

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

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The National Science Foundation

ExxonMobil Corporation

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2010-2011 PROJECTS

FORMATION OF BASEMENT-INVOLVED FORELAND ARCHES: INTEGRATED STRUCTURAL AND SEISMOLOGICAL RESEARCH IN THE BIGHORN MOUNTAINS, WYOMING

Faculty: *CHRISTINE SIDDOWNAY*, *MEGAN ANDERSON*, Colorado College, *ERIC ERSLEV*, University of Wyoming

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.

EXPLORING THE PROTEROZOIC BIG SKY OROGENY IN SOUTHWEST MONTANA

Faculty: *TEKLA A. HARMS*, *JOHN T. CHENEY*, Amherst College, *JOHN BRADY*, Smith College

Students: *JESSE DAVENPORT*, College of Wooster, *KRISTINA DOYLE*, Amherst College, *B. PARKER HAYNES*, University of North Carolina - Chapel Hill, *DANIELLE LERNER*, Mount Holyoke College, *CALEB O. LUCY*, Williams College, *ALIANORA WALKER*, Smith College.

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO

Faculty: *DAVID P. DETHIER*, Williams College, *WILL OUIMET*, University of Connecticut

Students: *ERIN CAMP*, Amherst College, *EVAN N. DETHIER*, Williams College, *HAYLEY CORSON-RIKERT*, Wesleyan University, *KEITH M. KANTACK*, Williams College, *ELLEN M. MALEY*, Smith College, *JAMES A. MCCARTHY*, Williams College, *COREY SHIRCLIFF*, Beloit College, *KATHLEEN WARRELL*, Georgia Tech University, *CIANNA E. WYSHNYSZKY*, Amherst College.

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Faculty: *SUZANNE O'CONNELL*, Wesleyan University

Students: *LYNN M. GEIGER*, Wellesley College, *KARA JACOBACCI*, University of Massachusetts (Amherst), *GABRIEL ROMERO*, Pomona College.

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Faculty: *KELLY MACGREGOR*, Macalester College, *CATHERINE RIIHIMAKI*, Drew University, *AMY MYRBO*, LacCore Lab, University of Minnesota, *KRISTINA BRADY*, LacCore Lab, University of Minnesota

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GEOLOGIC, GEOMORPHIC, AND ENVIRONMENTAL CHANGE AT THE NORTHERN TERMINATION OF THE LAKE HÖVSGÖL RIFT, MONGOLIA

Faculty: *KARL W. WEGMANN*, North Carolina State University, *TSALMAN AMGAA*, Mongolian University of Science and Technology, *KURT L. FRANKEL*, Georgia Institute of Technology, *ANDREW P. deWET*, Franklin & Marshall College, *AMGALAN BAYASAGALN*, Mongolian University of Science and Technology.

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LATE PLEISTOCENE EDIFICE FAILURE AND SECTOR COLLAPSE OF VOLCÁN BARÚ, PANAMA

Faculty: *THOMAS GARDNER*, Trinity University, *KRISTIN MORELL*, Penn State University

Students: *SHANNON BRADY*, Union College. *LOGAN SCHUMACHER*, Pomona College, *HANNAH ZELLNER*, Trinity University.

KECK SIERRA: MAGMA-WALLROCK INTERACTIONS IN THE SEQUOIA REGION

Faculty: *JADE STAR LACKEY*, Pomona College, *STACIL LOEWY*, California State University-Bakersfield

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EOCENE TECTONIC EVOLUTION OF THE TETONS-ABSAROKA RANGES, WYOMING

Faculty: *JOHN CRADDOCK*, Macalester College, *DAVE MALONE*, Illinois State University

Students: *JESSE GEARY*, Macalester College, *KATHERINE KRAVITZ*, Smith College, *RAY MCGAUGHEY*, Carleton College.

