KECK GEOLOGY CONSORTIUM

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

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FORMATION OF BASEMENT-INVOLVED FORELAND ARCHES: INTEGRATED STRUCTURAL AND SEISMOLOGICAL RESEARCH IN THE BIGHORN MOUNTAINS, WYOMING
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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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Research Advisor: Dr. Julie Newman

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FAULT ANALYSIS OF BASEMENT ROCKS IN THE BIGHORN MOUNTAINS

ELIZABETH DALLEY, Oberlin College
Research Advisors: Steve Wojtal and Christine Siddoway

INTRODUCTION

The 2010 Keck Bighorns project, in collaboration with the Earthscope Bighorns Arch seismic experiment [BASE] is investigating the mechanism for uplift of the Bighorn Mountain range, primarily through fracture analysis and seismic imaging. The Bighorn Mountains are a classic Laramide foreland arch that formed in response to NE-SW shortening (Erslev 2005), evident from the vast doubly plunging anticline that affected Phanerozoic strata (e.g. Stone 2003). As of yet, no detailed investigation of basement fracture arrays has been carried out within the homogenous Archean Bighorn batholith of the central Bighorn Mountains, although previous workers drew attention to basement lineaments (Hoppin) and range boundary faults (Wise and Obi, 1992).

A specific aim for work in the Archean basement rocks was to analyze fractures and faults, and to assess whether some/all of the faults and fractures have a favorable geometry and contain kinematic criteria of the type expected for faults that were active during Laramide NE-directed regional compression (Erslev and Koenig 2009). The focus of study is long, straight topographic lineaments that transect the range (e.g. Hoppin, 1974; Stone, 2003). Field work focused on the Edelman, North Paint Rock Creek, and Tongue River lineaments that cut the Bighorn batholith at lower structural levels of the Bighorn arch. Brittle kinematic analysis of faults and fractures (e.g. Petit, 1987; Marrett and Allmendinger, 1990) is used to determine the prevalent orientations and motion sense of faults and fractures.

The results will be compared with the results of fracture studies in sedimentary cover rocks, carried out by three Keck students. Within Mesozoic units subjected to Laramide deformation, they found a fault array that includes three prevalent fault types: NW-SE-striking reverse faults, E-W-striking left-lateral strike-slip faults, and NE-striking right-lateral faults. Their results are consistent with those from minor fault data which were collected around the entire arch, reported by Erslev et al. (2011). The northern Bighorns region is newly recognized as a wide left lateral wrench zone (Erslev et al., 2011). The work should contribute significantly to the understanding of the characteristics of deformation and identification of structures responsible for formation of the basement arch within the Bighorns and other Laramide ranges, something that has not been determined at the scale of the lithosphere. More than four competing hypotheses exist for arch formation (Erslev, 2005). An additional, vital contribution is identification of the dominant orientations and tectonic history of large-scale basement faults, which will aid the understanding of seismic velocity characteristics of the lower crust and mantle being interpreted by the Keck shear wave splitting group consisting of three students. The fault geometries may be relevant for interpretation of seismic reflectors discovered by the BASE active source seismologists, as well. This collaboration between the three Keck research teams is fundamental to our understanding of the picture seen within the deep level basement rocks.

METHODS

Data collection in 2010 focused on two main lineaments, the Edelman lineament that trends ~040 and the North Paint Rock Creek (NPRC) lineament, oriented ~ 060, together with subsidiary work on the Tongue River lineament (Doane, 2010). Both are zones of pervasive fracturing, with mesoscopic shears in orientations similar to and different than that of the lineaments. The data we collected on fault, fracture and joint surfaces included strike and dip of the plane (using right hand rule), and plunge and trend or rake of the striae. Kinematic interpretation of fault planes in the field relied on a number of movement criteria outlined by Petit (1984) and Hancock (1985), including Riedel fractures, crystal growth fibers, rhombochasms, offset markers and smooth/rough textures. In a few instances, we used cross cutting relationships for kinematic sense, but reliable geological markers are scarce. Lastly, we took note of mineralization associated with the fault surfaces. Oriented samples acquired within and south of the Edelman Creek lineament were cut into thin sections for characterization of microstructures and kinematic determinations.

