Application of the Paleomagnetic Fold Test to Determine the Relative Timing of Sill Intrusion and Deformation in the Southwest Helena Salient, Montana

Stephen Christopher Whisner
APPLICATION OF THE PALEOMAGNETIC FOLD TEST TO DETERMINE
THE RELATIVE TIMING OF SILL INTRUSION AND DEFORMATION
IN THE SOUTHWEST HELENA SALIENT, MONTANA

by

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Stephen Christopher Whisner
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Stephen Christopher Whisner, M.S.
Western Michigan University, 1998

The Doherty Mountain fold complex is a highly folded and faulted region along
the southern boundary of the Helena Salient in southwestern Montana. This region has
a complex deformation history that is a key to deformation within the Helena Salient as
a whole. A structural interpretation of the deformed rocks of this area was conducted
using field mapping and cross section construction at 1:24,000 scale providing insight
to the internal deformation processes involved. Fourteen folds and three major faults
were mapped and analyzed showing the influence of the Southwest Montana
Transverse Zone and late stage detachment faulting on fold orientation. Restored cross
sections of the detailed map show more shortening than previously estimated for this
area. Sills intruded into this complexly folded regions were also studied. In an
attempt to determine relative timing of sill emplacement and deformation, the
paleomagnetic fold test of McElhinny (1963) was applied to sills which pervasively
intrude the sedimentary rocks. The results indicate intrusion occurred before or early in
the deformation. Combined with an $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric age date of 77 Ma, this work
provides the first estimate of minimum age of deformation in this area.
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This thesis focuses on a structurally complex portion of the Cordilleran fold and thrust belt of southwestern Montana (Figure 1). Detailed geologic mapping and cross section construction, as well as paleomagnetic work were completed in an effort to more clearly understand the structural style, mechanism, and timing of deformation. These data are to be incorporated into a larger regional study of the Southwest Montana disturbed belt to determine the regional structural setting during the Laramide orogeny of Late Cretaceous to Early Tertiary time.

The senior mapping project from which this thesis evolved initially focused on creating a geologically and structurally detailed map of the Doherty Mountain fold complex. This was part of a larger regional study by Dr. Christopher Schmidt to gain an understanding of fold and fault geometry and deformation history along the southern margin of the Helena salient. Trajectories of principal shortening were inferred from fold and fault orientations obtained from 1:24,000 field mapping during the summers of 1994 and 1995.

The aforementioned project was also intended to determine the magnitude of shortening accommodated by folding and faulting in Middle Proterozoic through Cretaceous rocks in the Lombard thrust sheet. The amount of shortening here had been brought into question by a wildcat well (Norcen) drilled 10 miles to the north in the core of the Devil’s Fence Anticline (Figure 2). This well was drilled through 1707
Figure 1. Study Area Location Map.
Figure 2. Southwest Helena Salient (portions of map outside Doherty Mountain Fold Complex compiled from Schmidt [1975, 1979] and Lozier [1996]).
meters (m) of Middle Proterozoic Belt Supergroup units when it crossed the Lombard thrust fault and encountered footwall rocks of Cretaceous age. This well data, along with seismic data, are interpreted by Schmidt and others (1990) and Ballard and others (1993) to suggest the Lombard thrust is the roof thrust of a large duplex structure composed of Belt supergroup and Phanerozoic rocks.

In this study, paleomagnetic and $^{40}$Ar/$^{39}$Ar techniques are used to determine the age of deformation, based on the relative timing of sill intrusions and folding events. The Doherty Mountain fold complex is a good candidate for these techniques because it is highly intruded by igneous sills concordant with deformed sedimentary rocks. These intrusions were sampled for paleomagnetic analysis and radiometric dating.

Location

The Doherty Mountain fold complex is located in southwestern Montana, eight miles east of the town of Whitehall, and is transected by Interstate 90 (Figure 3). It is part of the Montana portion of the Rocky Mountain foreland fold and thrust belt. Access during both the mapping and sampling phases of this project to the mapped area was obtained primarily on foot from Bureau of Land management and private roads, with permission of the property owners.

Stratigraphy

The stratigraphy in the study area consists primarily of sedimentary rocks of Late Precambrian through Paleozoic age. The complete stratigraphic column is presented here in Figure 4. The oldest rocks are Middle Proterozoic Belt Supergroup shales of varying thickness between 3000 m and 9000 m thick. Resting unconformably on top these Proterozoic rocks are Cambrian sedimentary rocks consisting of Flathead sandstone followed by alternating shale and limestone units.
Figure 3. Geology and Structure of the Doherty Mountain Fold Complex.
Figure 4. Stratigraphic Column for the Doherty Mountain Fold Complex Area.
Upper Devonian Jefferson Formation limestone and dolomite are then overlain unconformably by the lithologically variable Three Forks Formation. The uppermost units within the Doherty Mountain fold complex are the limestones of the Mississippian Madison Group. This group consists of the lower Lodgepole Formation and the upper massively-bedded Mission Canyon Formation. The remaining Paleozoic and Mesozoic stratigraphic section is only present in the Big Mountain-Negro Hollow syncline (Figure 2), to the north and was not the focus of this study.

Regional Structural Setting

The Montana portion of the Cordilleran Foreland Fold and Thrust Belt is thought to have developed during the Laramide Orogeny, which occurred in Late Cretaceous to Early Tertiary time (Schmidt, 1981). The Helena Salient is a large oroclinal bend where the Cordilleran thrust belt (Figure 1) exploited an embayment filled with Proterozoic Belt sediments and floored by Archean crystalline basement. The main thrust fault of the Helena salient is the Lombard thrust fault, and the study area lies within the Lombard thrust sheet 15 miles east of this thrust). The southern boundary of the Lombard sheet is defined by a fault zone (southwest Montana transverse zone) (Schmidt and O’Neill, 1982) which places Belt Supergroup (LaHood Formation) rocks in the hanging wall against rocks as young as the Late Cretaceous Elkhorn Mountains Volcanics in the footwall (Figure 2). The southern boundary of the Doherty Mountain fold complex is defined by a single fault of this zone, the Jefferson Canyon - Cave fault. The Lombard thrust and the basal decollement of the Helena Salient are both inferred to terminate at the Jefferson Canyon - Cave fault. Therefore the Jefferson Canyon - Cave fault serves as a large-scale up-toward-the-south lateral ramp for both the basal decollement and the Lombard thrust sheet (Schmidt, 1982).
By far the largest fold of the Lombard thrust sheet, the Devil’s Fence anticline (Klepper and others, 1957), is geographically in the center of the sheet (Figure 2). It is a large, doubly-plunging anticline cored by clastic rocks of the Middle Proterozoic Belt Supergroup. The Belt supergroup is at least 1250 m thick (McMannis, 1963) in the mapped area, but is probably closer to 3500 to 4000 m thick below the anticline. These rocks are inferred to have been deposited on Archean basement in a depositional trough (Helena embayment of the Belt basin, Harrison and others, 1974) that more or less coincides with the Helena structural salient. Earlier structural syntheses of the Lombard sheet (e.g. Woodward, 1981, and Schmidt and O’Neill, 1982) assumed that, although the Lombard thrust existed at a relatively shallow depth [4 - 5 kilometers (km)] below the anticline, the thrust here was a basal decollement above basement rocks. Schmidt and O’Neill (1982) ascribed the anticline to regional warping of the decollement surface related to coeval basement - involved folding similar to that which can be observed south of the southwest Montana transverse zone. They further estimated that the Lombard sheet had moved eastward along this basal decollement a comparatively short distance (at most about 15 km; Schmidt and O’Neill, 1982).

Exploration seismic data, acquired across the anticline in the late 1970’s and early 1980’s, led independent petroleum geologists Jack Warne and Irvin Kranzler to interpret the structure as a major structural culmination in the Lombard sheet formed by the development of a duplex fault zone in the footwall, and to infer that the footwall was composed of Phanerozoic (probably Cretaceous) rocks and not basement. Drilling of the structure (Norcen Balcron UTP # 1-11 Kimpton Ranch) confirmed the existence of the Lombard thrust at 1707 m, and micropaleontologic data indicated that the footwall rocks are Cretaceous in age (Ballard and others, 1993; Burton and others, 1996). In addition, the seismic data reported by Schmidt and others (1990) and by Ballard and others (1993) were interpreted to indicate that the Lombard thrust is the
roof thrust of a duplex of Belt Supergroup and Phanerozoic rocks and that the Devil’s Fence anticline is a major thrust culmination in the Lombard sheet. The contact between the basement rocks and the overlying Belt Supergroup rocks (basal decollement - floor thrust of the duplex?) exists at a depth of about 15 km below the anticline.

The faults and folds of the Lombard sheet between the Devil’s Fence Anticline and the Jefferson Canyon - Cave fault comprise the Doherty Mountain fold complex, and Big Mountain-Negro Hollow area, and have been described in previous papers (e.g. Alexander, 1957; Schmidt and O’Neill, 1982; Schmidt and others, 1988). This thesis presents a new interpretation of the internal structure of the Helena Salient between the Devil’s Fence Anticline and the Jefferson Canyon - Cave fault.
CHAPTER II

STRUCTURAL STYLE OF THE DOHERTY MOUNTAIN FOLD COMPLEX

The folds and faults of the Doherty Mountain fold complex lie within the Lombard thrust sheet near the southern boundary of the Helena Salient (Harrison and others 1974) between the Devil’s Fence anticline and the southern lateral ramp boundary of the sheet (Jefferson Canyon - Cave Fault system) (Figure 2).

