KECK GEOLOGY CONSORTIUM

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

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Faculty: *CHRISTINE SIDDOWAY*, *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.

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Research Advisor: Dr. Julie Newman

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BRENNAN YOUNG, Utah State University
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BRENNAN YOUNG, Utah State University
Research Advisors: John Shervais and James Evans

INTRODUCTION

The goals of this project are to conduct a detailed structural study of the Cloverly Formation in the eastern Bighorn Basin in order to document and compare differences in deformation style from one site to another. Particularly, this project analyzes and tests hypotheses for the relative timing and mechanics of fracturing in the study areas, and provides kinematic information for Laramide deformation. Questions driving the project include: 1) what are the geometrical relationships among these fractures, 2) what is the relative timing of fracture arrays in the Early Cretaceous Cloverly Formation in the Bighorn Basin, 3) what was the orientation of stresses that caused these fractures and were they applied in one or more stages or events? Answering these questions will clarify ambiguities concerning the relative timing and mechanics or fracturing in the Bighorn Basin, particularly of Sheep Mountain, and provide kinematic information for Laramide deformation.

Study sites in the Early Cretaceous (pre-Laramide) Cloverly Formation examine the difference in fracture arrays formed within very shallowly dipping strata on the eastern margin of the Bighorn Basin, termed the Shell Shelf, versus moderately dipping strata near the Sheep Mountain Anticline. Sites on the Shell Shelf included Devil's Kitchen and Red Gulch Road (from Interstate 14). Sites were selected on the east and west sides of Sheep Mountain. A site near the Greybull River was selected for study of the Tertiary Fort Union Formation to serve as a control for post-Laramide deformation. The distributed locations and the opportunity to compare fractures in differently dipping strata will provide a more accurate determination of paleostress fields in the Bighorn Basin from this study.

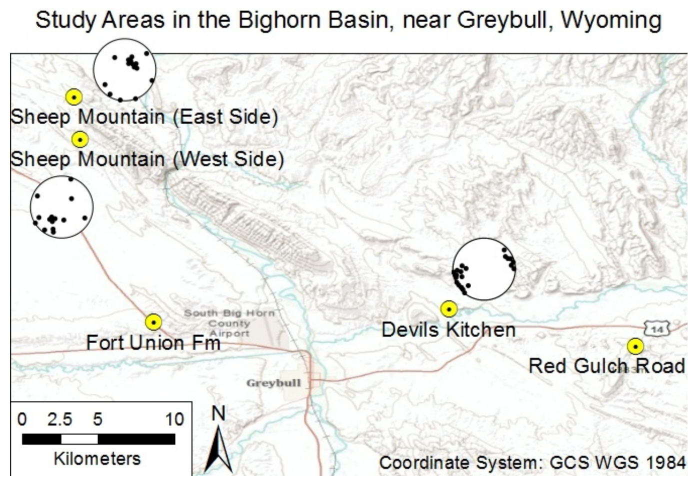

Figure 1: Map of study sites. Stereonets show slickenline data.

GEOLOGICAL BACKGROUND

Overlying Archean metamorphic belts and plutons in the Bighorn Basin (Stoke, 1997) are Paleozoic sandstones, shales, limestones, and dolomites (Amrouch et al., 2010). Ancestral Rocky Mountain deformation occurred during the Pennsylvanian and Permian, followed by a period during which the region was a virtually featureless stable shelf (Amrouch et al., 2010; Snoke, 1997). An interior seaway advanced on the province during the Cretaceous (Snoke, 1997). The bentonitic mudstone and sandstone of the lower Cretaceous Cloverly Formation, the focus of this project, was deposited in shallow seas and records distant volcanic activity, perhaps from the Sierra Nevadas. Above the Cloverly Formation are Cretaceous shales and sandstones, the Tertiary Fort Union Formation, and the Willwood Formation (WGA, 1975).