The geometrical and kinematic results from the two lineaments of the central Bighorns are compared to the Tongue River lineament, a fault zone with an orientation similar to that of the NPRC. Some firsthand observations of the TRL were made near Burgess Junction, where Ordovician Bighorn Dolomite is folded into a steep asymmetrical monocline that strikes ~E-W, formed in response to north-side-down motion across the Tongue River lineament (Doane, 2010). The Bighorn Dolomite contains a dense fracture and fault network, to be used to obtain kinematic information. In the central Bighorn Mountains, there is no stratigraphic control from this or other sedimentary units; however, due to the systematic geometry (near-parallelism) of the ENE-striking TRL and NPRC, their response to Laramide compression probably was similar.

Quality control on all data for faults was performed using an excel spreadsheet application, Select.xls, written by Eric Erslev (unpublished). Data were entered into Stereonet 6.0, and FaultKin 3.4.5 computer programs designed by R.W. Allmendinger (2005 and 2004 respectively) for stereographic and kinematic analysis. Kinematic solutions from FaultKin use the orientation of planes and striae together with motion sense to determine contractional, P, and extensional, T, strain axes for fault and fracture arrays using a dihedral method (Marrett and Allmendinger, 1990). Using 2010 data for fractures with measured striae and kinematic sense, I calculated kinematic axes, P and T, for fault subsets sorted first according to motion sense and then by orientation of faults. The results help us evaluate specifically which fault sets may have been active in the Laramide.

RESULTS

Cumulative fracture data from the Edelman lineament (n = 628) falls into three prevalent orientations: generally NNE, NE and E-W (Figure 1).

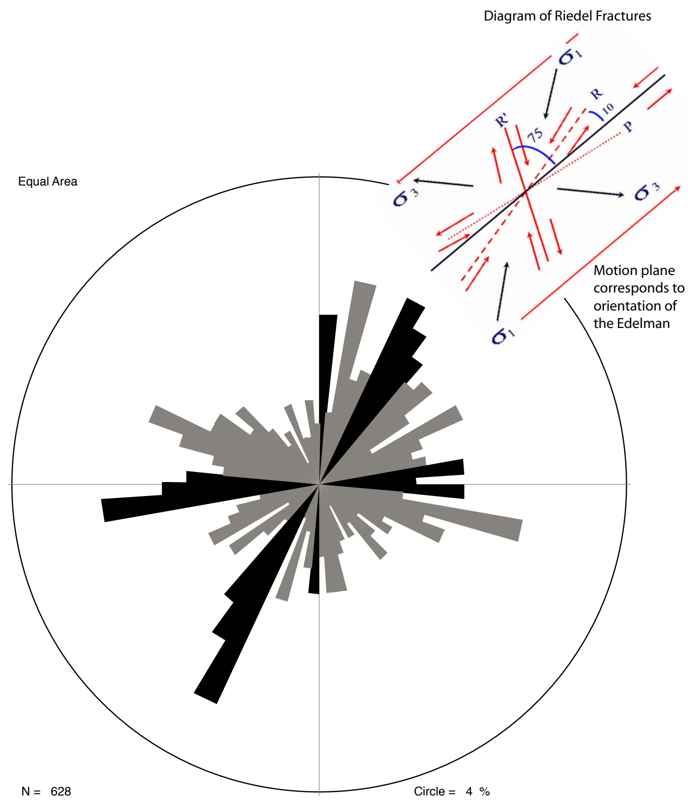
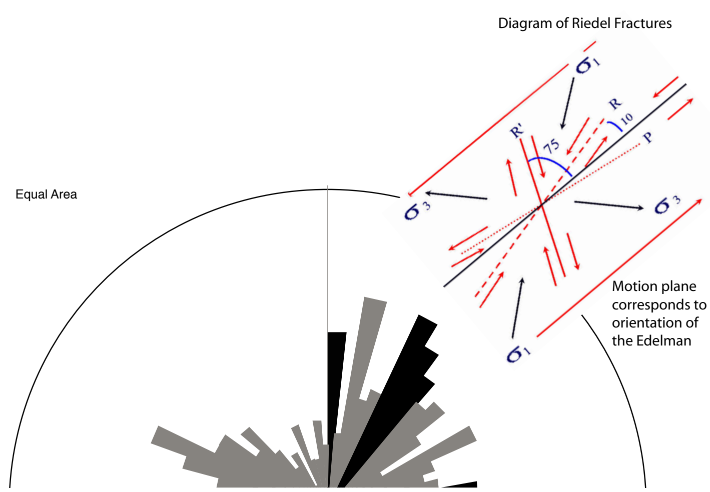


Figure 1: Fault trends in the Edelman Lineament, prominent arrays of NNE-SSW, NE-SW and E-W are highlighted.



