Brittle fracture studies in post-Permian strata of the western flank and crystalline core of the Bighorn Arch, Wyoming: An undergraduate research component of the NSF EarthScope Bighorn Project

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Pervasive brittle fractures within Phanerozoic strata and Precambrian basement of the Laramide Rocky Mountains (Figure 1) provide a rich repository of kinematic information for characterization of Laramide deformation and paleostress state. A regional inventory of the structures (Erslev and Koenig, 2009) determined average Laramide slip and compression to be oriented ENE-WSW, but persistent questions remain about the timing of formation and the deformation mechanisms for the prevalent fracture arrays. Exposures of the siliciclastic and carbonate succession on the central western flank of the Bighorn Mountains offer sites with contrasting bedding geometries where these questions can be explored. The contrasting geometries are a long continuous homocline, termed the “Shell shelf,” between Shell and Greybull, WY, and the renowned Sheep Mountain anticline northwest of Greybull (Fig. 2). Formed in strata with extremely gentle westerly dips, the fractures within the “Shell shelf” represent a brittle response to very minor bedding rotation and layer-parallel shortening. Within the asymmetric doubly plunging anticline at Sheep Mountain where sedimentary formations attained moderate dips, fractures formed in response to greater bedding rotation and higher strain. Within the Archean granite and gneiss that forms the “basement arch” of the Bighorn Mountains, range-scale topographic lineaments (Figure 2) correspond to large faults containing meters-thick mylonitic zones; breccia and damaged rock; and/or extensive polished slickensides within narrow valleys. Distinct from the range-bounding faults that are parallel to the mountain arch, the basement structures transect the range (Figure 2).

RATIONALITY: Of particular interest for analysis of Laramide fracture arrays are the Permian and younger formations that were deposited after the Ancestral Rocky Mountains orogeny and therefore contain a record of Laramide and younger events. Undergraduate researchers from the Keck Geology Consortium undertook a study of systematic fracture arrays in Permian and younger strata, with a primary aim to determine the prevalent fracture orientations (Figure 3) and mode of slip (Petit, 1987; Angelier, 1984) for the western flank of the Bighorns. Standard methods of brittle fracture analysis were used (e.g. Marrett and Allmendinger, 1990). In addition, a comparison of fractures in Cretaceous pre-tectonic units versus Tertiary syn- to post-tectonic deposits (Fort Union Formation). The results contribute to the creation of balanced serial cross sections and development of a 4D (3D space plus time) restorable Earth model of the Bighorns arch being constructed by the EarthScope Bighorn Project. A final aim was to compare the microstructural deformation mechanisms within Mesozoic carbonate units in the contrasting structural settings, as a means to gauge the response of a competent unit to the regional stress and clarify the mechanism of formation of a NW-SE fractures.

Within the crystalline core of the Bighorn Arch, structural inheritance is a virtual certainty due to the profound age of the rocks that have been affected by all of the tectonism imposed upon the Wyoming Province since 2.65 Ga. This is corroborated by observations of brecciated mylonite zones, crosscutting striae upon single slickenside surfaces, contradictory kinematic sense within single fault zones; and strongly differing striation orientations upon planes of a single geometrical array. The motivations for structural analysis within the complexly fractured basement are 1) to gather evidence for or against
Figure 1. Photographs of striated fracture surfaces in a) Archean granite and b) siliciclastic sedimentary rock. Such surfaces yield geometrical information (strike, dip, trend, plunge) that, together with a determination of motion-sense, can be used to determine strain and stress axes and slip trend.

Figure 2. Location map for the Bighorn Mountains, northern Wyoming. Field research sites and selected structures are noted. The location for lines for the BASE active source experiment is shown. Inset provides the regional determination of compression trends and slip trends from Erslev & Koenig (2009). Digital elevation and geological data from Wyoming Geographic Information Science Center (WyGISC; www.uwyo.edu/wygisc).
Laramide reactivation of preexisting structures; 2) to characterize crustal scale faults that may project to depth and form seismic reflectors imaged by the Bighorns Arch Seismic Experiment (BASE) active profiles; and 3) to determine the mechanism(s) for deformation of competent Archean crystalline rocks into an arch. The outcomes also may bear on the question of sources of crustal anisotropy that is identified by the shear wave splitting analysis (Anderson et al., 2011) that makes part of the broadband seismology component of BASE. A hindrance to the investigation is that there are few/no prospects for determining the age of motion upon those faults that do not cut sedimentary cover.