The Bighorn Basin area was virtually undeformed immediately prior to and since the Laramide orogeny, which occurred from Late Cretaceous to Middle Eocene time (about 75-45 Ma). A Neogene feature nearby, the Yellowstone hotspot, seems to have had little effect in terms of post-Laramide regional deformation despite its proximity. Sheep Mountain and the nearby Bighorn Mountains formed in response to ENE-WSW shortening during the Laramide orogeny (Erslev and Koenig, 2009), though Sheep Mountain and similar anticlines may be sited over previous highs as is evidenced by thinning of the Tensleep Formation over their crests, suggesting that some previous deformation has occurred in the region (Amrouch et al., 2010). Those features are Laramide arches—elongate, asymmetric thick-skinned folds upon basement highs in the foreland of the Sevier thrust belt (Amrouch et al., 2010). They are associated with deep thrust faults that developed or were re-activated in the basement (Amrouch et al., 2010). Erslev and Koenig (2009) determined that the faults formed in response to ENE-WSW compression, σ1, oriented 067° during a single event, whereas Allison (1986) and Gries (1983) attribute the deformation to a multi-stage event with varying σ_1 directions. From a study of fractures at Sheep Mountain, Bellahsen et al. (2006) interpreted a set of joints striking 110° to be pre-Laramide (stage I), a set of fractures striking at 045° to be early-Laramide (stage II), and a fracture array striking at 135° to be late-Laramide (set III). These workers observed evidence for a reactivation of set I fractures during fold growth, forming 'stage IV' joints and oblique thrust faults.

My fracture analyses of the Cloverly Formation at Sheep Mountain, where bedding dips are moderately steep, and Devils Kitchen, where bedding dips are shallow, will help to establish whether the structural progression interpreted by Bellahsen et al. is regionally applicable.

The Cloverly Formation contains two distinct members, the Greybull Sandstone Member and Rusty Beds Member (sandstone) that were studied, in addition to ash pavement measured at Devil's Kitchen.

METHODS

Brunton compass measurements constrain the attitudes of bedding, cleavage, fractures, joints, faults, and striae and grooves ("slickenlines"). Criteria for characterizing the structural arrays include: continuous or repeated planar structures, cataclasite coating (Fig. 2), and mineralization (gypsum, calcite, and iron-oxides). Abutting and cross-cutting relationships were noted. Kinematic sense was interpreted on-site using offset markers, apparent conjugate fault pairs, Riedel fractures, and crystal growth patterns. Oriented samples of representative features were collected to be examined in thin section, particularly to verify kinematic sense along fault planes.

Figure 2: Example of fine-grained quartz cataclasite coating on Greybull Sandstone at Devil's Kitchen.

Structural data were entered into the spreadsheet document Select.xls (Erslev, unpublished) where lineation measurements were corrected with respect to their host planes. The data were then sorted using the Select.exe program (Erslev, unpublished) and plotted onto lower-hemisphere spherical projection stereonets or rose diagrams using StereoWin v.1.2.0 (Allmendinger, 2006). StereoWin was also used to remove bedding tilt and apply a cylindrical best fit to calculate ideal principal stress directions, σ_1.

σ_1 is derived from slip vectors (taken from slickenlines on fault surfaces), to which it is assumed to be parallel for a homogenous, non-rotated block of material, and can be determined by analyzing the geometries of conjugate fault pairs (Angelier, 1994). However, a variety of slip vectors can be caused by the same regional stress, so stress tensors are determined from a "best fit" of slip vectors, for which the cylindrical best fit in StereoWin was used.

RESULTS

Bedding at Devil's Kitchen is sub-horizontal. The ash beds there host fractures striking mostly 081° and 210° (Fig. 3a), with the 210° array more frequently abutting the 081° array. Greybull Sandstone that crops out at that same location and at Red Gulch Road have similar fracture arrays, particularly one striking 085°. The Greybull Sandstone at Devil's Kitchen and at Red Gulch Road also host another set striking 320° and the Rusty Beds bear fractures striking 155° and 315°, nearly perpendicular to the 081°-210° set (Fig. 3b, c). Bedding near Sheep Mountain dips 23° to the NE on the east side and 37° to the SW on the west side. Fractures at both sites near Sheep Mountain strike generally at 145°, similar to those in the Rusty Beds at Devil's Kitchen (compare Fig. 3a-c and 3e-g). Nearly all joints in the Greybull Sandstone were coated or stained with up to 1 cm of iron-oxides, which in thin section either replace or coat prior calcite cementation, and some joints in the Greybull Sandstone on the west side of Sheep Mountain bear arrest lines. Post-Laramide fractures found in the Tertiary Fort Union Formation almost all strike 109° and 146° (Fig. 3h). Joints striking 030°, 086°, and 146° abut against the 109° joint set.