Two major faults cut through the Doherty Mountain area. One is a north-south striking, west-dipping, east-verging fault, designated the Doherty Mountain thrust, which cuts through the entire Doherty Mountain fold complex. The other major fault is an east-striking, north-dipping fault interpreted as an exposed decollement surface. Several other thrust faults are also observed throughout the Doherty Mountain fold complex (Figure 3).

Units from the Proterozoic Belt Supergroup (La Hood Formation) to the Mississippian Madison Group are folded in a nearly similar style with thinned limbs and thickened hinges, especially in the less competent formations such as the Cambrian Wolsey and Park Formations, and the Devonian Three Forks Formation. The fold geometry is frequently distorted by concordant intrusions of intermediate to mafic composition igneous rocks of probable Cretaceous age (Appendix A, Figure 3).

\( \Pi \)-diagrams of poles to bedding for all of the folds in the Doherty Mountain fold complex (Appendix B) indicate that fold axes plunge generally north at an average of 41° (Figure 5). The trends of the folds in this region fan from northwest to northeast. The westernmost folds, on the hanging wall of the Doherty Mountain thrust,
Figure 5. Structural Regions of the Doherty Mountain Fold Complex.
have generally steeper plunges and trend west of north; folds on the east side of the area, on the footwall of the thrust have more shallow plunges and trend east of north.

Most of the anticlines are east to east-southeast verging with steep to overturned forelimbs. Many are missing their associated forelimb synclines. This suggests the folds originated as fault-propagation or detachment folds which were transported to the east over each other on fore-limb or synclinal breakthrough faults, placing anticline on anticline and eliminating the intervening syncline. Other folds on the footwall of the Doherty Mountain thrust appear to be disharmonic folds which developed in younger units in response to crowding in the center of a large syncline.

The Doherty Mountain fold complex is divided into four regions based on fold location relative to the major faults (Figure 5). Region I is an anticline-syncline pair and isolated syncline on the west side of the study area, above an inferred decollement; Region II is a set of folds lying above the fault interpreted as a local detachment surface in the hanging wall of the Doherty Mountain thrust; Region III contains the folds south of and below the east-trending thrust (decollement); and Region IV comprises the eastern-most folds in the study area which lie in the footwall of the Doherty Mountain thrust.

Region I

The folds in Region I lie on the northwestern edge of the study area, and are found in Proterozoic Belt and Cambrian rocks. Compared with the other folds in the Doherty Mountain fold complex, fold axes in this region trend mostly west of north and have the steepest plunges in the study area (Figure 5).

The westernmost folds are an anticline-syncline pair (folds 1 and 2) previously studied by Hendrix and Stellavato (1976). They are located to the north and west, across the South Boulder River from the main body of the Doherty Mountain fold
the South Boulder River from the main body of the Doherty Mountain fold complex, and form a small fold system in Middle Cambrian to Lower Devonian rocks. The outcrops are isolated by Tertiary normal faults. The anticline (fold 2) trends 330° and plunges 47°; the syncline (fold 1) trends 339° and plunges 40° (Figure 5).

The other folds of Region I are located at the westernmost edge of the main body of the Doherty Mountain fold complex (Figure 5). The syncline-anticline pair (folds 3 and 4) in Proterozoic Belt to Cambrian Park on the westernmost thrust sheet are oriented 36°, 318° and 66°, 334°, respectively. The folds are the westernmost trending folds of the entire complex and are unique in being a west-verging fold pair on an east verging thrust sheet. The fold pair is bounded on the south by an east-trending thrust which is interpreted to be the surface expression of a minor north-dipping decollement that cuts across the hinges of the fold pair and then steepens on the eastern anticlinal limb. The fold style varies between the syncline and anticline, although both are generally parallel in style (Ramsay, 1967). For instance, the competent Cambrian Flathead sandstone is very angular in the core of fold 4, yet only gently folded around the adjacent syncline (fold 3). Andesitic sills in the Cambrian Wolsey Formation have added to the substantial thickening in the hinge of fold 4.

On the eastern limb of fold 4, an outcrop of vertical beds of the Cambrian Flathead and Wolsey Formation rest on moderately (45°) west-dipping and overturned Cambrian Meagher Formation. These beds are interpreted as a klippe, resting on younger Meagher limestone which completely surrounds this outcrop.

To the south and east of this fold pair is an out-of-sequence thrust fault which places the Cambrian Meagher Formation on the older Cambrian Wolsey Formation. It dips to the north along its southern exposure and changes to a northwesterly orientation along the eastern exposure. The surface expression of this fault is of a right
lateral strike slip fault. Movement along this thrust fault is thought to have rotated the fold axes of the folds structurally above it to the northwest and increased their plunge.

To the south of the anticline-syncline pair and structurally beneath the out-of-sequence thrust fault, is an isolated syncline (fold 5) oriented 33°, 345°. It is the tightest fold in the Doherty Mountain fold complex and is bounded by two other faults. One is a west-dipping, nearly vertical thrust fault runs north through the Cambrian Wolsey Formation, parallel to the axial surface near the Wolsey-Meagher contact, and places nearly vertical Wolsey and Flathead Formations on west-dipping Flathead and an igneous intrusion. The other is a north dipping east-west striking detachment fault which cuts across the entire fold complex.

Region II

The folds in region II are located on the hanging wall of the Doherty Mountain thrust. Stratigraphic units in this area range from the Mississippian Mission Canyon Limestone on the north, to the Cambrian Flathead Sandstone on the southwest. The structure consists of another anticline-syncline pair: an east-verging overturned syncline (fold 7) cored by Mississippian Mission Canyon Limestone and an east-verging overturned anticline (fold 8) cored by Devonian Jefferson Formation (Figure 5). The folds are oriented 31°, 358° and 44°, 331°, respectively (Figure 5). They are bounded on the south and east by a fault surface which dips about 40° north. The Mississippian limestones in the core of fold 7 are highly intruded by the intermediate and mafic composition sills common to the west and south (Figure 5). The largest intrusion is a small stock referred to as the North Doherty pluton. Based on an apparent missing volume of Mississippian units and abundant scarns, the intrusion seems to have assimilated much of the limestone from the surrounding area. To the north, Mississippian Mission Canyon limestone within the main syncline dips north and
disappears under Tertiary fill. The infilling with Tertiary sediment on the north boundary of the Doherty Mountain fold complex is due to a north dipping normal fault along the northern boundary which has caused formation of a minor basin and obscured the intervening rocks between the Doherty and Big Mountain - Negro Hollow areas.

Several smaller map-scale structures are also observed in this area, such as a small splay off the detachment fault, which displaces Devonian Maywood Formation 100 m, smaller map-scale folds on the west limb of fold 7, and two horses. One horse is a small sliver of Cambrian Wolsey formation near the intersection of the detachment and the fault which separates regions I and II. The other, with only a few meters of displacement, occurs between regions II and III where the decollement meets the Doherty Mountain thrust, and places Devonian Three Forks shales over Mississippian Lodgepole Limestone.

Region III: The Doherty Mountain Anticline-Syncline Pair

The region III anticline-syncline pair (folds 9 and 10) lies in the center of the Doherty Mountain fold complex, and consists of stratigraphic units of Proterozoic Belt through Devonian Jefferson Formation (Figure 5). These folds have been separated from their counterparts to the north by movement along the east-striking decollement, and from the adjacent syncline to the east by movement on the Doherty Mountain thrust. Here the Doherty Mountain thrust places Devonian Jefferson Formation on Mississippian Madison Group. The syncline and anticline are oriented 53°, 331° and 56°, 335°, respectively (Figure 5). The trends in this region are more west of north and the plunges are steeper than those of adjacent folds in the footwall of the Doherty Mountain thrust (region IV), suggesting that the fold axes may have been rotated to the west and down during movement on the Doherty Mountain thrust.
The anticlinal hinge is angular, with some thickening in the hinge, and thinning on the limbs in all formations. The synclinal hinge is more rounded, with more uniform bed thickness around the fold. The fold pair is heavily intruded by intermediate sills which occur predominately in the Cambrian Flathead and Wolsey Formations and appear to be folded along with these units. The pervasive intrusions may have made the rocks in folds 9 and 10 more ductile, permitting flow into the hinges and development of a similar fold style (Ramsay, 1967). This contrasts with folds 3 and 4 (region I), which are less intruded, and have a dominantly parallel style.

The southernmost fold in region III is a tight syncline (fold 12). The Doherty Mountain thrust appears to originate from the core of this syncline and displacement increases upward and to the north. The point of origin of the thrust is obscured by Tertiary cover. The fold axis (32°, 39°) is less steep and trends more easterly than the other two folds in region III (Doherty Mountain anticline - syncline pair, folds 9 and 10) and its orientation is closer to that of region IV. At its southern limit, where the fold axis was measured in Cambrian units, the fold has not been rotated by thrusting.

