Combined plate motion and density-driven flow in the asthenosphere beneath Saudi Arabia: Evidence from shear-wave splitting and seismic anisotropy

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ABSTRACT

We analyzed mantle anisotropy along the Red Sea and across the Arabian Peninsula using shear-wave splitting recorded by stations from three different seismic networks—the largest, most widely distributed array of stations examined across the Arabian Peninsula 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 observations across Arabia are statistically the same (at a 95% confidence level), with north-south–oriented fast directions and delay times averaging ~1.4 s. Since end-member models of fossilized anisotropy and present-day asthenospheric flow do not adequately explain these observations, we interpret them as a combination of plate- and density-driven flow in the asthenosphere. The combination of northeast-oriented flow associated with absolute plate motion with northwest-oriented flow associated with the channelized Afar upwelling along the Red Sea produces a north-south resultant that matches the observations and supports models of active rifting.

Keywords: Arabia, Red Sea, anisotropy, shear-wave splitting, continental rifting, mantle flow.

INTRODUCTION

When deformed by dislocation creep, olivine in the upper mantle develops lattice preferred orientations (LPO), where the crystallographic *a*-axes [100] become parallel to the induced shear, leading to velocity variations with propagation direction (Mainprice and Silver, 1993). Shear waves encountering such anisotropic regions split into two orthogonal components, one traveling faster than the other. The anisotropy can be characterized by the polarization direction of the fast wave (φ) and the delay time between the fast and slow waves (δt), and these measurements can be used to provide constraints on the mechanisms causing deformation in the upper mantle (Silver and Chan, 1991; Vinnik et al., 1992). In rift environments, one may expect a rift-perpendicular φ, since LPO should develop parallel to extension for dry upper-mantle conditions (Ribe, 1992). However, in a number of rift environments, such as the Baikal Rift zone, the Rio Grande Rift, and the East African Rift, the observed φ is actually closer to rift-parallel (Gao et al., 1997; Gashawbeza et al., 2004; Walker et al., 2004). This may indicate more complex rifting mechanisms or other deformation processes that dominate extension signatures. It has also been suggested that anisotropy observations may reflect previous tectonic episodes where the anisotropic signature has been "frozen" into the lithosphere (Gashawbeza et al., 2004; Walker et al., 2004).

Saudi Arabia and the Red Sea Rift zone offer an excellent environment in which to study the seismic anisotropy associated with rifting and extension. Several different types of models have been proposed to explain how rifting in the Red Sea developed. The passive rifting model assumes that extensional stresses due to far-field body forces are accommodated on large-scale detachment planes extending through the lithosphere below the rift. This results in passive upwelling of asthenospheric material below the rift, often accompanied by the extrusion of tholeiitic lava (Camp and Roobol, 1992). Flow beneath the rift is parallel to the direction of extension, which would predict a rift-perpendicular φ (Wernicke, 1985; Voggenreiter et al., 1988). The active rifting model involves thermal erosion of the lithosphere by flow in the underlying asthenosphere and requires the presence of hot, ascending material (Camp and Roobol, 1992; Daradich et al., 2003). The rift flanks are thermally uplifted, with elevation decreasing away from the rift axis, and associated lavas have an alkalic composition, reflecting a deep-mantle source. Local convection may lead to more complicated flow patterns and therefore more complex anisotropy at depth. Several studies have suggested that these two end-member models may not be mutually exclusive; rifting in the Red Sea may have been initiated by passive processes, followed by more recent active processes associated with a mantle upwelling (Camp and Roobol, 1992; Ebinger and Sleep, 1998; Daradich et al., 2003).

Several previous anisotropy studies near the Red Sea have revealed fairly consistent patterns. Wolfe et al. (1999) analyzed shear-wave splitting from eight Incorporated Research Institutions for Seismology (IRIS) stations across western Arabia (Fig. 1), which were operated as part of the Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL), and found δt values of 1.0–1.5 s and φ oriented approximately north-south. Receiver function analysis by Levin and Park (2000) found evidence for a more complex anisotropic structure beneath one Global Seismographic Network station, consisting of two dipping layers at depth, but with a resultant φ oriented north-south. Further north, Schmid et al. (2004) and Levin et al. (2006) examined splitting at several stations near the Gulf of Aqaba and the Dead Sea transform fault, where they found average δt of 1.3 s and φ slightly east of north, with some evidence for a more complex, two-layer anisotropic model. However, each of these studies was somewhat limited in their station distribution and data sampling.

