KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FOURTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2011
Union College, Schenectady, NY

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ISSN# 1528-7491

The Consortium Colleges   The National Science Foundation   ExxonMobil Corporation

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Students: *MOLLY CHAMBERLIN*, Texas A&M University, *ELIZABETH DALLEY*, Oberlin College, JOHN *SPENCE HORNBUCKLE III*, Washington and Lee University, *BRYAN MCATEE*, Lafayette College, *DAVID OAKLEY*, Williams College, *DREW C. THAYER*, Colorado College, *CHAD TREXLER*, Whitman College, *TRIANA N. UFRET*, University of Puerto Rico, *BRENNAN YOUNG*, Utah State University.

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Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1005122
ExxonMobil Corporation

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BRITTLE DEFORMATION IN THE EDELMAN LINEAMENT, BIGHORN MOUNTAINS, WYOMING

DAVID OAKLEY, Williams College
Research Advisor: Paul Karabinos

INTRODUCTION

The Bighorn Mountains are a basement-cored arch in north-central Wyoming formed during the Laramide orogeny (70-45 Ma). The range and orogeny are exemplary of mid-continent deformation distant from a plate boundary, yet there are many unanswered questions about the structures that accommodated the deformation. The Archaean crystalline basement rocks at the core of the Bighorns Arch and the prominent topographic lineaments within them are particularly understudied parts of the range. For my research, I conducted brittle structural analysis of faults and microstructural study of fault materials within the Edelman Creek lineament, a narrow valley trending approximately 040° northeast that is one in a series of lineaments of likely structural significance (Hoppin, 1974; Stone, 2003). My objectives are to characterize the conditions of deformation within the zone and to determine whether the structures were active during Laramide arch formation.

GEOLOGIC BACKGROUND

The basement rocks exposed in the center of the range are heavily faulted migmatitic granites of the Bighorns batholiths, about 2844±5 Ma (Frost and Fanning, 2006) in age, that lack deformational fabrics (Frost et al. 2006) but can be expected to hold a long record of deformation. Many of the faults are mineralized, principally with chlorite or epidote, but a lack of offset markers and of fault materials to be dated make timing and motion sense difficult to determine. Several lineaments cut the basement and are likely to have accommodated Laramide motion (Hoppin, 1974; Stone, 2003). That they remain straight despite varying elevation implies that the underlying structure is steeply dipping.

Laramide compression, oriented 066°-246° during formation of the Bighorns arch (Erslev and Koenig, 2009) will have left its mark on the basement, but pre-Laramide deformation affected it as well. Minimal work has been done on the pre-Laramide brittle tectonic history of the Wyoming craton in the Bighorns range. Neighboring areas of Wyoming and the Rocky Mountains show evidence of Precambrian extensional faulting upon north to northeast and west to northwest striking normal faults, which may have controlled the orientation of Laramide uplifts, including the Bighorns (Marshak et al. 2000). The fracture arrays and lineaments attracted attention in the 1960s and 1970s (e. g. Hoppin 1965, 1974), but brittle kinematic analysis of mesoscopic faults was not performed.

The depth of mineralization in the Bighorns and other Laramide arches has received some study but remains uncertain. Mitra and Frost (1981), working in the Wind River Mountains, noted that chlorite and epidote form at temperatures higher than expected for Laramide conditions based on the geothermal gradient. Wise and Obi (1992), however, interpret chlorite and epidote on faults in the Bighorns to be Laramide in age. Possible heat sources include frictional heating along faults and movement of hot water through the fault zones. The hydrothermal mineralization hypothesis is supported by stable isotope work done by Esser (2000).

METHODS

In order to perform brittle structural analysis on the Edelman lineament, a large fault and fracture data set was collected in the field. Strike and dip were measured for each fracture plane, and trend and plunge or rake of any lineations were measured. Type of mineralization, motion sense indicators such as Riedel fractures or crystal fiber steps, and overprinting or cross-cutting relationships were noted. I also collected several, mostly oriented, hand samples from fault surfaces to be used for thin section petrography and microstructural analysis.

