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Key Points:
- Uniform N-S fast orientations on both sides of the Red Sea
- The results are inconsistent with plume or fossil fabric models
- Anisotropy may originate from upper asthenosphere due to long-term subduction

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Seismic anisotropy and subduction-induced mantle fabrics beneath the Arabian and Nubian Plates adjacent to the Red Sea

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Abstract For most continental areas, the mechanisms leading to mantle fabrics responsible for the observed anisotropy remain ambiguous, partially due to the lack of sufficient spatial coverage of reliable seismological observations. Here we report the first joint analysis of shear-wave splitting measurements obtained at stations on the Arabian and Nubian Plates adjacent to the Red Sea. More than 1100 pairs of high-quality splitting parameters show dominantly N-S fast orientations at all 47 stations and larger-than-normal splitting times beneath the Afro-Arabian Dome (AAD). The uniformly N-S fast orientations and large splitting times up to 1.5 s are inconsistent with significant contributions from the lithosphere, which is about 50–80 km thick beneath the AAD and even thinner beneath the Red Sea. The results can best be explained by simple shear between the lithosphere and the asthenosphere associated with northward subduction of the African/Arabian Plates over the past 150 Ma.

1. Introduction

In spite of numerous shear-wave splitting (SWS) studies, the mechanisms leading to observed seismic anisotropy in a given study area are usually ambiguous, and reliable interpretation of SWS measurements requires understanding tectonic history, mantle structure, plate motions, and results of geodynamic modeling of mantle flow. It is often not clear whether anisotropy reflects a fossil lithospheric fabric or asthenospheric flow. The region around the Red Sea is well suited for examining what are the important controls, because this is a region with well-characterized plate motions, possible mantle plume effects, a nascent ocean basin, and deformed lithosphere. These competing effects have been evaluated using data from Arabia [e.g., *Wolfe et al.*, 1999; *Hansen et al.*, 2006] but without constraints from NE Africa, especially Egypt. The recent availability of broadband seismic data from Egypt (Figure 1) provides a new opportunity to investigate mantle dynamics and anisotropy-forming mechanisms.

The study area includes most of the Arabian Plate and the NE part of the Nubian Plate. The Red Sea and the Afro-Arabian Dome (AAD) [*Camp and Roobol*, 1992] occupy the central part of the study area, and the Arabian-Nubian Shield (ANS) comprises the core of the AAD (Figure 1). The basement fabrics of Arabia and northern Nubia formed as a single lithospheric block in Neoproterozoic time associated with accretion of juvenile arcs and back arc basins to form the ANS at ~900–630 Ma followed by collision of East and West Gondwana about 630–600 Ma, through mostly east-west convergence. In the study area (Figure 1), the dominant strike of basement structures including that of the suture zones ranges from NE-SW to NW-SE and is mostly N-S on the ANS but is largely unknown beneath Egypt due to limited exposure [*Berhe*, 1990; *Stern and Johnson*, 2010]. The crust of Africa west of the Nile is thought to be reworked older crust of the Saharan metacraton [*Abdelsalam et al.*, 2002], followed by orogenic collapse, delamination, and north directed tectonic escape ~600–580 Ma [*Stoeser and Camp*, 1985; *Avigad and Gvirtzman*, 2009; *Stern and Johnson*, 2010]. Mantle fabrics formed by Neoproterozoic tectonics and magmatism were likely modified by opening of the Red Sea and the uplift of flanking regions beginning ~30 Ma [*Bosworth et al.*, 2005; *Lazar et al.*, 2012]. We have some idea of how thick the lithosphere is beneath western Arabia but not NE Africa. *Hansen et al.* [2007] used *S* wave receiver functions and Gravity Recovery and Climate Experiment gravity data and concluded that the lithosphere thickness is ~50–80 km near the coast and thickens to ~120 km beneath the eastern edge of the ANS [*Hansen et al.*, 2007, Figures 5 and 6], which is at a distance of about 500 km from the Red Sea.

