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Shear-wave splitting across western Saudi Arabia: The pattern of upper mantle anisotropy at a Proterozoic shield

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Abstract. We constrain upper mantle anisotropy across the Arabian Shield from shear-wave splitting analyses of *SKS* phases at eight temporary broadband stations that operated in Saudi Arabia. The direction of fast polarization is consistently aligned north-south and the delay time between fast and slow shear waves is generally 1.0 to 1.5 s, indicating that the mantle anisotropy is relatively homogeneous and coherent. We cannot distinguish between two possible models for the origin of this signal. The observed splitting may reflect fossil upper mantle anisotropy associated with the dominantly east-west accretion of oceanic terranes and formation of the Proterozoic Arabian lithosphere. Our results may also be compatible with present-day asthenospheric anisotropy caused by the northward absolute plate motion of the Arabian plate or northward asthenospheric flow from an Ethiopian mantle plume.

Introduction

Shear-wave splitting measurements yield the direction of polarization ϕ of the fast shear wave and the delay time δt between the fast and slow shear waves [*Silver and Chan*, 1991; *Vinnik et al.*, 1992]. Because olivine is anisotropic and develops strain-induced lattice-preferred orientation, splitting results may be used to infer mantle strain fields [see review by *Savage*, 1998]. However, there is an ongoing dispute over whether ϕ at continental cratons is parallel to past geologic features and reflects the fossil lattice-preferred orientation (LPO) of olivine minerals within the Precambrian continental lithosphere [*Silver and Chan*, 1991; *Silver*, 1996], or if ϕ is directed parallel to the present-day absolute plate motion and reflects LPO associated with asthenospheric shear [*Vinnik et al.*, 1992, 1995]. *Silver* [1996] presents an extensive compilation of the continental splitting results, showing that several continental shields (the Canadian Shield, Brazilian Craton, and Kaapval Craton) display ϕ parallel to ancient geologic structures, consistent with anisotropy caused by vertically coherent deformation of the crust and mantle during Precambrian orogenesis. This hypothesis is also consistent with the existence of a "tectosphere" [*Jordan*, 1978]: a stable chemical boundary layer that forms the mantle roots of continental shields and maintains a layer of fossil seismic anisotropy and fast seismic velocities down to depths of 200-300 km [*Gaherty and Jordan*, 1995]. Thus shear-wave splitting patterns at cratons may potentially provide insight into the dynamics of the generation and stabilization of the continental lithosphere. On the other hand, in the absence of a more viscous and stable tectosphere, the fossil anisotropy at temperatures > 900°C could be reset by subsequent deformation [*Vinnik et al.*, 1992], and splitting might reflect present-day asthenospheric shear associated with the absolute plate motion.

In this paper, we present the first analysis of mantle shear-wave splitting at the Arabian Shield. Saudi Arabia is an atypical shield and it is uncertain whether it would be underlain by an old and stable tectosphere for two reasons. First, the Arabian Shield is relatively young, formed in the late Proterozoic [*Stein and Goldstein*, 1996] rather than in the Archean. It has been suggested that only Archean lithosphere has a chemically distinct tectosphere, because the thermal state of the Earth may have changed at the Archean-Proterozoic boundary [*Richter*, 1988]. Second, Saudi Arabia has not been tectonically stable since its formation [*Almond*, 1986]. Continental rifting commencing at 30 to 20 Ma separated the formerly conjoined Arabian and Nubian Shields and created the Red Sea spreading center, and several volcanic fields in western Saudi Arabia erupted from 30 Ma to Recent [*Camp and Roobol*, 1992]. Western Arabia is also topographically high and was uplifted ~1000 m after continental rifting and seafloor spreading, which has been proposed to reflect the presence of hot, low-density upper mantle beneath Saudi Arabia [*Almond*, 1986; *Camp and Roobol*, 1992].

Shear-wave Splitting Data and Analysis

We analyze *SKS* phases recorded on eight portable broadband three-component stations (Figure 1) deployed across the Saudi Arabian Shield from November 1995 to March 1997 (a ninth station, BISH, was damaged early in the experiment and did not yield sufficient data for our analysis). The stations consisted of STS-2 seismometers and REFTEK data recorders and the aperture of the array was on the order of 850 km. All sites except RIYD were located on the crystalline basement rock of the Arabian Shield and away from the volcanic fields associated with Cenozoic rifting. Stations TAIF and SODA were located 70-110 km from the western coast; stations RANI, HALM, RAYN, and AFIF were located farther inland; and station RIYD was located on the Phanerozoic sedimentary cover that extends throughout eastern Saudi Arabia and masks the geology of the underlying

