Bulletin of the Seismological Society of America, Vol. 98, No. 5, pp. 2526–2532, October 2008, doi: 10.1785/0120080107

Ⓔ

Short Note

Shear-Wave Splitting and Mantle Flow beneath the Colorado Plateau and Its Boundary with the Great Basin

by Xinling Wang, James F. Ni, Richard Aster, Eric Sandvol, David Wilson, Christopher Sine, Stephen P. Grand, and W. Scott Baldridge

Abstract Shear-wave splitting measurements from *SKS* and *SKKS* phases show fast polarization azimuths that are subparallel to North American absolute plate motion within the central Rio Grande Rift (RGR) and Colorado Plateau (CP) through to the western rim of the CP, with anisotropy beneath the CP and central RGR showing a remarkably consistent pattern with a mean fast azimuth of $40° \pm 6°$ E of N. Approaching the rim from the southeast, fast anisotropic directions become north-northeast–south-southwest (NNE-SSW), rotate counter clockwise to north–south in the CP-GB transition, and then to NNW-SSE in the western Great Basin (GB). This change is coincident with uppermost mantle *S*-wave velocity perturbations that vary from +4% beneath the western CP and the eastern edge of the Marysvale volcanic field to about −8% beneath the GB. Corresponding delay times average 1.5 sec beneath the central CP, decrease to approximately 0.8 sec near the CP-GB transition, and increase to about 1.2 sec beneath the GB. For the central CP, we suggest anisotropy predominantly controlled by North American plate motion above the asthenosphere. The observed pattern of westward-rotating anisotropy from the western CP through the CP-GB transition may be influenced to asthenospheric flow around a CP lithospheric keel and/or by vertical flow arising from edge-driven small-scale convection. The anisotropic transition from the CP to the GB thus marks a first-order change from absolute plate motion dominated lithosphere-asthenosphere shear to a new regime controlled by regional flow processes. The NNW-SSE anisotropic fast directions of split *SKS* waves in the eastern GB area are part of a broad circular pattern of seismic anisotropic fast direction in the central GB that has recently been hypothesized to be due to toroidal flow around the sinking Juan de Fuca–Gorda slab.

Online Material: *SKS* and *SKKS* splitting results from LA RISTRA 1.5.

Introduction

LA RISTRA (Colorado Plateau Rio Grande Rift/Great Plains Seismic Transect) is a seismological exploration of the crust and mantle using two temporary deployments (LR1 and LR1.5) of broadband linear arrays to study the Great Plains (GP), Rio Grande Rift (RGR), Colorado Plateau (CP), and the western Great Basin (GB) (Fig. 1). LR1 extends from west Texas to Lake Powell and LR1.5 extends from Lake Powell to western Utah. The combined length of the entire transect is 1278 km. This part of the southwestern United States was formed by a series of continent building events in which Proterozoic island and continental arcs, oceanic plateaus, and marginal basins were accreted to North America (NA) from northwest to southeast, culminating in the formation of the Rodinia supercontinent (e.g., Condie, 1982; Karlstrom *et al.*, 1999, 2001). The bulk of the CP lies within two major Proterozoic terranes, the Mazatzal and Yavapai (Magnani *et al.*, 2004) (Fig. 1). The western margin of Rodinia is proposed to have rifted away from the continent at about 650 Ma (e.g., Karlstrom *et al.*, 1999), forming the present-day western edge of cratonic North America, and marine Paleozoic and Mesozoic units deposited on the CP indicate that it was at or near sea level for the next ~500 Ma (Spencer, 1996). The northwestern, western, and southwestern edges of the CP experienced intense thrust faulting during the Sevier orogeny beginning in the late Jurassic or earliest Cretaceous.

