Published as:

Sandvol, E., Turkelli, N., Zor, E., Gok, R., Bekler, T., Gurbuz, C., Seber, D., and Barazangi, M. Shear wave splitting in a young continent-continent collision: An example from eastern Turkey, *Geophys. Res. Lett.,30(24),* 2003.

Shear Wave Splitting in a Young Continent-Continent Collision: An Example from Eastern Turkey

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Abstract. We have determined the shear wave splitting fast polarization direction and delay time using data from the ETSE broadband experiment (Eastern Turkey Seismic Experiment), a deployment of 29 broadband seismic stations across the collision zone of the Arabian, Eurasian, and Anatolian plates. Our results show that the fast polarization directions are relatively uniform and they exhibit primarily NE-SW orientations. No abrupt changes in anisotropy directions are observed across the main tectonic units in the region: the Bitlis Suture (BS) and the North and Eastern Anatolian Fault zones. The fast polarization directions are determined to be sub-parallel to the Anatolian, Arabian, and Eurasian absolute plate velocities, except for those stations in the northeastern corner of the Anatolian Plateau. Observed delay times range from 0.7 to 2.0 seconds with an average value of 1.0 second; the largest values are within the northern Anatolian Plateau which is underlain by an exceptionally low velocity zone in the uppermost mantle.. We interpret shear wave splitting as the vector difference of the Eurasian lithosphere and northeastern or southwestern directed flow of the asthenospheric mantle. Comparisons of the polarization anisotropy with measurements of Pn azimuthal anisotropy suggest vertical anisotropic layering except in those areas which are underlain by partially molten uppermost mantle.

Introduction

In order to construct a meaningful geodynamic model for young continent-continent collision it is critical to understand the role of mantle flow. Upper mantle lithosphere dynamics are primarily controlled by shear and normal tractions associated with both large-scale plate motions and with local mantle dynamics. Lattice preffered orientation (LPO) of anisotropic mantle minerals such as olivine produces seismic velocity anisotropy [e.g. *Nicolas and Christensen*, 1987; *Ribe*, 1991]. Seismic anisotropy in the mantle lithosphere, asthenosphere, or both, can yield teleseismic shear-wave splitting.. Asthenospheric LPO induced seismic anisotropy is likely due to plate-motion-controlled flow and/or to more localized flow (e.g. Fouch et al., 2000; *Silver and Holt*, 2002). However, within a stable thick lithosphere, seismic anisotropy may reflect the cumulative history of formation and modification. This study is the first extensive investigation of mantle anisotropy along the Arabia-Eurasian plate boundary.

The Arabia-Eurasian plate boundary is characterized by a 2 km topographic high (Anatolian plateau) which is underlain by uppermost mantle with extremely low seismic velocities (*Al Lazki et al*., 2003, this issue). The Bitlis suture/thrust zone and the East Anatolian strike-slip fault mark this distributed, irregular, and young continental collision zone . Westward tectonic escape of Anatolia is taking place, as evidenced by the right-lateral strike-slip movement along the North Anatolian fault system (NAF) (*Sengor*, 1979) and by left lateral movement along the East Anatolian fault system (EAF) (*Jackson and McKenzie*, 1988). The North and East Anatolian faults have been active since the Miocene (e.g., *Barka and Kadinsky-Cade*, 1988) and are associated with large pull-apart basins, such as the Karliova Basin located at the junction of these two fault systems (*Hempton*, 1985). Geologic estimates of the rate of westward escape of Anatolia tend to indicate that the Arabian convergence cannot be accounted for entirely by the westward escape (Dewey et al., 1986), however GPS measurements would indicate that the westward escape of the Anatolian plate is currently accommodating the northward vergence of the Arabian plate (McClusky et al., 2000). There is no consensus on precisely when collision between the Eurasian and Arabian plates began. Estimates of the initiation of uplift range from 12 Ma, based on stratigraphic discontinuities in Eastern Anatolia (*Yilmaz*, 1993) and the beginning of collision related volcanism (*Pearce et al*., 1990), to 20 Ma based on the convergence rate of the two plates (*Dewey et al*., 1986).

