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Shear wave splitting and mantle flow beneath LA RISTRA

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[1] Shear-wave splitting parameters (fast polarization direction and delay time) are determined using data from LA RISTRA (Colorado pLAteau RIo Grande Rift/Great Plains Seismic TRAnsect), a deployment of broadband seismometers extending from the Great Plains, across the Rio Grande Rift and the Jemez Lineament, to the Colorado Plateau. Results show that the fast polarization directions are sub-parallel to North American absolute plate motion. The largest deviations from the plate motion are observed within the western edge of the Great Plains and in the interior of the Colorado Plateau where lithospheric anisotropy may be significant. Delay times range from 0.8 to 1.8 seconds with an average value of 1.4 seconds; the largest values are along the Jemez Lineament and the Rio Grande Rift which are underlain by an uppermost mantle low velocity zone extending to depths of ~200 km. The anisotropy beneath the central part of LA RISTRA shows a remarkably consistent pattern with a mean fast direction of 40° ± 6°. Seismic anisotropy can be explained by differential horizontal motion between the North American lithosphere and westerly to southwesterly flow of the asthenospheric mantle. The approximately N-S fast direction found beneath western Texas is similar to that observed beneath the southern rift and may reflect a different dynamic regime. *INDEX TERMS:* 7203 Seismology: Body wave propagation; 7218 Seismology: Lithosphere and upper mantle; 7209 Seismology: Earthquake dynamics and mechanics. **Citation:** Gök, R., et al., Shear wave splitting and mantle flow beneath LA RISTRA, *Geophys. Res. Lett.*, *30*(12), 1614, doi:10.1029/2002GL016616, 2003.

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1. Introduction

[2] LA RISTRA is a seismological exploration of the crust and mantle using broadband seismometers deployed along a great-circle transect at intervals of approximately 18 km, extending 950 km from the Great Plains (GP) of western Texas through the Rio Grande Rift (RGR), Jemez Lineament (JL), and into the interior Colorado Plateau (CP) (Figure 1). The JL, an alignment of volcanic centers, does not correlate with upper crustal structure in an obvious way, although it may be associated with a Proterozoic age boundary [*Karlstrom and Humphreys*, 1998]. The basement crust of the CP, RGR and adjacent GP consists of intra-oceanic island arc and marginal basin terranes accreted to North America (NA) between 1.8 and 1.0 Ga. This region of the Southwest was bordered by a passive margin from the Neoproterozoic until the late Devonian (~360 Ma), after which time the Antler orogeny and successive crustal-shortening events indicate the presence of an active margin [*Dickinson*, 1981]. From the late Paleozoic until the late Cretaceous, the CP-RGR-GP region was not strongly affected by active processes along the plate margin. However, during Late Cretaceous and early Tertiary time (~80–40 Ma), low-angle subduction of the Farallon plate drove crustal shortening, crustal thickening, and basement-cored uplifts of the Laramide orogeny. After ~40 Ma, crustal shortening ceased and the southwestern Cordillera underwent crustal extension and magmatism is inferred to have resulted from steepening and subsequent removal of the Farallon slab [e.g., *Lipman*, 1992]. Return-flow of hot asthenospheric mantle into the region previously occupied by the slab caused substantial melting and thinning of the lithosphere, and voluminous volcanism, lasting until about 27 Ma. Over the last 30 Ma the CP has remained largely intact, but the RGR has undergone

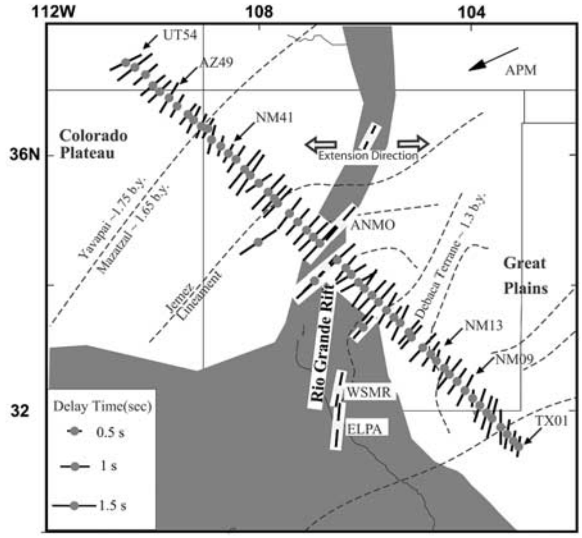

Figure 1. Average fast direction and delay time estimates. Shear wave splitting measurements shown with an open symbol are taken from *Sandvol et al.* [1992]. Proterozoic geological province boundaries are shown by dotted lines. Shaded regions are under Late Cenozoic extension. The black arrow indicates absolute plate motion of the North America Plate [*Gripp and Gordon*, 1990].