In this study, we present a more comprehensive analysis of the anisotropic signature along the Red Sea and across Saudi Arabia by analyzing shear-wave splitting recorded by stations from three different seismic networks. This is the largest, most widely distributed ar-

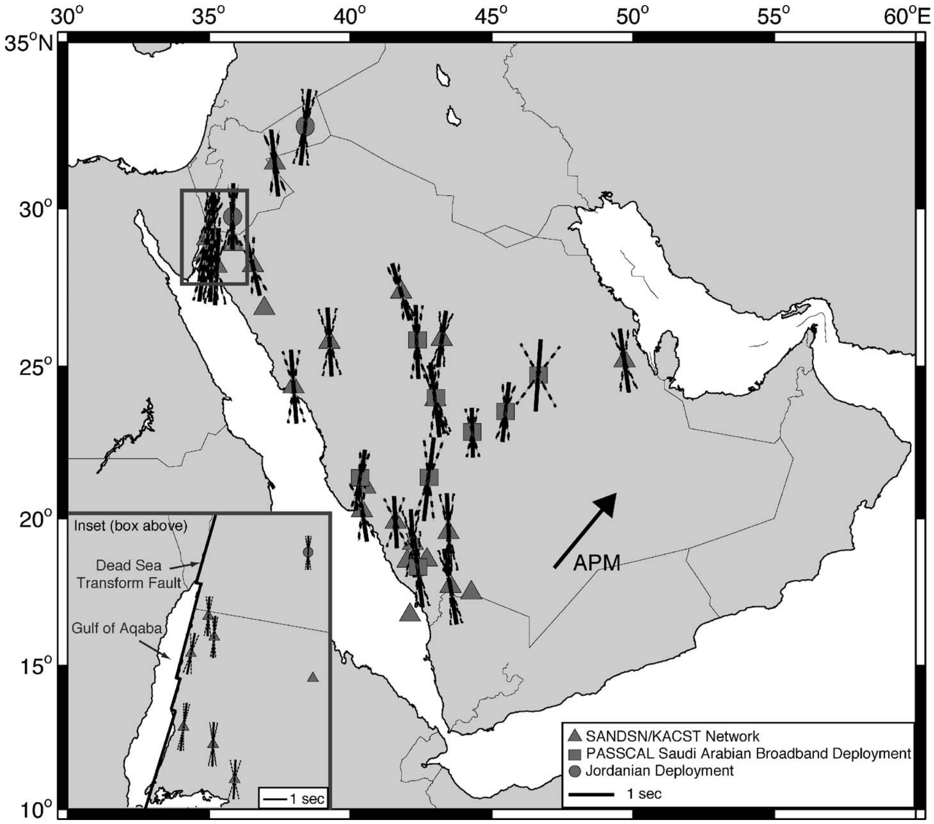

Figure 1. Map showing average splitting parameters. Bold, center lines at each station are oriented in station's average φ and length of line is scaled to average δt. Dashed "fans" show one standard deviation of fast angle. Inset provides closer view of Gulf of Aqaba stations (gray box). Triangles—SANDSN stations, squares—PASSCAL stations, circles—Jordan stations. Black arrow shows average absolute plate motion direction based on global positioning system (GPS) models (Reilinger et al., 1997; McClusky et al., 2003). APM—absolute plate motion.

ray of stations examined across Saudi Arabia to date. We demonstrate that the north-south φ is not just valid at isolated sites, but extends throughout the whole of Arabia. These observations cannot be adequately fit by previously proposed models of fossilized anisotropy or present-day absolute plate motion, and we present a new model that consists of a combination of both plate- and density-driven flow in the asthenosphere.