Unlike the Tibetan plateau, there is extensive basaltic volcanism (Figure 3) with all dated lavas being younger than 8 Ma (e.g., *Innocenti et al*., 1982; *Pearce et al*., 1990) and the majority younger than 3 Ma. Based on their geochemistry, all of these basaltic lavas are inferred to be derived from the lower portion of the lithospheric mantle; although in the light of recent work which has demonstrated that the uppermost mantle has very slow seismic velocities, these interpretations may need to be reconsidered (*Al Lazki et al.*, 2003, this issue). *Innocenti et al*. (1982) suggested that during the initial collision of Arabia and Eurasia the Neo-Tethys oceanic slab was detached from the Arabian continental lithosphere, allowing asthenospheric magma to flow into the subsequent gap between the detached slab and the overriding plate (*Sengor et al., 2003 this issue*). The resulting thermal perturbation would cause melting of the metasomatized overriding lithosphere and result in the observed alkaline volcanism (*Davies and Blanckenburg, 1995*). Given that there does not appear to be a slab beneath the Anatolian plateau, it is reasonable to expect that detachment of the Neo-Tethyan oceanic lithosphere may have significantly affected asthenospheric mantle flow beneath the Northern Arabian plate and Anatolian plateau.

Data and Method

To address the regional tectonics and dynamics of the Northern Arabian plate and the Eastern Anatolian plateau, a 29 station broadband array was deployed for twenty one months across most of eastern Turkey. These instruments were broadband STS-2 seismometers (20 to 0.01 Hz) and a 24 bit digital acquisition system that recorded continuously at 40 samples per second. Over 750 Gigabytes of data were collected in a region where, prior to this experiment, no modern seismic stations existed.

The main assumptions in measuring splitting parameters are that the anisotropic medium is laterally homogeneous and that there is a coherent anisotropic symmetry. SKS, PKS, or SKKS core phases are commonly used to determine receiver side seismic polarization anisotropy. Two parameters are used to define a split shear wave: the polarization direction of the first arrival phase (fast direction) and the time delay between the fast and slow polarizations (lag time). Splitting measurements provide excellent lateral resolution but poor vertical resolution of polarization anisotropy. We have used both the automated technique of *Silver and Chan* [1991] and visual inspection to determine the optimal single layer shear wave splitting parameters. For SKS and SKKS, shear wave splitting parameters are found by a grid search over the parameter space by minimizing energy in the tangential component. The results were checked by analyzing the particle motion of each phase used in this study; elliptical particle motions are indicative of shear wave splitting. After correcting the seismogram with the parameters determined from minimizing the energy in the measurement window of the seismogram's tangential component.

The error analysis used in this study utilizes the inverse f test method described by *Silver and Chan* [1991]. The test is performed for each set of possible parameters to determine whether or not the shear wave splitting parameters are within the bounds of a 95% confidence region. For those events with questionable signal to noise ratio we employed a Monte-Carlo simulation technique [*Sandvol and Hearn*, 1994]. We used these error estimates when there was some ambiguity regarding the error estimates using the method of *Silver and Chan* [1991].

Results

We analyzed 945 sets of high quality (signal to noise > 5) SKS, PKS, and SKKS phases for evidence of shear wave splitting; from these data we obtained 615 sets of well constrained shear wave splitting parameters. The weighted means of the shear wave splitting parameters for each station are shown in Figure 1. The measurement of the fast direction and delay times typically had errors of about $\pm 10^\circ$ and ± 0.3 seconds, respectively (two standard deviations). We have not included fast directions with errors higher than 20° or delay times higher than 0.5 seconds. We also discarded measurements with delay time errors larger than half of the delay time itself. We also analyzed data from two nearby permanent Global Seismic Network stations at Malatya, Turkey and Garni, Armenia (MALT and GNI).

The shear wave splitting parameters for ETSE stations in the northern Arabian plate show, within our estimated errors, fairly consistent northeast-southwest fast directions with lag times of approximately 1.0 second. The mean fast direction for these stations is $35^\circ \pm 15^\circ$ with a mean delay time of 1.0± 0.2 seconds; the western Arabian plate stations consistently have more northerly fast directions than the eastern Arabian stations (Figure 1). This direction is sub-parallel to the absolute Arabian plate motion from the data of McClusky et al. (2000) and the model of *Kreemer et al.* (2003) (47° for No Net Rotation Reference Frame). The average fast direction and lag time for the five stations within the Anatolian plate are $35^\circ \pm 10^\circ$ and 1.1 ± 0.3