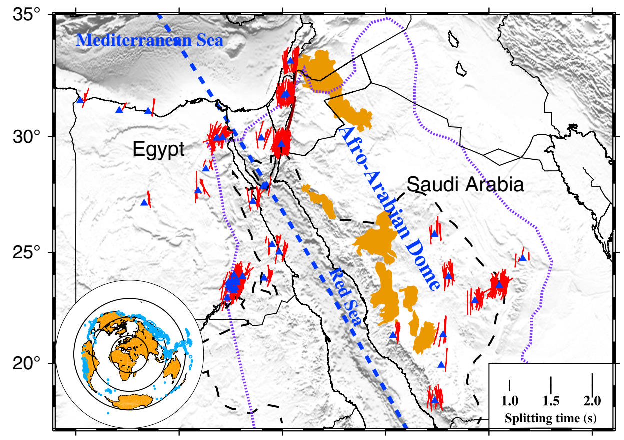

Figure 1. A topographic relief map of the study area showing the seismic stations (triangles) used in the study and shear-wave splitting measurements (red bars) plotted above ray-piercing points at the depth of 150 km. The orientation of the bars represents the fast orientation, and the length indicates the splitting time. Brown areas are covered by Cenozoic volcanic rocks. The dashed blue line is a great circle arc approximately along the Red Sea axis, the dashed purple line outlines the northern part of Afro-Arabian Dome, and the dashed black line outlines the Arabian-Nubian Shield [*Camp and Roobol*, 1992]. The inset shows distribution of earthquakes (blue circles) used in the study.

The direction and strength of mantle flow beneath the Red Sea and adjacent Arabian and Nubian Plates were investigated by a number of seismic anisotropy [*Wolfe et al.*, 1999; *Levin and Park*, 2000; *Schmid et al.*, 2004; *Hansen et al.*, 2006; *Levin et al.*, 2006; *Kaviani et al.*, 2011, 2013] and geodynamic modeling [*Conrad and Behan*, 2010; *Forte et al.*, 2010; *Faccenna et al.*, 2013] studies. Figure 2 shows results from the previous studies. Except for a few of them [*Wolfe et al.*, 1999; *Hansen et al.*, 2006], most previous SWS studies focused on the vicinity of the Dead Sea Transform Fault separating the Nubian and Arabian Plates. Based on SWS measurements at eight stations in southern Saudi Arabia, *Wolfe et al.* [1999] reported dominantly N-S fast orientations (measured clockwise from the north) with larger-than-normal splitting times. The models that they proposed include N-S trending lithospheric fabrics formed by E-W Neoproterozoic convergence, northward absolute plate motion (APM) of the Arabian Plate, and northward asthenospheric flow from a mantle plume beneath Afar. *Hansen et al.* [2006] measured SWS parameters at about 20 stations in Arabia (Figure 2). Similar to *Wolfe et al.* [1999], they found dominantly N-S fast orientations and attributed the observed seismic anisotropy to a combined effect of two flow systems: a northeastward flow from GPS-determined APM of the Arabian Plate [*Reilinger et al.*, 1997] and a NW oriented flow along the strike of the Red Sea from the Afar plume.

Using SWS parameters and geodetic measurements as constraints, *Faccenna et al.* [2013] investigated mantle flow beneath Arabia and northern Nubia. The model that fits the observed seismic anisotropy in Arabia the best invokes slab pull, upwelling from the lower mantle beneath southern Africa, and a N-S oriented zone of thinned lithosphere ("lithospheric channel") beneath the AAD that directs flow from a mantle plume beneath Afar. Other models proposed by *Faccenna et al.* [2013] use different assumptions about the relative roles of slab pull and mantle heterogeneities. Most of these models and models from other geodynamic modeling studies [*Forte et al.*, 2010; *Conrad and Behan*, 2010; *Kreemer*, 2009] predicted that the flow direction beneath southern Arabia is more northeasterly than that beneath the northern part, mostly due to the influence of flow from the Afar mantle plume to the south and the stronger influence of northward subduction in the north.

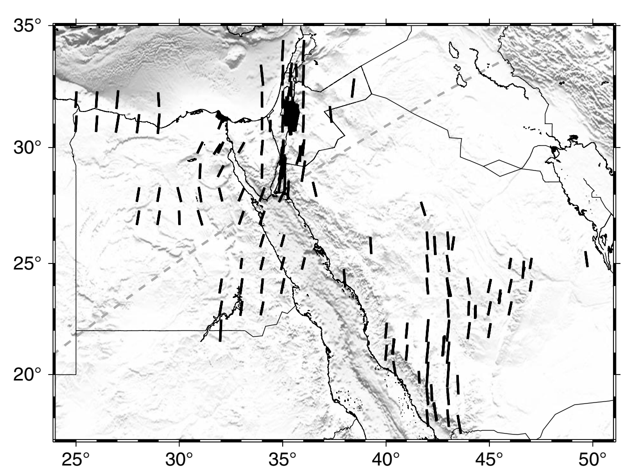

Figure 2. Spatially averaged shear-wave splitting parameters from this study and station-averaged splitting parameters from previous studies [*Wolfe et al.*, 1999; *Levin and Park*, 2000; *Schmid et al.*, 2004; *Hansen et al.*, 2006; *Levin et al.*, 2006; *Kaviani et al.*, 2011, 2013]. Station-averaged splitting parameters to the southeast of the gray dashed line are plotted in Figures 3d and 3e.