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

Keck Geology Consortium: Projects 2010-2011 Short Contributions—Bighorn Mountains

FORMATION OF BASEMENT-INVOLVED FORELAND ARCHES: INTEGRATED STRUCTURAL AND SEISMOLOGICAL RESEARCH IN THE BIGHORN MOUNTAINS, WYOMING

Project Faculty: CHRISTINE SIDDOWAY, MEGAN ANDERSON, Colorado College, ERIC ERSLEV, University of Wyoming

CARBONATE DEFORMATION IN THE BIGHORN BASIN OF WYOMING

MOLLY CHAMBERLIN, Texas A&M University
Research Advisor: Dr. Julie Newman

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ELIZABETH DALLEY, Oberlin College
Research Advisors: Steve Wojtal

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JOHN SPENCE HORNBUCKLE III, Washington and Lee University
Research Advisor: Jeff Rahl

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BRYAN MCATEE, Lafayette College
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DAVID OAKLEY, Williams College
Research Advisor: Paul Karabinos

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CHAD TREXLER, Whitman College
Research Advisor: Kevin Pogue

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BRENNAN YOUNG, Utah State University
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TOPOGRAPHIC LINEAMENTS AND EXPRESSION OF FRACTURE ARRAYS IN THE EDELMAN AND NORTH PAINT ROCK CREEK LINEAMENTS, BIGHORN MOUNTAINS, WYOMING

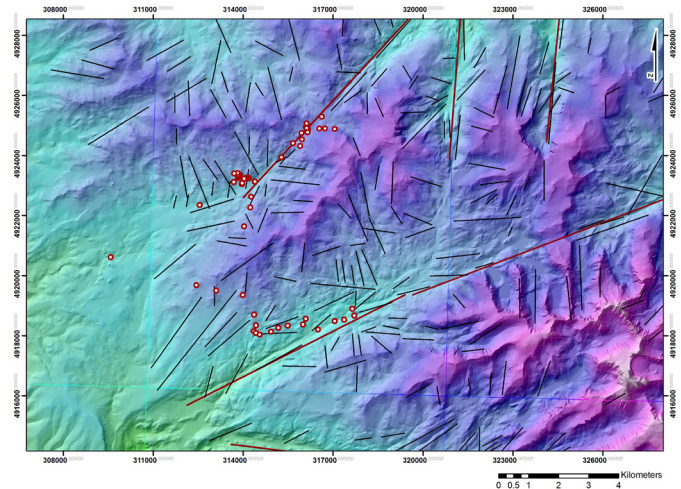
CHAD TREXLER, Whitman College
Research Advisor: Kevin Pogue

INTRODUCTION

The Bighorn Mountains of north central Wyoming are a basement-cored arch formed during the Laramide Orogeny. Working in association with the Bighorn Arch Seismic Experiment (www.bighorns.org), the Bighorns Keck project seeks to develop a better understanding of the structures active within crystalline basement and sedimentary cover rocks during the formation of the arch. Little is known of the origin of the brittle structures within the crystalline rocks at the core of the arch, and distinguishing Laramide-related features from older features is not an easy task. Large-scale linear topographic features are prominent throughout the core of the Bighorn Arch (Hoppin, 1974). This study focuses upon two specific lineaments, the drainages of Edelman Creek and North Paint Rock Creek in the central Bighorn Mountains. I combine detailed field measurements and geographic information systems (GIS)-based topographic lineament analysis in an attempt to understand the relationship between outcrop-scale brittle fractures in the crystalline basement and regional-scale lineaments in the Bighorn Mountains, and advance the understanding of the manner of deformation of the crystalline basement formation of the Laramide arch.

GEOLOGICAL BACKGROUND

The Bighorn Arch formed as a result of compression during the Laramide mountain-building event that began approximately 70 million years ago. The primary compression direction for Laramide events in the Bighorn Mountains is approximately 060. Strike slip faults observed in sedimentary rocks on the flanks of the arch show strikes of approximately 040 for right-lateral and 080 for left-lateral (Erslev, 2005; confirmed by work of other members of this project).



WGS 1984 UTM Zone 13N
Figure by Chad Trexler

Figure 1. Map of field area and lineaments, drawn in ArcGIS, overlaid on elevation-based color ramp and hillshade. Entire extent of field area in this summer's project is visible on this map. The area of lineament analysis extends approximately one 7.5min quadrangle in each direction beyond the region visible on this map. Field locations (red circles) are found along both the Edelman (to the north) and North Paint Rock Creek (to the south) lineaments. Major lineaments (dark red lines) follow obvious linear features visible at 1:200,000, and linear features visible at 1:50,000 are defined as lineaments (black lines).