seconds respectively. Station MALT's (the westernmost station near EAF) fast direction is considerably more north-south ($17° \pm 10$) than the other five Anatolian Plate stations. This is consistent with the fast directions for events with a back-azimuth (BAZ) of $270°$ for stations near the EAF. Although azimuthal variations are often associated with two anisotropic layers (*Silver and Savage*, 1994) we attribute these observation primarily to lateral variations in the seismic anisotropy beneath the Arabian and Anatolian plates. Shear wave splitting parameters for stations within the Eurasian plate (east of the Karliova triple junction or north of the NAF) have a mean fast direction of $55° \pm 8°$ and a delay time of 1.3±0.3 seconds. This fast direction is sub-parallel to the absolute plate motion of the Eurasian Plate (No Net Rotation Reference $27°$). There are three stations within the northeastern corner of the Anatolian Plateau with an average fast direction of $75° \pm 10°$, nearly parallel to absolute plate motion (Figures 1). We also observed a similar fast direction isolated just to the north of the NAF at station MSDY that is also very nearly parallel to the Eurasian plate motion.

We observed evidence of distance or possibly azimuth dependent splitting at five stations within the ETSE array (Figure 2). Those five stations are marked with stars in Figure 1. In general there was very little variation in the fast polarization directions with either ray parameter or BAZ; however, we observed fairly consistent variations in lag time with azimuth and incidence angle. These variations are shown for four stations in the ETSE array. There is also some evidence for variation at station BNGL; however, it is not as clear as the other four.

Discussion and Conclusions

This study presents the results of the first detailed measure of seismic polarization anisotropy beneath the Arabian-Eurasian collisional belt. Seismic anisotropy beneath station ANTO (shown on inset map in Figure 1, [*Vinnik et al*., 1992]), in central Anatolia has a NE-SW fast direction and lag time similar to that observed from ETSE stations within the Anatolian plate, indicating that the anisotropic fabric may be relatively uniform throughout the upper mantle beneath the Anatolian plate. The extensive young basaltic volcanism, regional travel time tomography, and regional phase attenuation tomography all indicate that the lithosphere beneath the Anatolian plateau, Lesser Caucasus, and most of the central Anatolian lithosphere has largely been removed [*Pearce et al.*, 1989; *Yilmaz*, 1993; *Al-Lazki, et al.*, 2003, this issue; *Gok et al.*, 2003, this issue] or contains significant amount of partial melt. Unless exceptionally high (approximately 12%) anisotropy exists in the thinned lithosphere, the main contribution to the observed delay times (of order 1 s) must therefore be asthenospheric. Assuming 4% upper-mantle anisotropy, a 1 s delay time corresponds to a layer of highly oriented pyrolite approximately 120 km thick [*Christensen*, 1984]. Furthermore, the lack of correlation between surface deformation and the observed shear wave splitting parameters would suggest that the measured anisotropy is primarily asthenospheric. The measured fast direction of stations across the EAF, NAF and BS does not change significantly, clearly not reflecting the change in lithospheric or crustal strain [*McCluskey et al.*, 2000]. This discrepancy in the orientations between the fast direction and the approximate infinitesimal strain direction argues that, at least over short time scales, crustal strain is not a major cause of the observed anisotropy.

We also note some correlation between the average Pn velocities and the measured delay times and fast directions. The correlation between larger delay times and low Pn velocities is consistent with higher levels of anisotropy in the warmer/slower portions of the anisotropic asthenosphere, such as might be due to increased mantle deformation. The observed correlation could also be caused by a thickening of uniformly anisotropic asthenosphere or coherent deformation between the asthenosphere and a mechanically weak lithosphere. If the plate is also laterally translating relative to the hot mantle, material may be entrained, creating an extended warm feature that is elongated in the direction of plate motion and creating an anisotropic fabric that is roughly parallel with the absolute plate motion. This process may be contributing in part to the observed fast directions in this portion of the Anatolian, Arabian, and Eurasian plates.

Analysis of the splitting fast directions along the Arabia-Eurasian collisional belt can constrain mantle flow because only very recent tectonic events (<10 Ma) could have had significant impact on upper mantle anisotropy. In this region we interpret that the anisotropy is either entirely in the asthenosphere or partly within a mechanically weak lithospheric mantle and that the azimuth of the fast direction is determined by the vector difference between the lithospheric velocity vector and the mantle flow vector [*Silver and Holt*, 2002]. If we assume the mantle flow velocities are equal to or less than 7 cm/yr, then we can calculate a range of mantle flow vectors that will fit the observed fast directions. Figure 3 demonstrates that the mantle must either have a fairly uniform northeastern mantle flow or a fairly complex primarily western directed flow field. Using the kinematic model of *Kreemer et al.* (2003) our uniformly northeastern directed flow are nearly parallel with the plate motion (Figure 3).

