

KECK GEOLOGY CONSORTIUM

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

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2010-2011 PROJECTS

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.

EXPLORING THE PROTEROZOIC BIG SKY OROGENY IN SOUTHWEST MONTANA

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

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

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KECK SIERRA: MAGMA-WALLROCK INTERACTIONS IN THE SEQUOIA REGION

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EOCENE TECTONIC EVOLUTION OF THE TETONS-ABSAROKA RANGES, WYOMING

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

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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

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

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

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BRENNAN YOUNG, Utah State University
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SEISMIC ANISOTROPY BENEATH THE BIGHORN MOUNTAINS

JOHN SPENCE HORNBUCKLE III, Washington and Lee University

Research Advisor: Jeff Rahl

INTRODUCTION

Seismic studies are one of few techniques that enable scientists to study and analyze the subsurface. Shear wave splitting studies are able to map upper mantle structures and are possibly able to constrain the depths they occur at. The enigma this study will be useful in resolving is the upper mantle response to crustal deformation in continental interiors where the nature of this relationship is poorly understood. I have worked on documenting the anisotropy beneath the Bighorn Mountains in Wyoming, a northwest trending range that represents a northeastern spur of the Rocky Mountains. The Bighorn Mountains are thought to have formed from uplift during the Laramide Orogeny at 75-45 Ma (Snoke 1997). The range is one of a number of large block uplifts in Wyoming and neighboring states. An unresolved question is why the Bighorns were formed in the continental interior of the North American plate. One theory is that low angle subduction of the Farallon plate beneath the North American plate caused an eastward migration, away the subduction zone, of mountain building (Bunge et al. 2000). The result was widespread faulting and uplift of crystalline basement as far inland as 1,500 km (Bunge et al. 2000). Seismic anisotropy is caused by mantle deformation from past and present tectonic activity (Silver 1996), through the use of shear wave splitting, the study of this property could help constrain asthenospheric flow and past deformation in the lithospheric mantle, likely occurring during the Archean.

Anisotropy is a general term used to describe a medium whose elastic properties are functions of orientation (Silver 1996). When a shear wave passes through an anisotropic medium, the wave is split into two separate shear waves, each having orthogonal polarization to the other, and traveling at different velocities. Such an affect can be caused by shape preferred orientation (SPO) or lattice preferred orienta-

tion (LPO). The effects of orogenic deformation with regards to the mantle and its relationship with the crust are hotly debated and several theories on their interactions exist. One hypothesis is that the mantle is not important, as mountain building could be a crustal process, and only serves as a mechanism to transport the crust to an orogenic zone (Silver 1996). Another regards orogeny as a whole plate deformation, inferring the crust and mantle should deform coherently as parts of the plate (Silver 1996). Alternatively, the mantle could dominate the orogenic process because of its potential greater strength, and the crust would passively deform along with the mantle (Silver 1996). Using shear wave analysis to study seismic anisotropy beneath the Bighorn Mountains, Wyoming, greater knowledge of upper mantle structures beneath continental interiors and their relationship with crustal deformation is attained.

SHEAR WAVE SPLITTING BACKGROUND

Shear wave splitting arises when a seismic shear wave propagates through an anisotropic medium and splits into two quasi-shear waves, shear waves of lesser energy, with perpendicular polarizations that propagate at different velocities (Fouch et al. 2006). These separate components are captured at broadband receivers, a specific type of seismometer that record a wide range of frequencies, and are converted into two splitting parameters. These are the polarization direction of the fast shear wave, ϕ , and the splitting delay time between the fast and slow shear-waves, δt (Gao et al. 2010). The values of ϕ and δt represent the effects of anisotropy on the shear wave based on the specific path through the earth taken by the wave and are highly dependent upon the simplicity or complexity of the geometry of the anisotropic material (Fouch et al. 2006). ϕ and δt parameters reveal the type of anisotropy, whether LPO or SPO.

Seismic anisotropy resulting from SPO is due to

geometrical patterns of velocity impedance contrasts (Fouch et al. 2006). Beneath stable continental interiors, SPO results from aligned structures such as joint systems, and sediment layering. LPO in the crust and mantle is due to alignment of systematically fast crystallographic axes of elastically anisotropic minerals (Fouch et al. 2006). In the upper mantle, olivine is assumed to play a dominant role in the generation of seismic anisotropy, as it is the most abundant mineral in the upper mantle, and deforms in the dislocation creep regime to depths of 200-400 km in the upper mantle (Fouch et al. 2006). The ϕ for LPO is expected to be parallel to shear direction or stretching direction (Karato et al. 2008). However, this is not always the case as experimental results show that water content and the presence of partial melt can drastically affect ϕ in olivine (Karato et al. 2008).