Region IV

The easternmost folds in the study area lie on the footwall of the Doherty Mountain thrust, and have been designated region IV (Figure 5). These folds (11,13, and 14) are in strata ranging from Cambrian to Mississippian and have been highly intruded by sills. Their axes are the most easterly-trending of the Doherty Mountain fold complex and are oriented 30°, 24°; 40°, 24°; and 12°, 16° respectively (Figure 5). Two anticlines (folds 13 and 14) are juxtaposed by thrusting with no intervening syncline. Fold 14 marks the eastern edge of the Doherty area and is bounded to the east by Tertiary Bozeman Group sediments.
CHAPTER III

APPLICATION OF THE PALEOMAGNETIC FOLD TEST TO DETERMINE THE AGE OF FOLDING AND IGNEOUS INTRUSION

Because sills are found throughout much of the Doherty Mountain fold complex, it should be possible to use paleomagnetic techniques on sill samples to determine the relative timing of folding and intrusion. If the age of intrusion is also dated using radiometric techniques, then the age of deformation can be inferred regardless of whether the intrusions are pre-, syn-, or post- folding. Samples were collected from 23 sites around the Doherty Mountain fold complex (Figure 6). These sample locations will be referred to by the designation PMD (PaleoMagnetic Doherty) and the sample site number. Sampling techniques are detailed in Appendix C. The process of demagnetization can be found in Appendix D and the results of demagnetization are in Appendix E.

Fold Test

A goal of this thesis is to determine when sills were intruded relative to folding. To do this, the paleomagnetic fold test is used. The fold test is the analysis of the change in paleomagnetic pole directions of individual samples as stratigraphic beds, and, in this case, their intruded sills are stereographically unfolded and unplunged from the present orientation (deformed) to an original horizontal orientation (undeformed). In the process, the paleomagnetic samples and their magnetic orientations also rotate
Figure 6. Paleomagnetic Sample Locations.
with the surrounding sedimentary beds. Complicating matters somewhat is the fact that the rocks being analyzed are not only folded, but also faulted. Rotation and tilting of these folds on fault surfaces was taken into account.

Timing of sill intrusion can be determined by the direction of travel of the primary remnant magnetization directions as sills are stereographically unfolded removing effects of deformation. This effect is determined by the igneous bodies recorded paleomagnetic signature and when it was recorded relative to a deformation event. Sills which are intruded before a deformation event will have paleomagnetic poles that travel towards a common point as deformation is removed (Figure 7, example A). Sills which are intruded after a deformation event will move from a common point away from one another to a random distribution on the stereonet (Figure 7, example B). A sill intruded during deformation will have some combination of the two previous cases (Figure 7, example C).

Unfolding was accomplished using two different methods. The first method was a simple rotation of the beds from present position to horizontal and did not account for the plunge of the folds. The second method, proposed by MacDonald (1980), takes into account the plunge of the folds in the unfolding process by unplunging and unfolding the fold beds during the same procedure instead of applying a complete unfolding to the beds first and then removing the plunge or vice versa. This method more closely models the true mechanical motion of the rocks.

After the rotations were completed, the McElhinny (1964) fold test was applied to the results. The fold test is a measure of the statistical relevance of clustering of the paleomagnetic poles from various sites within a fold as deformation is removed. This type of test was first proposed by Graham (1949). It has been refined by a number of authors: McElhinny (1964), McFadden (1981), Tauxe (1994) and others. The McElhinny fold test compares the ratio of dispersion of paleomagnetic pole directions
Schematic intrusions with recorded magnetic orientation are shown below the stereonet in each case. (X’s indicate paleomagnetic direction of sill; Arrows indicate paleomagnetic direction change with removal of deformation)

Figure 7. Stereonet Examples of Possible Effects of Removal of Deformation on Sills.
before folding \( (k_2) \) to the dispersion after folding \( (k_1) \). The variables \( k_1 \) and \( k_2 \) are Fisher statistical parameters measuring the degree of clustering of paleomagnetic poles and \( f \) is the ratio of \( k_2 \) to \( k_1 \).

The equation for the McElhinny fold test is,

\[
f = \frac{k_2}{k_1}
\]

Comparison of \( f \) values (Table 1) provides minimum acceptable \( f \) values, given a number of paleomagnetic pole directions \( (n) \) and a specific confidence level \( (\alpha 95\%) \). The \( \alpha 95\% \) confidence cone is an angular measurement describing a circle on an equal area net in which 95% of the measurements lie. If the result \( (f) \) is greater than the number on McElhinny’s table, the fold test is significant at that confidence level and is called “positive”. Clustering of site means toward a specific point after rotation is complete suggests the sills were intruded before folding. If site means cluster after some amount of mechanical unfolding and then disperse as unfolding continues, syn-folding intrusion is indicated. Dispersion of site means as unfolding progresses indicates post-folding intrusion. A positive fold test suggests clustering of site means is related to the mechanical unfolding being performed, and therefore intrusion must have occurred either before or during deformation. A negative fold test indicates site means become more scattered as unfolding is performed, and implies that the intrusion cooled below its magnetic blocking temperature after deformation.

Results

The simple rotation method was first applied to the northern syncline, fold 3 (Figure 6). Sites in fold 3 (PMD 20, 21, and 22) were used as a test sample to see if McElhinny’s technique could be used in this area. When the initial fold test result came
Table 1

Minimum Variance Ratios at 95% and 99% Confidence Cones Indicating Positive Fold Tests*

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<td>2.33</td>
<td>3.37</td>
</tr>
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<td>10</td>
<td>2.22</td>
<td>3.13</td>
</tr>
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<td>2.12</td>
<td>2.94</td>
</tr>
<tr>
<td>12</td>
<td>2.05</td>
<td>2.79</td>
</tr>
<tr>
<td>13</td>
<td>1.98</td>
<td>2.66</td>
</tr>
</tbody>
</table>

(*After McElhinny, 1963)

back positive, the remaining sites were analyzed, and McElhinny's test was performed on all sites from which usable data were obtained after demagnetization (Table 2 and Figure 6). Table 3 shows results of McElhinny's test at various stages of unfolding of these sites.

The fold test gave positive results when sites PMD 20, PMD 21, and PMD 22 in syncline 3 were used, with greatest clustering (highest k value) occurring at 70% unfolding. First, mean paleomagnetic pole directions from sites PMD 20, PMD 21, and PMD 22 were plotted in present day orientations, and their k value was calculated ($k_1$). These were then unfolded along with corresponding bedding measurements using Allmendinger's Steronet© program (1995). Instead of simply rotating the beds to horizontal, rotation was done stepwise at 10% intervals and plotted on a stereonet (Figure 8) (Table 4).
Table 2

Sample Locations From Which Usable Paleomagnetic Site Means Were Obtained

<table>
<thead>
<tr>
<th>Site name</th>
<th>Dec.</th>
<th>Inc.</th>
<th>k</th>
<th>α95</th>
<th>n</th>
<th>Strike of Bedding</th>
<th>Dip of Bedding</th>
</tr>
</thead>
<tbody>
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<td>PMD 1</td>
<td>306.4</td>
<td>-8.7</td>
<td>17.1</td>
<td>15.2</td>
<td>6</td>
<td>15</td>
<td>83 e</td>
</tr>
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<td>PMD 2</td>
<td>306.7</td>
<td>10.9</td>
<td>46.8</td>
<td>9</td>
<td>6</td>
<td>15</td>
<td>83 e</td>
</tr>
<tr>
<td>PMD 4</td>
<td>270.5</td>
<td>10.4</td>
<td>158</td>
<td>4.5</td>
<td>7</td>
<td>355</td>
<td>88 e</td>
</tr>
<tr>
<td>PMD 5</td>
<td>277</td>
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<td>8.8</td>
<td>17.2</td>
<td>9</td>
<td>3</td>
<td>103 e</td>
</tr>
<tr>
<td>PMD 6</td>
<td>318</td>
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<td>12.4</td>
<td>16.4</td>
<td>7</td>
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<td>70 w</td>
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<tr>
<td>PMD 9</td>
<td>62.6</td>
<td>-38.2</td>
<td>3.5</td>
<td>33.1</td>
<td>7</td>
<td>284</td>
<td>47 e</td>
</tr>
<tr>
<td>PMD 10</td>
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<td>5.6</td>
<td>6.6</td>
<td>23.2</td>
<td>7</td>
<td>30</td>
<td>85 e</td>
</tr>
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<td>12.8</td>
<td>15</td>
<td>8</td>
<td>16</td>
<td>95 w</td>
</tr>
<tr>
<td>PMD 12</td>
<td>130</td>
<td>7.4</td>
<td>20.3</td>
<td>9</td>
<td>13</td>
<td>52</td>
<td>94 w</td>
</tr>
<tr>
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<td>97.6</td>
<td>58.2</td>
<td>5.9</td>
<td>27.1</td>
<td>6</td>
<td>285</td>
<td>41 e</td>
</tr>
<tr>
<td>PMD 15</td>
<td>137.3</td>
<td>40.7</td>
<td>35</td>
<td>7.5</td>
<td>11</td>
<td>72</td>
<td>64 w</td>
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<td>PMD 16</td>
<td>166</td>
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<td>12.4</td>
<td>20.1</td>
<td>5</td>
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<td>67 w</td>
</tr>
<tr>
<td>PMD 18</td>
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<td>56.2</td>
<td>5.7</td>
<td>27.6</td>
<td>5</td>
<td>10</td>
<td>88 e</td>
</tr>
<tr>
<td>PMD 20</td>
<td>196</td>
<td>60.3</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>270</td>
<td>58 n</td>
</tr>
<tr>
<td>PMD 21</td>
<td>230</td>
<td>45.3</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>26</td>
<td>70 w</td>
</tr>
<tr>
<td>PMD 22</td>
<td>101.1</td>
<td>53.4</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>300</td>
<td>70 e</td>
</tr>
</tbody>
</table>

