KECK GEOLOGY CONSORTIUM

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

April 2011
Union College, Schenectady, NY

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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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Students: *HANNAH BOURNE*, Wesleyan University, *JONATHAN GRIFFITH*, Union College, *JACQUELINE KUTVIRT*, Macalester College, *EMMA LOCATELLI*, Macalester College, *SARAH MATTESON*, Bryn Mawr College, *PERRY ODDO*, Franklin and Marshall College, *CLARK BRUNSON SIMCOE*, Washington and Lee University.

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

CHRISTINE SIDDOWAY, Colorado College
MEGAN ANDERSON, Colorado College
ERIC ERSLEY, University of Wyoming

INTRODUCTION

The mechanism for the formation of mountain ranges within continental interiors, far from tectonic boundaries where differential motion between plates causes focused crustal deformation, is in some respects just as mystifying today in the 21st century as when Plate Tectonic Theory became the accepted unifying model for geological processes on Earth in the 1960s (Oreskes and LeGrand, 2005). The foundations of geological knowledge of foreland mountain ranges comes from the Rocky Mountains of the western

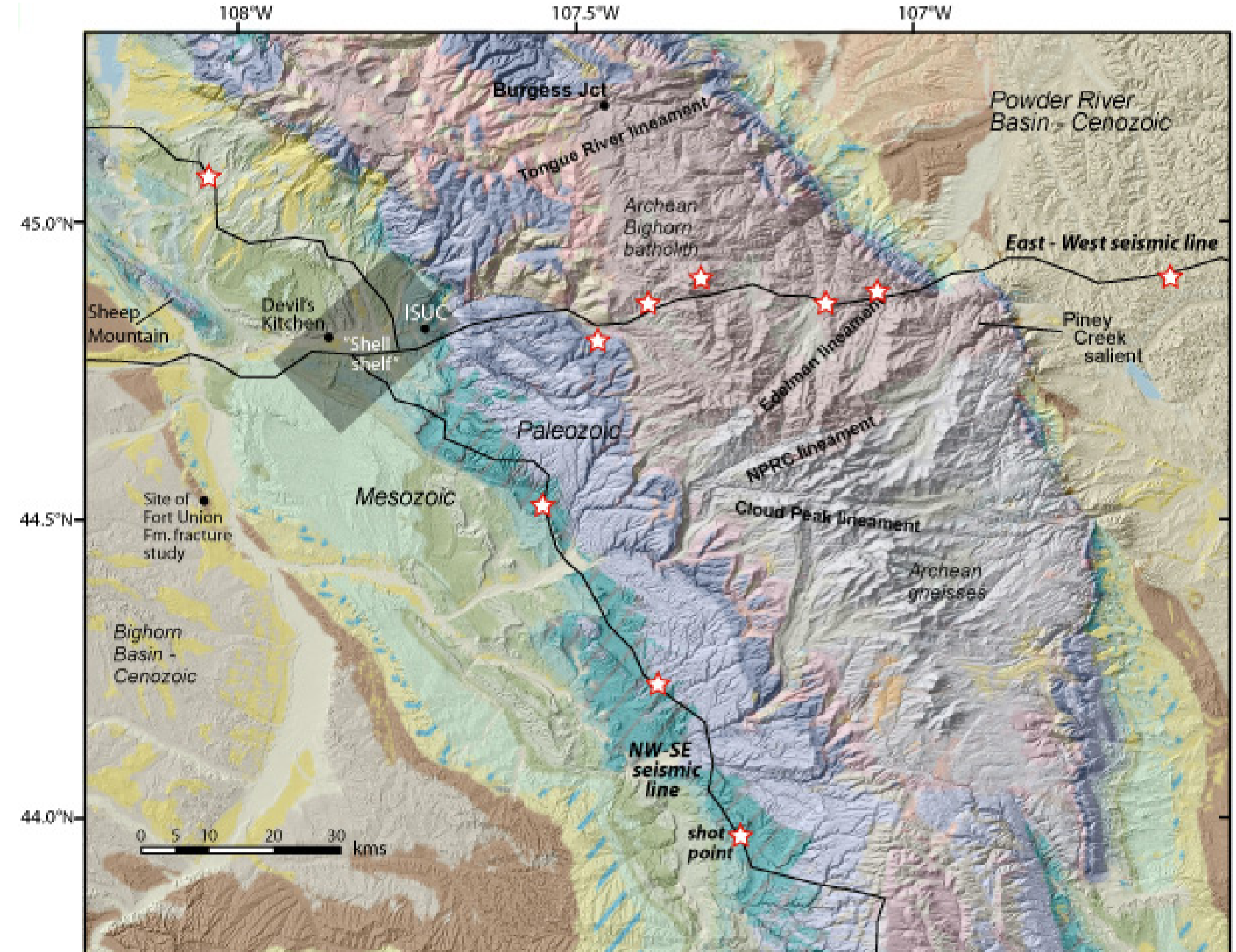

Figure 1. Map view of the Bighorn Mountains arch, northern Wyoming. Locations of Keck study sites and selected structures are noted.

USA, and particularly the ranges of central Wyoming where the term Laramide orogeny originated (e.g., Coney, 1976). The structural geology of the Laramide mountain ranges is world-renowned because of the inspiring grand-scale fold form of sedimentary cover rocks upon Precambrian crystalline basement. In such a quintessential example as the Bighorn Mountains of Wyoming (Figures 1, 2), cover strata define the shape of an elongate arch upon a barrel-roll of crystalline basement rock.

It is paradoxical that the geological structure of the Bighorn Mountains is so well described and characterized at the scale of the upper crust but is so poorly understood at the scale of the lithosphere (Erslev, 2005). Four viable competing models exist for the lithospheric structure of the Rocky Mountain foreland, and with them as many hypotheses for the deformation processes responsible for their formation (Figure 3). A test of these models is the aim of an NSF EarthScope project for 2009-1012 named the Bighorn Project, which combines structural studies with the Bighorn Arch Seismic Experiment (BASE), a collaboration that involves the Bighorns Keck faculty and four additional principal investigators.