The variations in shear wave splitting lag times with incidence angle may suggest a purely horizontal symmetry axis for stations BNGL, EZRM, SILN, and MUSH (Figure 1) where more steeply incident waves will have smaller lag times that more obliquely incident waves. However, the observed differences (> 0.5 seconds) indicate that lateral variations in either the strength or thickness of the anisotropic layer is responsible for these observations. At station MSDY we observed variations in lag times that decrease with increasing incidence angle which would be consistent with an inclined symmetry axis. Perhaps localized mantle shear related to the NAF may lead to a more three dimensional flow near station MSDY (Figure 1).

In summary these results suggest there is a fundamental difference in the asthenospheric flow directions and surface deformation across the Arabian and Anatolian Plates. This result further suggests that large surface faults do not have any influence on upper mantle flow patterns or deformation.

Acknowledgements

We would like to thank all people who help deploy the ETSE array including the PASSCAL instrument center. The ETSE study was supported by National Science Foundation under Grant No EAR-9804780. Additional support was provided by Boğaziçi University Research Fund under Grant No 99T206. We thank many local Turkish military and government offices and local landowners for their assistance with this project. We also thank Bill Holt, Dave Wilson, and Frekerik Tillman for useful discussions regarding mantle flow and polarization anisotropy.

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Figure Captions

Figure 1. Averaged fast directions and delay times from SKS and SKKS measurements. Shear wave splitting with an open star show evidence of either distance or azimuthal dependence. Major Faults and plate boundaries are shown by solid grey lines. NAF- North Anatolian Fault; EAF – East Anatolian Fault; KTJ – Karliova Triple Junction.

Figure 2. Shear wave splitting a) lag times as a function of BAZ and b) of the Moho incidence angle. Error bars represent 95% confidence intervals for each of the lag time estimates. The most consistent variations are observed as a function of incidence angle with the lag time increasing at all stations except at station MSDY (located at the northwestern corner of the ETSE array). These kind of variations would either argue for a largely horizontal symmetry axis (at all stations except MSDY) or rather rapid lateral variations in the thickness and/or strength of the anisotropic fabric.

Figure 3. Range of allowable mantle flow vectors (thick gray arrows) using the assumptions and method of *Silver and Holt* [2002]. We have used an averaged fast directions and the absolute plate motion vectors (large arrows with white fill) for the Eurasian, and Arabian plates using a No Net Rotation Reference Frame (*Kreemer, et al.*, 2003). The different flow vectors are calculated using different assumed mantle flow rates (3.0, 5.0, and 7.0 cm/yr).