Table 3

K Values for Progressive Unfolding of Syncline 3

<table>
<thead>
<tr>
<th>Fold</th>
<th>Percent Unfolding</th>
<th>n</th>
<th>Trend of Mean</th>
<th>Plunge of mean</th>
<th>k</th>
<th>α95</th>
<th>Sites Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syn 3</td>
<td>100</td>
<td>3</td>
<td>341.6</td>
<td>60.5</td>
<td>20</td>
<td>22.8</td>
<td>20, 21, 22</td>
</tr>
<tr>
<td>Syn 3</td>
<td>90</td>
<td>3</td>
<td>339.5</td>
<td>65.8</td>
<td>42</td>
<td>15.6</td>
<td>20, 21, 22</td>
</tr>
<tr>
<td>Syn 3</td>
<td>80</td>
<td>3</td>
<td>336.3</td>
<td>70.8</td>
<td>136</td>
<td>8.7</td>
<td>20, 21, 22</td>
</tr>
<tr>
<td>Syn 3</td>
<td>70</td>
<td>3</td>
<td>331</td>
<td>75.7</td>
<td>485</td>
<td>4.6</td>
<td>20, 21, 22</td>
</tr>
<tr>
<td>Syn 3</td>
<td>60</td>
<td>3</td>
<td>320.4</td>
<td>80.2</td>
<td>114</td>
<td>9.5</td>
<td>20, 21, 22</td>
</tr>
<tr>
<td>Syn 3</td>
<td>0</td>
<td>3</td>
<td>184.9</td>
<td>66.3</td>
<td>3.4</td>
<td>62</td>
<td>20, 21, 22</td>
</tr>
</tbody>
</table>
Sites from the southern anticline/syncline pair were also unrotated using this same stepwise method (Figures 9 and 10). The McElhinny fold test was applied to the southern anticline/syncline pair next. Sites PMD 1, PMD 2, PMD 4, PMD 5, PMD 6, PMD 8, PMD 9, PMD 10, PMD 11 and PMD 12 from anticline 10, and PMD 12, PMD 14, PMD 15, PMD 16, and PMD 18 from syncline 9 were used at rotation steps of 60%, 70%, 80%, 90%, 95% and 100% (Figures 9 and 10, Table 5).

Paleomagnetic site mean directions can be seen clustering as unfolding of the folds progresses in Anticline 10 (Figure 9). When all of the sites are plotted together on an equal area net, sites PMD 5, PMD 9 and PMD 11 skew the statistical calculation, due to their upper hemisphere orientation, causing a random dispersion of site means. Removal of these sites gives statistically significant fold test results, as can be seen in the increase in k values listed in Table 5. The fold test is positive (if sites 5, 9, and 11 in the upper hemisphere are removed) for all degrees of unrotation with the greatest clustering occurred between 90% and 100% unfolding (Figure 9 and Table 5). Sites in Syncline 9 do not cluster with progressive unfolding (Figure 10) and the fold test is negative.

MacDonald’s method of unrotation was also applied to all three folds in which samples were collected. Mean paleomagnetic pole directions in folds 3 (Figure 11, Table 6), 9 (Figure 12), and 10 (Figure 13) were both unplunged and unrotated to remnant magnetization directions which also cluster not only after simple unrotation, but also after applying MacDonald’s stepwise unplunging and unfolding (Figure 11). However, greatest clustering occurs at 100% using the MacDonald method, as opposed to clustering at 70% in the case of simple unfolding. This method was performed on syncline 9 with similar results to the simple unfolding method, i.e. random distribution (Figure 12). The fold test was also applied to Anticline 10 using
Figure 8. Simple Unfolding for Syncline 3

Shows in situ and unfolded locations of site means for PMD 20, 21, and 22.

- Arrows represent the approximate path to 100% unfolding
- Closed circles are in situ points in lower hemisphere

Data courtesy of Steve Harlan, U.S. Geological Survey
Table 4

Data for Unfolding Syncline 3 (PMD 20, 21, and 22) at 10% Intervals

<table>
<thead>
<tr>
<th>Percent Unfolding</th>
<th>Site</th>
<th>Strike and Dip of Bedding</th>
<th>Declination</th>
<th>Inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>PMD 20</td>
<td>N84W 58N</td>
<td>196</td>
<td>60.3</td>
</tr>
<tr>
<td>60</td>
<td>PMD 20</td>
<td>N84W 23N</td>
<td>323</td>
<td>82.6</td>
</tr>
<tr>
<td>70</td>
<td>PMD 20</td>
<td>N84W 17N</td>
<td>342.2</td>
<td>77.7</td>
</tr>
<tr>
<td>80</td>
<td>PMD 20</td>
<td>N84W 12N</td>
<td>349.6</td>
<td>72.2</td>
</tr>
<tr>
<td>90</td>
<td>PMD 20</td>
<td>N84W 6N</td>
<td>353.5</td>
<td>66.6</td>
</tr>
<tr>
<td>100</td>
<td>PMD 20</td>
<td>N84W 0N</td>
<td>355.8</td>
<td>60.9</td>
</tr>
<tr>
<td>0</td>
<td>PMD 21</td>
<td>N26E 70W</td>
<td>101.1</td>
<td>53.4</td>
</tr>
<tr>
<td>60</td>
<td>PMD 21</td>
<td>N26E 28W</td>
<td>350.6</td>
<td>79.2</td>
</tr>
<tr>
<td>70</td>
<td>PMD 21</td>
<td>N26E 21W</td>
<td>329.9</td>
<td>74.1</td>
</tr>
<tr>
<td>80</td>
<td>PMD 21</td>
<td>N26E 14W</td>
<td>320.1</td>
<td>67.9</td>
</tr>
<tr>
<td>90</td>
<td>PMD 21</td>
<td>N26E 7W</td>
<td>314.7</td>
<td>61.4</td>
</tr>
<tr>
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<td>PMD 21</td>
<td>N26E 0W</td>
<td>311.4</td>
<td>54.7</td>
</tr>
<tr>
<td>0</td>
<td>PMD 22</td>
<td>N60W 70E</td>
<td>230</td>
<td>45.3</td>
</tr>
<tr>
<td>60</td>
<td>PMD 22</td>
<td>N60W 28E</td>
<td>296</td>
<td>76.0</td>
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<tr>
<td>70</td>
<td>PMD 22</td>
<td>N60W 21E</td>
<td>323.1</td>
<td>74.8</td>
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<tr>
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<td>PMD 22</td>
<td>N60W 14E</td>
<td>342.4</td>
<td>71.0</td>
</tr>
<tr>
<td>90</td>
<td>PMD 22</td>
<td>N60W 7E</td>
<td>354.2</td>
<td>65.7</td>
</tr>
<tr>
<td>100</td>
<td>PMD 22</td>
<td>N60W 0E</td>
<td>1.4</td>
<td>59.8</td>
</tr>
</tbody>
</table>
Equal Area

Arrows show the direction of progressive unfolding

Unfolding PMD 1, 2, 4, 5, 6, 9, 10, 11, and 12 from in situ to 100% unfolded.

Closed circles are in situ points in lower hemisphere

Figure 9. Simple Unfolding for Anticline 10.
Unfolding PMD 12, 14, 15, 16, and 18 from in situ to 100% unfolded.

- Arrows show the direction of progressive unfolding
- Dashed lines indicate path in upper hemisphere
- Open squares are in situ points in upper hemisphere
- Closed circles are in situ points in lower hemisphere

Figure 10. Simple Unfolding for Syncline 9.
Table 5
Comparing K Values for Progressive Unfolding of Anticline 10 and Syncline 9

<table>
<thead>
<tr>
<th>Fold</th>
<th>Percent Unfolding</th>
<th>n</th>
<th>T&amp;P of Mean</th>
<th>k</th>
<th>α95</th>
<th>Sites Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ant 10</td>
<td>100%</td>
<td>6</td>
<td>21.7 71.9</td>
<td>30</td>
<td>11.3</td>
<td>1,2,4,6,10,12</td>
</tr>
<tr>
<td>Ant 10</td>
<td>100%</td>
<td>9</td>
<td>37.9 72.6</td>
<td>1</td>
<td>N/A</td>
<td>1,2,4,5,6,9,10,11,12</td>
</tr>
<tr>
<td>Ant 10</td>
<td>90%</td>
<td>6</td>
<td>10.6 73.4</td>
<td>29</td>
<td>11.5</td>
<td>1,2,4,6,10,12</td>
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<td>9</td>
<td>8.8 74.2</td>
<td>1</td>
<td>N/A</td>
<td>1,2,4,5,6,9,10,11,12</td>
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<td>358.3 74</td>
<td>15</td>
<td>16.2</td>
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<td>343.3 72.1</td>
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<td>352.0 72.8</td>
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<td>337.3 71.9</td>
<td>4.7</td>
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<tr>
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<td>9</td>
<td>317.4 58.9</td>
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</tr>
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<td>41.1 59.2</td>
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<td>34</td>
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<td>N/A</td>
<td>12,14,15,16,18</td>
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<td>50.7 62.4</td>
<td>10.6</td>
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<td>3</td>
<td>63.9 63.6</td>
<td>12.5</td>
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</tr>
<tr>
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<td>5</td>
<td>90.5 59.1</td>
<td>1</td>
<td>N/A</td>
<td>12,14,15,16,18</td>
</tr>
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<td>3</td>
<td>77.0 63.5</td>
<td>14.9</td>
<td>26.7</td>
<td>12,14,15</td>
</tr>
<tr>
<td>Syn 9</td>
<td>70%</td>
<td>5</td>
<td>100.4 56.0</td>
<td>1</td>
<td>N/A</td>
<td>12,14,15,16,18</td>
</tr>
<tr>
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<td>89.0 61.7</td>
<td>15.0</td>
<td>26.6</td>
<td>12,14,15</td>
</tr>
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<td>12,14,15,16,18</td>
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<td>5</td>
<td>N/A</td>
<td>12,14,15</td>
</tr>
<tr>
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<td>0%</td>
<td>5</td>
<td>115.0 43.9</td>
<td>5</td>
<td>N/A</td>
<td>12,14,15,16,18</td>
</tr>
</tbody>
</table>
Equal Area

