Paleomagnetism and $^{40}Ar/^{39}Ar$ Dating of Folded Sills in the Lombard Thrust Sheet, South Central Montana: Implications for the Timing of Fold and Thrust Deformation and Vertical Axis Rotations Along the Southern Margin of the Helena Salient

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Abstract

We report new paleomagnetic and $^{40}Ar/^{39}Ar$ data from sills exposed in folds of the Lombard Thrust Sheet along the southern margin of the Helena Salient in Southwest Montana. The folds in the Doherty Mountain fold complex represent the southern extension of the Devils Fence anticline structural culmination along the Southwest Montana Transverse Zone east of Whitehall, Montana. Numerous intermediate composition sills, probably temporally related to the Late Cretaceous Boulder Batholith, are well exposed in complexly deformed Cambrian through Mississippian strata in the hanging wall of the Jefferson Canyon-Cave fault system.

We report well defined paleomagnetic results from 14 sites in sills exposed in four different folds. After correction for fold plunge and followed by bedding tilt, all four folds yield positive fold tests at 100% unfolding. These results indicate that their remanence was acquired prior to folding. We suggest that these magnetizations are primary thermoremanent magnetizations acquired during sill emplacement prior to fold and thrust deformation.

$^{40}Ar/^{39}Ar$ dates on biotites from sills from two sills in two different folds yield identical plateau dates of 77.18 ± 0.31 Ma and 77.00 ± 0.31 Ma (2σ), consistent with a Late Cretaceous age for deformation.

Although the group mean directions from each of the four folds probably represent spot readings of the geomagnetic field and the number of spot readings is low, their structurally corrected grand-mean direction (*Dec.* = 344°, *Inc.* = 65°, *k* = 82, α_{95} = 10°, *N* = 4) is statistically indistinguishable from the expected Late Cretaceous cratonic reference direction from the Adel Mountain Volcanics of western Montana. Consequently, these results suggest that hanging wall strata in the Lombard Thrust Sheet of the Helena Salient in this vicinity have probably not experienced significant local vertical axis rotation (*R* = -8.5° ± 20.5°) due to thrust movement along the Southwest Montana Transverse Zone.

Tectonic Map of Major Laramide-age Structural Features in Western Montana

Introduction

The geology of southwest Montana is characterized by two distinct styles of Laramide-age (Late Cretaceous to early Tertiary) deformation: 1) thin-skinned folds and thrust faults of the Helena Salient of the Cordilleran thrust belt; and 2) basement-involved folds, reverse faults, and thrust faults of the Rocky Mountain foreland province. In general, deformation in the two provinces in this region are thought to have been approximately coeval, based on cross-cutting relationships of folds and faults in both provinces, but absolute dates on the age of deformation are rare due to a lack of synorogenic sediments that can be used to place upper and lower limits on the age of contractional deformation.

In the Doherty Mountain fold complex north of the Jefferson Canyon transverse zone, numerous concordant igneous intrusions are exposed in folds in the hanging wall of the Lombard thrust sheet of the Helena salient. Although exposed in folds, the relationship of sill intrusion to folding is unclear as several studies (*Harlan et al.* 1988; *Harlan et al.*, 1995) have shown that sill emplacement in folds sometimes occurs subsequent to folding and that the apparent fold geometry is an artifact of the sills following bedding parallel weaknesses associated with the folds. Determining the age of sill intrusion relative to folding, coupled with isotopic dating will yield important information regarding the timing of fold and thrust belt deformation.

Study Objectives

In order to determine the relationship between sill intrusion and folding in the Helena salient, we collected samples for paleomagnetic analysis from 30 sites exposed in five folds in the Doherty Mountain fold complex, which has been the subject of recent mapping and structural analysis by *Whisner* (1998) and Whisner *et al.* (in preparation). We collected paleomagnetic sills on both limbs of the folds and, where possible, fold hinges, in order to conduct paleomagnetic fold tests to determine the age of sill remanence relative to folding. We also collected samples for $^{40}Ar/^{39}Ar$ dating to precisely determine the age of sill emplacement. We present preliminary paleomagnetic results from twelve sites in four folds and $^{40}Ar/^{39}Ar$ dates from two sills in different folds.

In each the fold test analyses, incremental fold tests were applied following initial correction for fold plunge (*MacDonald*, 1980) using fold axes determined by pi-diagram analyses presented by *Whisner* (1998). Incremental fold tests were applied by untilting strata at 10% intervals and calculating the precision parameter *k*. The statistical significance of the fold tests were evaluated following the procedure of *McElhinny* (1964).

Results and Discussion

1) Paleomagnetic results from nine sites yield reasonably well-defined remanent magnetizations of moderate to high coercivity. Thermal demagnetization results and rock magnetic experiments indicate that the remanence in these samples in primarily carried by magnetite. Although minor hematite was observed in some samples, it does not contribute significantly to the observed characteristic remanent magnetization.

2) Individual site-mean directions are well-grouped to moderately well-grouped with α_{95} values ranging from 4° to 14°.

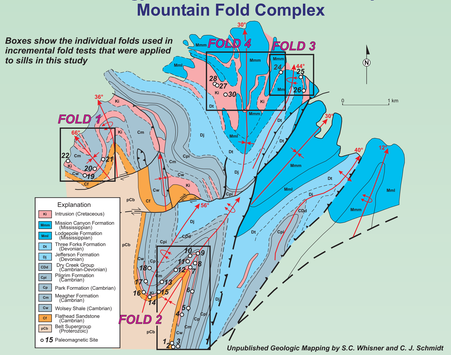
3) In situ site-mean directions are scattered for the four folds, but become well-grouped following plunge and tilt corrections. Incremental fold tests are positive, significant at the 95% confidence interval, and indicate that the precision parameter *k* is maximized at 100% unfolding. This result indicates that remanence acquisition occurred prior to folding of the host sedimentary rocks and we suggest that sill intrusion clearly predates fold and thrust deformation.