To analyze the data, I have divided it into subsets for stereographic analysis based on orientation of planes and/or striae, and according to mineralization type in order to identify distinct episodes of deformation and determine the significance of fault mineralization. I have also employed the stress tensor methods of Angelier (1984) to determine paleostress orientations, using the programs TectonicsFP (Ortner et al., 2002) and Mathematica.

OBSERVATIONS AND DATA ANALYSIS

Stereonet Analysis

Fracture and fault plane orientations are scattered with many outliers, but three general clusters are apparent: E-W to SSE-NNW striking (about azumith 080°-115° or 260°-295°), steeply dipping faults; N-S to NE-SW striking, steeply dipping faults; and N-S to NE-SW striking, moderately dipping faults. Lineations on the E-W to SSE-NNW striking, steeply dipping faults are mostly low plunge, indicating predominantly strike-slip, though slightly oblique, motion (Fig. 1). A smaller number of lineations suggest dip-slip motion upon the steep faults, with a cluster trending approximately south and plunging 70-90° (Fig. 1B), on which normal sense kinematic indicators were observed. Shallowly plunging lineations on N-S to NE-SW steeply dipping faults suggest predominantly strike-slip motion (Fig. 2A). The moderately dipping, N-S to NE-SW faults have more variable lineation orientation. On the majority east-dipping faults, three different lineation clusters indicate roughly strike-slip, NE trending oblique slip, and SE trending dip-slip motion. A smaller group of west-dipping faults in this orientation shows oblique, NW trending motion (Fig. 2B).

Fault Mineralization

Chlorite-mineralized faults are most concentrated in the E-W to SE-NW striking group (Fig. 3A) and epidote mineralized faults in the N-S to NE-SW striking group (Fig. 3B), particularly the moderately east dipping subset, including all three groups of lineation orientations. Both types appear, however, in a wide range of orientations, even those more common to the other. A few faults, with orientations characteristic of either or neither mineral, contain both epidote and chlorite mineralization. On these faults, the chlorite appears as a layer on top of the epidote, and in at least two instances, two different lineation orientations were observed on a single fault surface. Unmineralized fractures are most commonly E-W to SE-NW striking, but there are several with NE-SW strikes and a scattering of other orientations.

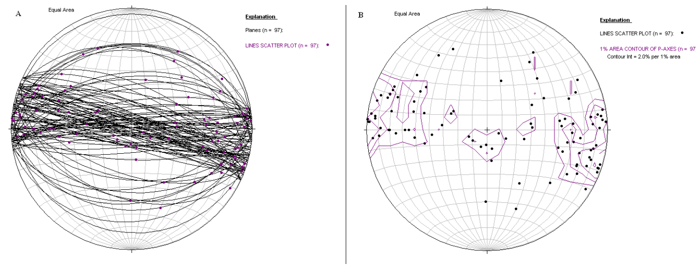

Figure 1: (A) Plot of 180-115° or 260-295° striking fault planes and their lineations, showing predominance of steeply-dipping faults. (B) Contoured plot of the lineations.

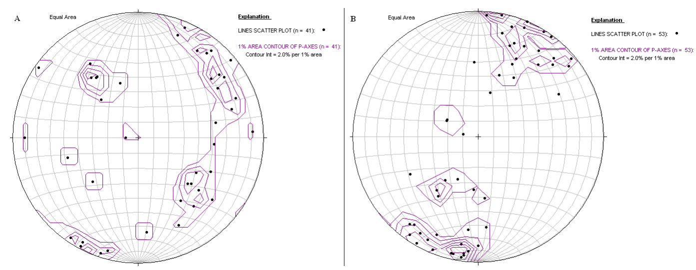

Figure 2: Plots of lineations on faults striking 000-050° and dipping (A) 00-60° and (B) 61-90°.

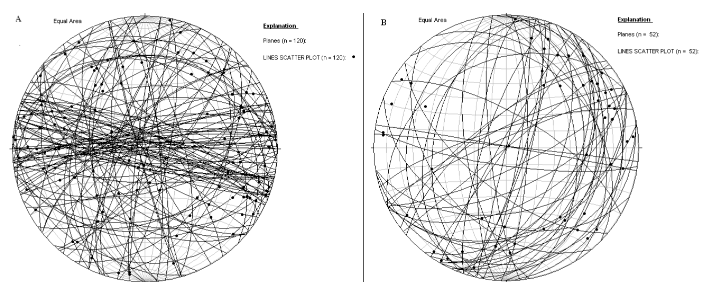

Figure 3: (A) Plot of chlorite-mineralized faults with lineations and their lineation orientations. (B) Plot of epidote mineralized faults with lineations and their lineation orientations.