Mean @ 100% unplunging & unfolding

PMD 21
PMD 20
PMD 22

Shows in situ and unfolded & unplunged (undeformed) locations of site means for PMD 20, 21, and 22. Site error cones are not available for PMD 20, 21, and 22.

Arrows represent the approximate path to 100% unplunging and unfolding
Dashed lines indicate path in upper hemisphere
Open squares are in situ points in upper hemisphere
Closed circles are in situ points in lower hemisphere

Figure 11. MacDonald's Method Applied to Syncline 3.
Table 6

Data for Applying MacDonald's Method (Unfolding and Unplunging) to Syncline 3 (PMD 20, 21, and 22) at 0% and 100% Retrodeformed

<table>
<thead>
<tr>
<th>Percent Unfolding</th>
<th>Sample</th>
<th>Strike and Dip of Bedding</th>
<th>Declination</th>
<th>Inclination</th>
<th>Rotation</th>
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<tbody>
<tr>
<td>0</td>
<td>PMD 20</td>
<td>N84W 58N</td>
<td>196</td>
<td>60.3</td>
<td>0</td>
</tr>
<tr>
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<td>PMD 20</td>
<td>304.8 40.3N</td>
<td>330.0</td>
<td>59.9</td>
<td>-40.3</td>
</tr>
<tr>
<td>0</td>
<td>PMD 21</td>
<td>N26E 70W</td>
<td>101.1</td>
<td>53.4</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>PMD 21</td>
<td>193.1 37.9W</td>
<td>335.0</td>
<td>55.2</td>
<td>-37.9</td>
</tr>
<tr>
<td>0</td>
<td>PMD 22</td>
<td>N60W 70E</td>
<td>230</td>
<td>45.3</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>PMD 22</td>
<td>315.8 63.4E</td>
<td>326.7</td>
<td>99.4</td>
<td>-63.4</td>
</tr>
</tbody>
</table>

sites PMD 1, PMD 2, PMD 4, PMD 5, PMD 6, PMD 8, PMD 10, PMD 11, and PMD 12 in one test and PMD 1, PMD 2, PMD 4, PMD 6, PMD 8, PMD 10, PMD 12 in a second test (Figure 13). Results from anticline 10 were less clear. The highest value occurred at 100% unfolding and unplunging in the second test with a k value of 30 and an α95% of 11.3° (Figure 11 and Table 5). McElhinny statistics result in a positive fold test for anticline 10, indicating that the sites cluster in a meaningful way as they are undeformed, but the points seem to still be moving towards a particular point on the stereonet when 100% unfolding is reached. Sites PMD 1 and PMD 20 were analyzed using ⁴⁰Ar/³⁹Ar method (Merrihue and Turner, 1966) by Dr. Steve Harlan at the United States Geological Survey in Denver, Colorado. PMD 20 in syncline 3 was dated at
Equal Area

Shows in situ and unfolded & unplunged (undeformed) locations of site means for PMD 12, 14, 15, 16, and 18.

Figure 12. MacDonald's Method Applied to Syncline 9.
Figure 13. MacDonald’s Method Applied to Anticline 10.
77.18 ± 0.31 Ma while PMD 1 in Anticline 10 was dated at 77.00 ± 0.31 Ma (Figure 14). Both dates were from biotite grains.
Figure 14. $^{40}$Ar/$^{39}$Ar Apparent Age Dates for PMD 20 and PMD 1.
CHAPTER IV

CONCLUSIONS

Structural Interpretation

A great deal of information about the structural style of the Doherty Mountain fold complex the deformation history, and order of deformation events can be inferred from geologic maps and cross sections constructed for the area (Figure 15).

Cross sections B-B’, C-C’, and D-D’ (Figures 16, 17, and 18) were constructed for this area based on, and consistent with, the geologic map, stereonet data, and a simple down-plunge section (Figure 19). Subsurface structures have been inferred from map and stereonet data; no seismic or well data are available for the Doherty Mountain fold complex.

The map cross sections, and stereonet patterns clearly indicate that much of the faulting in the Doherty Mountain fold complex occurred after significant folding. This is based on the fact that the east-trending fault (decollment) between regions II and III cuts across fold hinges and displaces the fold hinges toward the east, and on the inference that movement on thrusts have rotated fold axes toward the northwest producing observed dispersion in the pattern of fold axis orientations. In addition, attempts to restore the cross sections make it clear that several folds and fold pairs are entirely missing because they have been cut out by thrusting. Although at least two of the thrust faults (Doherty Mountain thrust and the thrust between region I and II) cut across steep anticlinal forelimbs, the Doherty Mountain thrust originated out of the core of a tight syncline. The existence of well-developed footwall synclines in the western
Figure 15. Doherty Mountain Fold Complex Diagram Showing Cross-Section Locations.
Figure 16. Cross Section B-B' Across the Doherty Mountain Fold Complex.

Figure 17. Cross Section C-C'.

Figure 18. Cross Section D-D'.

This section has been generalized by assuming all folds trend due North and plunge 41.75°

Figure 19. Generalized Downplunge Section of the Doherty Mountain Fold Complex.
part of regions II and III further supports thrusting after folding (e.g. McNaught and Mitra, 1993). This fact and the dominance of fold shortening over thrust shortening in the area suggests that the folds may have begun as detachment folds above the Lombard-Jefferson Canyon-Cave-thrust and were later modified by faulting across fold hinges and steep fold limbs or out of tight synclines. This is apparent when looking at the individual regions.

In region I, the hinge of syncline 5 is cut off on the south by an east-striking fault, interpreted as a north-dipping decollement surface. The lack of an associated anticline or an obvious structural link to the surrounding folds has led to the interpretation that the companion anticline to syncline 5 has been faulted out by the thrust fault discussed above and eroded away. The orientation of the axis of this fold more closely parallels those in region II (i.e. more northerly instead of northwest trend). This is interpreted to be a result of less rotation on bounding faults than occurred with folds 3 and 4.

Within region II the southern bounding fault, interpreted to be a decollement, cuts upsection across fold hinges from the Cambrian Flathead Formation on the west to the Mississippian Madison Group on the northeast, and then ramps upward across the steep forelimb of fold 8. The decollement itself is slightly folded, but it is clear that most of the shortening by folding was complete before the decollement developed and that it allowed the already tight folds to be translated further east. Folds 7 and 8 above the decollement appear to have been the same folds as 9 and 10 below the decollement, allowing calculation of the amount of eastward translation on the decollement and the degree of fold shortening before faulting.
The decollement ramps upward, across the steep limb in Devonian and Mississippian units and places Devonian Three Forks Formation on Mississippian Mission Canyon Limestone, progressively losing displacement upward. The hanging wall anticline (fold 8) immediately above the thrust ramp was rotated back to the west, changing its trend from northerly to slightly northwesterly and steepening its plunge slightly in a way similar to the folds above the thrust in region I. The companion syncline (fold 7) lies on the flat (decollement) part of the thrust and was therefore not rotated back toward the west as much as the anticline. The fold axis orientation for this fold may represent the “original” orientation of the Doherty Mountain fold complex in regions I, II, and probably III before faulting.

The fold axes in region IV do not appear to have been rotated to the west significantly by thrusting and therefore represent the general “original” trends in this more easterly region (Figure 15). This reflects a gradual change (from E - W to WNW - ESE) in shortening direction as one proceeds from west to east across the fold complex.

In a regional sense, the character of the Lombard thrust sheet changes from the Devil’s Fence anticline near the center of the Helena salient to its southern margin at the Jefferson Canyon fault (Figure 2). The most obvious change is the position of the leading edge as the trace of the Lombard thrust curves westward on approaching the Southwest Montana Transverse Zone from the north. However, there are other important changes. The depth of the Lombard thrust (thickness of the sheet) also clearly changes. It is only 1.7 km thick below the Devils Fence Anticline, and, it surfaces 30 km to the south as the Cave-Jefferson Canyon fault. In between, based on changing plunge directions of the folds within the sheet, it forms a large depression or sag (Boulder depression) that has an estimated maximum thickness of 5 km (Figure 19).
Shortening in the Big Mountain-Negro Hollow area on the southerly plunge of the Devils Fence Anticline occurs principally by W-E thrusting. Anomalous west-vergent structures such as asymmetrical folds and east dipping thrusts account for a relatively minor amount of shortening (6 km) and appear to be produced by simple shear crowding out of a large scale depression (Radersburg syncline) to the east of, and comparable in size to, the Devil’s Fence Anticline culmination.