SHEAR-WAVE SPLITTING ANALYSIS AND RESULTS

Teleseismic data recorded on broadband instruments from three different seismic arrays were used. The largest array, the Saudi Arabian National Digital Seismic Network (SANDSN), includes 25 broadband stations distributed along the eastern edge of the Red Sea and across Saudi Arabia (Fig. 1; Al-Amri and Al-Amri, 1999). SANDSN data from events occurring since 2000 were used for this study. To supplement the SANDSN coverage, we also analyzed data recorded by the eight IRIS-PASSCAL Saudi Arabian Broadband Array stations, which operated from November 1995 to March 1997 (Vernon and Berger, 1998), as well as data recorded between 1998 and 2001 from two stations deployed in Jordan (Rodgers et al., 2003; Fig. 1).

We primarily analyzed SKS phases recorded at these stations, but some S and SKKS phases were also included to improve the incidence angle and back-azimuth coverage. The data were bandpass-filtered between 0.05 and 1 Hz to isolate the shear-wave energy, and measurements of the splitting parameters and their associated errors were made using the approach of Silver and Chan (1991). In total, we used 135 events including 247 SKS phases, 12 SKKS phases, and 52 S phases (see the GSA Data Repository material for details[1]).

Average splitting parameters from different events at each station are shown in Figure 1. Broadly, all stations display a north-south φ with an average δt of 1.4 s, similar to previous findings throughout the area (Wolfe et al., 1999; Levin and Park, 2000). Statistical methods were used to examine the variation in splitting observations at individual stations more closely and to compare the observations from different stations to one another. None of the stations showed significant back-azimuth variation, implying that multiple layers of anisotropy or dipping anisotropic symmetry axes are not required, and the observations at most stations were statistically indistinguishable. Stations near the Gulf of Aqaba (Fig. 1, inset) are a notable exception. While statistically similar to one another, this group of stations displays a statistically different (at a 95% confidence level) average φ that is rotated further east than the other stations that we examined.

[1]GSA Data Repository item 2006188, shear-wave splitting analysis, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

DISCUSSION

Gulf of Aqaba Stations

Our results in the Gulf of Aqaba region are similar to observations made at nearby stations by Schmid et al. (2004) and Levin et al. (2006). At the two stations they examined, Schmid et al. (2004) found an average φ of 3°–8° east of north and a δt of 1.3 s. They argued that φ is parallel to the Dead Sea transform fault due to the strike-slip motion between Arabia and Africa. Levin et al. (2006) postulated that their data are better fit by a two-layer model, where neither layer has a φ parallel to the Dead Sea transform fault. Their interpretation is that the two-layer model reflects deformation in the asthenosphere caused by absolute plate motion overlain by fossilized anisotropy. Our observations near the Dead Sea transform fault can be fit by a two-layer model similar to the one proposed by Levin et al. (2006); however, this fit is not statistically better than our one-layer model given the greater degrees of freedom. Therefore, we conclude that a one-layer model that has a φ parallel to the Dead Sea transform fault can best explain the splitting observations at the Gulf of Aqaba stations. This concurs with the findings of Schmid et al. (2004) and is similar to anisotropy observations made along other transform boundaries (Vinnik et al., 1992; Bostock and Cassidy, 1995).

Stations across Saudi Arabia

Aside from the Gulf of Aqaba stations, most of the splitting observations across Saudi Arabia are very consistent; yet, a straightforward explanation for these observations is difficult to apply. Wolfe et al. (1999) concluded that the predominantly north-south φ reflects either fossilized anisotropy or present-day asthenospheric flow. We believe that neither of these end-member models adequately fits the observations. A majority of the examined stations are located on the Arabian Shield, an area composed of Proterozoic terranes that mostly strike north-south (Fig. 2; Stoeser and Camp, 1985). Therefore, the splitting observed at these stations might be attributed to fossilized structure associated with the convergence of these terranes during the Arabian