What makes the Bighorn Arch unique is its scale (over 100km by 30km) and its core of crystalline rock. The Archean core of the Bighorn Mountains is composed of a granite batholith of 2.75 to 2.89 Ga in the northern part of the range and a gneiss complex in the south (Frost and Fanning 2006). Mafic dikes intrude the other units, with subvertical dip and predominant orientations of NE-SW, NW-SE, and E-W (Ross and Heimlich, 1972). Two generations of dikes are circa 2.8 Ga and 2.2 Ga (Stueber, 1976). The Edelman and North Paint Rock Creek lineaments

are within the Bighorn batholith just north of the boundary with the gneiss complex. The Edelman and NPRC lineaments trend toward and subparallel to the northern margin of the Piney Creek salient, a north-east-directed thrust along the northeastern flank of the Bighorn Arch (Stone, 2003). An inferred structure named the Granite Creek transfer zone is identified as the northern boundary of the Piney Creek salient.

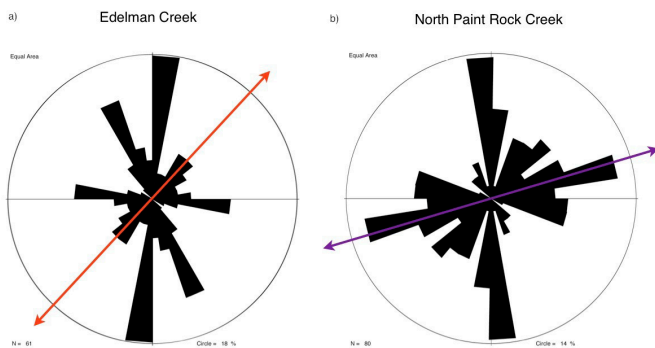


Figure 2. Rose diagrams showing orientation of topographic lineaments, drawn in ArcGIS, within 3km radius of Edelman and NPRC drainages, unweighted and unsorted by length or type. Red and purple arrows indicate major lineament orientation in Edelman and NPRC valleys, respectively. Note the prominent N/S, NE/SW, and E/W trends in both datasets, as well as the prominence of trend-parallel lineaments.

Along with brittle fractures, ductile fabrics are also present in the core of the Bighorn Arch. Near the Piney Creek salient east of the field area, lineations in the gneisses are poorly developed and foliations are at a distinct angle to the trend of the range, suggesting that that Precambrian structure has little relationship to the trend of the mountain range (Hudson, 1969). Weak foliation in the gneisses of the Edelman and NPRC area is variably oriented with evidence of magmatic flow alignment.

Within the field area, significant subvertical E-W trending mafic dike swarms are crosscut by the N-S trending subvertical fracture set. Elsewhere in the Bighorn Mountains, these E-W trending dike swarms have been dated as at least 2.2 Ga in age (Stueber, 1976), giving a possible age bracket for the E-W trending fracture set, along with a relative age of the most recent activation of N-S fractures. These E-W

mafic dikes may make up part of the E-W trending lineament set seen in the data (fig. 2).

Previous studies of linear topographic features in the Bighorn Mountains have focused on much larger features than those in this study. Hoppin (1974) defined lineaments as “rectilinear lines or zones of structural discordance of regional (100km or longer) extent (emphasis mine).” Hoppin referred to the much smaller features examined in this study (which we’ve called lineaments) as ‘linears.’

Studies in other locations have shown the correlation of topographic lineaments to structural features. Rahiman and Pettinga (2008), Gabrielsen et al. (2002), and others (see references) have done work in many locations and in both crystalline and sedimentary rocks confirming the relationship between topographic lineaments and tectonic fractures. Their work also provides methods of lineament analysis using geographic information systems that were used as a basis for analysis in this project.