Outcrops of macroscopic fault breccia were found within part of the Edelman Lineament. On one outcrop, there is a ~30m long, highly polished fault surface oriented 235°/ 78° NW, with oblique striae oriented 28, 048 and ambiguous kinematic sense. The orientation of this fault and the trend of the wide breccia zone are close to the orientation of the Edelman lineament itself. Chlorite and quartz are found throughout these rocks, but epidote is not present.

Thin Sections

Study of thin sections shows distinctions between epidote and chlorite mineralized faults. The four epidote mineralized faults studied, from a mix of orientations, show deformation including grain size reduction, fractured wall rock grains, and multiple, often interconnected fractures filled with epidote. In contrast, chlorite mineralized faults contain narrow chlorite-filled fractures with sharp edges and little or no grain size reduction. Epidote mineralization is fine-grained, suggesting syntectonic growth that prevented large crystals from forming, although no shape or crystallographic preferred orientation is present. Material from the fault breccia zone shows significant grain size reduction, particularly of quartz, as well as quartz veins that have not been brecciated but appear to have been shortened by pressure solution. Chlorite along faults does not show strong foliation, so the timing of mineralization relative to faulting is uncertain. Undulose extinction of quartz is present in the wall rock of all samples, suggesting pervasive ductile deformation in the past, but deformation along the faults studied is brittle.

Paleostress Analysis

Using TectonicsFP to perform the Angelier paleostress inversion on 111 fractures, for which I have full fault plane, lineation, and kinematic sense information, produced stress orientations of σ_1 = 02, 273, σ_2 = 17, 182, σ_3 = 73, 011, and φ = 0.1296, where $\varphi = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$, which suggests E-W compression. For many of the data, however, the angle between predicted and observed lineation direction is large (Fig. 4), indicating that one paleostress solution cannot describe the entire dataset, so the faults are unlikely to all be products of one tectonic event. Calculated paleostress orientations for subsets defined by mineralization are σ_1 = 69, 282, σ_2 = 20, 086, σ_3 = 05, 178, φ = 0.8545 for chlorite and σ_1 = 01, 002, σ_2 = 87, 251, σ_3 = 03, 092, φ = 0.8545 for epidote. These are somewhat better fits, but for neither do all data fit the solution well. Taking an alternative approach, I used Angelier's equations to test an expected Laramide stress orientation of horizontal σ_1 trending 066° and vertical σ_3. Even the best fit predicted slip directions are within 45° of those observed for only 39 of 111 data (Fig. 5). The same calculation with σ_2 vertical gives similar results (43 in the best case).

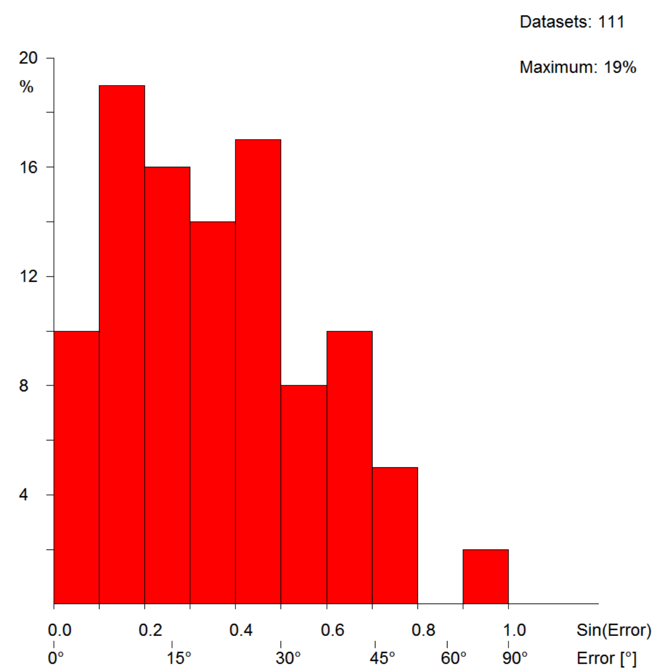

Figure 4: Histogram of the angle between the observed and expected lineation direction for the Angelier stress inversion of all data with full kinematic information.