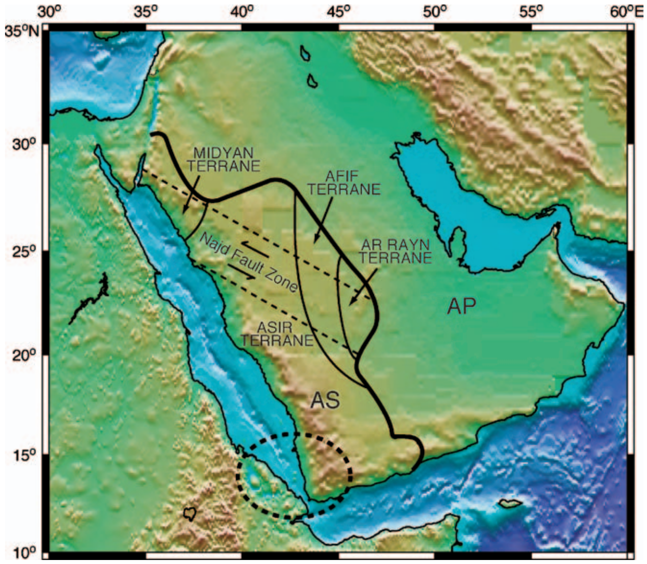

Figure 2. Topographic map with geologic boundaries. Boundary between Arabian Shield (AS) and Arabian Platform (AP) is marked by solid bold line, and approximate location of Afar upwelling is enclosed by dashed black circle. Thin dashed lines show trend of Najd fault zone, and thin solid lines show boundaries of major terranes, names of which are listed (modified from Stoeser and Camp, 1985).

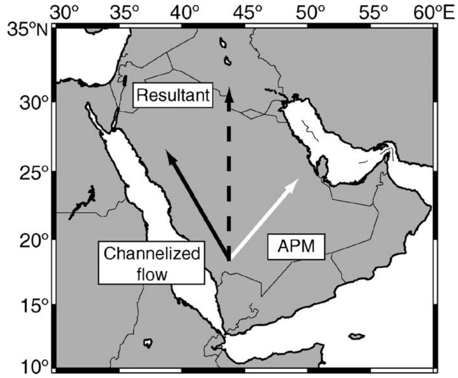

Figure 3. Vector examination of plate motion (white arrow) coupled with channelized upwelling flow (solid black arrow) beneath Saudi Arabia. If we estimate that absolute plate motion is oriented N40°E at a rate of 22 mm/yr (Reilinger et al., 1997; McClusky et al., 2003) and that channelized hotspot flow is oriented approximately N30°W (Camp and Roobol, 1992; Ebinger and Sleep, 1998), then the rate of hotspot flow needed to obtain a north-south resultant (black dashed arrow) is ~27 mm/yr. APM—absolute plate motion.

Shield's assembly. However, a 50–100-Myr-period of postaccretionary tectonics produced the northwest-trending strike-slip Najd fault zone, which has had 200–300 km of displacement (Fig. 2; Stoeser and Camp, 1985). Therefore, it seems unlikely that anisotropy imparted during Proterozoic assembly of the Arabian Shield was not disturbed by more recent deformation. For stations on the Arabian Platform (Fig. 2), there is little geologic constraint on any potential fossilized anisotropy because the Proterozoic basement is covered by a thick layer of Phanerozoic sediments (Stoeser and Camp, 1985).

Fossilized anisotropy can also be constrained by lithospheric thickness. Using common percentages of anisotropy (4%–5%; Mainprice and Silver, 1993), the lithosphere beneath Saudi Arabia would need to be ~140 km thick to accumulate the observed δt. Although sparse in this region, estimates of lithospheric thickness have been determined with seismic refraction and receiver function methods and are 100–120 km near the Arabian Shield-Platform boundary (Mooney et al., 1985) and 80–100 km within the Arabian Shield (Sandvol et al., 1998). Closer to the Red Sea, xenolith and isotope studies have indicated that the lithosphere thins to as little as 40 km (Altherr et al., 1990; Camp and Roobol, 1992). This substantial thinning is corroborated by seismic waveform modeling, P-wave tomography, and Sn attenuation studies in western Arabia (Rodgers et al., 1999; Benoit et al., 2003; Al-Damegh et al., 2004). Therefore, the lithosphere is probably not thick enough, especially near the Red Sea Rift, to generate the δt observed. In addition, because the lithosphere thins from the Arabian Shield to the Red Sea, fossilized anisotropy should produce a pattern of increasing δt at stations from west to east. No such pattern exists, and instead our δt values across Saudi Arabia are remarkably consistent (Fig. 1), casting further doubt on fossilized anisotropy as a viable model for this region.