moderate extension. We do not yet know if plate-boundary forces or localized asthenospheric convection cause the extension of the RGR.

[3] Mantle deformation and its role in orogeny on continents have been investigated from shear wave splitting parameters [e.g., *Savage and Silver*, 1993]. Strain-induced orientation of anisotropic mantle minerals such as olivine produces seismic velocity anisotropy because the fast olivine [100] axes align with the shear of a flow, or along the maximum elongation direction of the strain ellipsoid. The crustal component of anisotropy is often small (~0.2–0.3 seconds delay time between fast and slow wave), thus, SKS anisotropy arises either in the asthenosphere, or in the lithospheric mantle, or both. Western NA displays variable shear-wave splitting fast directions. Shear wave splitting parameters in the Great Basin, Snake River Plain and the Yellowstone area are compatible with asthenospheric flow models [*Savage and Sheehan*, 2000]. However, upper mantle anisotropy beneath the Colorado Rocky Mountains is highly variable, suggesting either a complex pattern of asthenospheric flow or a significant and spatially variable component of lithospheric anisotropy [*Savage et al.*, 1996]. *Silver and Holt* [2002] infer an eastward asthenospheric flow (5.5 ± 1.5 cm/yr) in western NA from seismic anisotropy and surface motion of the NA plate. Asthenospheric effects are likely due to plate-motion-controlled flow or to localized flow. Plate-controlled flow would produce anisotropic directions parallel to the absolute plate motion. Localized asthenospheric flow beneath the CP-RGR-GP region might result from upwelling associated with lithospheric extension of the RGR or back-flow behind the trailing edge of the Farallon slab. Effects arising within the lithosphere are likely to reflect the cumulative history of deformation of the NA lithosphere, including assembly of the Protoerozoic crust in a series of northwestward-directed accretionary events, late Paleozoic orogeny (Ancestral Rocky Mountains), early Tertiary (Laramide) crustal shortening, and middle-to-late Tertiary extension. In this paper we present a shear-wave splitting analysis of LA RISTRA data in order to elucidate which process is responsible for the late Cenozoic extension while putting it into context with larger scale mantle deformation beneath western NA.

2. Data and Method

[4] LA RISTRA consisted of 57 densely spaced, continuously recording (20 Hz) IRIS PASSCAL stations deployed between August 1999 and May 2001. High signal-to-noise SKS and SKKS core phases from 30 events were used in this study. Most high quality core phases were from western Pacific earthquakes (backazimuths 230°–260°); three were from the Hindu Kush (backazimuths ~360°) and one from the Scotia arc (backazimuth ~150°).

[5] Shear wave splitting occurs when a shear wave passes through an anisotropic medium. We make the traditional assumption of one-layer anisotropy with a horizontal symmetry axis. The splitting delay is proportional to the thickness of the anisotropic layer and the strength of anisotropy. Splitting parameters at several closely spaced stations provide good lateral resolution, but only indirect information about the depth of the anisotropic material. Here we use the method of *Silver and Chan* [1991] to determine shear wave splitting parameters. The analysis window begins ~10 seconds before the core phase and ends just after the phase. After determining parameters by minimizing the energy on the tangential component, we checked to ensure that corrected seismograms had roughly linear particle motion.

[6] The error analysis utilizes the inverse f test method described by *Silver and Chan* [1991]. We also estimate errors using a bootstrap technique [*Sandvol and Hearn*, 1994].

3. Results

[7] Analysis of SKS and SKKS phases yielded 296 sets of shear wave splitting measurements (see Auxiliary Material Table)[1]. The shear wave splitting parameters for each station and weighted mean fast direction and delay time are shown in an electronic supplemental figure. Fast direction and delay time estimates have typical 95% confidence intervals of ±13° and ±0. 4 seconds, respectively. Fast directions with errors higher than 25° or delay times greater than 0.7 seconds or larger than 50% of the corresponding delay time estimate were eliminated.