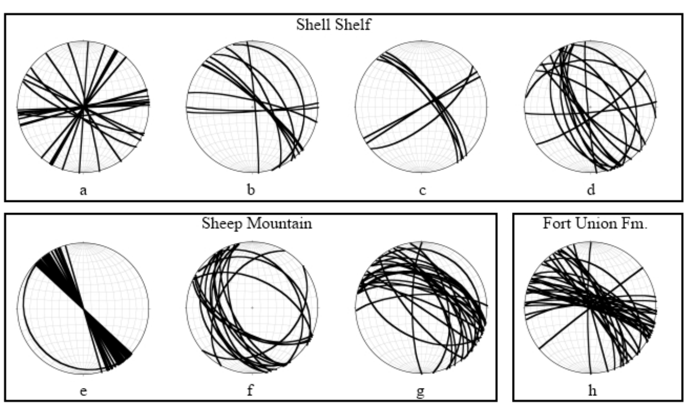

Figure 3: Joints and fractures of unknown type. "DK" means Devil's Kitchen, "RGR" means Red Gulch Road, "SME" means the east side of Sheep Mountain, and "SMW" means the west side of Sheep Mountain. a) Ash Pavement at DK. b) Greybull Sandstone at DK. c) Rusty Beds at DK. d) Greybull Sandstone at RGR. e) Greybull Sandstone at SME. f) Rusty Beds at SME. g) Greybull Sandstone at SMW. h) Fort Union Formation.

Figure 4: Example of gypsum crystal ridges that grew within faults in ash pavements in the Cloverly Formation at Devil's Kitchen.

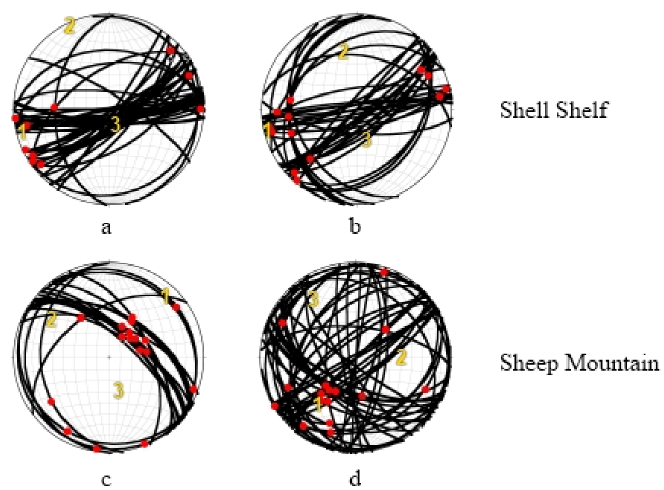

Figure 5: Faults, with slickenlines marked in red and principal stress directions (σ_1, σ_2, and σ_3) are marked as "1, 2, and 3." a) Ash pavement at Devil's Kitchen. b) Greybull Sandstone at Devil's Kitchen. c) Rusty Beds at the east side of Sheep Mountain. d) Greybull Sandstone at the west side of Sheep Mountain.

The ash pavements in Devil's Kitchen hosted primarily strike-slip faults. In the center of some of these faults were ridges of gypsum crystals that grew in the direction of slip (Fig. 4), and along some of these faults were Riedel fractures. From these criteria, a set striking 054° was determined to have right-lateral shear sense, and a conjugate set striking 085° was determined to have left-lateral shear sense (Fig. 5a). In the ash was also a reverse fault striking almost directly N-S. The maximum horizontal stress direction, σ_1, in the ash was calculated to plunge 1° and trend 246.6° (067°). Shear zones in the Greybull Sandstone were invariably marked with very fine, quartz cataclasite. Though Red Gulch Road hosted no measurable blocks with fault surfaces, the Greybull Sandstone in Devil's Kitchen yield a conjugate pair of faults similar to those in the ash pavements (right-lateral striking 052° and left-lateral striking 081°) and a pair of thrust fault arrays striking 039° and 183° (Fig. 5b). Structures in the Greybull Sandstone at Devil's Kitchen yield σ_1 plunging 4.9° and trending 251.2° (071°). The Rusty Beds on the east side of Sheep Mountain host shallowly-dipping conjugate dip-slip faults striking 318° and 158°, and a reverse fault striking 234° (Fig. 5c). σ1 calculated for these faults plunges 16.7° and trends 043.2°. Strike-slip faults on the west side of Sheep Mountain are oriented 050° and 060° and dip-slip faults strike 120° (Fig. 5d) and give a calculated σ1 plunging 34.9° and trending 214.8° (35°).