An alternative explanation for the observed splitting is the alignment of φ with absolute plate motion due to shear at the base of the lithosphere. Several estimates of the absolute plate motion for Arabia have been proposed using a variety of global plate models. Gripp and Gordon's (2002) HS3-NUVEL1A model produces an absolute plate motion direction for Arabia of about N55°W. However, their model is based only on Western Hemisphere hotspots and does not fit African hotspots well. Therefore, this model probably does not provide the best estimate for Arabian absolute plate motion. Instead, global positioning system (GPS) plate models indicate that Arabia is moving northeast, with an average rate and direction of 22 mm/yr and N40°E, respectively (Reilinger et al., 1997; Sella et al., 2002; McClusky et al., 2003). The GPS results are comparable to Wolfe et al.'s (1999) absolute plate motion calculation, based on the O'Conner and le Roex (1992) African absolute plate motion model. When compared to the GPS-determined absolute plate motion direction, the orientation of φ is at least 30° different; therefore, this explanation also fails to fit the observations.

Since these end-member models do not fit the splitting observations, we conclude that the anisotropy is the result of an interaction of mantle flow in the asthenosphere. Shear caused by absolute plate motion, directed approximately N40°E at 22 mm/yr (Reilinger et al., 1997; McClusky et al., 2003), may affect the alignment of mantle minerals. However, based on variations in the topography and the distribution of alkalic volcanics, it has also been suggested that flow radiating from the Afar mantle upwelling is channelized toward the Red Sea Rift (Camp and Roobol, 1992; Ebinger and Sleep, 1998), in a direction oriented at about N30°W. Assuming that the strain caused by this upwelling is comparable to that caused by plate motion, we can combine these two flow orientations, similar to the vector approach of Silver and Holt (2002), to obtain a north-south–oriented resultant (Fig. 3).

Several other lines of evidence also help support our conclusions. Seismic tomography models show that the upper mantle beneath western Arabia is anomalously slow, with velocities increasing toward the continental interior (Debayle et al., 2001; Benoit et al., 2003). These observations are attributed to thermal differences and indicate much hotter mantle beneath the Red Sea, which is consistent with flow directed beneath the rift. Daradich et al. (2003) demonstrated that the higher elevations along the Red Sea and the overall tilt of the Arabian plate result from viscous stresses associated with large-scale mantle flow from the Afar upwelling. Walker et al. (2005) compared splitting results from both Wolfe et al. (1999) in Saudi Arabia and Gashawbeza et al. (2004) in Ethiopia to the parabolic asthenospheric flow model expected from a plate moving over a stationary hotspot. Over 90% of the splitting observations are consistent with radial flow, and they attributed the remaining variations to flow-modifying factors, such as channelization by topography at the base of the lithosphere. In addition, Schilling et al. (1992) found isotopic evidence for mantle mixing between depleted asthenosphere and plume flow in Saudi Arabia, supporting the idea of flow interaction at depth. This combination of both plate- and density-driven flow explains the consistent anisotropic signature across Saudi Arabia. Additionally, the rift-oblique φ, the higher topography, and the presence of alkalic lava extrusions near the Red Sea Rift are all consistent with an active rifting model.

CONCLUSIONS

Teleseismic shear-wave splitting along the Red Sea and across Saudi Arabia reveals that stations near the Gulf of Aqaba display φ aligned parallel to the Dead Sea transform fault. The remaining observations across Saudi Arabia show a consistent north-south φ with δt averaging 1.4 s. Present-day plate motion does not match the observed φ orientation, and lithospheric thickness constraints indicate that fossilized anisotropy cannot explain the observed δt. Therefore, we interpret the anisotropic signature as a combination of plate- and density-driven flow in the asthenosphere. A combination of the northeast-oriented flow associated with absolute plate motion with the northwest-oriented flow associated with the channelized Afar upwelling generates a north-south–oriented resultant that matches our splitting observations. Other evidence supporting channelized flow is also consistent with active rifting processes.

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REFERENCES CITED

Al-Amri, M., and Al-Amri, A., 1999, Configuration of the seismographic networks in Saudi Arabia: Seismological Research Letters, v. 70, p. 322–331.