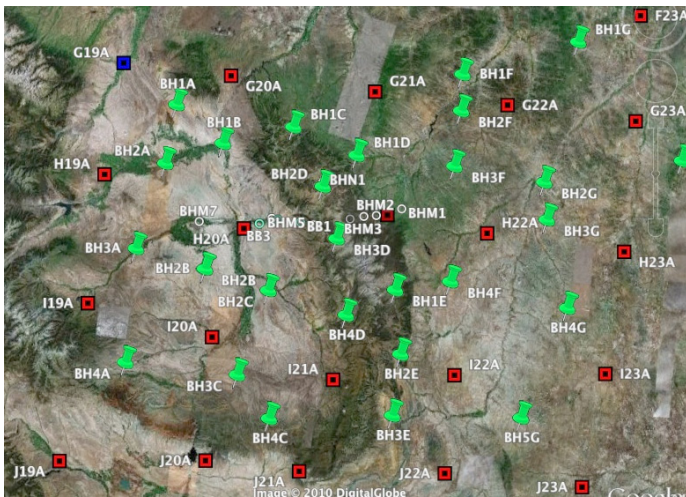


Figure 1: Broadband stations distribution of study area which extends from the Bighorn Basin to the Powder River Basin. The red squares are the US array broadband stations and the green thumbtacks are the BASE array broadband stations.

DATA

In this study we used a broadband station array that stretches from the Bighorn Basin across the Bighorn Mountains and ends in the Powder River Basin (Fig. 1). The broadband network includes stations within the US Array and the Bighorn Arch Seismic Experiment (BASE) forming a dense array that collected a large number of seismic events generated from spatially diverse locations in relation to our study area

(Fig. 1). The twenty one US-Array stations have been recording data since 2008, and the 38 BASE stations have been recording data since 2009, with data stored at the IRIS data center. One advantage of our study is that we have more broadband stations than most studies of continental interiors in the past, and although the broadband stations used in our study recorded seismic events for a shorter period of time than other short-term station deployments, they recorded an above average number of events due to high global earthquake activity. This resulted in a dense array which has collected a huge number of seismic events with great spatial coverage relative to our study area. In our study, the seismic events used occurred in the epicentral distance range of a minimum of 85° of arc to a maximum of 145° of arc away from our stations (defined as teleseismic). This parameter insured that all waves received by our stations had first passed through the outer core, erasing noise obtained near the epicenter. We analyzed all seismic events that had a magnitude of 5.75 Mw to 10 Mw, and put no depth constraints on the earthquakes we studied. We used splits derived from SKS, SKKS, and PKS phases, applied a band pass filter, which allows us to analyze data within a frequency range, with an upper limit of 1 Hz and a lower limit of 0.02 Hz. This filter was chosen because it cut out unwanted noise. All data were processed in Split Lab, a graphical interface which facilitates the processing of teleseismic shear-wave splitting observations (Wustefeld et al. 2008). After the splits had been analyzed, the results were assessed for quality based on parameters designed by Megan Anderson and Colorado State University graduate student Mindy Solomon. Based on these quality ratings, splitting results with a quality rating of 50 or higher are used for analysis described below.

METHODS

While the study of seismic anisotropy through shear wave splitting is not new, my analysis uses a technique we termed pierce point analysis (Gao et al. 2010), which until recently had not been applied to shear wave splitting, and offers significant advantages over past methods. In previous studies, the splitting results, including δt and ϕ , had been averaged at each station. This is problematic for several reasons: (1) this approach assumes that the path of the XKS wave from the outer core to the receiver is coming in per-

factly vertical. Therefore, it is impossible to constrain depth of anisotropy along the path without using other methods in conjunction with shear wave splitting; (2) this method assumes that there is only one homogeneous layer of anisotropy with its fast axis parallel to the surface, overlooking the possibility of multiple layers of anisotropy, laterally homogeneous layers of anisotropy, and anisotropic layers containing a plunging axis. Although pierce point plots do not overcome the problems associated with multiple layers of anisotropy, or anisotropic layers containing a dipping axis, we plot backazimuth (ray path orientation from receiver to earthquake epicenter) vs. ϕ and δt to determine the likely number of anisotropic layers (Fig. 2 and 3).