The cross section structural interpretation (Figure 20) is based on map and fold orientation data and on the various cross section interpretations (Figure 16, 17, and 18). Shortening in the Doherty Mountain fold complex probably occurred initially by detachment folding above the Lombard thrust, followed by thrust faulting across fold hinges and limbs or out of synclinal hinges (Figure 21). Folds or fold pairs were thrust over other fold pairs eliminating intervening folds (Figure 21, events 4 and 5). Fold axes of early-formed north to northeast trending folds were rotated back towards the northwest and steepened slightly as they were carried on thrust ramps. This dispersion of fold axes may be the result of imbrication, in which the fold axes of older folds were rotated back as they were faulted over younger folds and faults forming beneath them in a west-to-east sequence. A more likely possibility is that the back rotation was caused by movement on listric fault surfaces that cut across folds after they had formed.

One of the last contractional events was the folding of the Jefferson Canyon fault itself (Figure 2) along with the coeval development of the Cave-Greer Gulch fold pair (Figure 21, event 6), the easternmost folds of the train. This was followed by renewed movement on the Jefferson Canyon segment of the fault as a result of movement on the footwall ramps that intersect it from below and by local backthrusting of the Cave-Greer Gulch fold pair westward over the Doherty Mountain fold complex (Schmidt, unpublished data). Total shortening is 64% of which 28% was due to folding and 36% was due to thrust faulting. Some layer parallel shortening occurred
Figure 20. Generalized North-South Cross Section A-A' Through the Central and Southern Helena Salient.
Figure 21. Schematic Tectonic Evolution of the Doherty Mountain Fold Complex.
prior to folding and faulting as evidenced by spotty bedding normal spaced cleavage within the Lodgepole Formation. It is hard to determine the location of the Doherty Mountain fold complex when deformation began. If the amount of travel that was interpreted is true, this area was certainly not originally within the present salient boundaries. Further structural and paleomagnetic analysis would have to be done to support this hypothesis.

Paleomagnetic Interpretation

The fold test is positive when applied to both the undeformation techniques outlined earlier. The simple unfolding of sills back to a horizontal orientation yields results which indicate early syn-deformation intrusion in folds 3 and 10 (greatest clustering at 70% unfolding). As discussed in the structural interpretation, the Doherty mountain fold complex underwent more deformation than just folding.

Interpretations after application of the MacDonald method of retrodeformation also result in a positive fold test. The problem here is the apparent difference in timing of intrusion relative to deformation. Removal of plunge and folding concurrently still results in clustering of paleomagnetic site means, but at 100% unplunging and unfolding. Even at 100% retrodeformation, they still appear to be traveling toward a common point (Figures 12 and 13). This indicates a pre-folding intrusion event.

This thesis set out to determine the tectonic history of the Mt. Doherty area and show whether the paleomagnetic fold test can be applied to the sills to determine timing of folding. The map and cross sections generated present a modern interpretation of this complicated area. The results show that the paleomagnetic fold test can be applied, resulting in a definite trend toward clustering upon unfolding of a good number of site means. This trend, in combination with the $^{40}$Ar/$^{39}$Ar dating, suggests a minimum age for deformation of approximately 77 Ma.
Recommendations for Future Work

Two possible sources of uncertainty lie in interpretation of the paleomagnetic data. One is the elimination of data from potentially good sites. When unfolding, and when MacDonald’s methods were applied to Anticline 10, three sites which plotted on the upper hemisphere were eliminated from the calculations. Two of the three sites have good site means (Table 2). It is possible that the sills did not cool all at once or that they were intruded in multiple events along the same planes of weakness. This may have allowed the sills in question to record a reversal event. The case for such a reversal is rather strong when looking at the movement of PMD 5 and 11 on the upper hemisphere of the stereonet as deformation was progressively removed. The reversal test, as described by Butler (1992) is a clustering of site means antiparallel to normal site means with the angle between the two of about 180°. PMD 11 especially exhibits this character, as can be seen in Figure 8. The ocean floor paleomagnetic record demonstrates a reversal event’s end at 78 ma. (Cox and Hart, 1986) This presents a very real possibility given the known age of deformation in this region.

A second possible source of error lies in the large uncertainty in some paleomagnetic site means. A more sophisticated method of determining site means (Halls, 1976) (Figure 22) could have been used to remove some uncertainty from the initial site means used in the fold test if interference from a secondary magnetization component had been suspected. Halls’ method involves extrapolating data to a stable site mean which has not been reached at the end of demagnetization. This is done by projecting the individual sample’s demagnetization trace as a great circle on a Wulff net. The location at which all the great circles for that site cluster is the site mean. (This method might produce tighter site means if secondary magnetization is the cause for the low confidence of some of the site means). Interpretation is complicated by the fact
Figure 22. Example of Converging Remagnetization Circles to Determine a Site Mean.
that there are two places in which this clustering occurs, on the upper and the lower hemisphere of the stereonet which is why this method was not used initially in this study.

Other potential sources of error come from the translation of the structural interpretation and tectonic history into a form usable during paleomagnetic analysis. Neither of the retrodeformation attempts indicates an unequivocal relationship between folding and intrusion. This relationship can only be made clear if the interpretations of the tectonic history of the area are accurate and correctly incorporated into the retrodeformation, as subtleties of the relations between intrusion, folding, faulting, and detachment faulting could substantially influence the paleomagnetic results. For instance, it is possible that not enough rotations were taken into account when the fold test was applied. In addition to unfolding and unplunging folds (rotations which have a vertical component), folds above later stage decollements may need an additional undeformation stage that incorporates a map-view rotation (x-y plane) component. Folds nearest the Southwest Montana transverse zone may also require additional rotations to compensate for displacement on the lateral ramp. The complicated combination of faults which cut through this area may make it impossible to ever obtain a true original position.

The tectonic history shown in Figure 20 is only speculation based on available structural data. More outcrop-scale mapping may provide details of how the sedimentary beds and sills must be manipulated to return them to their original position and make a paleomagnetic interpretation more plausible and complete as well as pinning down relative timing and magnitude of deformation by folding and faulting. This could include more widespread studies of slickensides to determine the direction of movement on faults and offset intrusions or beds.
Internal deformation within the fold complex was not widely analyzed. Further study in this area could include a comprehensive look at mesoscopic and microscopic deformation of the sills as well as sedimentary rocks. A systematic search for mineral grain rotation could indicate the relative timing of intrusion and folding in sills, and quantify the amount of strain taken up by fracturing and rotation of grains in sedimentary and igneous rocks. A grain size analysis could help determine whether microlitic sill texture was a result of rapid cooling or deformation within the sills. Calcite and oolite strain analyses could determine primary stress directions, giving clues to direction of movement, and be another way of quantifying internal strain. A more detailed study of outcrop-scale folding and cleavage directions would also be helpful in identifying layer parallel shortening and other small-scale deformations, better quantifying the magnitude of shortening. In addition, a detailed petrologic study comparing sills throughout the Doherty Mountain fold complex could determine age differences between different sill suites and test the hypothesis of multiple injections over time.
Appendix A

Sill Petrology
Sills were sampled at various locations in anticipation of positive results from
the paleomagnetic analysis. Hand sample analysis was performed in the field and
samples seemed to be of same rock type throughout, an aphanitic amphibole and
plagioclase rich rock type, probably a diorite or maybe anorthosite. Thin section
analysis was performed on a random grouping of samples due to lack of bulk sampling
taken at each site and the fact that a majority of bulk samples taken were crushed for
$^{40}\text{Ar}/^{39}\text{Ar}$ dating. Samples made into thin sections were from stations PMD 3, PMD 6,
PMD 16, PMD 19, PMD 20, PMD 21, and PMD 22. Sample point counts can be
found at the end of this section. Due to the microlitic texture of the samples, structural
relationships as well as positive mineral identification within each sample were difficult
or impossible to come by. Samples PMD 3, PMD 6, and PMD 16 were all from the
southern anticline/ syncline while PMD 19, PMD 20, PMD 21, and PMD 22 were from
Syncline 3. No fabric or preferred orientation was observed in most of these samples,
suggesting they were intruded pre- or post-deformation, but care must be taken when
making that assumption considering the extremely small size of the grains. PMD 16
had some fracturing through it but this could be a postdeformational relaxation event
due to its proximity to the hinge.
Sill petrology for the most part seems to be andesitic with Plagioclase content of about
50%, hornblende or biotite content of about 20%, pyroxenes about 15% and other
minerals 5%. Magnetite is seen in trace amounts in all samples. Detailed petrologic
analysis and microscope work did not yield more than a general composition of the sills
due to their fine grained texture.
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<th>Hbl</th>
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Pyr= Pyroxene, Pl= plagioclase, Biot= biotite, Hbl= hornblende, Chl= chlorite, Opq= opaque, Acc= accessory, Unk= unknown.
Appendix B

Stereoplots
Trend and Plunge
339, 56

Fold 1
Trend and Plunge
330, 47

Fold 2
Trend and Plunge
334, 66

Fold 3
Trend and Plunge
318,36

Fold 4
Trend and Plunge
345, 33

Fold 5
Trend and Plunge
358, 31

Fold 7
Trend and Plunge
335, 56

Fold 10
Trend and Plunge
24, 30

Fold 11
Trend and Plunge
16, 12

Fold 14
Appendix C

Paleomagnetic Sampling Techniques
Sample cores were drilled at 18 sites across folds 9 and 10 (Figure 6) in three semi-continuous sills. Four other sites were sampled from the northern anticline-syncline pair, folds 3 and 4, along one continuous sill (Figure 6). Cores measured 1 inch in width, and varied between 1 and 3 inches in length depending on the hardness of sill rock, fracturing of sill, operator skill and time of day, which determined the sheer exhaustion of the operator. Sample sites were chosen based on:

1). Degree of weathering. Sills which are even moderately weathered may have changed in chemical composition enough to affect Paleomagnetic and radiometric “memory”. Thin sections showed a moderate degree of weathering, with some biotites altered to chlorite, and feldspars partially altered to white micas.