After this period of stability and deposition, the northwestern, western, and southwestern edges of the CP experienced intense Sevier orogeny thrust faulting beginning in the

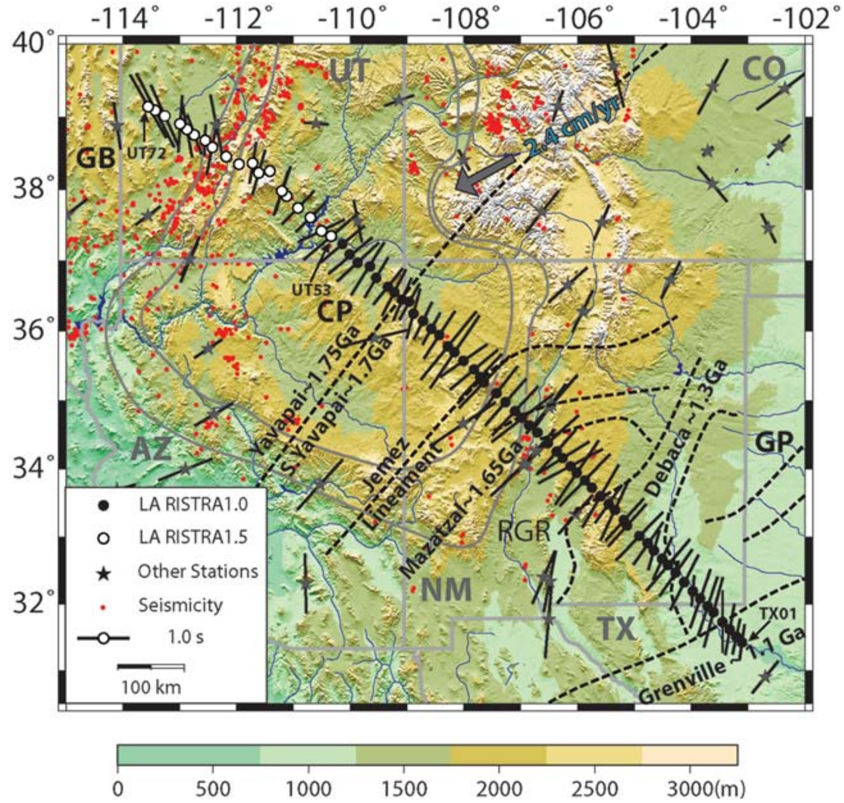

Figure 1. Mean fast direction and delay time estimates from *SKS* and *SKKS* measurements in from LR1 and LR1.5. Named physiographic provinces are Great Plains (GP), Rio Grande Rift (RGR), Colorado Plateau (CP), and Great Basin (GB). Approximate CP inner and outer margins are shown by the gray contours. Gray lines are state boundaries. The arrow indicates absolute plate motion (241.5°) of the NA plate in hot spot reference frame HS2-NUVEL-1A (Gripp and Gordon, 1990; Demets *et al.*, 1994). Proterozoic accretionary terranes are indicated with ages. Representative seismicity is concentrated at the edges of the CP (U.S. Geological Survey [USGS] Preliminary Determination of Epicenters catalog, 1973–2007).

latest Jurassic or earliest Cretaceous (~150 Ma), reaching its peak during the late Cretaceous (~75 Ma) (Willis, 1999). The culmination of thrust faulting resulted in upper crustal thickening of ~16 km, producing crust that was >50 km thick and with elevations most likely greater than 3 km. Much of the western margin of the CP at this time may have been a high-elevation plateau with a rugged topographic front similar to the central Andean fold-and-thrust belt (DeCelles and Coogan, 2006)