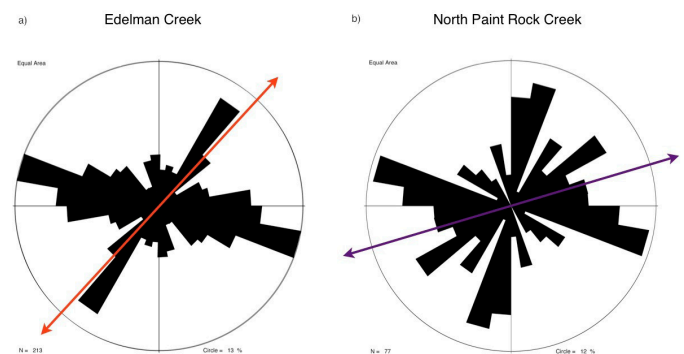


Figure 3. Rose diagrams showing orientations of steeply dipping (80 degrees or greater) fractures from field measurements. As in figure 3, red and purple arrows indicate the orientation of the major lineament in each region of study. Particularly prominent are the WNW/ESE and NE/SW trends in both data sets, and the N/S set in the NPRC dataset. Interestingly, the NW/SE lineament orientation is more or less absent in these datasets.

METHODS

Fracture orientation data were collected along the Edelman Creek and North Paint Rock Creek (NPRC) valleys, over an area of approximately 70 km². Primary data for fractures include strike/dip of the plane,

appearance and type of mineralization on the plane, orientation of striae, scale, and notes on cross-cutting relationships of fractures or striae. Motion criteria for kinematic sense were not apparent in the majority of field exposures, and were recorded for approximately 1/3 of the mesoscopic fractures. A category of “major faults” was designated for throughgoing fracture systems with trace length >20 m. Data on gathered on each major fault and its subsidiary fractures were the same as those gathered on mesoscopic fractures. All 12 members of the Keck research group contributed to the task of data collection in order to acquire large numbers of data over a large area. The data were compiled into the Select.xls spreadsheet application (Erslev, 2010) for quality control.

For the initial step in data analysis, data subsets were developed on the basis of field location and used for kinematic analysis (Marrett and Allmendinger, 1990; Petit, 1984). Subsequently, we used other criteria to sort fractures and faults into subsets. These include mineralization type, geometry of fault plane and/or fault striae, and crosscutting relationships between fractures. Allmendinger’s Stereonet 6.0 software and Almendinger and Cardozo’s OSXStereonet 1.0 software were utilized to perform stereographic analysis of each data subset.

To acquire information at the regional scale, in the second phase of work I used geographic information systems (GIS) to determine number and orientation of prominent linear topographic features within the field area. GIS lineament analysis was pursued in part because it is not limited by accessibility in the way that ground based field work data are. Methods used were similar to those of Rahiman and Pettinga (2008) and Ekneligoda (2010). Using 10 m resolution digital elevation models (DEMs) from the Wyoming Geological Survey, hillshades of an approximately 1600 km² area of the central Bighorn Mountains (40 km north to south by 40 km east to west, centered on field area) were created from three illumination directions (azimuths of 045, 180, and 315). Lineaments were hand drawn at two scales -- 1:50,000 and 1:200,000. Each linear feature was required to be clearly visible at the viewing scale in each of the three illumination directions before it was accepted as a lineament of potential structural significance. I then sorted linea-

ments by azimuth, length (most were between .5 km and 2 km long), and topographic character (whether the lineament was a ridge or valley). Two location subsets were also created: all lineaments within a 3 km radius of the trace of the Edelman Valley were grouped into the Edelman dataset, while those within 3 km of the trace of North Paint Rock Creek were grouped into the North Paint Rock Creek (NPRC) dataset. I used rose diagrams to assess the prevalent lineament orientations (fig. 2). The results of the GIS lineament analysis were then evaluated together with field structural data, in particular the steeply dipping fracture arrays that have highest potential to be expressed in topography (Rahiman and Pettinga, 2008).

RESULTS

Rose diagrams of lineament orientations in the Edelman and NPRC areas, without sorting by length or type (Fig. 2), both show three prominent orientations: N-S, WNW-ESE, and NE-SW. The direction of each major lineament (approx. 045 in Edelman and 072 in NPRC) is well-represented in its respective dataset, an indication that there are distributed structures in that orientation throughout the delimited area. While the 045 trend is apparent in both rose diagrams, the 072 trend is not as apparent in the Edelman dataset as in the NPRC dataset. The Edelman dataset contains a prominent NW-SE lineament set that is much less prominent in the NPRC dataset.

To assess other factors such as scale and rock competence, data subsets of length and geomorphic type were plotted on rose diagrams. Lineaments were sorted into bins by 500 m increments, and also into standard deviation bins by length. Neither of the length sorting methods showed results that differed from total datasets beyond the margin of error. Sorting by lineament type (whether the lineament was a ridge or valley) did not produce results that differed from total datasets and were statistically significant.

