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

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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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CONSTRAINTS ON DEPTH AND LATERAL DISTRIBUTION OF ANISOTROPY IN THE BIGHORN MOUNTAINS: ANALYSIS OF FREQUENCY DEPENDENCE IN SHEAR-WAVE SPLITTING

DREW C. THAYER, Colorado College
Research Advisor: Megan Anderson

INTRODUCTION

The Bighorn Mountains in northern Wyoming are one of many basement-block uplifts of the Laramide Orogeny. Researchers attribute this orogeny to a shallowing of the subducting Farallon oceanic slab in the Californian Pacific subduction zone during the Cretaceous (e.g. Coney and Reynolds, 1977, but do not understand the mechanisms of crustal and lithospheric deformation which made the uplift possible. Furthermore, there is considerable debate concerning why the Bighorn arch, and the Rocky Mountains in general, were uplifted so far from the Pacific subduction zone, and in the middle of a stable craton (Snelson, 1998; Sigloch, 2011). Proposed models of crustal deformation (Erslev et. al, 2010) cannot be tested without first understanding the deep crustal and upper-mantle structure beneath northern Wyoming.

It is not in fact clear that the Archean lithospheric mantle remains beneath the Wyoming craton, as it may have been tectonically eroded or otherwise greatly modified by the Farallon slab (Saleeby, 2003). The BASE project has collected high-resolution broadband seismic data beneath the Bighorn Mountains, and this study analyzes shear-wave splitting in the BASE data to investigate patterns of anisotropy in the crust and lithosphere of the Wyoming craton (a record of Archean and Proterozoic deformation) and/or the flow of asthenospheric mantle caused by current tectonic processes. If the lithospheric mantle has been sheared off, we would expect to find anisotropy characteristic of asthenospheric flow, which is well documented in the western US (Waite, et. al., 2005). If the Archean lithospheric mantle has been preserved, we have these questions: A) Is there anisotropy in both the lithospheric mantle and the asthenosphere beneath the Bighorn region, and if so, B) is the orientation of anisotropy vertically heterogeneous (a difference between the lithosphere and asthenosphere), and C) do orientations of anisotropy within the lithosphere and asthenosphere correspond with known geologic and tectonic features?

To constrain measurements of anisotropy to specific depths, this study analyzes frequency dependence in the BASE data, a technique shown to be useful in constraining depth and orientation of anisotropy in other regions (e.g. Long, 2010). The relationship observed between the frequency of wave energy and the thickness of an anisotropic layer that can affect that wave allows us to assume a general relationship of depth and frequency dependence: that splitting in high-frequency waves is caused by shallow anisotropy, and splitting in low-frequency waves is caused by deeper anisotropy. This study provides new constraints on the structure of the deep crust and upper mantle of northern Wyoming and finds that both asthenosphere and lithospheric mantle exist, asthenospheric anisotropy corresponds with absolute plate motion, and lithospheric anisotropy is laterally heterogeneous.

METHODS

This study uses data from two broadband seismometer arrays in the Bighorns region of Wyoming. The Earthscope US-Array has been in place for 2 years and consists of 24 stations in a 70 km grid across the region. The BASE array supplements this grid with 40 stations in place for 1.25 years, increasing station density to 15-25 km average spacing. Each station uses a Guralp CMG-3T seismometer and a Quanterra 330 digitizer. During their deployment, the stations recorded energy from earthquakes covering 355 degrees of backazimuth (the direction from a receiver to an earthquake source).

I collaborated with Keck Consortium researchers John Hornbuckle (Washington and Lee College) and Triana

Ufret (University of Puerto Rico) to process the raw data using Splitlab, a program developed by Wustefeld, et al. (2008), for determining the splitting parameters of split shear waves: a fast direction ϕ and a delay time δt. For each station, we determined splitting parameters for earthquakes greater than magnitude 5.75 and between 85° and 145° from the station. We assign each splitting result a quality rating according to its signal/noise ratio, initial and corrected particle motion, and the correlation of the three mathematical methods, in order to eliminate low-quality results. As a diagnostic test for complex anisotropy, we make plots of backazimuth vs ϕ and δt; Silver and Savage (1994) find that these plots can show patterns associated with different geometries of anisotropic structure. The periodicity of the plotted data can reveal a single horizontal anisotropic layer, a single dipping layer, or two layers of anisotropy. We also record null results (no splitting) and their backazimuth.

