Shear-Wave Splitting beneath Saudi Arabia: Evidence for Plate and Density Driven Flow

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Abstract
Mantle anisotropy across Saudi Arabia was analyzed using shear-wave splitting recorded by stations from three different seismic networks: the largest, most widely distributed array of stations examined across the area to date. Stations near the Gulf of Aqaba display fast orientations aligned parallel to the Dead Sea Transform Fault, most likely related to the strike-slip motion between Africa and Arabia. However, most of our stations across Saudi Arabia are statistically the same, with north-south-oriented fast directions and delay times averaging about 1.4 sec. Since end-member models of fossilized anisotropy and flow-dependent anisotropy are inconsistent with our observations, we interpret them as a combination of plate and density-driven flow in the asthenosphere. Combining near-east orientation flow associated with absolute plate motion with northwest orientation flow associated with the channelized Afar plume along the Red Sea produces a north-south resultant that matches the observations.

Introduction
Understanding of Saudi Arabia’s complex tectonic environment has been restricted by limited data availability and station distribution. Using data uniquely available to us from a new, larger network of stations, our goal is to extend previous studies to generate a more complete characterization of the lithospheric structure in this area. As part of this work, shear-wave splitting analysis has been employed to measure seismic anisotropy across Saudi Arabia. This allows us to compare the anisotropically signature obtained with different candidate models of mantle deformation and rigidity mechanisms.

Obvious in the upper mantle can develop lattice preferred orientations, where the fast axes become parallel to the shear direction and can cause velocity variations with propagation direction. When a shear-wave encounters an anisotropic region, it splits into two orthogonal components, one traveling faster than the other (Figure 1). The anisotropy can be characterized by the polarization direction of the fast wave (β) and the delay time (δ) between the two waves. These measurements can be used to constrain the deformation mechanisms in the upper mantle.

Data and Methodology
Teleseismic data recorded on three different arrays were used (Figure 2). We primarily analyze SKS phases, but S phases and a few SKR observations were also included. Core-refracted phases like SKS and SKR are well suited to study anisotropy because the phase conversion in the outer core removes any source-side-effects, leaving the waves completely radially polarized. However, the SKS (and SKR) splits of these phases is usually limited to direct 5 phases were also included. In total, we selected 247 records of SKS phases, 12 records of SKR phases, and 52 records of 5 phases, using a total of 135 events (Figure 3).

Figure 1. Cartoon of Shear-Wave Splitting. When a shear-wave encounters an anisotropic region, it will split into orthogonal components, separated by some delay time δ. Taken from http://geophysics.ucsc.edu/research/gilbert.

Results and Discussion
In general, the stations display a north-south δ with an average δ of 1.40 sec (Figure 5). Stations near the Gulf of Aqaba (Figure 6) are a notable exception. These stations display an average δ that is rotated further east than the other stations examined.

The Gulf of Aqaba stations are fast by a one-layer model whose β is parallel to the Dead Sea Transform Fault, similar to Rümpker et al. and Schmid et al. (2004). The remaining stations across Saudi Arabia are very consistent, yet a straightforward explanation for these observations is difficult to apply.

Wolfe et al. (1999), who found similar splitting results in this area, concluded that the anisotopic signature is either fossilized anisotropy or present-day asthenospheric flow. Most of our examined stations sit on the Arabian Shield (Figure 7), an area of north-south striking Proterozoic terranes. The anisotropy here could be related to the Shield’s assembly. However, later tectonics produced the Najd fault zone, which likely disturbed any fossilized Proterozoic signature (Steele and Camp, 1985). Also, many studies indicate that the lithospheric thickness, especially near the Red Sea, is too thin for fossilized anisotropy to accumulate the observed δ (e.g. Camp and Roobol, 1992; Rodgers et al., 1999; Benoit et al., 2003). Additionally, the observed δ does not match the APM direction (e.g. Figure 5). The two end-member explanations suggested by Wolfe et al. (1999) do not adequately fit the observations.

Therefore, we conclude that the anisotropy is the result of a complex interaction of flow in the asthenosphere. Based on topography variations and volcanic distribution, it has been suggested that flow radiating from the Afar plume (Figure 7) is channeled beneath the Red Sea (Camp and Roobol, 1992; Ebinger and Sleep, 1998). Combining this northwest oriented, channelized plume flow with northeast oriented flow associated with APM produces a north-south resultant (Figure 8). This conclusion is supported by other geologic evidence, including seismic tomography, mantle flow modeling, and isotope studies (Schilling et al., 1992; Benoit et al., 2003; Danarchi et al., 2003).

Conclusions
We have analyzed shear-wave splitting using the method of Silver and Chen (1991) over the largest network of stations examined across Saudi Arabia to date. We find that:

- Stations near most stations have similar observations, with north-south oriented fast polarization directions and average delay times of 1.40 sec.
- Neither present-day plate motion nor fossilized anisotropy adequately explain the observed splitting parameters.
- The splitting observations are matched by a combination of plate and density driven flow in the asthenosphere, related to absolute plate motion and channelized flow from the Afar plume.

References
Stoeser and Camp, 1985
Rodgers et al. (1999).
Schilling et al., 1992
Schilling et al., 1992