[8] Results show that fast directions are generally subparallel to NA plate motion and delay times range from 0.8 to 1.8 s; both vary systematically along the LA RISTRA transect (Figure 2). Stations located at the western edge of the GP, through the central RGR, to the southeastern CP (NM14 to NM40), show largely coherent fast directions and delay times (Figures 1 and 2) averaging 42° ± 6° and 1.3 ±

[1] Supporting material is available via Web browser or via Anonymous FTP from ftp:/ftp.agu.org, directory "apend" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic suppplements is found at http://www.agu.org/pubs/esupp_about.html.

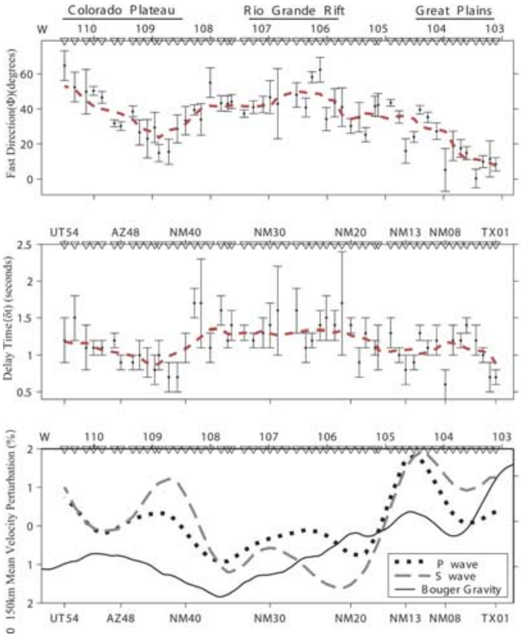

Figure 2. Shear wave splitting a) fast azimuths and b) delay times along the LA RISTRA. Error bars represent 95% confidence intervals. Dashed lines for fast directions and delay times are 7-point (~100 km) weighted running averages. c) Mean P- and S-wave velocities for 0–150 km depths (taken from tomography results), and Bouguer gravity anomaly.

0.2 seconds. This direction is systematically more N-S than the NA absolute plate motion (~62° for hot spot reference frame). In the margin of CP (station NM41-AZ49), both fast directions and delay times vary significantly from the central part of LA RISTRA (Figure 2). The fast directions trend from 20° to 30° with smaller delay times averaging 0.8 ± 0.2 seconds. For these stations we found different fast directions and delay times from events with slightly different backazimuths. Such a phenomenon is often associated with two or more anisotropic layers [*Silver and Savage*, 1994]. Unfortunately, LA RISTRA core phase data had an insufficient backazimuthal range to constrain more complicated anisotropic models. Stations located in the interior of CP (AZ50-UT54) have an average fast direction of about 54° ± 6° and an average delay time of 1.2 ± 0.2 seconds. The 8 southernmost stations in the GP (TX01-NM08) show a fast direction of approximately 11° ± 7° and a delay time of 1.0 ± 0.2 seconds (Figures 1 and 2) which deviates significantly from stations to the north, but is similar to the parameters found in the southern RGR [*Sandvol et al.*, 1992]. The stations on the western edge of the GP (NM9-NM13) have an average fast direction of NNE-SSW, which is transitional from the N-S to NE-SW direction observed at adjacent stations.

4. Discussion

[9] Results of this and previous studies in southwestern NA have revealed lateral variations in seismic anisotropy in the GP, RGR, and CP tectonic provinces. Seismic anisotropy beneath station ANMO, Albuquerque and Socorro [*Vinnik et al.*, 1992; *Sandvol et al.*, 1992] has a NE-SW fast direction similar to that observed from LA RISTRA stations in and around the RGR. *Vinnik et al.* [1992] argued that because the fast direction beneath NA is roughly parallel/antiparallel to the absolute plate motion, the anisotropy mainly resides in the asthenosphere and is indicative of mantle flow due to broad-scale plate/asthenosphere interaction. Petrological data and LA RISTRA surface wave analyses beneath the central RGR and JL [*West et al.*, 2002] suggest that the lithosphere beneath the rift and adjacent regions has been thinned to about 70 km [*Perry et al.*, 1987]. Assuming 4% upper-mantle anisotropy, a 1.25 s delay time corresponds to a layer of peridotite 138 km thick. Therefore, unless exceptionally high anisotropy exists in the thinned lithosphere, a large contribution to the observed delay times must be asthenospheric. Geologic structure and stress data indicate that the present least principal horizontal stress direction is oriented E-W across the RGR [e. g. *Aldrich et al.*, 1986]. The discrepancy in the orientations between the fast direction and least principal horizontal stress direction argues that lithospheric tensile stress is not a major cause of the observed anisotropy.