To search for frequency dependence in the data, I filtered high-quality split waves into four distinct frequency bands to determine which bands contain split XKS energy. First, I determined that the vast majority of wave energy in our dataset is between 0.04 Hz and 1 Hz. I then designated low-frequency (0.04-0.1 Hz), intermediate (0.1- 0.2 Hz), high (0.2- 0.5 Hz) and very high (0.5-1.0 Hz) bands. My low, intermediate, and high bands match those used by Long (2010), which will facilitate a comparison of our data to other regions .

RESULTS

The anisotropy we measured in the Bighorn region has an average δt of 0.73 s (+/- 0.26 s) and shows significant lateral variation in ϕ over tens of kilometers. Our plots of backazimuth vs ϕ and δt do not show any systematic periodicity, which indicates complex lateral heterogeneity of anisotropic structure rather than two layers of homogeneous anisotropy (Silver and Savage, 1994)

This study finds that splitting characteristics vary with frequency in most of the Bighorn region. The majority of split XKS energy in the BASE dataset is high frequency (0.2-0.5 Hz). The majority of low-frequency XKS energy found is null energy. High-frequency ϕ measurements vary between the western Bighorn region (Bighorn Basin and Bighorn arch) and the Powder River basin to the east. In the west, ϕ is tightly constrained from W to WNW; the Powder River basin is dominated by a W group but also contains N, NW, SW, and SSW orientations (figure 1). Low-frequency φ and null orientations are consistent across the entire study area with a two tightly constrained groups, NW and SW; with an additional NNW group in the northern Powder River basin (figure 1). In both the western Bighorn region and the Powder River basin, high-frequency ϕ is distinctly different from low-frequency ϕ and null orientation; an exception is in the Powder River basin, where a small SW group of high-frequency ϕ matches low-frequency orientation.

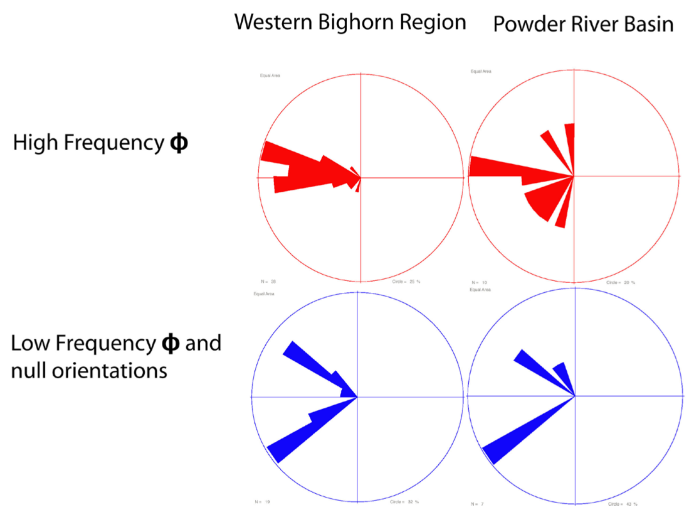

Figure 1. High-frequency ϕ (red) varies between the Western Bighorn Region and the Powder River Basin, while low frequency ϕ and null orientations (blue) are consistent in both regions.

DISCUSSION

If the lithosphere beneath the Bighorn region was removed by the Farallon slab, we would expect to measure split waves largely influenced by anisotropy of the asthenospheric mantle. Waite, et. al., (2005) measures mantle anisotropy in the greater Yellowstone region, including northwestern Wyoming, and finds station averages of ϕ to be consistent in most of the region and parallel to current North American absolute plate motion (246°), which is the expected result for a signal dominated by current shearing of the asthenosphere. Waite et al. finds a mean δt of 0.9 s, which he explains by a 100 km thick 4% anisotropic layer. (Figure: mantle anisotropy from Waite, 2005, in group intro). This is consistent with asthenospheric anisotropy measurements in other continental interiors, which find large-scale parallel orientation of ϕ and δt ranging from 1.0 s to 2.5 s (Fouch and Rondenay, 2006). In the Bighorn region of northern Wyoming, we find an average δt of 0.73 s and highly variable ϕ measurements, which contrasts greatly with these studies and suggests that the dominant anisotropy beneath the region is in not in the asthenosphere.