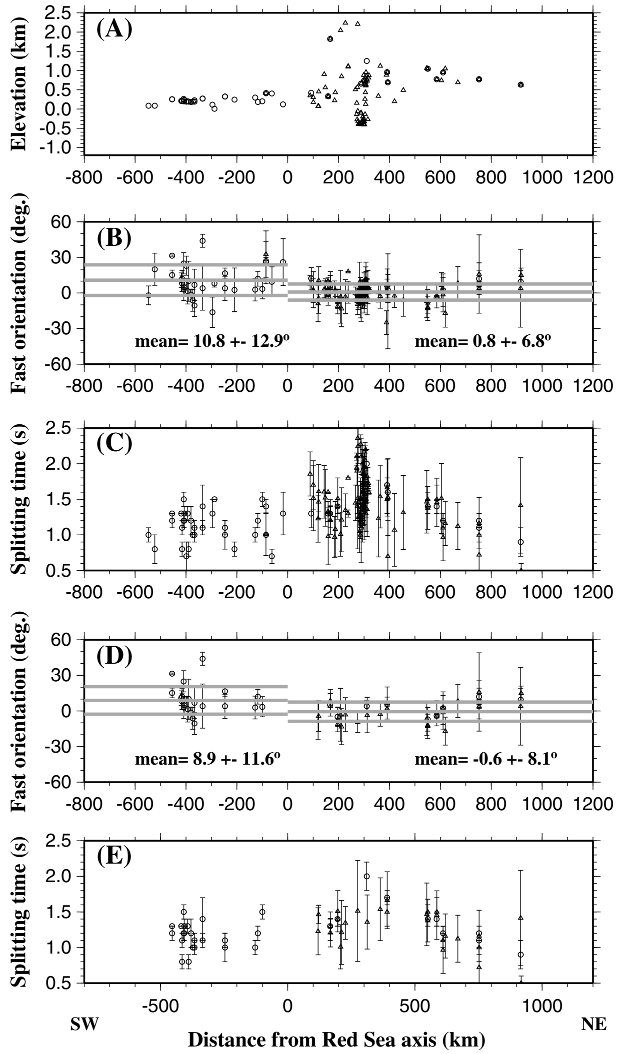

Figure 3. Cross-section views of (a) surface elevation and (b–e) station-averaged shear-wave splitting parameters. Figures 3b and 3c are fast orientations and splitting times, respectively, of all the measurements, and Figures 3d and 3e are measurements beyond the Red Sea, located in the area to the southeast of the Red Sea perpendicular line in Figure 2. Circles represent data from this study, and triangles from previous studies shown in Figure 2. The horizontal lines in Figures 3b and 3d show the mean (central lines) and mean plus/minus the standard deviation.

In addition, most models predict that the flow direction beneath Arabia is more northeasterly than that beneath Nubia, due to the east-northeastward movement of Arabia relative to Nubia [*DeMets et al.*, 1994]. Until now, the predictions for mantle flow beneath NE Africa could not be tested due to the unavailability of broadband seismic data for Egypt.

2. Data and Methods

The study uses three seismic phases: *SKS* which leaves the source as an *S* wave, converts to a *P* wave at the boundary between the mantle and the liquid outer core, and converts to an *S* wave at the core-mantle boundary on the receiver side; *SKKS* which is similar to *SKS* but the *P* leg bounces back to the outer core; and *PKS* which leaves the source and travels through the outer core as a *P* wave and converts to an *S* wave at the core-mantle boundary. Hereafter the three phases are collectively called *XKS*. Data from stations located east of the Red Sea were obtained from the IRIS (Incorporated Research Institutions for Seismology) DMC (Data Management Center) for the recording period of early 1990 to middle 2013. The rest of the data were recorded by the Egyptian National Seismic Network (ENSN) for the period of late 2010 to the end of 2012. The epicentral distance used for *PKS*, *SKKS*, and *SKS* is 120°–180°, 95°–180°, and 84°–180°, respectively [*Liu and Gao*, 2013].