DISCUSSION

The complexity of fault orientations and slip directions in the Bighorns basement differs from the simple geometries that would be expected in isotropic rock fractures formed in a single tectonic event, and it is more readily interpreted as the result of multiple deformations over time. Evidence of reactivation under different stress conditions comes directly from the observation of multiple sets of differently oriented lineations on some fault planes and also from the finding that multiple lineation orientations are associated

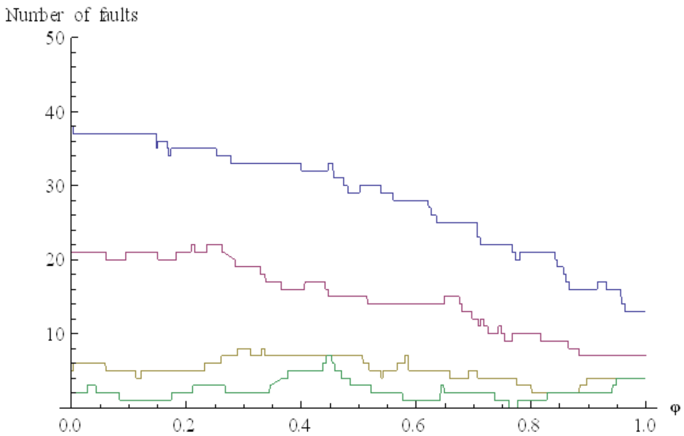

Figure 5: Plot of number of data (out of 111) versus φ = (σ2 – σ3) / (σ1 – σ3) for which the angle between the predicted shear stress under Laramide stress conditions and the observed slip direction is less than 5° (green), 10° (yellow), 25° (red), and 45° (blue) with a vertical σ3.

with geometrical subsets of fault planes. Whether reactivation occurred during wholly different events from fracture formation or during different stages of a single event (such as the Laramide orogeny) is difficult to determine in the absence of age constraints.

With its ENE compression direction (about 066°), the Laramide orogeny could have formed strike-slip faults about 20° to either side of this orientation or thrust faults striking perpendicular to it. Sinistral E-W and dextral NE-SW striking strike-slip faults are candidates for Laramide formation, while the more SE-NW and N-S strike slip faults are unlikely to be Laramide in origin but could have been reactivated in the Laramide. Other faults in these orientations, however, are dip slip or the wrong motion sense and are more likely to be pre-Laramide faults. The results of Angelier stress tensor calculations that fit non-Laramide stress orientations to many of the data and show that many faults do not fit the expected Laramide geometry also indicate that a substantial portion of the lineations observed did not form during the Laramide.

The presence of normal faults and the Angelier analyses indicating extension for some data subsets suggest that normal faulting and extension played a role in basement deformation. Since the Laramide was a compressional event, this lends support to theories of pre-existing normal faults. The N to NE and W to NW orientations suggested by Marshak et al. (2000) are observed here, although the variety of fault orientations is even greater than that bimodal model would predict.

The association between mineralization and orientation and the fact that chlorite and epidote mineralized faults show different styles of microscopic deformation suggest that mineralization is a useful criterion for distinguishing faults formed under different conditions in the Bighorns basement. Chlorite and epidote mineralized faults, which Wise and Obi (1992) grouped together in their study area, have different characteristics in the Edelman Lineament. Interpretation is complicated by the variability of fault orientation and slip direction within mineralization-defined subsets. A likely explanation is that both chlorite and epidote mineralization are associated with different episodes of reactivation, not with initial fracture formation. Reactivation would likely show a preference for fault orientations that would slip most easily under the particular stress conditions of the event but could affect a range of different orientations. Even this interpretation is complicated by the results of the Angelier analysis, which indicate that neither chlorite nor epidote mineralized faults can be fit to a single stress orientation. It is possible either that more than one episode of deformation involved formation of each type of mineralization or that the mineralization was deposited by fluid flow significantly after fault motion, though crystal fiber steps and some microstructural evidence indicate that at least some mineralization was syntectonic.