The 2010 Keck Bighorn Project contained a seismologic shear-wave splitting component and a structural geology component. In addition, all Keck students were offered a singular opportunity to gain direct acquaintance with seismological research methods through participation in the installation of portable seismometers ("Texans") for BASE's large active-source seismic experiment conducted in the Bighorns in July-August 2010. To allow time for the applied experience, the duration of the Keck project was extended and students were compensated for the additional week of field research time.

The structural geology component engaged student researchers in field-based structural studies that address 1) the longstanding controversy about how strong, old lithosphere, including exposures of Archean Wyoming Province rocks, have deformed within the continental interior; and 2) origins, mechanisms, and timing of formation of fracture arrays in the eastern Bighorn basin, a subject that has been under active debate (e.g. Hallberg et al. 1999 vs. Stanton and Erslev, 2004; Amrouch et al. 2010).

Field sites for structural geology were chosen within Mesozoic units that were not subjected to pre-Laramide tectonism and in Archean crystalline rocks that lack the layer-anisotropies (bedding) found in sedimentary rocks. They are localities where students could determine whether deformation in the Bighorns occurred in response to 1) regional ENE-WSW shortening along sub-parallel strain axes throughout the range, as is the assumption for 2D profiles such as the ones in Figure 2b; 2) strike-slip accommodation upon transfer faults or wrench systems that extend across the axis of the arch; or 3) gravitational sliding radial to the arch or 'relaxation' in a direction counter to that for Laramide shortening. Standard geometrical and kinematic methods (e.g. Marrett and Allmendinger, 1990) and stress tensor techniques (Angelier, 1984) were used to determine the coordinates of regional shortening, and to distinguish wrench versus gravitational components; and thin section observations of brittle microstructures were used by some students to characterize host rocks and determine deformation mechanisms.

The seismological method employed by students in the Keck group is shear wave splitting analysis (e.g. Long and Silver, 2009), applied to data acquired by EarthScope's transportable USArray (www.usarray.seis.sc.edu) and BASE's more closely spaced broadband array for determination of crustal and mantle anisotropy for the regions that underlie and surround the Bighorns arch. Anisotropy is expressed by seismic fast orientations and degree of strain. Using innovative new approaches such as pierce point analysis (Gao et al. 2010) and frequency analysis (Long, 2010), the aim is to delineate spatial patterns of anisotropy beneath the Bighorns arch that unveil the hidden structure of the Wyoming craton. The SWS analyses may reveal deformation fabrics associated with cratonic amalgamation in the Archean Eon, on the one hand, or patterns of current asthenospheric flow, on the other.