In these data analyses, the relative importance of individual lineaments was not taken into account — large-scale linear features may not be adequately represented in analysis when they are counted equally with much shorter linear segments. To address this concern, an attempt was made to weight lineaments

by their length in rose diagrams. Lineaments were again sorted into bins by 500 m increments. Under the assumption that two 500 m lineaments would be required to equal one 1 km lineament, and so on, each bin was added to the dataset an additional time for each 500 m increase in length (e.g., a 1.2 km lineament would appear in the dataset twice, and thus be represented twice on the rose diagram; and a 2.1 km lineament would appear 4 times). Patterns and trends seen in earlier analysis remained apparent, but no new patterns emerged. There is a non-Gaussian distribution of lineament lengths, however, so the accuracy and value of this weighting method was questionable, and further techniques for statistical weighting were not applied. Rather, a comparison of lineament orientations to mesoscopic fracture data was carried out.

Steeply dipping fractures in the field data (Fig. 3) have strikes similar to ArcGIS-based lineament trends (Fig. 2), particularly in the Edelman dataset. The WNW trend in both the Edelman and NPRC areas is prominently represented as steeply dipping fracture planes (Fig. 4). The NE-trending set is also apparent, particularly in the fracture data from the Edelman zone. N-trending lineaments form a prominent set that is matched by strong N-S subvertical fractures in the NPRC zone, only minimally represented in the Edelman zone. The relationships suggest that the mesoscopic fractures are part of a systematic distributed structural array, and that the NE and WNW lineaments are fault zones with a geometry and kinematic history compatible with that recorded upon the measured fractures. The field data show that NE-striking fractures of the Edelman zone have two orientations: subvertical and moderately SE-dipping (Fig. 4a). In the NPRC, the majority of ENE-striking fractures are moderately dipping, with dips to both NW and SE. Fault striae offer critical information about the kinematics, or sense of motion, recorded in the lineament fault zones. For the NE-striking Edelman fracture array (Fig. 5a), the majority of striae plunge gently to the NE or SW, and indication of strike slip displacement at some time in the fault zone's history. A nearly comparable number of down dip striae were measured, however; these indicate an interval of dip slip faulting when the zone accommodated slip at nearly right angles. Field observations of striae in multiple orientations upon a single fault surface are consistent

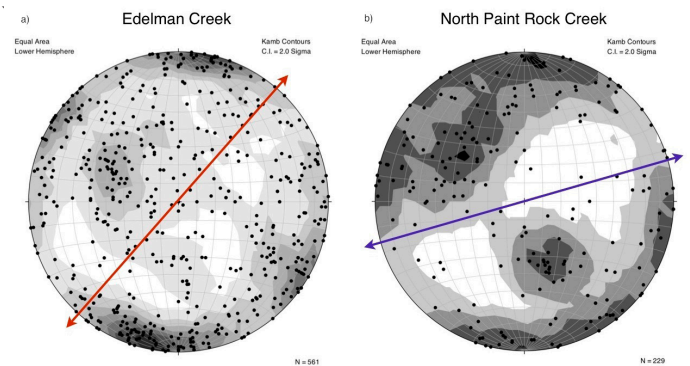


Figure 4. Stereonets showing poles of all field fracture measurements in each region of study. Red and purple arrows show orientation of Edelman and North Paint Rock Creek lineaments, respectively. Contours were drawn using the Kamb contour method, and are standard deviation-based. Subvertical data is prominent in both Edelman and NPRC data, as shown by populations of poles along the primitive in both stereonet. Other populations of poles (in central NW and SE quadrants) particularly prominent in the NPRC dataset suggest concentrations of NE/SW trending fractures moderately dipping both N and S. Populations of subvertical planes parallel to the trend of the Edelman lineament appear important in its topographic expression. The NPRC lineament appears more strongly influenced by prominent sets of moderately dipping planes.

experienced slip in more than one direction, probably in unrelated events.

The NPRC striae have no consistent direction (Fig. 5b), in part due to the small number of striations measured. The WNW fracture array also has striae in multiple orientations, with approximately even numbers of dip-slip and strike-slip striae.