[10] We note a strong correlation between average seismic velocities from LA RISTRA tomography models for 0–150 km depth and the measured delay times and fast directions (Figure 2). The correlation between larger SKS delay times and low S-wave velocities is consistent with global observations that higher levels of anisotropy exist in the warmer/slower portions of the asthenosphere. A thickening of uniformly anisotropic asthenosphere or coherent deformation between the asthenosphere and a thermally weakened lithosphere could also cause the observed correlation.

[11] If plate motion is not parallel/antiparallel with the fast direction, the net relative shear field between plate motion

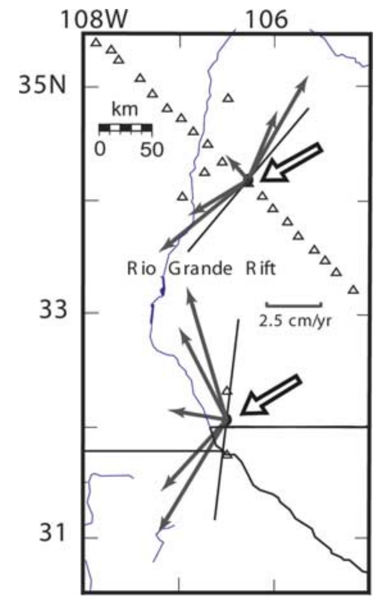

Figure 3. Range of allowable mantle flow vectors (thick gray arrows) producing observed shear wave splitting fast directions (thin black lines) from the given APM vectors (large arrows with white fill) for the central and southern RGR, using the assumptions and method of *Silver and Holt* [2002]. The different flow vectors are calculated using different assumed mantle flow rates.

and underlying mantle flow may control anisotropy. In this model, horizontal shear within the asthenosphere may, to first order, be aligned with the vector difference between the horizontal velocity of the lithosphere and the horizontal component of mantle flow [*Silver and Holt*, 2002].

[12] Given the discrepancy between fast directions and the E-W extension in the central and southern RGR, we relate the fast direction to the direction of mantle flow. We assume that the anisotropy is either entirely in the asthenosphere or partly within a thermally weakened lithosphere and that the azimuth of the fast direction is by the vector difference between the lithospheric velocity vector and the mantle flow vector [*Silver and Holt*, 2002]. We can thus calculate a range of mantle flow vectors that will fit the observed fast directions. Figure 3 demonstrates that the mantle must have a westward component of flow in the southern and central RGR if we make the reasonable assumption that the general direction and magnitude of mantle flow does not vary greatly over length scales of 200 km. If the eastward mantle flow field in westernmost NA [*Silver and Holt*, 2002] is due to heterogeneity in mantle density associated with subduction of the former Farallon plate, the westward or southwestward mantle flow that we infer for the RGR region may represent counter flow in the mantle wedge above the subduction path of the Farallon plate.

[13] Southernmost stations in the GP (TX01-NM08) show an approximately N-S fast direction which differs significantly from all the stations to the north, but is similar to the parameters found in the southern RGR [*Sandvol et al.*, 1992]. Since the southern LA RISTRA and RGR stations are near the southern Basin and Range (BR) province, it is conceivable that the anisotropy is affected by mantle flow beneath the southern BR province.