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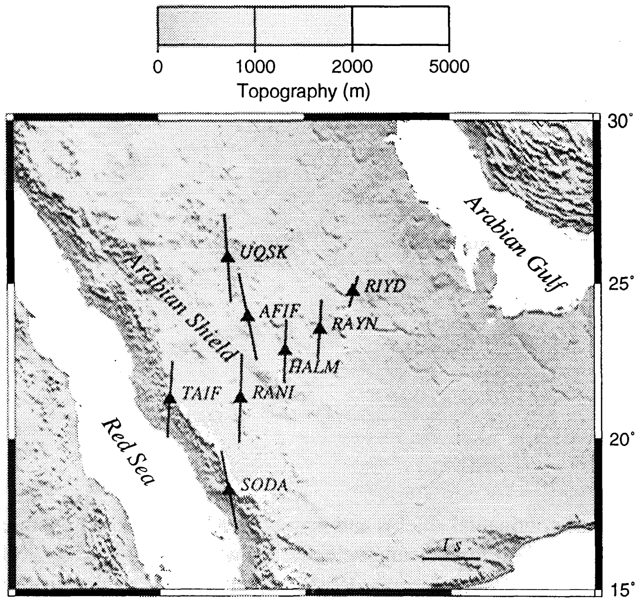

Figure 1. Topographic map of the Arabian peninsula. The broadband stations used this study are shown are solid triangles and splitting results (Table 1) are plotted. The fast direction ϕ is consistently oriented to the north and the delay time δt ranges from 0.5 to 1.5 s.

basement. The stations were quiet [*Mellors*, 1997;*Vernon and Berger*, 1998] and recorded high quality teleseismic waveforms (Figure 2). Measurements of shear-wave splitting parameters, the fast polarization direction ϕ and the delay time δt, were made using the method of *Silver and Chan* [1991] as modified by *Wolfe and Silver* [1998], which allows for the estimation of a single set of splitting parameters by stacking data errors from a multiple set of earthquake events. As discussed below, we obtain well-constrained splitting parameters (Table 1) for all stations.

Table 1. Shear-wave splitting parameters

Station	Lat. (°N)	Lon. (°E)	ϕ (°)	δt (s)
AFIF	23.9310	43.0400	-12±2	1.5±0.1
HALM	22.8454	44.3173	2±2	1.1±0.1
RANI	21.3116	42.7761	2±2	1.5±0.2
RAYN	23.5220	45.5008	4±2	1.0±0.1
RIYD	24.7220	46.6643	15±6	0.5±0.1
SODA	18.2921	42.3769	-11±2	1.4±0.1
TAIF	21.2810	40.3490	4±4	1.3±0.2
UQSK	25.7890	42.3600	-4±2	1.5±0.2

The direction ϕ of shear-wave polarization is measured clockwise from north. Uncertainties for ϕ and δt are at one standard deviation.

Figure 2a gives an example of waveform splitting at station AFIF. The final solution, obtained by applying the method of *Wolfe and Silver* [1998] to 7 *SKS* phases, is shown in Figure 2b. The 1-contour is the 95% confidence interval and indicates that the splitting parameters are well constrained. Table 1 lists the solutions determined using the method of *Wolfe and Silver* [1998]. The backazimuths of the phases, which also reflect*SKS* polarizations, are mostly at 20° and 70°-90° in the northeast quadrant, with occasional additional arrivals from the southwest quadrant (210° and 260°). We find no indication of a variation of splitting with *SKS* polarization, such as might be produced by a two-layer model of anisotropy, although high-quality data from a larger range of backazimuths are needed to discount this possibility.

The solutions obtained from our analyses are plotted in Figure 1. Splitting parameters of *SKS* phases reflect the path-integrated effects of upper mantle anisotropy beneath the receiving seismometer and provide information on the orientation of the anisotropy as well as the combined effects of the thickness of the anisotropic layer, the degree of anisotropy, and the isotropic velocity. The fast direction ϕ consistently trends northward and