Al-Damegh, K., Sandvol, E., Al-Lazki, A., and Barazangi, M., 2004, Regional seismic wave propagation (Lg and Sn) and Pn attenuation in the Arabian plate and surrounding regions: Geophysical Journal International, v. 157, p. 775–795.

Altherr, R., Henjes-Kunst, F., Puchelt, H., and Baumann, A., 1990, Volcanic activity in the Red Sea axial trough—Evidence for a large mantle diapir: Tectonophysics, v. 150, p. 121–133.

Benoit, M., Nyblade, A., VanDecar, J., and Gurrola, H., 2003, Upper mantle P wave velocity structure and transition zone thickness beneath the Arabian Shield: Geophysical Research Letters, v. 30, doi: 10.1029/2002GL016436.

Bostock, M., and Cassidy, J., 1995, Variations in SKS splitting across western Canada: Geophysical Research Letters, v. 22, p. 5–8, doi: 10.1029/94GL02789.

Camp, V., and Roobol, M., 1992, Upwelling asthenosphere beneath western Arabia and its regional implications: Journal of Geophysical Research, v. 97, p. 15,255–15,271.

Daradich, A., Mitrovica, J., Pysklywec, R., Willett, S., and Forte, A., 2003, Mantle flow, dynamic topography, and rift-flank uplift of Arabia: Geology, v. 31, p. 901–904, doi: 10.1130/G19661.1.

Debayle, E., Lévêque, J., and Cara, M., 2001, Seismic evidence for a deeply rooted low-velocity anomaly in the upper mantle beneath the northeastern Afro/Arabian continent: Earth and Planetary Science Letters, v. 193, p. 423–436, doi: 10.1016/S0012-821X(01)00509-X.

Ebinger, C., and Sleep, N., 1998, Cenozoic magmatism throughout east Africa resulting from impact of a single plume: Nature, v. 395, p. 788–791, doi: 10.1038/27417.

Gao, S., Davis, P., Liu, H., Slack, P., Rigor, A., Zorin, Y., Mordvinova, V., Kozhevnikov, V., and Logatchev, N., 1997, SKS splitting beneath continental rift zones: Journal of Geophysical Research, v. 102, p. 22,781–22,797, doi: 10.1029/97JB01858.

Gashawbeza, E., Klemperer, S., Nyblade, A., Walker, K., and Keranen, K., 2004, Shear-wave splitting in Ethiopia: Precambrian mantle anisotropy locally modified by Neogene rifting: Geophysical Research Letters, v. 31, doi: 10.1029/2004GL020471.

Gripp, A., and Gordon, R., 2002, Young tracks of hotspots and current plate velocities: Geophysical Journal International, v. 150, p. 321–361.

Levin, V., and Park, J., 2000, Shear zones in the Proterozoic lithosphere of the Arabian Shield and the nature of the Hales discontinuity: Tectonophysics, v. 323, p. 131–148, doi: 10.1016/S0040-1951(00)00105-0.

Levin, V., Henza, A., Park, J., and Rodgers, A., 2006, Texture of mantle lithosphere along the Dead Sea Rift: Recently imposed or inherited?: Physics of the Earth and Planetary Interiors, (in press).

Mainprice, D., and Silver, P., 1993, Interpretation of SKS-waves using samples from the subcontinental lithosphere: Physics of the Earth and Planetary Interiors, v. 78, p. 257–280, doi: 10.1016/0031-9201(93)90160-B.

McClusky, S., Reilinger, R., Mahmoud, S., Ben Sari, D., and Tealeb, A., 2003, GPS constraints of Africa (Nubia) and Arabia plate motions: Geophysical Journal International, v. 155, p. 126–138.

Mooney, W., Gettings, M., Blank, H., and Healy, J., 1985, Saudi Arabian seismic refraction profile: A traveltime interpretation of crustal and upper mantle structure: Tectonophysics, v. 111, p. 173–246.

O'Conner, J., and le Roex, A., 1992, South Atlantic hot spot–plume systems: 1. Distribution of volcanism in time and space: Earth and Planetary Science Letters, v. 113, p. 343–364.