During the Laramide (80–50 Ma) orogeny, the region underwent further compression as the Farallon slab was subducting along the North American west coast, with crustal deformation characterized by fault-bounded, basement-cored uplifts with an estimated mean lateral contraction of 5% (Spencer, 1996). During this period, the Farallon slab probably subducted at a low angle (e.g., Dickinson and Snyder, 1978). Between approximately 43 to 20 Ma, the flattened Farallon slab likely detached, and the accompanying mantle upwelling, coupled with lithosphere-scale hydration of the uppermost mantle, may have been the controlling factor for the space-time evolution of massive (ignimbrite flare-up) mid-Tertiary igneous activity (e.g., Humphreys, 1995). In stark contrast to the surrounding region, the central CP experienced low levels of magmatism. CP mantle xenoliths suggest that at the time of eruption (30–20 Ma) the CP was characterized by a lithospheric root analogous to those beneath cratons (Roden and Shimizu, 1993). This root extended to depths of approximately 140 km at the time of xenolith transport (Riter and Smith, 1996) and persists today, as indicated by recent surface- and body-wave tomography results (Gao *et al.*, 2004; West *et al.*, 2004; Sine, 2007; Sine *et al.*, 2008) that show high-velocity lithosphere beneath the CP to 140–160-km depth. Since the foundering of the Farallon plate, upwelling hot asthenosphere and regional extension have initiated rifting of the RGR and collapse of the Basin and Range province, and subsequent small-scale convection in the upper mantle has thickened the lithosphere on the edges of the CP (Gao *et al.*, 2004; West *et al.*, 2004; Aster, *et al.*, 2007; Sine, 2007; Sine *et al.*, 2008). Over the last 10 Ma, the CP has become a distinct tectonic province, remaining a high plateau with its western, eastern, and southern margin uplifted by buoyant mantle and dynamically supported by an upwelling flow from edge-driven small-scale convection (Aster, *et al.*, 2007; Ni *et al.*, 2007).

Mantle deformation, and its role in continental dynamics, has been widely investigated from measurements of seismic anisotropy (e.g. Savage and Silver, 1993; Savage, 1999). Strain-induced orientation of dry anisotropic mantle minerals, such as olivine, produces latticed preferred orientation seismic anisotropy through the alignment of the fast olivine [100] axis with the maximum elongation direction of the strain ellipsoid. This maximum finite strain direction is generally parallel to the shear flow direction, and hence, anisotropy parameters are often used to infer mantle flow. Splitting measurements from SKS and $SKKS$ core phases provide excellent lateral resolution (but poor vertical resolution), allowing direct comparison between anisotropy, geologic terrains, and features imaged from tomography. Teleseismically observed anisotropy is typically attributed to the asthenosphere, the lithospheric mantle, or both, with crustal contributions thought to be significant only at higher frequencies. Asthenospheric effects likely arise due to plate-motion-controlled and/or localized flow. Localized asthenospheric flow on the edges of the CP may arise from edge-driven small-scale convection induced by large lateral temperature differences between the hot asthenosphere beneath the GB and RGR and the cold CP lithospheric mantle (Ni *et al.*, 2007; Sine *et al.*, 2008). Flow around and below the CP as the NA plate moves southwestward in the absolute plate motion reference frame at approximately 2.4 cm/yr (Fig. 1) (e.g., Gripp and Gordon, 1990) may significantly affect the anisotropic properties of the mantle in this region. Strain fabrics within the lithosphere likely reflect the cumulative history of deformation of the NA lithosphere, including assembly of Protoerozoic accreted terrains and the late Mesozoic Laramide orogeny.