The splitting parameters were measured and ranked using the procedure developed by *Liu* [2009] and *Liu and Gao* [2013] based on the transverse component energy minimization technique [*Silver and Chan*, 1991]. The seismograms were filtered in the frequency band of 0.04–0.5 Hz, and the *XKS* time window used to compute the splitting parameters starts at 5 s before and ends at 20 s after the predicted *XKS* arrival times. A manual check was applied to adjust the *XKS* window and to verify the automatic-ranking results to ensure that no high-quality events were ignored and no low-quality results were selected [*Liu and Gao*, 2013].

3. Results

A total of 1144 well-defined nonnull SWS measurements are obtained at 47 stations (Figure 1). Null measurements are characterized by the lack of observable energy on the transverse component as a result of the back azimuth directions being either parallel or perpendicular to the fast orientation or the medium traveled by the *XKS* phase being isotropic [e.g., *Silver and Chan*, 1991]. Two or more null events with nonparallel or orthogonal back azimuths indicate the paucity of anisotropy. We observed clear splitting at all stations in the study area, and thus, the null measurements are not used in the discussions below. In addition, we do not observe clear systematic variations of the splitting parameters as a function of back azimuth, suggesting that a single layer of anisotropy with a horizontal axis of symmetry is adequate to represent the SWS measurements. To better visualize the measurements, we compute the coordinates of ray-piercing points at 150 km depth and spatially average the SWS parameters in consecutive circles with a radius of 1°. The distance between the center of neighboring circles is 1°. The resulting spatial distribution of the measurements is shown in Figure 2, in which station-averaged measurements from previous studies are also plotted.

The station-averaged results are also displayed against the perpendicular distance to the Red Sea axis (Figure 3), for the purpose of identifying subtle spatial variations of the splitting parameters. The most remarkable feature of the measurements (Figures 2 and 3) is the almost consistently N-S fast orientations in the entire study area. This is especially true for the areas to the NE and SW of the Red Sea (Figure 3d). The splitting times are the largest (about 1.5 s) in the study area along the axial region of the AAD (which is centered approximately along the 42°E longitudinal line) and decrease gradually toward the NE and SW.

4. Discussion

The uniform N-S fast orientations and the systematic spatial variation of the splitting times have several important implications on mantle flow models and on the formation mechanisms of seismic anisotropy beneath the study area, including

1. The uniform N-S fast orientations, large splitting times observed in areas with thin lithosphere, and apparently spatially varying dominant orientations of basement fabrics [*Berhe*, 1990; *Stern and Johnson*, 2010] make it unlikely for the lithosphere to be the main source of the observed anisotropy. A lithosphere origin predicts that areas with thin lithosphere such as the area between the Red Sea and the axial area of the AAD [*Hansen et al.*, 2007; *Chang and Van der Lee*, 2011] should have small splitting times, not the observed large splitting times. To produce the 1.5 s splitting time observed on the AAD with a commonly accepted mantle anisotropy of 4% [*Mainprice and Silver*, 1993], the required layer thickness is about 170 km, which is more than 2 times of the thickness of the lithosphere beneath the AAD [*Hansen et al.*, 2007]. If we use the shear-wave anisotropy value of 2.64% measured from upper mantle kimberlite nodules acquired on the Kaapvaal craton [*Ben-Ismail et al.*, 2001], the required thickness is as large as 255 km. Additionally, spatially varying fast orientations and reduction in splitting times are expected beneath the Sahara metacraton due to disturbance of the accretion-related lithospheric fabrics by the tectonic reactivation events and lithospheric delamination. Such expected changes are not observed. Because fabric directions on a lithospheric scale beneath the study area especially beneath Egypt is poorly known, our data cannot completely exclude contributions from the lithosphere to the N-S directed anisotropy.
2. Magmatic dikes parallel to the Red Sea contribute insignificantly to the observed anisotropy. The dikes should lead to Red Sea parallel fast orientations and large splitting times in the Red Sea basin, neither of which is observed (Figure 2). The lack of a significant amount of dikes in the lithosphere is consistent with the notion that the Red Sea was the product of passive rifting, probably as a result of slab pull along the subduction zones to the north and northeast [*Stern and Johnson*, 2010].
3. Neither the fast orientations nor the splitting times support the existence of a flow system along a lithospheric channel beneath the Red Sea. It has been proposed that such a channeled flow, when combined with the northeastward APM of Arabia, could give rise to the N-S fast orientations observed on Arabia [*Hansen et al.*, 2006]. In order to produce the N-S fast orientations on the AAD, the Red Sea parallel flow system must extend beyond the surface expression of the Red Sea, probably on both sides of it. If this is the case, one would expect that the fast orientations observed on the Egyptian side would be parallel to the strike of the Red Sea, due to a lack of a NE directed APM-driven flow system. Additionally, if the two flow systems produce lattice-preferred orientation (LPO) at different depths, azimuthally varying splitting parameters are expected [*Silver and Savage*, 1994]. None of these predictions are consistent with the observed splitting parameters.
4. Anisotropy with a uniform N-S fast orientation observed beneath the AAD is unlikely the result of channeled flow beneath the AAD. The coexistence of N-S directed anisotropy and a zone of low-seismic velocity was proposed to be the result of mantle flow beneath the thinned AAD lithosphere [*Wolfe et al.*, 1999; *Chang and Van der Lee*, 2011]. The fact that N-S fast orientations are also observed outside the AAD in Egypt places doubts on this interpretation (unless the off-AAD N-S fast orientations are coincidental).