Reilinger, R., McClusky, S., Oral, M., King, R., Toksoz, M., Barka, A., Kinik, I., Lenk, O., and Sanli, I., 1997, Global positioning system measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone: Journal of Geophysical Research, v. 102, p. 9983–10,000.

Ribe, N., 1992, On the relation between seismic anisotropy and finite strain: Journal of Geophysical Research, v. 97, p. 8737–8747.

Rodgers, A., Walter, W., Mellors, R., Al-Amri, A., and Zhang, Y., 1999, Lithospheric structure of the Arabian Shield and Platform from complete regional waveform modeling and surface wave group velocities: Geophysical Journal International, v. 138, p. 871–878.

Rodgers, A., Harris, D., Ruppert, S., Lewis, J., O'Boyle, J., Pasyanos, M., Abdallah, A., Al-Yazjeen, T., and Al-Gazo, A., 2003, A broadband seismic deployment in Jordan: Seismological Research Letters, v. 74, p. 374–381.

Sandvol, E., Seber, D., Barazangi, M., Vernon, F., Mellors, R., and Al-Amri, A., 1998, Lithospheric seismic velocity discontinuities beneath the Arabian Shield: Geophysical Research Letters, v. 25, p. 2873–2876.

Schilling, J., Kingsley, R., Hanan, B., and McCully, B., 1992, Nd-Sr-Pb isotopic variations along the Gulf of Aden: Evidence for Afar mantle plume–continental lithosphere interaction: Journal of Geophysical Research, v. 97, p. 10,927–10,966.

Schmid, C., van der Lee, S., and Giardini, D., 2004, Delay times and shear wave splitting in the Mediterranean region: Geophysical Journal International, v. 159, p. 275–290, doi: 10.1111/j.1365-246X.2004.02381.x.

Sella, G., Dixon, T., and Mao, A., 2002, REVEL: A model for recent plate velocities from space geodesy: Journal of Geophysical Research, v. 107, doi: 10.1029/2000JB000033.

Silver, P., and Chan, W., 1991, Shear wave splitting and subcontinental mantle deformation: Journal of Geophysical Research, v. 96, p. 16,429–16,454.

Silver, P., and Holt, W., 2002, The mantle flow field beneath western North America: Science, v. 295, p. 1054–1057.

Stoeser, D., and Camp, V., 1985, Pan-African microplate accretion of the Arabian Shield: Geological Society of America Bulletin, v. 96, p. 817–826, doi: 10.1130/0016-7606(1985)96<817:PMAOTA>2.0.CO;2.

Vernon, F., and Berger, J., 1998, Broadband seismic characterization of the Arabian Shield: Final Scientific Technical Report, Department of Energy Contract No. F 19628-95-K-0015, p. 36.

Vinnik, L., Makeyeva, L., Milev, A., and Usenko, A., 1992, Global patterns of azimuthal anisotropy and deformations in the continental mantle: Geophysical Journal International, v. 111, p. 433–447.

Voggenreiter, W., Hötzl, H., and Jado, A., 1988, Red Sea related history of extension and magmatism in the Jizan area (southwest Saudi Arabia): Indication for simple-shear during Red Sea rifting: Geologische Rundschau, v. 77, p. 257–274, doi: 10.1007/BF01848688.

Walker, K., Nyblade, A., Klemperer, S., Bokelmann, G., and Owens, T., 2004, On the relationship between extension and anisotropy: Constraints from shear wave splitting across the East African Plateau: Journal of Geophysical Research, v. 109, doi: 10.1029/2003JB002866.

Walker, K., Bokelmann, G., Klemperer, S., and Nyblade, A., 2005, Shear wave splitting around hotspots: Evidence for upwelling-related mantle flow?, *in* Foulger, G., et al., eds., "Plates, plumes, and paradigms: Geological Society of America Special Paper 388, p. 171–192.

Wernicke, B., 1985, Uniform-sense normal simple-shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, p. 108–125.

Wolfe, C., Vernon, F., and Al-Amri, A., 1999, Shear-wave splitting across western Saudi Arabia: The pattern of upper mantle anisotropy at a Proterozoic shield: Geophysical Research Letters, v. 26, p. 779–782.

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