DISCUSSION AND CONCLUSIONS

Striation data for the Edelman fault zone indicate strike slip deformation at some time in the geological history of the region. Kinematic criteria from the Edelman are inconclusive, with an approximately even number of right lateral and left lateral indicators. Kinematic criteria are meager for the NPRC, but supporting information may come from two subsidiary fracture arrays that exist in each fault zone. In the 072-striking NPRC zone, the N-S set apparent in both lineament and fracture rose diagrams (figs.

2 and 3) lies at an angle of $\sim 65^\circ$ to the NPRC, in the expected orientation for antithetic Riedel (R') shears (Petit, 1984) in a left-lateral subsidiary fracture array. The NE-SW set, at an angle of $\sim 20^\circ$, is that expected for the synthetic Riedel (R) shears, and the E-W set at 90° is situated in the expected orientation for P shears (Petit, 1984). If the disparate orientations represent an array that initiated within homogeneous isotropic rock, they indicate sinistral motion along the NPRC zone. The 045-trending Edelman zone would function as a dextral conjugate fault, with its N-S subsidiary array at an angle of $\sim 20^\circ$ to the Edelman zone, the location expected for P shears. The E-W set, at $\sim 60^\circ$ to the Edelman master fault aligns with R' shears.

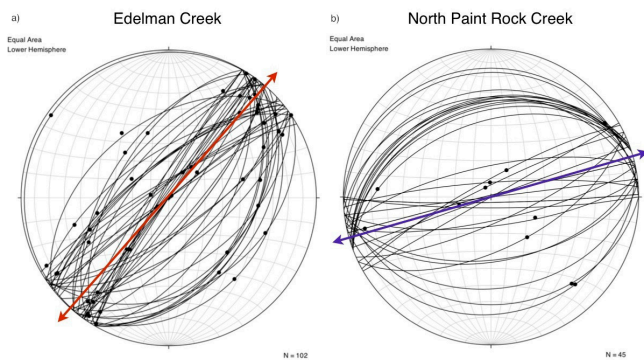


Figure 5. Stereonets of trend-parallel faults and their striae, from field data in the Edelman and NPRC lineaments. Red and purple arrows once again indicate major lineament direction. The majority of trend-parallel faults in the Edelman lineament are steeply dipping, and concentrations of shallowly plunging striae indicate strike-slip movement along the Edelman zone. Trend-parallel faults in the NPRC lineament are generally moderately dipping, suggesting that the NPRC zone itself may be a moderately dipping feature. Striae in the NPRC zone have less consistent slip direction.

If the interpretation of the subsidiary fracture geometries is correct, it suggests that the Edelman and NPRC faults functioned as a conjugate system. One way to assess whether the pair of faults may have been active in the Laramide is to compare the geometry and kinematics of basement fractures to those from Phanerozoic rocks that were not subjected to tectonism in Precambrian time. The maximum principal stress direction for Laramide events in the Bighorn Mountains is 060 based on Keck fracture data gathered in sedimentary cover rocks and the regional

results of Erslev (2005). Conjugate strike slip faults oriented 040 (right-lateral) and 080 (left-lateral) are found in the cover rocks. By parallelism, the geometry of the basement fault zones was therefore favorable for left-lateral motion along the NPRC zone (trend of 072) and right-lateral slip on the Edelman Zone (trending 045). The deformation characteristics of cataclasites in the zones (Dalley, 2011) and the evidence of overprinting striae, together with multiple orientations of striae, suggests that the basement faults are ancient structures that have been reactivated.

The Piney Creek salient along the eastern margin of the Bighorn Mountains is a thrust block that must be bounded by transfer faults, with left lateral slip on along its north and right lateral along its south margin (Stone, 2003). It has not yet been demonstrated that the Edelman and NPRC faults do accommodate slip associated with the Piney Creek block, but if so their motion sense would be opposite of that expected motion for Laramide compression.

Further work will be needed to explore these relationships and to verify whether the NPRC zone is moderately dipping rather than subvertical, as is suggested by fracture geometries. New perspectives will come from the Bighorns Arch active-source Seismic Experiment, since moderately and shallowly dipping fracture zones can appear as prominent reflectors in seismic profiles.

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