2). Likelihood of lightening strikes. Lightening, being a strong electromagnetic field as well as heat generator, has a tendency to reset the Paleomagnetic direction of any rock it strikes or comes near. For this reason, sills which were likely to have been struck, such as those on peaks and tops of ridges, were avoided as drilling sites.

3). Outcrop size. Between 8 and 12 cores had to be collected at each site. The sill outcrop had to be large enough to support that much drilling, assuming some fracturing could occur and ruin a core. The smallest outcrop size used was about 15 ft² based on these conditions.

4). Fracturing of sills, especially in fold hinges. Sills which were highly fractured had a tendency to disintegrate while being drilled making orientation of cores impossible. This in turn made drilling these sites worthless.

5). Sill accessibility. The terrain in which the sills are located has 1400 feet of relief, which made it impossible to sample all acceptable looking outcrops.

6). Measurable bedding bounding a sill is important because it is used as the orientation of the sill at present.
Sampling of the sills was carried out using a hand-held rotary drill on a chainsaw body. Sample orientations were measure using a "brunton on a stick". This device was simply a Brunton compass on top of an aluminum sleeve which could be placed around the core before it was removed from the rock. The aluminum sleeve is mounted on a clinometer to measure plunge of the sample or hade. A sun compass is also part of the tool. This is an aluminum pole in the center of the brunton with which the angle of the sun is measured. This was recorded along with the time of day and the latitude where the measurement was taken. Then, with charts available from the United States Geological Survey as well as a number of educational institutions, the azimuth orientation of the core could be independently determined. This is an extremely important option to have if the sills one happens to be measuring are magnetized and affect the Brunton compass measurements. The cores were then marked with a brass wire for reference orientation. Finally, the core was broken from the outcrop, its location and sample number were recorded on it, and the sample was placed in a bag with other cores from the same sampling location. Between 8 and 12 core samples were taken at each site so a statistically significance site mean could be determined. A total of about 240 cores were taken throughout the two fold pairs. Bedding orientations from the surrounding host rock were measured and recorded at each drilling site. These measurements were used to apply structural rotations to paleomagnetic pole directions. Sill rock samples were also taken from these various sites for $^{40}$Ar/$^{39}$Ar radiometric age dating. Some dating has been done at USGS labs in Denver, Colorado (Figure 13) by Dr. Steve Harlan.
Appendix D

Paleomagnetic Analysis
Paleomagnetic analysis examines the orientation of magnetic moments of various mineral grains which make up a rock sample. The overall orientation of the sample's magnetic moment is a combination of various remnant magnetizations acquired over the rock's life. How mineral grains acquire magnetization is dependent on a number of factors. The most important is mineralogy; this affects all other factors. Magnetic properties such as coercivity or relaxation time are examples of characteristics which are dependent on mineral type. The exponential magnetic decay equation (from Butler 1992) relating these properties is

$$J_r(t) = J_{t0}^\left(\frac{-t}{\tau}\right)$$

where,

- $J_r(t)$ = present remnant magnetization
- $J_{t0}$ = initial remnant magnetization
- $t$ = time
- $\tau$ = relaxation time

Time also influences magnetization acquisition; the longer a ferromagnetic mineral remains in a magnetic field, the greater its chances of acquiring some magnetization.

Mineralogy determines relaxation time, which is the amount of time it takes for a mineral's magnetization to decay after the field inducing the magnetization has been removed.
The equation (Néel, 1955) for this decay is

\[ \tau = \frac{1}{C} \exp \left( \frac{v h_c j_s}{2kT} \right) \]

\[ C = \text{frequency factor} \sim 10^8 \text{ s}^{-1} \]
\[ v = \text{volume of grain} \]
\[ h_c = \text{coercivity of grain} \]
\[ j_s = \text{saturation magnetization} \]
\[ kT = \text{thermal energy} \]

Relaxation time is important because paleomagnetic analysis require minerals which have relaxation times on a geologic time scale, around $10^9$ years for this study, in order for the sites to have preserved the orientation of the earth’s magnetic field when they were intruded. Relaxation time is also dependent on coercivity; the amount or intensity of an external magnetic field needed to alter the magnetic moment of the mineral. Coercivity is temperature dependent; the higher the temperature, the lower the $h_c$ of the mineral becomes. Mineralogy also affects the blocking temperature ($T_B$), which is the temperature above which acquired magnetization decays quickly.

The resultant magnetic vector or Natural Remnant magnetization (NRM) of a sample is a combination of the primary remnant magnetization vectors (acquired at the time of formation) plus the secondary remnant magnetization vectors (acquired during the rock’s life).

$$\text{NRM} = \text{Primary NRM} + \text{Secondary NRM}$$

Making up these primary and secondary magnetizations are three types of remnant magnetizations important to this study. Characteristic Remnant magnetization
or Thermal Remnant magnetization, is the magnetic orientation the rock acquires as it cools below the Curie temperature in an external magnetic field. The Curie temperature is the temperature below which a substance will have some sort of magnetization (580°C for magnetite, 680°C for hematite). Magnetic moments of minerals cooling below this temperature orient parallel to the earth’s magnetic field. This magnetization tends to be extremely stable because it is acquired above the $T_B$ of most minerals within a rock and these temperatures need to be reached again to cause decay of the magnetization. This primary remnant magnetization is the one this study focuses on.

Viscous Remnant magnetization is a secondary magnetization which is acquired as mineral grains making up rock sit in a external magnetic field (example: the earth’s magnetic field in its current orientation). Some of the magnetic grains within the rock relax into this new orientation. Because this magnetic field is most likely of a different orientation than the one in which the rock originally acquired its Characteristic Remnant magnetization when cooling, this has the effect of changing the Natural Remnant magnetization of the rock sample and masking the Characteristic Remnant magnetization. The intensity of this new magnetization is generally not as strong as Characteristic Remnant magnetization and can be removed by various techniques. Many directions of Viscous Remnant magnetization can be acquired by a rock before it is sampled and studied. For example, as the rock sits in place for millions of years in a slowly-changing magnetic field, some grains may relax into the orientation of the new field. After the rock is sampled, it may then sit in a building somewhere exposed to various weak magnetic fields created by lights, computers, electrical wiring, and the like. All these fields may induce some sort of Viscous Remnant magnetization in the sample which must be removed.

The other secondary remnant magnetization of concern is Isothermal Remnant magnetization. This magnetization is acquired by a sample when it is in the vicinity of,
or is actually hit by a lightning stroke. Lightning produces a very brief but intense magnetic field which may effectively erase the paleomagnetic memory of the rock. It also produces intense heat which may raise some magnetic domain-carrying grains above their Curie temperature and reset them to the current magnetic field orientation. Both of these effects make lightning-struck samples useless or near useless for paleomagnetic analysis.
DEMAGNETIZATION

Magnetometers

The cores collected from the Doherty Mountain fold complex were taken by the author to the University of New Mexico in Albuquerque. There, for three weeks, in the basement of the Earth and Planetary Sciences Department under the direction of Dr. John Geissman, the Paleomagnetic orientation of the cores was measured. This was performed using a 2G Enterprises cryogenic magnetometer; an extremely sensitive and fast measurement device.

The 2G Enterprises cryogenic magnetometer was used in this study because it is completely automated and extremely sensitive. The device measures magnetic moments using a Superconducting Quantum Interference Device (SQUID). The SQUID is cooled by liquid helium to about 4°K (-269°C). This makes the superconducting magnetometer sensitive to less then $10^{-7}$ G cm$^3$. The main advantage of this magnetometer is automation. Sample data such as sample number, bedding orientation, and sample orientation were entered on a computer before magnetic measurements were taken. Samples were then placed in a computer controlled, rotating tube. The rotating tube fed the sample into the SQUID allowing the computer to automatically control the orientation of the sample as it was being measured. Each sample could be measured in about a minute and this measurement was recorded onto disk. The speed and automation of this system are major advantages over earlier magnetometers and allowed the work to be done in a quick and efficient manner.
Magnetic Field (H)
Magnetization (J)
Magnetic Dipole Moment/Unit
Volume
Magnetic Moment

adapted from Butler, 1992

Magnetometer sensitivity is extremely important to paleomagnetic research.
Remnant magnetizations typical of basalt are around 10^{-3} Gauss cm^{-3} or 1 Ampere/meter; granite has a remnant magnetization of around 10^{-4} Gauss cm^{-3} or 0.1 Ampere/meter.
The intermediate composition sill samples have remnant magnetization of between 5 \times 10^{-4} and 10^{-7} G which is on the edge of astatic and spinner magnetometers’ range but well within that of the 2G Enterprises instrument.