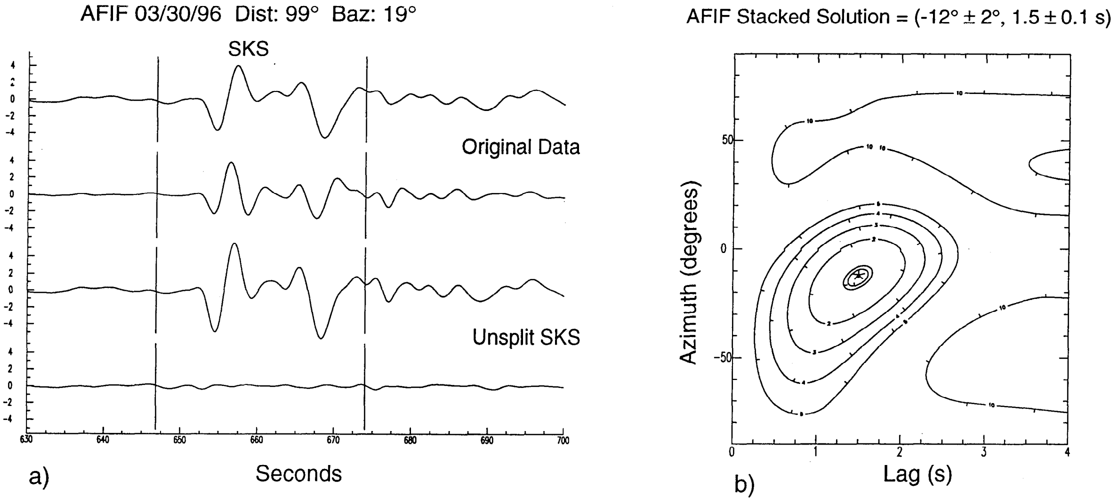

Figure 2. An example of splitting at station AFIF. a). Waveforms rotated into the radial and transverse direction. (Note that we do not fix waveform polarization to the earthquake backazimuth but rather obtain the polarization from the splitting solution: i.e., we search for the splitting parameters that minimize the smaller eigenvalue of the covariance matrix of corrected particle motion [*Silver and Chan*; 1991].) The top two waveforms show the original seismograms, while the lower two waveforms show the result after correcting for splitting using the solution parameters (ϕ=-12°, δt=1.5 s). b). The final solution, obtained by applying the method of *Wolfe and Silver* [1998] to 7 *SKS* phases. The 1-contour is the 95% confidence interval and indicates that the solution is well constrained.

displays only minor (±15°) variations across the network. Except for the small splitting (0.55 s) at RIYD, where the underlying basement geology is unknown, the delay times δt are also similar, ranging from 1.10 to 1.55 s. Since crustal splitting is typically small (≤ 0.2 s) [e.g., *Savage*, 1998], these measurements dominantly reflect upper mantle anisotropy across the seismic network. Splitting parameters lack vertical resolution and do not constrain the depth extent of anisotropy. Assuming values of intrinsic anisotropy from naturally-occurring peridotites, the thickness of the anisotropic layer may be estimated from the delay time, with every 1 s of splitting time delay, δt, implying about 100 km of anisotropic material (see *Silver* [1996]). The splitting values across Saudi Arabia therefore are consistent with anisotropic layers of 50- to 150-km thicknesses in the uppermost mantle, although these estimates have large uncertainties.

Possible Interpretations

We find a coherent splitting pattern across the Saudi Arabia network, indicating that the mantle beneath the Arabian Shield has nearly uniform anisotropy. ϕ shows only slight variations (±15°) across the network, though there is a systematic decrease in the delay time δt from 1.5 to 0.5 s along the northeast line of stations RANI, HALM, RAYN, and RIYD As discussed below, the northward-trending ϕ is compatible with the predictions of lattice-preferred orientation of olivine *a*-axes due to either fossil lithospheric structure or present-day asthenospheric flow.

Predicted fossil anisotropy

Western Saudi Arabia (Figure 1) is made up of 900-600 Myr-old crust, and the geology is divided into a series of Proterozoic island arc, ophiolite, and oceanic plateau terranes [*Bentor*, 1985; *Stoeser and Camp*, 1985; *Stern*, 1994; *Stein and Goldstein*, 1996], with many terranes and sutures having a northerly strike [c.f. *Stoeser and Camp*, 1985; *Stern*, 1994] consistent with dominantly east-west convergence. The northward ϕ directions may therefore be caused by fossil upper mantle anisotropy associated with accretion and convergence during formation of the Proterozoic Arabian lithosphere, as similarly proposed for several other cratons where ϕ is parallel to Precambrian geologic features [*Silver*, 1996]. However, the Arabian orogenesis was followed by a 50-100 Myr episode of intracratonic tectonism, generating the prominent northwest trending Najid fault zone, a major left-lateral strike-slip fault system that has as much as 200-300 km of displacement [c.f. *Stoeser and Camp*, 1985]. Thus, if the mantle anisotropy is associated with Proterozoic accretion and cratonization, it was not reset by the subsequent intracratonic deformation, which would have rotated ϕ to a northwest direction parallel to the Najid fault zone.