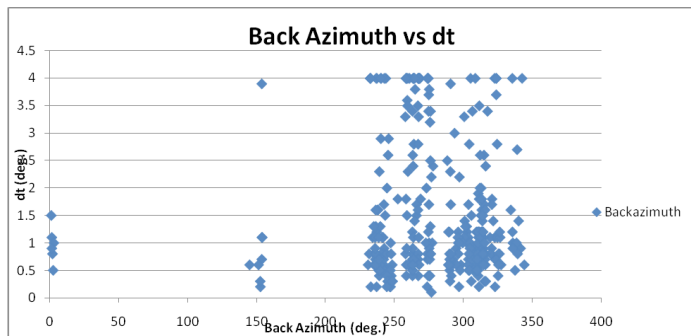


Figure 2: Backazimuth vs. δt . No noticeable trend indicating 2 layers of anisotropy, which would be seen as a $\pi/2$ period.

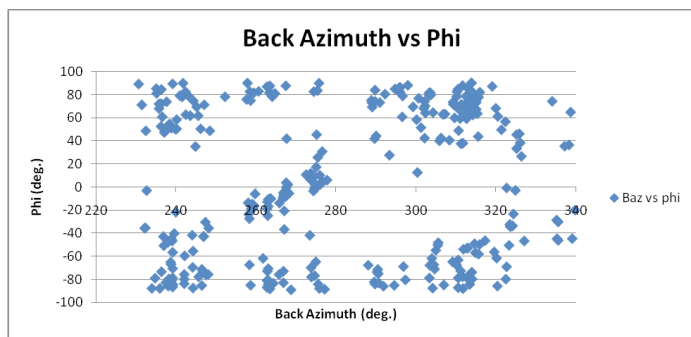


Figure 3: Backazimuth vs. ϕ . No noticeable trend indicating 2 layers of anisotropy, which would be seen as a $\pi/2$ period.

The pierce point analysis takes all of the splitting results at each station and analyzes them individually at various depths by back projecting the splitting results along the non vertical ray path, resulting in varying latitude, longitude, and ϕ for each depth designation. In this way, pierce point plots offer a more complete view of anisotropy in areas where a single layer has been established through its ability to image lateral heterogeneity and the likely depth of anisotropy. In conjunction with the pierce point plots, we determine the depth that provides the most spatially coherent map of the splitting observations, with local variation of ϕ minimized between samples. Using the variation plot (fig. 4), I am able to distinguish the pierce point plot which most accurately displays the anisotropy, by calculating the variation factor (standard deviation of δt 's and ϕ 's within regions of the map for each pierce point plot) (Gao et al. 2010), allowing me to find the source of the observed anisotropy.

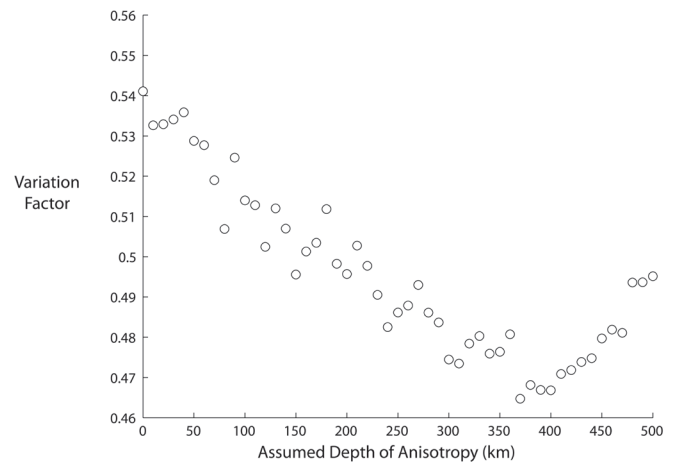


Figure 4: Variation plot displaying the variation of splitting parameters at depths from 0 km to 500 km in increments of 10 km. Lowest variation observed at 370 km, indicating anisotropy at 370 km. Plot was made based on the algorithm seen in Gao et al. (2010).

