anticlines are consistent with the findings by Eldredge and Van der Voo (1988), observing clockwise rotation along the southern margin (Three Forks anticline) and counter-clockwise rotation along the northern margin (Turner anticline). The Devil’s Fence anticline reveals clockwise vertical-axis rotation within the interior of the Elkhorn plate and is not interpreted to be a reflection of buttressing effects
but rather a clockwise rotation of the Elkhorn plate associated with the sinistral Lewis and Clark line bounding the northern margin of the plate. The similarity in magnitude of rotation for Three Forks anticline along the southern margin of the Helena salient and Devil’s Fence anticline within the interior of the Elkhorn plate implies that the Elkhorn plate may have rotated clockwise in a rigid block fashion. As the Elkhorn plate rotated, thrust sheets along the northern margin buttressed against the foreland margin resulting in counter-clockwise rotation. Significant vertical-axis rotation in the region since the Late Cretaceous appears to be confined to the Elkhorn Plate and Helena salient, as thrust sheets have undergone little to no rotation in regions outside of the salient.
References


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