GEOLOGIC BACKGROUND

The Bighorn Mountains in Wyoming have a geological distinction that has long fascinated geologists

Figure 2a. View to NW along the northwest steep flank of the Bighorn range, showing V-shaped flatirons eroded upon the Bighorn Dolomite and neighboring units.

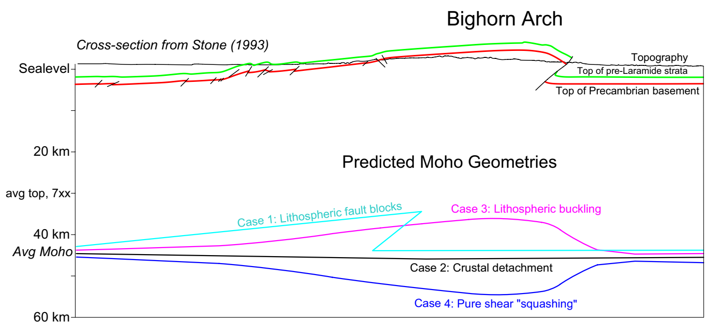

Figure 2b. Generalized profile showing the near surface structure of the Bighorns arch, known to a depth of ~10km (Stone, 2003), showing the contrasting Moho geometries predicted by each of the four lithospheric models shown in Figure 3. For line of profile, see Fig. 1.

and summer vacationers who traverse the range on U.S. Highways 14 and 16. The crystalline rocks and the layered sedimentary rocks that cover them form a very large anticline that is visible to the observer from the easterly dip of sedimentary layers on the east side of the range, and westerly dip of the strata on the west (Figures 1 and 2). Stretching >250 km to the NW and SE, the fold structure is an elongate, doubly-plunging arch that is bounded by faults on its east and west margins. The faults have range-side-up displacement and cause abrupt changes in the degree of dip of Paleozoic and Mesozoic sedimentary units, creating fault-associated folds at the range front that involve strata as young as Tertiary. The involvement of Mesozoic and younger rocks is evidence that the fault and fold deformation, therefore the creation of the Bighorns arch as a whole, are a consequence of the Cretaceous-Tertiary Laramide orogeny (e.g., Erslev 2005). Three of nine Keck students embarked on studies of fracture arrays in the Mesozoic and younger sedimentary rocks that were affected by this grand-scale deformation.

Crystalline rocks --granite and gneiss of Archean age-- form the high, interior parts of the Bighorn range. Often referred to as "basement" rocks due to their deep structural position, the granites and gneisses are old, cold, strong rocks that do not readily flex or bend since they lack the layer anisotropies of the sedimentary cover. Nonetheless, the basement domain and its upper contact—The Great Unconformity-- conform to the shape of the arch that is outlined by the sedimentary strata for the >250 km length and ~60 km width of the Bighorn range (Figures 1, 2). The mechanism that caused the strong crystalline rocks to bow up, forming the long crest of the Bighorn range, has not yet been specifically determined, nor have the specific faults responsible for differential motion, if that occurred. Three more students in the Structure team focused their work on large topographic lineaments of the central Bighorn Mountains (Figure 1) to determine the nature of the faults and assess whether it is likely that they accommodated Laramide motion or whether they are passive markers from much more ancient tectonic events.

The geological faults that flank the range displace basement and cover, and they certainly are a factor in the mountain uplift and arching, but they can be tracked to depths of just 10 km or so, using available published and industry data (e.g., Stone 2003, Fig. 2b). The resolution to the problem of formation of the Bighorns arch, and to the enigma of foreland deformation more generally, will come from new information that allows scientists to look deep beneath the range to determine lithospheric properties and identify lithospheric-scale structures that project to depth below the range.