Delay time is a function of the intensity of anisotropy and the thickness of anisotropic layers. Given this relationship, there is an upper limit to δt created by each structural unit of the Earth, and most workers consider the maximum δt resulting from the crust to be 0.5 s, that of the lithospheric mantle to be 1.0 s, and any larger δt to result from the asthenosphere (Long, 2010). The δt we find in the Bighorn region is too large for only crustal anisotropy, and not large enough for asthenospheric anisotropy, so it is most likely caused by anisotropy in the lithospheric mantle.

The depth constraint provided by δt is supported by the frequency content of XKS splitting. Previous studies analyzing frequency dependence have found most split XKS energy to be low-frequency (<0.1 Hz), with very little above 0.2 Hz, and interpret low-frequency splitting to be caused by asthenospheric anisotropy (Long, 2010). In contrast, the high-frequency splitting I find in the Bighorn region must be caused by a thinner layer than the asthenosphere, which indicates strong lithospheric anisotropy. Possible models of lithospheric mantle that could create an average δt of 0.73 s are: 50 km thick with 6.5% anisotropy; 100 km thick with 3.25% anisotropy; or 150 km thick with 2.2% anisotropy (table 1).

Table 1:

δt= L*δβ/ βo

δt= delay time
L= path length
δβ= dimensionless intrinsic anisotropy
βo= isotropic s-wave velocity

thickness (km)	δβ	βo (km/s)	δt (s)
50	6.5%	4.47	0.73
100	3.3%	4.47	0.73
150	2.2%	4.47	0.74
200	1.6%	4.47	0.72

Table 1: Models of lithospheric mantle with different thicknesses and % anisotropy (δβ) which could produce the observed δt of 0.73 s. Models are based on the δt equation from Silver (1996) and assume the global average s-wave velocity of 4.47 km/s for lithospheric mantle.

It is a critical discovery that high-frequency ϕ is distinctly different from low-frequency ϕ and null orientations in the majority of the Bighorn region. This frequency-dependent splitting indicates that there are two layers of anisotropy with different internal orientations (Long, 2010). Based on the frequency bands used, I interpret high-frequency ϕ to represent orientation of anisotropy in the lithosphere and low-frequency ϕ and null orientations to represent anisotropy in the asthenosphere.

CONCLUSIONS

This study finds that both lithospheric and asthenospheric mantle exist beneath the Bighorn region of northern Wyoming, and these mantle regions have different internal orientations. Lithospheric mantle structure could vary from 50 km of 6% anisotropy to 150 km of 2% anisotropy; the high-frequency nature of XKS splitting suggests that thinner models are more likely, but this is hard to constrain. A new tomography of North America (Sigloch, 2011) images a thick layer of high velocity material under Wyoming up to 300 km thick, most consistent with the existence of old, cold, lithospheric mantle. My results support her hypothesis that the Farallon slab was deep enough beneath central North America to pass beneath the lithosphere and not remove it. My results match expected spatial patterns of mantle anisotropy: orientation of asthenospheric anisotropy is consistent across the entire region and contains a NW (309°) group and a SW (240°) group. The SW group matches the anisotropy measured by Waite, et. al. (2005), which is caused by shearing of the asthenosphere due to absolute plate motion (244°).

There are some differences in orientations of lithospheric anisotropy between the western Bighorn region and the Powder River basin. Unfortunately, it is difficult to separate the affect of crustal anisotropy from the affect of lithospheric mantle anisotropy in high-frequency XKS splitting. Seismic reflection profiles (Snelson, 1998) running N-S though the Bighorn and Powder River basins suggest a difference in crustal structure between these regions. Based on these observations, I speculate that the eastern range-bounding fault of the Bighorn arch lies on an Archean-age boundary in the lithosphere. It is possible that this boundary is related to the Trans-Hudson orogen located further East, and that there exists a causal link between this lithospheric boundary and the location of the Bighorn arch within northern Wyoming.

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