RESULTS

The medium underneath the Bighorn Mountains appears to be a simple single layer of anisotropy based on backazimuth plots (Figure 3 and 4). Because there is no trend in the plots with a period of $\pi/2$, which

indicates two layers of anisotropy are present, we are able to infer that there is only one layer of anisotropy (Silver and Savage 1994). The depth of minimum variation is indicated at a depth of 370 km (Figure 4). At that depth, the pierce point plot reveals an average ϕ of \sim N80E to the west of the Bighorn Mountains, with an average δt of \sim .9 seconds, and to the east of the Bighorns, an average ϕ of \sim N40E with an average δt of \sim 1.0 seconds.

DISCUSSION

Our observed splitting results reveal two dominant ϕ , an east-west orientation on the western side of the Bighorn Mountains, and a north east orientation on the eastern side of the Bighorns. If the dominant anisotropy is observed in the crust, we would attribute this to SPO. However, depth of the anisotropy at 370 km is deep enough for the anisotropy to be due to mantle deformation and LPO; at such depths SPO is not expected (Gao et al. 2010). Therefore LPO arising from the apparent plate motion of the North American plate (N50E) (Fouch et al. 2006) is a plausible mechanism responsible for the observed anisotropy to the east of the Bighorns. The same mechanism cannot explain the shear wave ϕ to the west of the Bighorn Mountains (Fig. 5). This is problematic as there is only one observed layer of anisotropy that contains two spatially distinct ϕ . At such depths, a lithospheric keel associated with Wyoming Craton may be causing the lateral variation observed in ϕ . At the depth of observed anisotropy, 370 km, we hypothesize that observed anisotropy is both in the asthenosphere, due to apparent plate motion of the North American Plate, and also in the lithospheric mantle within the Wyoming Craton. The more variable ϕ to the east of the Bighorns is interpreted to be anisotropy within the Wyoming Craton, and the more homogeneous anisotropy to the west of the Bighorns is thought to be derived in the asthenosphere. This is supported by seismic tomographic data from Sigloch et al. (2008) study of the Farallon Plate beneath North America, in which they observe the Wyoming Craton's at shallower depths beneath and to the west of the Bighorn Mountains, and protruding to greater depths to the east of the Bighorn Mountains. Similar results are also seen in Drew Thayer's work (This Volume).

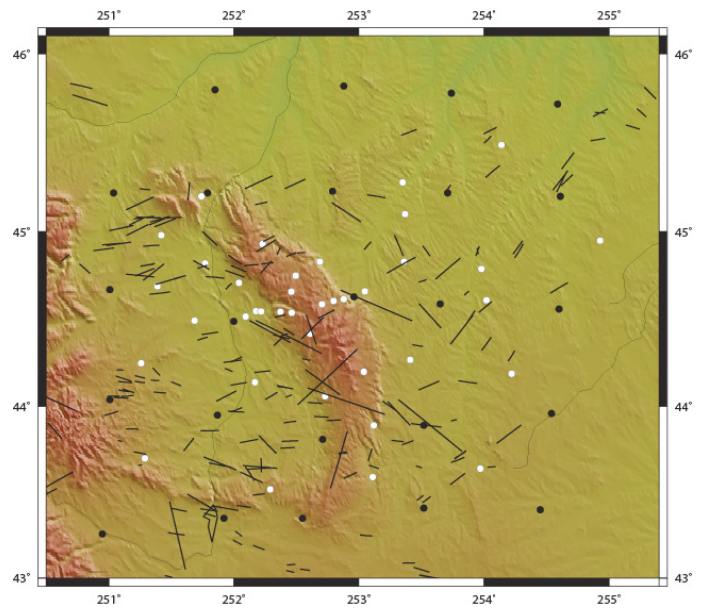


Figure 5: Pierce point plot representing the depth of dominant anisotropy beneath the Bighorn Mountains. The orientation of the lines represents ϕ , and the length of the lines represents the amplitude of δt . This plot is displaying the splitting parameters at the least variable depth of 370 km.

CONCLUSION

Backazimuth analysis of shear wave splitting data indicates that there is a single layer of anisotropy beneath the Bighorn Mountains. The most likely depth of the anisotropy is at 370 km and has an orientation of N80E to the west and N40E east of the Bighorns. Our interpretation is that anisotropy, at this depth, is observed in the asthenosphere to the west, and within the Wyoming Craton to the east. Our results show that the formation of the Bighorn Mountains did not significantly contribute to the dominant upper mantle anisotropy below, and provide strong evidence of lithospheric mantle strongly affecting asthenospheric structure to significant depths beneath continental interiors.

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