Earthscope Transportable and Flexible Array seismographic stations installed in northern Wyoming gathered records of earthquake energy that are being used to help answer this problem. A grid of 24 TA stations, deployed for 2 years, collected signals from distant tremors that traveled through the Earth to the Bighorns. Keck faculty member Megan Anderson and collaborators from University of Colorado added another 38 broadband seismic stations to densify the Transportable Array (see Figure 1 in Hornbuckle, 2011, this volume). By bringing the station spacing down to 20 km or less, they acquired very detailed records of the manner of seismic wave transmission through the lithosphere and asthenosphere that underpin the Bighorn Mountains. Three enthusiastic Keck students joined in the laborious task of processing, filtering and analyzing of shear waves that yields high resolution patterns of seismic anisotropy, where regions of faster versus slower transmission of seismic energy attributable to past tectonic movements or contemporary mantle flow, are revealed. The physical characteristics of these anisotropic regions, and/or or the presence of boundaries between one region and another, probably play a role in Laramide arch formation.

PROJECT ORGANIZATION, STUDENT PROJECTS AND RESULTS

Nine students and three faculty worked out of the Iowa State University field station on the west side of the Bighorn Mountains in Shell, WY. The five-week program in July and August coincided in time with the BASE active source seismic experiment and campaign deployment of intermediate-period seismic stations. Also residing at the ISU station were the many university faculty members, graduate students, and undergraduate interns involved in that work. A mix of researchers at varied stages of their professional lives, including the Keck group, was thus engaged in the effort to unveil the lithospheric structure of the Bighorns. The result was a vibrant scientific community in which all could learn something of the varied techniques being used and focused questions being studied by the others, with each question contributing to the collective goal.

In addition to field work in support of the active source seismology, another seismological approach used in more depth by the Keck group is shear wave splitting, analyzing passive source records from the instruments in EarthScope's transportable array and BASE's more closely spaced broadband array. Megan Anderson (Colorado College) headed up the Seismology Team, training members John Hornbuckle III (Washington & Lee University), Triana Ufret (University of Puerto Rico - Mayaguez), and Drew Thayer (Colorado College) in specialized techniques of shear wave splitting analysis for determination of lithospheric and mantle characteristics of the realms that underlie and surround the Bighorns arch.

All nine Keck students who worked on the Bighorns project became acquainted with methods of structural analysis of brittle fractures, where the term 'fractures' is used in the inclusive sense, encompassing very small striated surfaces, joints, shear fractures, and faults. Throughout the five weeks of the field program, all participated in data collection, measuring the strike/dip of fracture planes, plunge/trend (or rake) of striae, and with careful observation of movement criteria for kinematic sense. Principal sites for data gathering (Figure 1) were the "Shell shelf," a wide homocline of very shallowly dipping strata that extends from the western Bighorns range front at Shell, WY, to Sheep Mountain, a famed anticline within the Bighorn Basin that is wonderfully eroded to expose its long, narrow geometry and steep limbs; and the Archean granite of the high central Bighorn Range, where pronounced tectonic lineaments transect the crystalline basement rocks. All participated in the critical task of data quality assessment using spreadsheet applications, carried out prior to the step of kinematic and dynamic analysis for understanding of the differential stress configuration at the time of formation of the fracture arrays. Six students chose to undertake structural geology projects for their individual Keck research, with three working in each the sedimentary cover rocks and the crystalline basement of the Bighorns arch.

Eric Erslev (University of Wyoming) led the structural geology program and served as leader for the Cover Team, that included Molly Chamberlin (Texas A& M University), Brennan Young (Utah State University) and Bryan McAtee (Lafayette University). This group investigated the origins and relative timing of fractures within Mesozoic strata on the eastern margin of the Bighorn Basin. Keck project director Christine Siddoway (Colorado College) led the Basement Team, made up of students Elizabeth Dalley (Oberlin College), David Oakley (Williams College), and Chad Trexler (Whitman College). The Basement Team undertook a brittle kinematic and dynamic analysis of mesoscopic faults of the sort that has not been per-