A majority of fractures are steeply dipping with shallowly plunging groove striae and brittle features on the fault surfaces. Kinematic criteria give both right and left lateral motion sense (Table 1), but a dominance of field criteria give left lateral sense for E-W striking fractures. In an effort to identify homogeneous fracture subsets for analysis (e.g. Ortner et al.

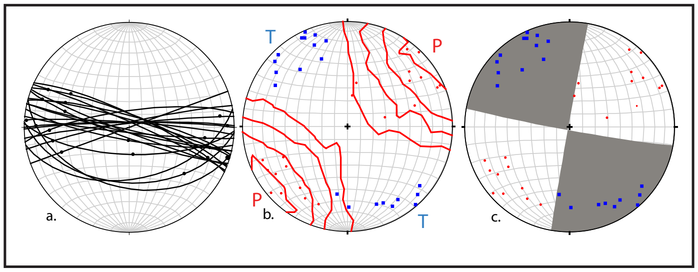


Figure 2: P/T analysis of a left lateral, E-W trending fracture array (a). Red dots correspond to P-axes (contoured), blue dots to T-axes (b). The kinematic solution (c) is for NE-SW contraction.

2010), the data were sorted by location and by fault geometry. The E-W and NNE faults were common throughout the whole lineament, while WNW and NNW faults were found in the center of the range Using a coherent subset of ~E-W faults (see Figure 2) that were determined to be left lateral from field kinematic criteria, I calculated a NE-SW contraction direction (Table 1) that is compatible with the 060 to 067 direction determined for the Laramide through structural analysis of cover rocks (see Introduction).

Clear evidence for the sense of displacement on the NNE structures is found north of the Edelman Lineament where a wide NNE striking shear zone displaces dolerite dikes in a left lateral sense, with ~30 m of offset (Figure 3). The crosscutting relationship offers little from the standpoint of age control, because the youngest age determined for mafic dikes in the Bighorns is circa 1900 Ma (K. Chamberlain, unpublished), however, the NNE shear zone, which has shallowly SSW-plunging striae, provides kinematic information that may apply to other strike-slip and strike-oblique faults of similar orientation.

NNE and NE fracture arrays are also found in the NPRC, together with a lesser number of fractures oriented WNW. An exposure of a NNE fault zone within Sheep Creek contains two distinct shear planes with brittle cataclasis that can be traced for a distance of at least 30m. Kinematics could not be determined, however, the fault has a similar orientation to the NNE Edelman array, and so may have similar kinematics (would be left lateral). Another site in the Bighorns where NNE- oriented faults are found is Amsden Creek, where Doane (2010) found evidence of left lateral motion, with kinematic solutions indicating WNW contraction. Also there are steeply dipping, NNE-striking strike slip faults within the Clear Creek thrust zone near Buffalo, WY, southeast of our area of study (Hoppin, 1961). The faults at this range front location, record right lateral movement. The setting of the strike slip faults within a thrust zone that involves Tertiary rocks in the footwall is evidence that the timing of right lateral slip was Laramide (Hoppin 1961). The P/T analysis of right lateral ~N-S faults from the central Bighorns does determine a rough contraction direction of NE, based on a small dataset.

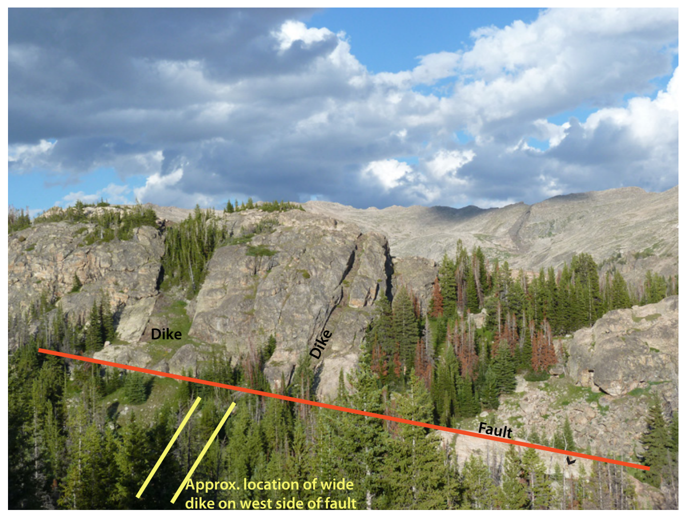


Figure 3. View of two mafic dikes that are cut by a NNE striking subvertical fault. The fault zone is marked by Chl-Qz mineralization, mylonitic foliation, and breccia.