The cores were cut into sections 1 centimeter long, starting at the end which came from the farthest into the rock. Analysis began with samples being placed in the magnetometer to determine their natural remnant magnetization. After the samples were
measured, they remained in the magnetic clean room which contained the magnetometer. This was done so they would not acquire any additional viscous component from external fields during storage.

Paleomagnetic studies focus on finding the primary magnetic orientation of the cores sampled. To do this, the viscous component of magnetization must be removed. This is done in two ways: Alternating Field Demagnetization and Thermal demagnetization.

Alternating Field demagnetization involves randomizing the viscous component of magnetization by applying an alternating external magnetic field to a sample. The field is applied along the three orthographic directions, x, y, and z, relative to the sample. Each step’s maximum field, 4 milliTeslas (mT) or 40 Oersteds (Oe) for instance, is applied in an arbitrary “up” direction. All the grains within the sample with a coercivity ($h_c$) less than or equal to 4 mT will orient themselves in this direction. As the field alternates to the “down” orientation it also drops slightly in intensity, to 3.9 mT (39 Oe) for example. All grains with a $h_c$ equal or less than 3.9 mT will orient themselves in this down direction. The field continues to alternate and decrease in intensity until it becomes zero. This type of demagnetization has the effect of canceling out the remnant magnetization because the all reoriented grains’ magnetic moments, when summed, equal zero. The sample is measured after each step for remnant magnetization. Grains with coercivities less than the last demagnetization step no longer contribute to the Natural Remnant magnetization of the sample. So, the higher the intensity of the applied field, the less viscous component remains and the more prominent the Characteristic Remnant magnetization becomes.

Thermal demagnetization is accomplished by repeatedly heating the sample to ever increasing temperatures below the Curie temperature of the mineral and then letting it cool back to room temperature in zero magnetic field. All minerals with a blocking
temperature below the temperature of the demagnetization step will acquire a magnetization of zero, thereby erasing their Natural Remnant magnetization. After each step, the sample is measured for Natural Remnant magnetization, and only minerals with blocking temperatures above those reached during the thermal demagnetization step will contribute to the Natural Remnant magnetization of the sample.

Samples were then demagnetized. Most samples were demagnetized using Alternating Field methods but at least one sample from each site was thermally demagnetized as a check of the Alternating Field demagnetization.

Sample Analysis

Samples were measured for Natural Remnant magnetization and then demagnetized either thermally or using alternating field. Sites PMD 1 through 22 were measured using the 2G magnetometer. Sample cores from each site were alternating field demagnetized and at least one core from each site was thermally demagnetized for comparison.

The alternating field demagnetization steps were most often increased in the following way. All cores were first measured for Natural Remnant magnetization before any demagnetization was performed. Site samples were then demagnetized stepwise at 2 mT, 4 mT, 7 mT, 10 mT, 13 mT, 16 mT, 20 mT, 25 mT, 30 mT, 40 mT, 50 mT, 60 mT, 70 mT, 85 mT, 100 mT, 115 mT, and 130 mT. Each sample had a magnetic field applied to it at each step in order, after which the natural remnant magnetization was measured. These measurements were recorded as a Zijderveld diagram.

Zijderveld diagrams are useful because they allow changes in magnetic vectors to be quickly recognized. Zijderveld diagrams present the magnetization direction and
intensity in one diagram by superimposing two coordinate systems. Declination is measured in compass directions, with north (by convention) to the right. Inclination uses the east/west declination axis to represent down and up directions. Points above the north/south axis have an up inclination while points below it have a downward inclination; both to a maximum of 90°. Intensity of magnetization is plotted as distance from the origin. Declination and inclination are plotted as two separate lines on the same diagram. Declination is shown as closed or solid symbols, and inclination is shown as open symbols. After all samples were measured, Zijderveld diagrams of the in situ magnetic vectors were made of all 18 sites. As demagnetization progresses and Viscous Remnant magnetization is removed, the total Natural Remnant magnetization of the sample changes in direction and the intensity decreases. When all Viscous Remnant magnetization is removed, the declination and inclination of the Characteristic Remnant magnetization, the primary magnetization component, is the only remaining component of Natural Remnant magnetization. This is displayed on the Zijderveld diagram as a stabilization of movement of magnetic vector and only a decrease in intensity.

From the diagrams, site means were determined by averaging the 8 to 12 sample measurements from each site. Only sites which seemed to have good agreement in magnetization direction between the thermally and the alternating field demagnetized samples and which were generally consistent in their remnant magnetization directions were accepted as accurate. All other sites were excluded from further analysis. Table 2 shows sites from which the most promising site means were obtained. Appendix E shows examples of Zijderveld diagrams from all of the sites.
Appendix E

Zijderveld Diagrams for Paleomagnetic Samples
Zijderfeld plot of sample CF 9.00A
Geographic coordinates
From NRM to AF 130

Each division = E-6 emu
Open=Inclination; Solid=Declination
Zijderveld plot of sample UCW 5.00A
Geographic coordinates
From AF 2 to AF 85

Each division = 6 emu
Open = Inclination; Solid = Declination

Zijderveld plot of sample UCW 7.00A
Geographic coordinates
From AF 2 to AF 130

Each division = 6 emu
Open = Inclination; Solid = Declination

Zijderveld plot of sample UCW 9.00A
Geographic coordinates
From AF 2 to AF 130

Each division = 6 emu
Open = Inclination; Solid = Declination
Zijderveld plot of sample UCW 9.00A
Geographic coordinates
From AF 2 to AF 130

Zijderveld plot of sample UCW 10.00A
Geographic coordinates
From TT 100 to TT 575

Each division = 6 emu
Open=Inclination; Solid=Declination
Zijderveld plot of sample CW 9.001
Geographic coordinates
From AF 2 to AF 130

Each division = 5°emu
Open = Inclination; Solid = Declination

PMD 4

Zijderveld plot of sample CW 10.001
Geographic coordinates
From TT 200 to TT 575

Each division = 5°emu
Open = Inclination; Solid = Declination
Zijderveld plot of sample CF 4.00A
Geographic coordinates
From AF 4 to AF 130

Each division = E: 5 emu
Open=Inclination; Solid=Declination

Zijderveld plot of sample CF 5.00A
Geographic coordinates
From TT 150 to TT 575

Each division = E: 5 emu
Open=Inclination; Solid=Declination

Zijderveld plot of sample CF 7.00A
Geographic coordinates
From AF 2 to AF 130

Each division = E: 5 emu
Open=Inclination; Solid=Declination

PMD 8

Zijderveld plot of sample CF 4.00B
Geographic coordinates
From AF 4 to AF 130

Each division = E: 5 emu
Open=Inclination; Solid=Declination

Zijderveld plot of sample CF 7.00A
Geographic coordinates
From AF 2 to AF 130

Each division = E: 5 emu
Open=Inclination; Solid=Declination
Zijderveld plot of sample UCW 5.001
Geographical coordinates
From AF 2 to AF 130

Zijderveld plot of sample UCW 7.001
Geographical coordinates
From TT 100 to TT 575

Zijderveld plot of sample UCW 8.001
Geographical coordinates
From AF 2 to AF 130
Each division = 6 cm

Zijderveld plan of sample CW 5.001
Geographic coordinates
From AF 2 to AF 130

Zijderveld plan of sample CW 6.001
Geographic coordinates
From TT 100 to TT 375

Each division = 6 cm

Note: The diagrams show the Zijderveld plan with geographic coordinates from AF 2 to AF 130 and TT 100 to TT 375.
Zijderveld plot of sample OW 9.00A

Geographic coordinates
From AF 2 to AF 130

Each division = E-5 emu
Open=Inclination; Solid=Declination

AF

AF 100

AF 50

AF 60

AF 10

AF 25

AF 40

AF 30

AF 20

AF 16

AF 13

AF 10

AF 7
Zijderveld plot of sample CM 0.001
Geographic coordinates
From AF 2 to AF 130

Zijderveld plot of sample CM 10.001
Geographic coordinates
From TT 280 to TT 575

Each division = 5 emu
Open = Inclination; Solid = Declination
Zijderveld plot of sample UCW 13.001
Geographic coordinates
From TT 150 to TT 575

Each division = $5 \text{ emu}$
Open=Inclination; Solid=Declination
Zijderveld plot of sample CM 10.001
Geographic coordinates
From TT 270 to TT 575

PMD 15

Each division = 6 emu
Open-Inclination; Solid-Declination
Zijderveld plot of sample CM 12.001
Geographic coordinates
From TT 270 to TT 575

Each division = 6 emu
Open-Inclination; Solid-Declination
Each division = 5 emu  Open = Inclination; Solid = Declination

Zijderveld plot of sample CM 0.001
Geographic coordinates
From NRM to AF 90

Zijderveld plot of sample CM 10.001
Geographic coordinates
From TT 200 to TT 575
BIBLIOGRAPHY