Western NA displays highly heterogeneous anisotropic mantle structure, which has been found to be generally characteristic of continental interiors and is generally attributed to a variety of lithospheric and asthenospheric causes reflecting both inherited and active components (e.g., Fouch *et al.*, 2000; Fouch and Rondenay, 2006). Little shear-wave splitting is observed for seismic recordings in the northern CP extending into northern Colorado, where upwelling asthenosphere and resultant vertical olivine *a*-axes alignment could be responsible. In the central GB, there is a circular pattern of anisotropic fast polarization direction of split SKS waves (Sheehan *et al.*, 1997; Savage and Sheehan, 2000; Zandt and Humphreys, 2008). This pattern cannot be attributed to either preexisting lithospheric finite strain or to asthenospheric strain related to NA plate motion. Zandt and Humphreys (2008) have recently suggested that mantle flow around the edge of the descending Juan de Fuca slab is responsible. Silver and Holt (2002) infer an eastward asthenospheric flow of ~6.0 cm/yr in southwestern NA from seismic anisotropy observations and motion of the NA plate. Plate-controlled asthenospheric flow alone would produce an anisotropic direction subparallel to the absolute plate motion. A remarkably consistent pattern of seismic anisotropy with a mean fast direction of $40° \pm 6°$, which is roughly parallel to plate motion, was noted by Gok *et al.* (2003) for LR1 data spanning the RGR and extending to near the center of the CP (Gok *et al.*, 2003). In the southern RGR and west Texas, a nearly north–south fast direction from split SKS phases is observed, where mantle flow may be affected by regional rift-parallel asthenospheric currents (Sandvol *et al.*, 1992; Gok *et al.*, 2003), asthenospheric flows between the GP and CP lithospheric roots, and/or fabric effects in the thicker lithosphere of the Great Plains. A dramatic change from the predominant northeast-trending fast directions (e.g., as measured from LR1 and LR1.5 SKS data in the central CP) to a north–south oriented fast direction in the CP-GB transition was first recognized from data recorded at both permanent and temporary CP-GB stations (Sheehan *et al.*, 1997; Savage and Sheehan, 2000). The details of this transition have been especially densely sampled and are reported on here using LR1.5 data.

Data and Methods

LR1.5 consisted of 18 densely spaced, continuously recording (20 Hz) broadband stations that extended LR1 and reoccupied two LR1 sites to facilitate tomographic and general integration. The sensors consisted of 10 Guralp CMG-3T, two Guralp CMG-3ESP, and six Nanometrics Trillium 40 seismometers. The LR1.5 stations were deployed between June 2004 and June 2006 and recorded over 140 teleseismic events with $m_b > 6.0$ from the useful SKS distance range of 86° to 135°. Detailed instrument and other deployment information can be found in Sine (2007). High signal-to-noise SKS and $SKKS$ core phases from about 13 events were used in this study. Most high quality core phases were from western Pacific earthquakes (back azimuths between 230° and 310°).

Under the assumption of single-layer anisotropy with a vertical symmetry axis, the splitting delay is simply proportional to the thickness of the anisotropic layer and the strength of anisotropy. More complicated anisotropy can only be resolved using data from a wide range of back azimuths, a situation that is generally only available at permanent stations with much longer recording durations. Splitting parameters at arrays of closely spaced stations, as here, provide good lateral resolution, but only indirect information about the depth of anisotropy. We applied the grid search method of Silver and Chan (1991) to determine fast azimuth and delay time. We used analysis windows beginning ~10 sec before the core phase arrival and ending immediately after one period of the phase and analyzed each phase that displayed the elliptical horizontal particle motion indicative of shear-wave splitting. After determining parameters that minimized tangential component energy, we checked to ensure that corrected seismograms had approximately linear particle motion. Null measurements, in which no splitting is inferred (Savage and Sheehan, 2000), are here defined as being when the fast direction is within 15° of being parallel or perpendicular to the event back azimuth and/or if the estimated delay time is less than 0.4 sec.

The error analysis utilizes the inverse F-test, as implemented 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. Only seismograms with variance reduction contours exhibiting clear minima were selected as reliable determiners of splitting parameters. We further obtained error estimates using the bootstrap technique of Sandvol and Hearn (1994) with compatible results.

Results

Analysis of *SKS* and *SKKS* phases yielded 60 sets of shear-wave splitting measurements (Fig. 1; see also Ⓔ Table 1 in the electronic edition of *BSSA*). Fast direction and delay time estimates have typical 95% confidence intervals of $\pm 12°$ and ± 0.4 sec, respectively. Fast direction estimates with errors exceeding 23° or delay time errors larger than 60% of the corresponding delay time estimate were discarded.