Predicted present-day anisotropy

The splitting parameters may be compatible with present-day asthenospheric anisotropy caused by the northward absolute plate motion (APM) of the Arabian plate. Figure 3 show the fast direction (ϕ) versus APM azimuths obtained from two different APM models, both of which yield slow velocities of 20-30 mm/yr. The *Gripp and Gordon* [1990] HS2-NUVEL1 model predicts APM directions of -20°-0° that are nearly parallel to ϕ. However, this APM model is based on Pacific hotspots and NUVEL-1 relative plate velocities, and may not be accurate for the distant Arabian plate. *O'Connor and le Roex* [1992] obtain an Euler vector for the absolute motion of Africa using Ar-Ar dates along the St. Helena and Gough volcanic chains. We recalculated the absolute motion of the Arabian plate using the *O'Connor and le Roex* [1992] model for the African APM and the relative motion Euler vector between Arabia and Africa from NUVEL-1A [*DeMets et al.*, 1994]. The APM azimuths from this second model are 20°-30°, slightly less consistent with the orientations of ϕ. Asthenospheric shear could alternatively be induced by a component of active mantle flow: for example, *Camp and Roobol* [1992] suggest that hot asthenosphere from the Ethiopian mantle plume may flow northward beneath west Saudi Arabia, which could also align ϕ in a northward direction.

Predicted anisotropy from continental rifting

The northward fast direction of anisotropy at stations near the western margin (TAIF and SODA, located 70-110 km from the western coast) is incompatible with the expected local signature of continental extension and breakup. This paleo-extension direction was to the northeast, as indicated by northwest (approximately coast parallel) trending normal faults and dikes generated at the western Arabian margin during this period [c.f. *Camp and Roobol*, 1992]. If the *a*-axes of mantle olivine grains were realigned parallel to this extension, then ϕ would be oriented at about 45°, which is not the case.

Discussion

Across the Arabian Shield, we find that the direction of fast polarization ϕ of shear-wave splitting is consistently aligned north-south and the delay time between fast and slow shear waves is generally 1.0 to 1.5 s. The tectonic origin of this mantle signal cannot be constrained at present. Arabia is an atypical shield because it is relatively young, formed in the late Proterozoic, and because the Arabian-Nubian Shield has been broken apart by Cenozoic continental rifting that formed the Red Sea spreading center. It is thus uncertain whether Saudi Arabia is underlain by an old and stable lithosphere or hot and deforming upper mantle.

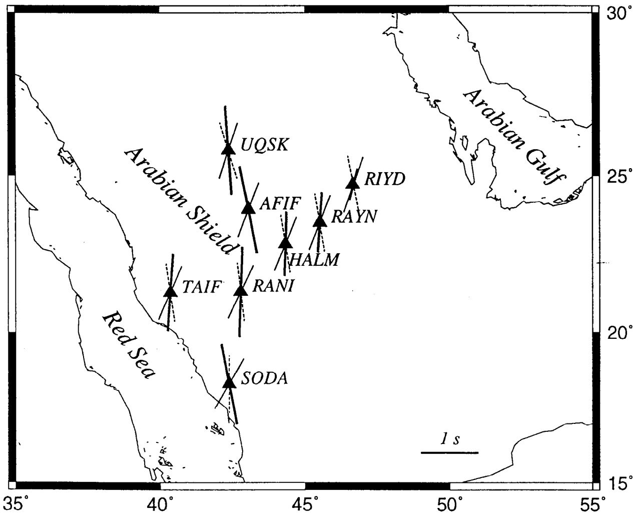

Figure 3. Plot of Saudi Arabia splitting parameters (thick lines) and absolute plate motion directions (APM) of the Arabian plate from two different models. Dashed lines note absolute plate motion direction from HS2-NUVEL1 [*Gripp and Gordon*, 1990]; thin lines denote absolute plate motion obtained by combining the African APM model of *O'Connor and le Roex* [1992] with the Arabia-Africa relative motion Euler vector of NUVEL-1A.

Paradoxically, previous geophysical and geochemical observations support opposite conclusions and do not resolve this question. Studies of global [*Su et al.*, 1994; *Li and Romanowicz*, 1996] and regional [*Hadiouche and Zürn*, 1992; *Mellors et al.*, 1998] seismic velocities suggest that the upper mantle beneath the Arabian shield may be slow compared to other Precambrian shields, which would imply a warm and actively deforming upper mantle beneath Saudi Arabia, and this result is consistent with the presence of a topographic high in western Saudi Arabia [*Almond*, 1986; *Camp and Roobol*, 1992]. Conversely, geochemical characteristics suggest that an old, intact continental lithosphere may remain present beneath the shield. In particular, peridotite xenoliths from Saudi Arabia, Israel, and Zabargad Island all yield old (400-800 Myr) Sm-Nd ages [e.g., *Blusztajn et al.*, 1995; *Stein and Goldstein*, 1996], indicating that the Arabian-Nubian continental lithosphere has remained chemically isolated since its initial formation and has not been removed by subsequent flow of hot upwelling mantle. Thus for the moment, the upper mantle beneath Saudi Arabia remains enigmatic, being characterized by low seismic velocities and an old geochemical signature, as well as a coherent pattern of mantle anisotropy.

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