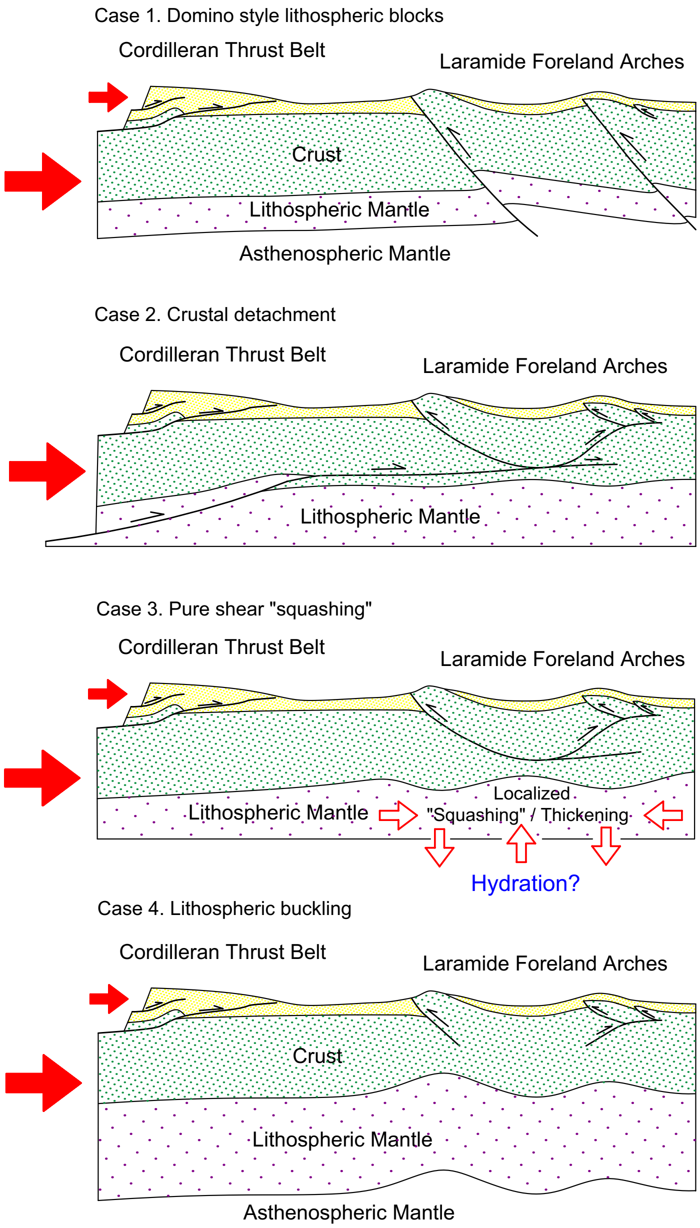

Figure 3. Four contrasting models for basement-involved foreland arches are: a) Lithospheric fault blocks (McQueen and Beaumont, 1989); b) lithospheric buckling (Dumitru et al., 1991; Maxson and Tikoff, 1996); c) crustal detachment (Fletcher, 1984; Erslev, 1993); and d) pure shear thickening (Egan and Urquhart, 1993; Kulik and Schmidt, 1989; Humphreys et al., 2003; Bird, 1988). The surface geology and structural configuration for the upper few kilometers is the same in all profiles. Diagram is from Erslev, 2005.

formed previously on the basement structures within the Bighorn basement.

The specific projects undertaken by students of the Bighorns Keck project are as follows. Their study locations are shown in Figure 1.

Molly Chamberlin (Texas A&M University) carried out a structural analysis of mesoscopic fractures in the Mesozoic Sundance Formation and Alcova Member of the Chugwater Formation, both units affected only by Laramide or younger brittle deformation. She compares sites of only small bedding rotation on the “Shell shelf” with sites where strata were rotated to moderate dips in the vicinity of Sheep Mountain. The structural analysis of field data is complemented by microstructural observations of thin sections, to which graphic techniques are applied for identification of deformation mechanisms in the two units subjected to varying amounts of strain.

Brennan Young (Utah State University) compares the fracture arrays developed in a distinctive ash-rich mudstone, the Cretaceous Cloverly Formation, at locations on the Shell Shelf versus Sheep Mountain, as a means to evaluate the geometry and timing of successive joint arrays and faults in the Bighorn Basin. His data are well-suited to determination of the orientation of the maximum principle stress during Laramide deformation. He compares his results for the Cloverly Formation with a Keck data set gathered on the Tertiary Fort Union Formation, a rock unit that provides a maximum age for the time of formation of a notable regional fracture array that is oriented ESE-WNW.

Bryan McAtee (Lafayette University) examines an array of sandstone dikes within Cretaceous siltstones on the flank of the Sheep Mountain Anticline. The porous, permeable dike material has different mechanical properties than the clay-rich host rocks. Bryan uses a sensational array of shears within the dikes for structural analysis, to determine whether the shears arise from regional tectonism or local effects such as compaction. Using geometrical considerations he is able to show evidence of site to site variations in records that suggest an interplay of tectonic and local effects.