Figure 1

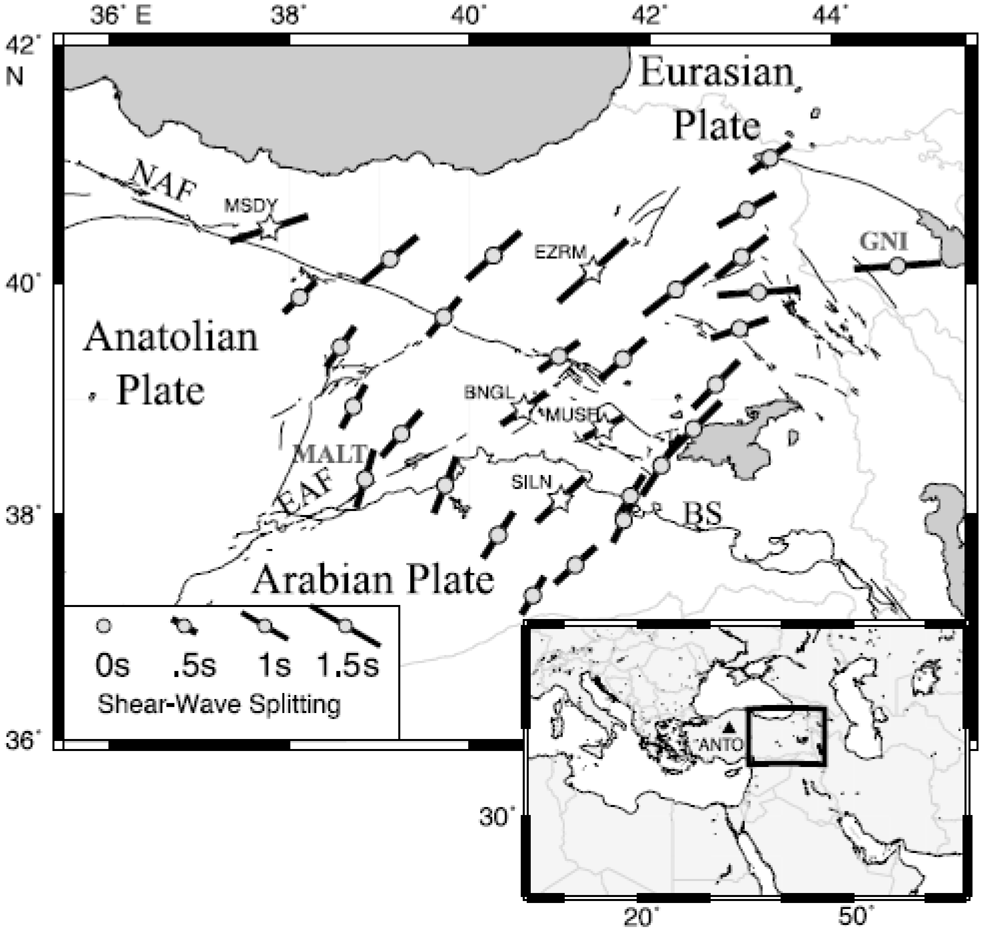

Figure 2a

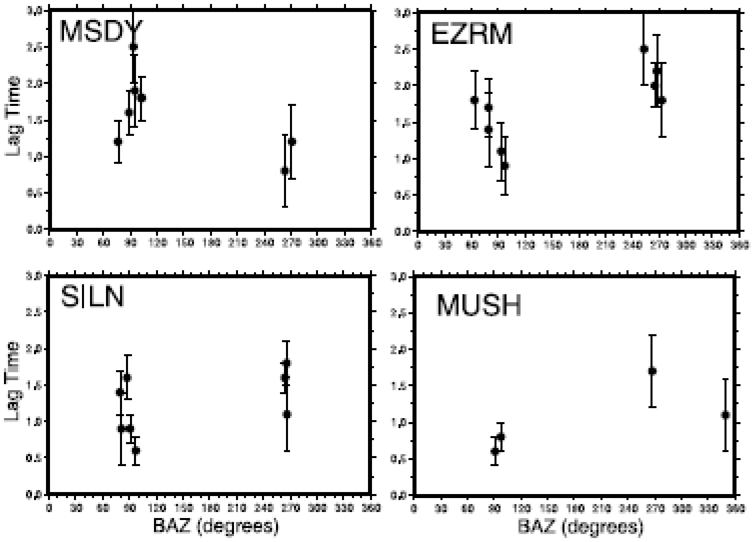

Figure 2b

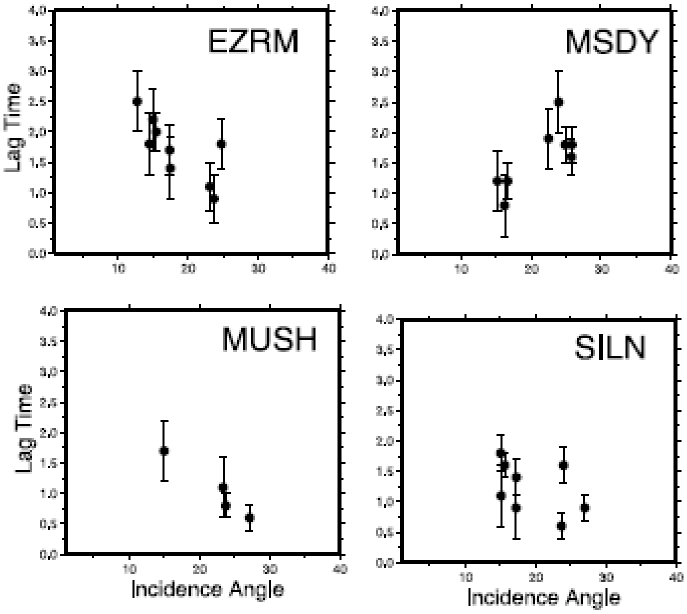

Figure 3