5. Conclusions

[14] Shear wave splitting measurements in the southeastern CP, RGR and the eastern edge of the GP are uniform with a NE-SW mean fast direction that is neither parallel nor perpendicular to the RGR rift axis, but sub-parallel to NA absolute plate motion. The differential horizontal motion between the NA lithosphere and a westward or southwestward horizontal flow of the asthenospheric mantle best explains the shear wave splitting data beneath the central LA RISTRA as well as the southern RGR. Deviation of the fast direction from NE-SW occurs in western Texas and the interior of the CP. Localized deformation of the CP stable lithospheric mantle associated with the Laramide or earlier orogenies may contribute to the observed NNE-SSW fast direction. Correlation among average seismic wave velocities for the upper 150 km, shear wave splitting parameters and a regional Bouguer gravity low are consistent with a systematic relationship between warm uppermost mantle and anisotropic properties in this region. Anisotropy measurements in the RGR indicate that the mantle finite strain beneath the rift is caused predominantly by shear between the NA plate and the mantle below, and the slow E-W spreading of the RGR has little effect on the seismic anisotropy. We conclude that vigorous upwelling, as might be expected if asthenospheric convection drives the rift, is responsible only for a minor component of the observed seismic anisotropic fabric. We conclude that the observed seismic anisotropy is mainly produced by deformation induced by the overriding plate.

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References

Aldrich, M. J., Jr., C. E. Chapin, and A. W. Laughlin, Stress history and tectonic development of the Rio Grande rift, New Mexico, *J. Geophys. Res.*, *91*, 6199–6211, 1986.
Dickinson, W. R., Plate tectonic evolution of the southern Cordillera, *Arizona Geol. Soc. Digest*, *14*, 113–135, 1981.
Gripp, A. E., and R. G. Gordon, Current plate velocities relative to the hotspots incorporating the NUVEL-1 global plate motion model, *Geophys. Res. Lett.*, *17*, 1109–1112, 1990.
Karlstrom, K. E., and E. D. Humphreys, Persistent influence of Proterozoic accretionary boundaries in the tectonic evolution of southwestern North America: Interaction of cratonic grain and mantle modification events, *Rocky Mountain Geology*, *33*, 161–179, 1998.
Perry, F. V., W. S. Baldridge, and D. J. DePaolo, Role of asthenosphere and lithosphere in the genesis of late Cenozoic basaltic rocks from the Rio Grande rift and adjacent regions of the southwestern United States, *J. Geophys. Res.*, *92*, 9193–9213, 1987.
Sandvol, E., J. Ni, S. Ozalaybey, and J. Schlue, Shear-wave splitting in the Rio Grande Rift, *Geophy. Res. Lett.*, *19*, 2337–2340, 1992.
Sandvol, E., and T. Hearn, Bootstrapping Shear-Wave Splitting Errors, *Bulletin of the Seismological Soc. of America*, *84*, 1971–1977, 1994.
Savage, M. K., A. F. Sheehan, and A. Lerner-Lam, Shear wave splitting across the Rocky Mountain front, *Geophys. Res. Lett.*, *23*, 2267–2270, 1996.
Savage, M. K., and A. F. Sheehan, Seismic anisotropy and mantle from the Great basin to the Great Plains, western United States, *J. Geophys Res.*, *105*, 13,715–13,7347, 2000.
Savage, M. K., and P. G. Silver, Mantle deformation and tectonics: Constraints from seismic anisotropy in western United States, *Phys. Earth Planet. Inter.*, *78*, 207–228, 1993.
Silver, P., and W. Chan, Shear-wave splitting and mantle deformation, *J. Geophys Res.*, *96*, 16,429–16,454, 1991.
Silver, P. G., and W. E. Holt, The mantle flow field beneath western North America, *Science*, 1054–1057, 2002.
Silver, P. G., and M. K. Savage, The interpretation of shear wave splitting parameters in the presence of two anisotropic layers, *Geophys J. Int.*, *119*, 949–963, 1994.
Vinnik, L. P., L. J. Makeyeva, A. Milev, and A. Y. Usenko, Global patterns of azimuthal anisotropy and deformations in the continental mantle, *Geophys. J. Int.*, *111*, 433–447, 1992.
West, M., R. Gök, J. Ni, S. Grand, W. Gao, D. C. Wilson, R. Aster, J. Schlue, S. Baldridge, and S. Semken, The role of the upper mantle beneath the Colorado Plateau/Rio Grande Rift/Great Plains transition, 14th annual IRIS workshop, Waikoloa, Hawaii, abstract, 2002.

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