4) $^{40}Ar/^{39}Ar$ plateau dates from biotite from two different fold localities give essentially identical apparent ages of 77.26 ± 0.36 Ma and 77.10 ± 32 Ma (both at 2σ). These ages temporally overlap with the Late Cretaceous Boulder Batholith and the Elkhorn Mountains volcanics.

5) A grand mean paleomagnetic direction from the four fold localites is *Dec.* = 344°, *Inc.* = 65°, *k* = 82, α_{95} = 10°, *N* = 4 group means). This result is essentially identical to the expected direction (*Dec.* = 352°, I*nc.* = 63°) for the ca. 75 Ma reference pole from the Adel Mountain volcanics of western Montana (*Gundersen and Sheriff*, 1991). This result suggests that hangingwall strata in the Lombard Thrust Sheet of the Helena Salient in this vicinity have not experienced significant local vertical axis rotation due to thrust movement and impingement with foreland structures along the Southwest Montana Transverse Zone.

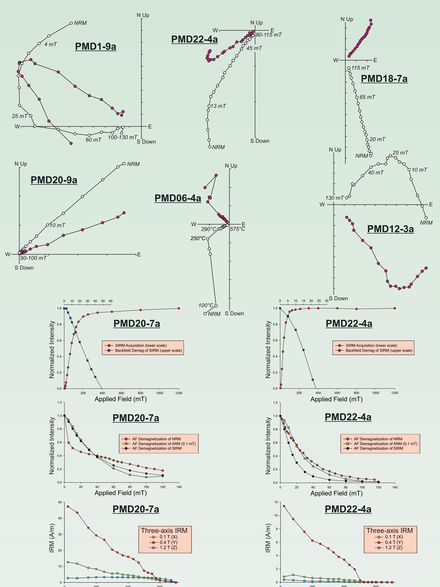
6) Future work will focus on using the paleomagnetic fold test and isotopic dating to investigate the age of folds and faults exposed to the south of the study area in the Rocky Mountain foreland province.

Geology and Structure of the Doherty Mountain Fold Complex

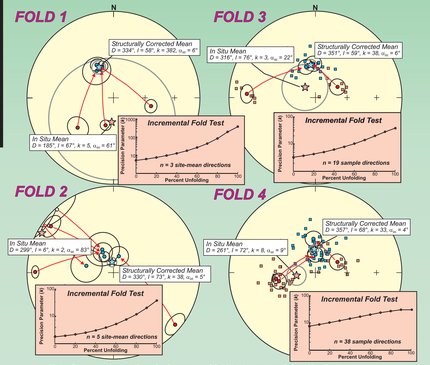


Unpublished Geologic Mapping by S.C. Whisner and C. J. Schmidt

Representative In Situ Orthogonal Vector Diagrams and Rock Magnetic Results

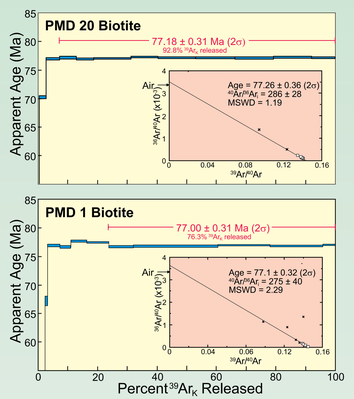


Paleomagnetic Fold Tests

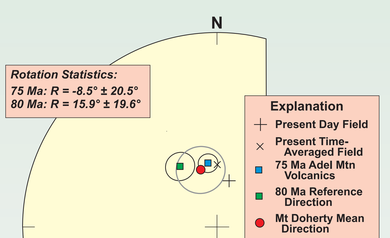


Note: Structural corrections for incremental fold tests were performed by first removing the effects of fold plunge, followed by bedding tilt corrections.

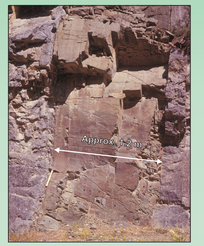
$^{40}Ar/^{39}Ar$ Geochronology

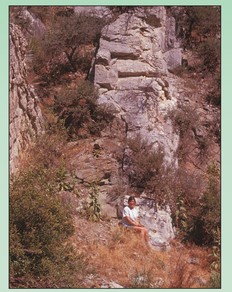


Comparison of Doherty Mean Direction With Late Cretaceous Reference Directions



Vertical to Slightly Overturned Mafic Sills in Paleozoic Carbonate Rocks in Cottonwood Canyon





Field Assistant Shiloh 1993-2002

Conclusions

1) Paleomagnetic incremental fold test results from diorite sills in the Doherty Mountain area of soutwestern Montana indicate that they were emplaced prior to fold and thrust belt deformation.

2) $^{40}Ar/^{39}Ar$ isotopic dating of biotite from two samples from two different localities give essentially identical apparent ages of about 77 Ma. These ages are broadly correlative with the nearby intrusive rocks of the Late Cretaceous Boulder Batholith and its satellite plutons and the Elkhorn Mountains Volcanics.

3) Combined paleomagnetic and geochronologic information provide a minimum age of ~77 Ma for the thin-skinned fold and thrust structures in the Doherty Mountain area.

4) Preliminary results suggest no evidence for local vertical axis rotations associated with impingement of thin-shinned folds and faults of the thrust belt with coeval foreland structures to the south as has been suggested by paleomagnetic results elsewhere along the southern and northern margins of the Helena Salient (*Eldredge and Van der Voo*, 1988; *Jolly and Sheriff*, 1992).

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