LR1 stations located in the interior of the CP show an average fast direction of about 54° east of north and an average delay time of 1.2 sec. LR1.5 results show that fast directions in the west-central CP (stations UT53–UT57) are oriented from 45° to 60° and that delay times range from about 1.2 sec near Lake Powell to 0.8 sec in Capital Reef National Park (Figs. 1 and 2). Stations located in the CP-GB transition (UT59–UT67) show coherent fast directions that trend from about 16° to $-1°$ and smaller delay times (Figs. 1 and 2) of less than ~0.8 sec. These transition fast directions are approximately parallel to the CP and

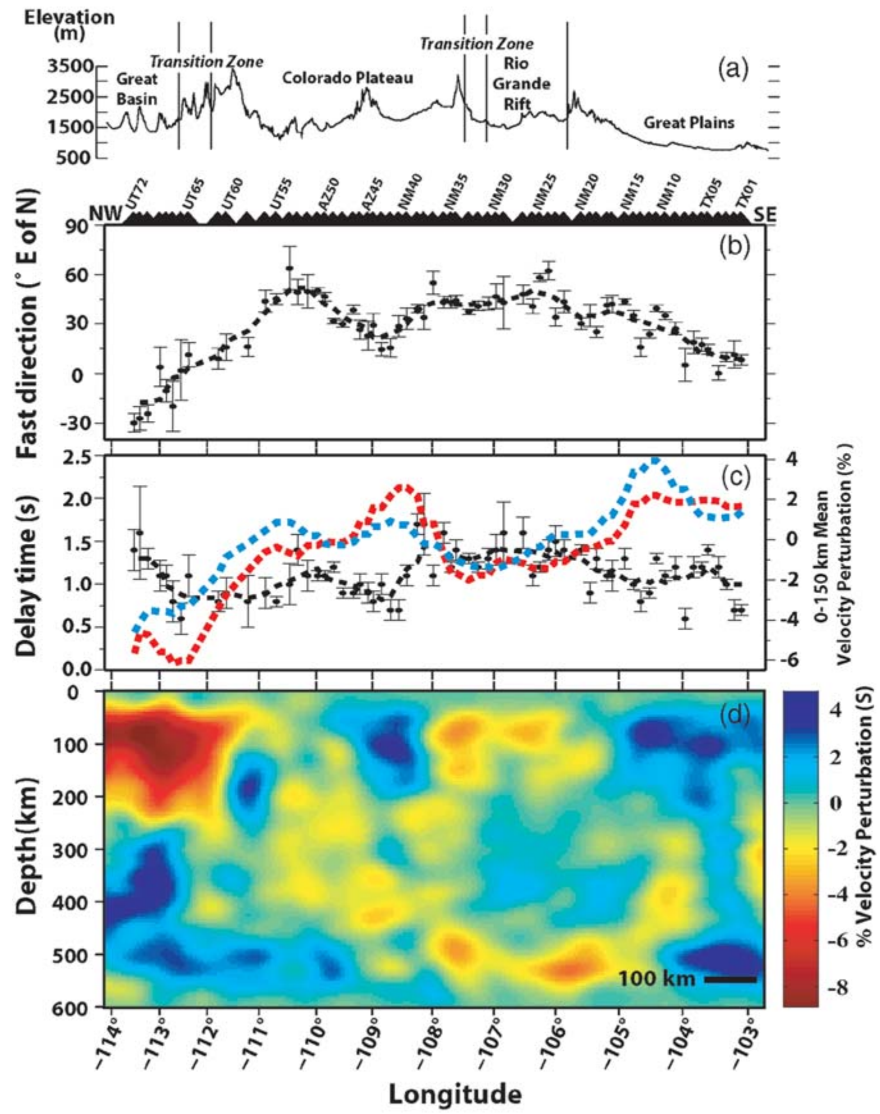

Figure 2. Topographic transect along LA RISTRA (a) and shear-wave splitting fast azimuths (b) and delay times (c). Error bars on anisotropic parameters represent 95% confidence intervals. Black dashed lines represent fast directions and delay times are five-point (~100 km) error-weighted running averages. The blue and red dashed lines in (c) are averaged *P*- and *S*-wave velocity anomalies (d) for 0–150-km depth. Note the general anticorrelation between seismic velocity and delay time in (b), excluding the CP-GB transition zone and eastern GB. This suggests that the thin lithosphere underlying the RGR is more susceptible to anisotropic orientation processes over a greater depth extent than areas of thicker lithosphere in the adjacent GP and CP, but that rift processes do not substantially affect the anisotropic alignment. *S*-wave velocity model for the upper mantle in (d) is after Sine *et al.* (2008) and was estimated relative to the International Association of Seismology and Physics of the Earth's Interior model of Kennett and Engdahl (1991).

GB boundary and to associated Cenozoic north–south-trending rifts (Fig. 1). Stations in the eastern GB (UT68–UT72) show fast directions of about −25° and delay times increasing to greater than 1.1 sec. Together, these fast directions show a very significant change in mantle anisotropy between the CP and GB, most notably reflected in a westward rotation as sampling moves westward through the transition.