Chad Trexler (Whitman College) undertook a GIS-based analysis of topographic lineaments within basement rock at the crest of the central Bighorns arch, to complement his field-based structural analysis of fractures from the NE-trending Edelman Creek and ENE-oriented North Paint Rock Creek lineaments.

Using a 10-meter digital elevation model supplemented by geological map and satellite imagery, Chad establishes that ~N-S and ESE-populations of subvertical fractures and faults have a regional expression as lineaments; thus verifying the validity of use of field datasets for structural analysis of the basement terrane. A persistent problem is the lack of geological markers for kinematic interpretation and age control.

David Oakley (Williams College) applied the stress tensor method (Angelier, 1984) to evaluate whether the prevalent basement structures within lineaments may have originated and accommodated slip in the Laramide orogeny, or whether they were inherited. Sinistral E-W and dextral NE-SW strike-slip faults do exist in suitable orientations for Laramide slip, according to paleostress determinations for fractures in cover strata. He points out that the acute bisector for the apparent strike-slip faults is ~26° clockwise from the mean principal stress direction of N60E for the Bighorns and ~20° clockwise from the Laramide regional average σ_1 direction of N66E (Erslev and Koenig, 2009). His results from Angelier stress tensor calculations show that many faults and a majority of fault striae do not fit the expected Laramide geometry, suggesting that the structures were formed during prior events and locally reactivated.

Elizabeth Dalley (Oberlin College) used large cumulative datasets for the central and northern Bighorns for kinematic analysis using methods of Marrett and Allmendinger (1990) to determine whether the geometry and kinematics of regional-scale basement structures are compatible with the Laramide regional stresses or rather, are a product of fault inheritance and reactivation. Two dominant structural geometries are premisdable: an array of ~E-W faults with dominant left lateral slip indicators, and a NNE-array with conficitng shear sense criteria – a possible sign of tectonic reactivation. She studied thin section microstructures to gain qualitative information about the crustal conditions for deformation of fault zone cataclasites. Finally, she makes a comparison of kinematic results from the central versus northern Bighorns, where sedimentary cover rocks provide some age limitations for basement deformation.

Drew Thayer (Colorado College) and John Hornbuckle (Washington & Lee University) undertook a shear wave splitting analysis of BASE data, with the aim of constraining depth and orientation of anisotropy. In a refinement of conventional approaches that merely address the lateral distribution of anisotropy via comparisons between seismic station averages, Drew evaluated the frequency-dependence of shear-wave splitting (Wirth and Long, 2010; Long, 2010) in his dataset to help constrain the depth of anisotropy regions, as a contribution to the BASE project objective to produce an accurate three-dimensional model of lithosphere beneath the Bighorns arch. John Hornbuckle employed backazimuth plots that compare the direction of arrival of the shear wave to its splitting parameters (fast seismic direction and arrival time differences between fast and slow waves) and pierce point analysis (Gao et al., 2010), another method of determining the likely depth of anisotropy below the region as well as small-scale regional variations in splitting parameters.

Using the different methods, they show that shear waves recorded on BASE stations are influenced by anisotropy in both the lithospheric and asthenospheric mantle beneath the Bighorn region. Lithospheric anisotropy seems to dominate the signal and has two regions of coherent alignment that are separated by a boundary coincident with the eastern front of the Bighorn range. Fast (and null) directions attributed to the asthenosphere are parallel to fast directions expected to result from shearing of the asthenosphere due to absolute plate motion (Waite et al. 2005). Back azimuth analysis reveals variations in the fast directions over a small lateral distances, an observation that may be indicative the presence of a lithospheric keel in the region.

Triana Ufret (University of Puerto Rico – Mayaguez) has completed a petrographic study of thin sections of mantle xenoliths to determine the presence or absence of lattice-preferred or shape-preferred orientations of mineral phases (LPO and SPO) that exert an effect on wave propagation and shear wave splitting. Mineral assemblages are used to determine the temperatures of equilibration and/or retrogression of the mantle materials, and to seek out evidence for introduction of water or application of a differential stress.

These factors are poorly known from direct observation of mantle materials from the Wyoming Craton, yet they have a primary role in anisotropic characteristics of seismic wave behavior.

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