DISCUSSION

Brittle Fractures

A lack of extensional faulting in the area striking N-S suggests that the Neogene Yellowstone hotspot has had little impact on the structures in the area.

Joints striking between NW-SE support NE-SW extension. These joints cut shear bands, so occurred during post- or late-Laramide extension. These joints are most apparent at Sheep Mountain, perhaps exaggerated by gravity sliding on bedding within the anticline.

Joints oriented 110° appear as the dominant fracture set in Tertiary Fort Union sandstone and other fracture sets abut against them. The orientation matches that for joints in the Tensleep Formation at Sheep Mountain (Bellahsen et al., 2006). The presence of the joint array in the Tertiary strata suggests that the 110° joint array is not pre-Laramide as was interpreted by Bellahsen et al. (2006). Rather, the 110° joint array formed post- or late-Laramide. It is possible that some joints in pre-Laramide strata were formed pre-Laramide and then were reactivated post-Laramide. Bellahsen et al. (2006) suggested that some of these fractures were reactivated as reverse faults in the late stages of Laramide deformation in this region. However, because Greybull Sandstone joints clearly cut shear planes, have iron-oxide staining replacing or coating calcite cementation (absent in shear planes), bear arrest lines, and appear to only have little or no separation except for having opened perpendicular to the strike of the joint, and share the same orientation as a dominant fracture array in the post-Laramide Fort Union Formation, these joints are almost entirely extensional and occurred after the shortening event.

Paleostress Orientations

σ_1 in the ash and Greybull Sandstone in Devil's Kitchen is oriented 247° (067°) (Fig. 5a), in agreement with σ_1 trending 067° determined by Erslev and Koenig (2009). Other orientations bearing 125° (035°) and 043° were calculated from fault data collected at Sheep Mountain, perhaps because Sheep Mountain seems to be a reactivated Pennsylvanian-Permian structure from Ancestral Rocky Mountain deformation. What were interpreted to be thrust faults striking NE-SW may be rotated normal faults, which would support the same NW-SE extension seen with NE-SW joint arrays. The presence of such NW-SE-dipping faults, found especially at Sheep Mountain, may explain the drastic change in σ_1 values between Shell Shelf and Sheep Mountain. Because the NE-SW-striking joints and dip-slip faults are more pronounced at Sheep Mountain, it is possible that strain produced from the NW-SE extension was exaggerated due to gravity sliding into the basin, or due to a local stress field anomaly related to the anticline being a reactivated Pennsylvanian-Permian structure.

CONCLUSIONS

Stresses during the Laramide orogeny primarily caused brittle deformation at all study sites. Sites on the Shell Shelf host very similar fracture and fault sets, though the west side of Sheep Mountain only hosted dip-slip faults and the fracture arrays on the east side of Sheep Mountain dipped more to the southeast. Joints striking 110° are due to post-Laramide extension. Faults typically occurred in strike-slip conjugate pairs with right-lateral motion on faults striking 054° and the left-lateral motion on faults striking 083°. Most dip-slip faults were thrust or reverse faults striking NW-SE with a few exceptions striking NE-SW, particularly on the east side of Sheep Mountain in the Greybull Sandstone, which may be due to gravity sliding into the basin. σ_1 directions in the Shell Shelf are in agreement with Erslev and Koenig's (2009) σ_1 of 067° though those on the east side of Sheep mountain trend 043° and those on the west side of Sheep Mountain are 125° (035°). This suggests a differing local stress field around Sheep Mountain which may be due to its prehistory as a Pennsylvanian-Permian structure.

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