The discovery of a wide zone of macroscopic fault breccia and a throughgoing fault close to parallel with the lineament supports the hypothesis that the lineament is controlled by a major strike-slip fault. Although definitive kinematic indicators were lacking, the fault zone geometry corresponds to predictions for dextral slip for the Laramide, for both newly formed and inherited faults. Since this area contains a large amount of chlorite, it may be of similar age as other chlorite-mineralized faults, which may also have accommodated Laramide slip.

CONCLUSIONS

The Archean basement rocks of the Bighorn Mountains record a long history of deformation. Field observations and paleostress analysis indicate that many faults have been reactivated under changed stress conditions subsequent to their formation. Chlorite and epidote fault mineralization correlate roughly with fault orientation and more closely with different microscopic characteristics, but neither mineralization type can be tied conclusively to a specific tectonic event or stress orientation and the timing of mineralization and fault movement remains a mystery. Evidence suggests that a regional scale strike-slip fault underlies the Edelman lineament. The age and order of formation of different brittle faults are still largely unknown, the complex relationship between fault mineralization and distinct subsets of faults has not been fully unraveled, and the question of what is Laramide in age has yet to be resolved. My work serves to characterize the brittle deformation found in the Edelman lineament and to hint at the history behind it, but more remains to be done.

REFERENCES

Angelier, J., 1984, Tectonic analysis of fault slip data sets: Journal of Geophysical Research, v. 89, p. 5835-5848.

Erslev, E.A., and Koenig, N.V., 2009, Three-dimensional kinematics of Laramide, basement-involved Rocky Mountain deformation, USA: Insights from minor faults and GIS-enhanced structure maps: in Kay, S.M., Ramos, V.A., and Dickinson, W.R., eds., Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision: Geological Society of America Memoir 204, p. 125–150.

Esser, V., 2000, Oxygen isotope analysis of mineralized fault planes, Five Springs region, Bighorn Mountains, Wyoming: 13th Keck Symposium Volume.

Frost, C.D., and Fanning, C.M., 2006, Archean geochronological framework of the Bighorn Mountains, Wyoming: Canadian Journal of Earth Sciences, v. 43, p. 1399-1418.

Hoppin, R.A., Palmquist, J.C, and Williams, L.O., 1965, Control by Precambrian Basement Structure on the Location of the Tensleep-Beaver Creek Fault, Bighorn Mountains, Wyoming.

Hoppin, R.A., 1974, Lineaments: Their Role in Tectonics of Central Rocky Mountains: The American Association of Petroleum Geologists Bulletin, v. 58, no. 11, p. 2260-2273.

Marshak, S., Karlstrom, K., and Timmons, J.M, 2000, Inversion of Proterozoic extensional faults: An explanation for the pattern of Laramide and Ancestral Rockies intracratonic deformation, United States: Geology, v. 28, no. 8, p. 735-738.

Mitra, G. and Frost, B.R., 1981, Mechanisms of deformation within Laramide and Precambrian deformation zones in basement rocks of the Wind River Mountains, in D.W. Boyd, ed., Rocky Mountain foreland tectonics: University of Wyoming Contributions to Geology, v. 19, p. 161-173.

Ortner, H., Reiter, F., and Acs, P., 2002, Easy handling of tectonic data: the programs TectonicVB for Mac and TectonicsFP for Windows: Computers & Geosciences, v. 28, p. 1193-1200.

Stone, D.S., 2003, New interpretations of the Piney Creek thrust and associated Granite Ridge tear fault, northeastern Bighorn Mountains, Wyoming: Rocky Mountain Geology, v. 38, no. 2, p. 205-235.

Wise, D.U., and Obi, C.M., 1992, Laramide basement deformation in an evolving stress field, Bighorn Mountain front, Five Springs area, Wyoming: The American Association of Petroleum Geologists Bulletin, v. 76, no. 10. p. 1586-1600.