GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L18602, doi:10.1029/2004GL020471, 2004

Shear-wave splitting in Ethiopia: Precambrian mantle anisotropy locally modified by Neogene rifting

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Received 7 May 2004; revised 30 July 2004; accepted 17 August 2004; published 16 September 2004.

[1] Twenty-six broadband seismic stations in an areal array spanning 500 × 500 km across Ethiopia were used for shear-wave splitting studies. Our results show small-to-moderate delay times (0.5–1.7s) with fast-polarization azimuths sub-parallel to the orientation of the East African Rift (NNE-SSW) and also to the Proterozoic tectonic fabric across the entire studied area. Our results imply Ethiopian upper-mantle anisotropy is controlled largely by the Proterozoic accretion of the Mozambique belt, with possible minor effects within the rift due to aligned cracks or melt pockets parallel to the rift axis. Our observations are not consistent with anisotropy created by asthenospheric flow parallel either to the Cenozoic extension direction (NW-SE) or to the modern absolute plate motion direction (NNW-SSE), or to asthenospheric radial flow from the "Afar" plume. *INDEX TERMS:* 0905 Exploration Geophysics: Continental structures (8109, 8110); 0910 Exploration Geophysics: Data processing; 7218 Seismology: Lithosphere and upper mantle. **Citation:** Gashawbeza, E. M., S. L. Klemperer, A. A. Nyblade, K. T. Walker, and K. M. Keranen (2004), Shear-wave splitting in Ethiopia: Precambrian mantle anisotropy locally modified by Neogene rifting, *Geophys. Res. Lett.*, *31*, L18602, doi:10.1029/2004GL020471.

1. Introduction

[2] In this paper we study seismic anisotropy from shear-wave splitting measurements to understand the relationship between splitting parameters and interaction of Cenozoic rifting and magmatism with the older Precambrian lithosphere fabrics in Ethiopia. In an anisotropic medium, one component of the shear-wave travels faster than the orthogonal component and the difference in wave speed causes the waves to separate and leads to shear-wave splitting [e.g., *Christensen*, 1966]. Measurement of polarization of the fast component and the delay time characterizes the anisotropic behavior of the medium. There is still much debate about the relation between strain and anisotropy [*Kaminski and Ribe*, 2002], and determining how much of the anisotropy is caused by past and present lithospheric deformation and how much of the anisotropy is caused by crustal, asthenospheric and lower-mantle sources [e.g., *Savage*, 1999].

[3] The East African rift system is one of the most spectacular geologic features of the world. This geologic environment offers a unique opportunity to observe the initiation of plate divergence in a Precambrian craton modified by Tertiary plume magmatism [*Baker*, 1972]. The northeastern part of this rift system is the key to understanding continental breakup as it lies at the transition between continental and oceanic rifting [*Ebinger and Casey*, 2001]. Most of the strain across the rift is accommodated within the central magmatic zone, although earthquake activity shows some deformation outside this zone [*Bilham et al.*, 1999].

[4] Shear-wave splitting data from some major rifts show fast azimuths parallel to extension direction (e.g., Baikal Rift [*Gao et al.*, 1997]), as is also observed in oceanic lithosphere (e.g., the Red Sea [*Vinnik et al.*, 1989]). Other rifts show fast directions parallel to the rift orientation (e.g., Rio Grande Rift [*Sandvol et al.*, 1992]). In continental cratons fast azimuths in some regions are parallel to frozen anisotropy in the lithosphere [*Silver and Chan*, 1991] but in other regions are parallel to modern absolute plate motion and hence presumably due to asthenospheric flow.

2. Data Analysis and Observations

[5] We analyzed SKS phases recorded by the Ethiopian Broadband Seismic Experiment [*Nyblade and Langston*, 2002] (Figure 1 and auxiliary material[1]), in which five broadband stations recorded data for a duration of two years and 21 additional stations recorded data for one year in an area of 500 × 500 km in central Ethiopia. Of the earthquakes recorded over the two-year period we analyzed those events with Mb ≥ 6.0 and favorable epicentral distances (90–110°) for observation of SKS phases. The shear-wave splitting parameters, i.e., the delay time and the fast polarization directions, were calculated using the method of *Silver and Chan* [1991] as modified by *Walker* [2003] (Figure 2). In order to distinguish splitting caused by anisotropy from noise, we applied a band-pass filter of 0.02 to 0.2 Hz to separate the dominant frequency of the teleseismic waveforms from the noise. The analysis method employed involves choosing a master time window around the picked phase. 30 different time windows are created by perturbing the main window, then anisotropy parameters that best remove the energy on the transverse component of the seismogram are calculated for all the time windows, and we stack all 30-misfit grids

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0094-8276/04/2004GL020471$05.00

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL020471.