In the absence of an existing model that can satisfactorily explain the spatial distribution of the SWS parameters, we search for other anisotropy-forming mechanisms in the study area that can lead to the observed distribution. Numerous studies demonstrated that relative to Eurasia, the African Plate has been moving northward since at least 150 Ma, most probably driven by the subduction of the Neotethys oceanic slab [*Dercourt et al.*, 1986; *Reilinger and McClusky*, 2011]. From 59 to 0 Ma, the African Plate moved more than 1200 km toward Eurasia without significant changes in the direction of motion but with variable plate velocities [*McQuarrie et al.*, 2003; *Reilinger and McClusky*, 2011]. From 59 to 25 Ma, the Nubia-Arabian Plate moved northward at about 32 mm/yr. The rate for Nubia reduced by more than 50% since 25 Ma, probably due to the collision of Africa and Eurasia which increased resistance to subduction [*Jolivet and Faccenna*, 2000] or the rifting along the Red Sea which reduced the north-northeastward pull on Nubia from the Arabian section of the subducting Neotethys slab [*Reilinger and McClusky*, 2011]. Numerical [e.g., *Lithgow-Bertelloni and Richards*, 1998; *Conrad and Hager*, 2001; *Behn et al.*, 2004] and laboratory [e.g., *Funiciello et al.*, 2006] studies suggest the existence of subduction parallel LPO beneath the horizontal portion of subducting plates. The LPO is induced by the relative movement between the partially coupled lithosphere and asthenosphere, as well as by trench rollback [*Conrad and Hager*, 2001]. We propose that the observed seismic anisotropy with N-S fast orientations in Arabia and northern Nubia represents mantle fabrics induced in the boundary layer by the long-term northward subduction of the African (before 24 Ma) and Nubian and Arabian Plates (after 24 Ma) beneath Eurasia. Under this model, the large splitting times observed beneath the axial area of the AAD can be explained by concentration of LPO associated with lithospheric thinning. Such thinning was suggested from numerous seismic tomography studies [e.g., *Chang and Van der Lee*, 2011]. The fact that the fast orientations are almost perfectly parallel to the direction of subduction implies that beneath the study area, subduction-induced LPO is much stronger than that produced by other processes, such as westward drift of the Earth's lithosphere [*Doglioni et al.*, 2007], and the opening of the Red Sea, which would lead to a more northeasterly fast orientation on Arabia.

5. Conclusions

For the first time, shear-wave splitting parameters are measured on both the Nubian and Arabian Plates adjacent to the Red Sea. Dominantly N-S fast orientations are observed at virtually all the 47 stations, which, when combined with the systematic spatial variation of splitting times, are inconsistent with previously proposed anisotropy-forming models invoking lithospheric fabrics, radial flow from an active mantle plume beneath Afar, or channeled flow from Afar beneath the Red Sea or the Afro-Arabian Dome. Conversely, the observations can best be explained by olivine LPO developed at the boundary layer between the lithosphere and the asthenosphere induced by the northward movement of the African Plate since at least 150 Ma.

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