The lack of offset markers, to provide for kinematic information and age constraints on basement faults, hinders the effort to determine relative timing of faults that are part of a systematic regional array in the central Bighorns. At one site along the TRL, there are mesoscopic fractures in the Upper Ordovician Bighorn Dolomite. The Bighorn Dolomite dips relatively steeply to the north (69 degrees average in the southern outcrop and more shallowly dipping to the north). The deformation of the dolomite represents an important age control for motion on the TRL (Doane, 2011) and indirectly for the similarly oriented NPRC, although it is unclear whether faulting occurred before or after tilting of beds. Analysis of unrotated planes in their present orientation shows a dominant trend of NNE. Dominant trends of fault orientations in restored bedding (rotated data) are N-S and ENE.

Samples selected for thin sections are representative of the material within lineaments under study, the prevalent structural orientations, and the mineralization types. Thin sections were cut in the plane of motion, perpendicular to fault surfaces and parallel to striations, in order to characterize microstructures and determine kinematic sense. The granitic host rock consists of coarse-grained plagioclase, some microcline, quartz and traces of chlorite and/or epidote in veins.

Traces of iron oxide in many samples indicate hydrothermal alteration that obscures fabrics, making it difficult to distinguish post tectonic from syntectonic mineralization. The fault rocks are non-penetrative brittle cataclasite with fractured fragmented feldspars and quartz with undulose extinction (Figure 4) indicative of deformation at temperatures of 100 to 200°C (Passchier and Trouw, 2005), consistent with the shallow crustal conditions of deformation during the Laramide (Crowley et al., 2002). Sense of shear indicators include offset grains, extensional veins, and asymmetric porphyroclasts.

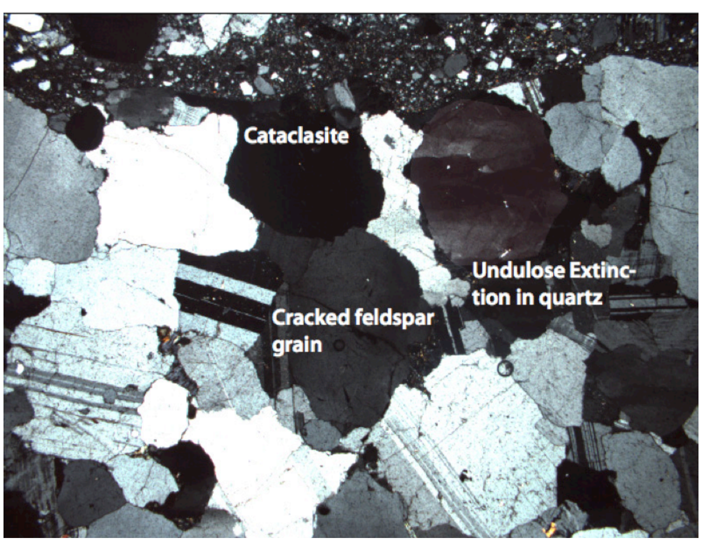


Figure 4

DISCUSSION

Given the age of the Archean basement (>2.5 Ga) and the likelihood it contains structures formed in many prior tectonic events, we expected to find a multitude of fault orientations that had incompatible geometries with the predicted Laramide compression direction of ~065 (Erslev 2005). We hoped that by collecting many data, we would be able to distinguish which fault arrays were suitably oriented to accommodate Laramide compression.

The kinematic analysis of four homogeneous subsets of faults results in 4 differing contraction directions; NE-SW, N-S, E-W and NW-SE. Based on our knowledge of the s_1 direction for Laramide compression and comparison with known Laramide faults, kinematic analysis of left lateral E-W oriented faults and right lateral NNE-SSW oriented faults shows that these structures are in orientations favorable for motion/reactivation in response to Laramide differential stress and likely accommodated relative motion that allowed formation of the BH arch. The structural geometries and kinematics are similar to or compatible with faults within cover rocks (Erslev, 2005), young enough to have been affected by only Laramide.

Kinematic solutions from fault sets different from those expected for the Laramide, are interpreted to be relict of prior (probably Precambrian) events or a product of Laramide reactivation, or a combination of the two. The N-S, E-W and NW-SE contraction directions must be attributed to pre-Laramide (whether they were again reactivated during the Laramide is not known).