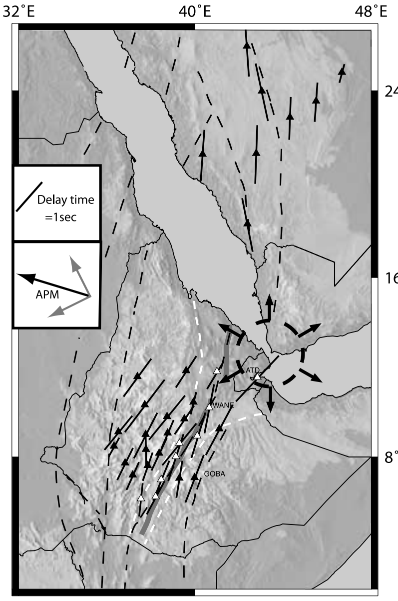

Figure 1. Fast splitting directions at 26 broadband stations in Ethiopia. Background is shaded topographic relief map of Ethiopia and neighboring countries. Line length proportional to delay time. Station ATD from *Barruol and Ben-Ismail* [2001], and stations in Saudi Arabia from *Wolfe et al.* [1999]. Dashed black lines: Ophiolitic sutures of the Mozambique belt [*Berhe*, 1990]. Arrow: absolute plate motion direction (APM) of Africa and uncertainties [*Gripp and Gordon*, 2002]. Dashed circle: location of Afar plume [*Montelli et al.*, 2004]. Dashed white lines: rift boundaries. Thick grey line: central magmatic axis [*Abebe*, 2000]. Open triangles are station locations within the rift and solid triangles outside the rift (Figure 3).

to find the global minimum and its 95% confidence interval (Figure 2).

3. Interpretation

3.1. Anisotropy is Not Due to Simple Plume Upwelling

[6] It is widely accepted that one or more plumes beneath East Africa explain the high elevation and the flood basalts erupted at 30 Ma [*Nyblade and Langston*, 2002]. The current location of the hotspot is much disputed with suggestions of a plume beneath Afar [*Marty et al.*, 1996] and/or much further south beneath the Tanzanian craton [e.g., *Nyblade et al.*, 2000]. The most recent tomographic imaging shows the plume head centered at 12°N, 43°E (location shown in Figure 1) [*Montelli et al.*, 2004]. Theoretical models suggest that fast splitting directions would approximately align with radial asthenospheric flow outwards from the plume head sheared in the direction of plate motion at significant distances from the conduit [*Kaminski and Ribe*, 2002]. Fast directions observed around Hawaii [*Walker et al.*, 2001] and in the Great Basin [*Walker et al.*, 2004] fit such a parabolic flow pattern. No radial pattern of azimuthal anisotropy is observed in our data, so there is no shear-wave splitting evidence of the existence of simple plume upwelling beneath Ethiopia, though station coverage, especially east of Afar may be inadequate to detect radial plume flow. If the plume location were in fact north west of the location given by *Montelli et al.* [2004] then our results could be consistent with plume flow, and of course, models of multiple plumes or channeled flow beneath the lithosphere/asthenosphere boundary that cause complex upwelling can always be contrived to fit the observations.

3.2. Anisotropy is Not Due to Absolute Plate Motion

[7] In the absence of mantle upwellings, absolute plate motion (APM) should align olivine a-axes in the asthenosphere, and hence fast split directions, parallel to the direction of motion [*Nicolas and Christensen*, 1987]. The current APM direction of Africa is 285 ± 45° at 15 ± 3 mm/yr [*Gripp and Gordon*, 2002] (vectors shown in Figure 1). Our