RESULTS: Minor fault populations within the post-Permian cover strata of the “Shell shelf” consist of dip-slip conjugate reverse faults striking ~ 335 and 160, and conjugate strike-slip faults striking ~055° (right-lateral) and ~085° (left-lateral). The sites yield a ENE-WSW average maximum horizontal compression direction (σ3) in good agreement with previous work (e.g. Erslev and Koenig, 2009). Joint arrays form a NW-SE set in an orientation consistent with formation as a longitudinal array parallel to the trend of the arch; however, they exist in the near-flat-lying strata of the Shell Shelf as well as in the tight Sheep Mountain anticline, so they cannot be attributed to tensional opening over the crest of the arch or anticline. Another joint set oriented 110° has a transverse geometry with respect to the trend of the Bighorns arch. Joints in that orientation form an array in the Tensleep Formation at Sheep Mountain that has been attributed to pre-Laramide fracturing by Bellahsen et al. (2006). However the presence of 110°-striking fractures in sandstone of the Tertiary Fort Union Formation, with other fracture sets abutting against them, show that the 110° joint array is not pre-Laramide. There is some evidence for late development of normal faults oriented 320/47NE that may be a product of gravitational collapse.

Structural analysis of basement structures in the central Bighorns range makes use of a large fault and fracture data set collected within and adjacent to topographic lineaments (Figure 2) that correspond to steeply dipping fault zones that transect the range. There is wide variability in the geometry of fractures and faults and their striae, but two orientations occur in the greatest abundance. These are ~E-W striking and N-S to NE-SW-striking steep planes (Figure 4), documented from landform analysis using ArcGIS and from field data collection. The prevalent plunge of lineations on the fractures is shallow, indicating predominant strike-oblique motion, and two large-scale faults oriented NNE and ENE do displace Phanerozoic strata. Those faults (Figure 2) are the Tongue River lineament that exhibits north-side-down displacement and cuts the Dry Fork Ridge anticline of Laramide age, and the Johnny Creek fault with west-side-down displacement. The structures have orientations suitable for right lateral and left lateral components of slip (Figure 3) during Laramide compression oriented ENE-WSW (Erslev & Koenig, 2009). Together these observations are taken as evidence of Laramide-age displacement on the faults, and probably on minor faults and fractures that have similar geometries.

At the same time, there is abundant evidence for reactivation of basement faults and fractures: multiple orientations of striae were measured upon planes within a geometrical array, including dip-slip striae upon faults oriented ~E-W and ~N-S (that have prevalent strike-slip or very shallowly plunging striae), fabrics indicative of crystal-plastic deformation are overprinted by brittle cataclasis, and epidote+chlorite+quartz mineralization is variably associated with the shears. To assess the inference of reactivation, the Angelier (1984) paleostress inversion was performed on a set of fractures for which

![Figure 3. Diagram showing the average Laramide maximum principal stress direction oriented ENE-WSW, together with the predicted strike orientations for brittle fractures and faults that would form in response to the stress state. Preexisting fractures and faults in these orientations could be reactivated.](image)
complete fault plane, lineation, and kinematic sense determination are available (n>100). The approach determines what stresses would produce the observed slip on an existing fault plane, rather than the stress state that would produce the initial fracture; for this reason it is suitable for situations of structural inheritance. The result from the full data set gave principal stress orientations of $\sigma_1 = 02$, $\sigma_2 = 17$, $\sigma_3 = \text{subvertical}$, indicative of $\sim$ E-W-oriented compression but with large dispersion. Tighter solutions come from subsets of faults defined by mineralization type; for example, chlorite-mineralized faults yield a maximum principle paleostress $\sigma_1$ oriented $69$, $282$, with the moderately steep plunge indicating an extensional state of strain during motion on chloritic faults. The mineralizing conditions (chlorite-quartz association indicative of crustal depths greater than those for the “upper basement” in the Bighorns arch) and the normal sense kinematics, if correct, are incompatible with the regional Laramide stress state and are likely to be the product of a pre-Laramide event.

**Conclusions** and applications of the Bighorn Project fracture studies are as follows. Data from fractures within cover strata indicates ENE-WSW Laramide compression. Steep conjugate strike-slip fault arrays are more prevalent than dip-slip reverse faults in basement than the cover. The information on geometry, location, and timing of development of successive fracture arrays is being integrated into a restorable 4D model of basement arch development. There is wide variability in the geometry of basement structures and there is clear evidence for structural inheritance in the crystalline terrain, but the dominance of steep faults with strike-slip motion suggests Laramide ENE-WSW compression and axis-parallel extension. Field data acquisition in the Archean basement is ongoing, with the aim to characterize crustal-scale faults that may appear as seismic reflectors or as boundaries of anisotropic regions.

**References cited**
Anderson, M. L. and 10 others, 2011 Earthscope abstract, this volume.