It is clear that further work throughout the range must be conducted, but if it can be verified that there has been Laramide reactivation of ~E-W and ~NNE steep strike slip faults, then they may provide a geometrical framework for understanding other fractures in the cumulative data set. One such framework may involve an array of riedel fractures associated with the Edelman lineament (see diagram within Figure 3). Prominent arrays of NNW to NW and NNE-NE oriented faults may be attributed to motion across the Edelman. The NNW faults are oriented 75 degrees to the lineament, as predicted for R' structures and the

NNE-NE faults are oriented 10 degrees to the lineament, as predicted for R structures by Petit (1984), indicating left lateral motion across the Edelman, which is in agreement with left lateral motion of Piney Creek salient. However, the NNW R' faults should exhibit right lateral motion, but few do, and therefore these findings are inconclusive.

The NNE fault array, do show a majority of left lateral faults over right lateral faults, as predicted for R faults in this orientation. Out of 24 mapped NNE faults, 46% were consistent with an interpretation of left lateral offset and 29% showed right lateral offset. Additionally, Tyler Doane observed a set of NNW oriented faults that cut cover rock in the Amsden Creek area, indicating that these faults were likely active during the Laramide.

Further work in this area may involve confirming this possibility and additionally, discovering other interactions between fault arrays not attributed to Laramide. Additionally, further characterization of microstructural deformation will also show timing of structures. Currently there are no known structures below 10km that were active during Laramide uplift of the Bighorns. Thin section analysis of our samples yielded results indicating formation in the shallow crust, which may indicate formation too deep to be attributed to Laramide, or may indicate that structures active in the Laramide did actually reach to this depth. Unfortunately, results from analyzing thin sections are not entirely clear enough to conclude this definitively.

Furthermore, the fault geometries and the observational characteristics of the fault rocks we have observed may have relevance for the shear wave splitting group. In this case, deeper faults (even around the brittle-ductile transition zone) would potentially cause an anisotropy in the basement. We can fairly reliably say that our NNE oriented faults do go to a depth that would affect shear wave pathways statement not supported by own observations. Many of our NNE faults are quite extensive linearly, such that the magnitude of this scale could indeed cause notable seismic anisotropy.

REFERENCES

Doane, T., 2010, Integrated Structural and Gravity Modeling Study: Lineaments and their role in Laramide basement deformation and implications for a crustal-scale response, Unpub. B. A. thesis, Colorado College, 104 pp.

Erslev, Eric A., 2005, 2D Laramide Geometries and Kinematics of the Rocky Mountains, Western U.S.A.: AGU Monographv. 154, p. 7-20.

Erslev, E., Aydinian, K., Sheehan, A.F., and 8 others, 2011, Imaging the Crustal Roots of the Laramide Rockies: The 3D Active-Passive Bighorn Project, 17th annual 3-D Seismic Symposium, Rocky Mountain Association of Geologists, Denver, CO [April 29].

Frost, Carol D., and C. M. Fanning., 2006, Geochronological Framework of the Bighorn Mountains, Wyoming: Canadian Journal of Earth Sciences, v. 43.10, p. 1399-418.

Hoppin, R. A., 1961, Precambrian Rocks and Their Relationship to Laramide Structure along the East Flank of the Bighorn Mountains near Buffalo, Wyoming: Bulletin of the Geological Society of America: v. 72, p. 351-68.

Hoppin, R. A., 1974, Lineaments: Their Role in Tectonics of Central Rocky Mountains: The American Association of Petroleum Geologists Bulletin, v. 58.11, p. 260-273.

Passchier, C. and Trouw, R., 2005, Microtectonics (2nd ed.), Springer, 366 pages.

Petit, J.P., 1987, Criteria for the sense of movement on fault surfaces in brittle rocks, Journal of Structural Geology, v. 9, issue 5-6, p. 597-608.

Stone, Douglas S., 2003, New Interpretations of the Piney Creek Thrust and Associated Granite Ridge Tear Fault, Northeastern Bighorn Mountains, Wyoming: Rocky Mountain Geosciences, v. 38.2, p. 205-35.

Wise, D., and C. M. Obi., 1992, Laramide Basement Deformation in an Evolving Stress Field, Bighorn Mountain Front, Five Springs Area, Wyoming: AAPG Bulletin, v. 76.10, p. 1586-600.