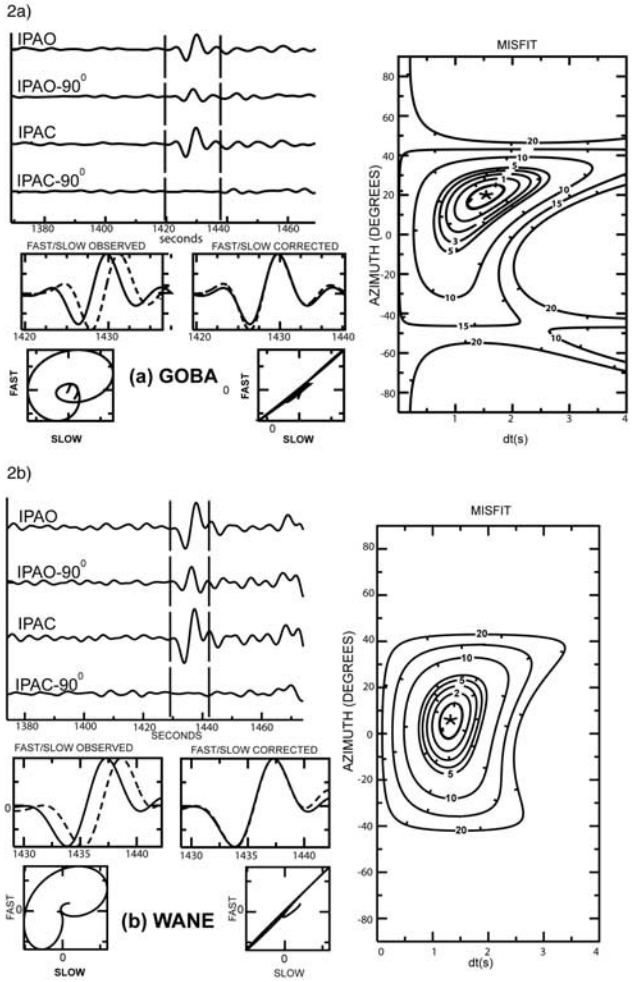

Figure 2. Examples of data from stations (a) GOBA and (b) WANE. In each part: Top left: recorded radial, transverse and rotated energy for the SKS phase. Vertical lines show picked time window on which splitting measurement is made. IPAO: observed incident polarization azimuth. IPAC: corrected incident polarization azimuth. Bottom left plots: fast (solid line) and slow (dashed line) components of split shear-waves and corresponding particle motion in the horizontal plane. Right plot: misfit grid shows the optimum fast polarization azimuth and delay time that minimizes the energy on the IPAC-90 component. For full methodology see *Walker* [2003].

observed fast azimuths show no correlation with this WNW APM direction of Africa. Observed anisotropy results in Ethiopia are therefore not explained by the simple asthenospheric flow hypothesis.

3.3. Anisotropy is Not Due to Extension

[8] Studies conducted at ocean ridges (e.g., the Red Sea [*Vinnik et al.*, 1989]) and on some continental rifts (e.g., Baikal rift [*Gao et al.*, 1997]) show fast splitting directions parallel to the extension direction. In such places, lattice preferred orientation (LPO) of olivine fast a-axes aligns with the direction of extension. In Ethiopia the modern extension direction of the rift is WNW-ESE. Our results show no correlation of fast azimuth with extension direction; in contrast our splits are aligned perpendicular to the direction of extension, and so extension-driven rift-perpendicular material flow is not a possible cause of the observed anisotropy. If indeed the Main Ethiopian Rift evolves in the future in to an ocean ridge, then presumably the splitting directions will also evolve in to the more normally observed extension-parallel directions.

3.4. Regional Anisotropy is Due to Proterozoic Accretion

[9] The late Proterozoic Mozambique Belt is one of the most important orogens in Africa, extending from Egypt across the Arabian-Nubian shield to Mozambique and Madagascar [*Berhe*, 1990]. Limited basement outcrop in Ethiopia makes correlations contentious [e.g., *Church*, 1991] but the reconstruction of *Berhe* [1990] shows three suture zones running broadly SSW-NNE through Ethiopia (dashed lines in Figure 1), suggesting Precambrian compressional directions orthogonal to the modern rift. This model is consistent with theoretical models and observations suggesting that rift propagation occurs parallel to older orogenic fabric [*Vauchez et al.*, 1997]. Our splitting parameters are comparable with the direction of the identified ophiolitic sutures especially on the eastern side of the rift, e.g., at Goba (Figures 1 and 2a). The suture that passes through the rift axis also correlates with splitting directions observed at most of our stations located in the rift floor, so it seems likely that the source of anisotropy even within the rift could be originally from the Precambrian fabric, albeit now slightly modified by Neogene magmatism (see below). Our results are somewhat less consistent with the identified ophiolitic suture in western Ethiopia, but still are within 30° of Berhe's reconstruction (Figure 1) [*Berhe*, 1990]. Indeed, given the uncertainties in projecting Precambrian trends beneath the widespread Phanerozoic cover in the Horn of Africa [e.g., *Berhe*, 1990; *Church*, 1991; *Abdelsalam and Stern*, 1996] we argue that our shear-wave splitting data - if our interpretation is correct - provide a more reliable measure of the lithospheric-scale trends of the Mozambique belt in this region.

3.5. Anisotropy is Locally Modified by Aligned Melt in the Main Ethiopian Rift

[10] The average fast shear-wave directions we observe on stations inside the rift are approximately parallel to the rift. Such parallelism suggests the anisotropy beneath these stations could be related to deep rift structures and rift processes. As suggested by *Gao et al.* [1997], fast azimuths along the trend of the rift could be related to preferred alignment of melt-filled pockets with a long axis parallel to the maximum compressive direction and a short axis parallel to the minimum compressive (extension) direction. Significant anisotropy may also be induced by flow of asthenospheric material channeled between two steeply dipping lithospheric walls, i.e., parallel to the rift [*Barruol and Ben-Ismail*, 2001]. It has been widely observed that the fast polarization of crustal shear waves is parallel to the local strike of cracks or direction of the maximum horizontal compressive stress [*Crampin and Lovell*, 1991].

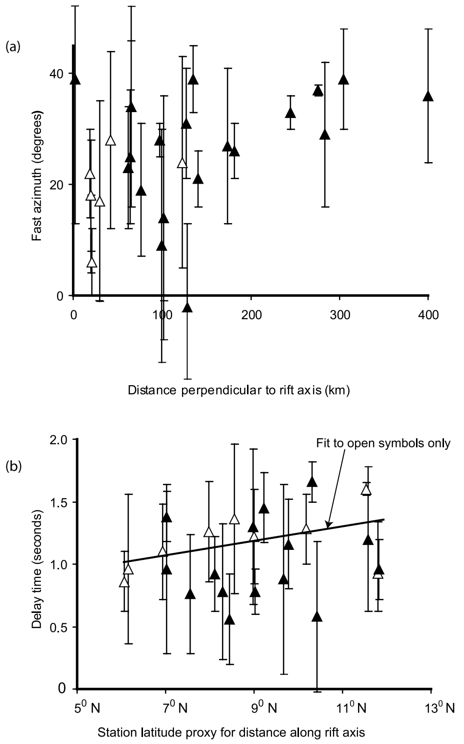

Figure 3. (a) Fast azimuth as a function of distance from the rift axis and (b) delay time as a function of latitude. Open symbols: stations within the active rift; closed symbols stations outside the rift. Black line in (b): best straight line fit for stations inside the rift.

[11] Total extension in the main Ethiopian Rift is only a few tens of kilometers and is strongly localized with in the modern rift that is less than 100 km wide. We expect that aligned melt inclusions in the mantle and crust contribute to the observed anisotropy within the rift; this is especially true where large delay times are observed in regions of thin lithosphere (e.g., 1.6 s at ATD in Djibouti [*Barruol and Ben-Ismail*, 2001]). In contrast we infer that the cause of rift ndash;parallel NE-SW anisotropy as much as 350 km NW and 150 km SE of the rift (Figure 1) is purely fossilized Proterozoic anisotropy. However, the variation of fast azimuth with distance from the rift axis (Figure 3a) (the greater proportion of more northerly azimuths close to the rift axis) suggests that there is a slight anti-clockwise rotation from NE-to-NNE-trends outside the rift to NNE-to-N trends within the rift, arguing for a component of anisotropy perpendicular to the modern extensional direction. This NNE-to-N splitting azimuth has also been seen on the more local EAGLE broadband array that is closely

focused on the rift valley itself [*Kendall et al.*, 2003; *Maguire et al.*, 2003]. The slight increase in delay time with distance along the rift axis, for stations within the rift (Figure 3b), hints at an increase in magmatic modification as the Ethiopian rift becomes increasingly magma-dominated to the north, towards the Afar triple junction.

4. Conclusions

[12] Our shear-wave splitting results from Ethiopia are consistently aligned NNE-SSW, parallel to the structures of the Main Ethiopian Rift. Our data are consistent with those obtained in Djibouti [*Barruol and Ben-Ismail*, 2001], near Addis Ababa [*Ayele et al.*, 2004] and by the EAGLE broadband array within the rift (M.-J. Kendall et al., Magma assisted rifting in Ethiopia, submitted to *Nature*, 2004, hereinafter referred to as Kendall et al., submitted manuscript, 2004) inferred by those authors to show rifting-related anisotropy. However, our conclusions are more consistent with a complex interplay of Precambrian and Neogene effects on splitting [cf. *Walker et al.*, 2004] and early extensional-phase modification of the older accretion-induced fabric. Our broad array of stations suggests that a simple model that relates splitting only to rifting is inapplicable. Anisotropy due to aligned melt pockets (Kendall et al., submitted manuscript, 2004), and the orientation of the old orogenic fabric that influenced the propagation of the rift [*Vauchez et al.*, 1997] presumably both contribute to the observed fast azimuths within the rift. For stations far from the rift axis where Quaternary magmatism is absent and our fast directions correlate with structural trends of the Mozambique Belt, fossil anisotropy is a better explanation of our data. There is no observed correlation between the absolute plate motion of Africa and our splitting orientations, or evidence for radial flow of asthenosphere outwards from an active plume beneath Ethiopia.

[13] **Acknowledgments.** We thank Laike-Mariam Asfaw, Atalay Ayele, and staff of the Geophysical Observatory of Addis Ababa University, for logistic and technical help with the Ethiopian Broadband Seismic Experiment. We thank the developers of SAC2000 and GMT for the packages used for the data analysis and presentation. We thank Paul Silver and George Helffrich for the splitting codes and IRIS-PASSCAL for the loan of broadband stations. Data acquisition was funded by NSF-EAR-Geophysics-9903093 and data analysis by NSF-EAR-CD-0208475.

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