Within the center of the CP (the four-corners region where New Mexico, Colorado, Utah, and Arizona meet), the fast direction averages about 40° with a delay time of about 1.0 sec (Gok *et al.*, 2003). In the region of the Laramide/post-Laramide Chuska Mountains (Cather *et al.*, 2008) near the Arizona–New Mexico border, fast directions rotate northward and trend from 20° to 30° with a relatively small delay time near 0.8 sec (Fig. 1). For these few stations, we also noted small variations in fast directions and delay times from events with slightly different back azimuths, consistent with more complex anisotropy (Silver and Savage, 1994). However, because we lacked the back-azimuth coverage to further constrain these features of the data, this variation is reflected in our reported errors, as estimated using the single-layer model assumption.

Discussion

Within the CP, the averaged fast directions of the split *SKS* and *SKKS* phases are subparallel (within 15°) of absolute NA plate motion (Gripp and Gordon, 1990). Savage and Sheehan (2000) suggested that shear-wave fast direction variations might be controlled by asthenospheric eddy formation or upwelling. We suggest that the principal contribution to seismic anisotropy across this transition arises from primarily horizontal shear strain generated by Couette flow of the asthenosphere beneath the overriding NA lithosphere. A detailed examination shows local variations of seismic anisotropy in the four-corners region and in the easternmost CP, such as the aforementioned rotation in the vicinity of the Chuska Mountains. Such variations suggest a component of anisotropic contribution from the lithosphere where accumulated finite strain in various parts of the lithosphere is frozen into the mantle lid from past tectonic events such as Proterozoic accretion and the Laramide orogeny (Gok *et al.*, 2003).

In the central RGR, the fast directions are approximately northeast–southwest oriented and generally subparallel to absolute NA plate motion. The anisotropy for stations in the central RGR is similar to that beneath the long-operational Global Seismographic Network station ANMO (Albuquerque, New Mexico), where *SKS* data are well fit by a single-layer model (Vinnik *et al.*, 1992). Because fast directions in the adjacent CP and GP regions are similar to those beneath the RGR, the large uppermost mantle velocity variations beneath this part of the rift (Gao *et al.*, 2004) have surprisingly little effect on the orientation of seismic anisotropy. However, the warmer and less viscous asthenospheric mantle beneath the RGR should accumulate larger shear strain, which provides an explanation for the observed association of a general increase in larger delay time with decreased lithospheric thickness crossing the rift (Fig. 2).

LA RISTRA anisotropy measurements show a strong anticorrelation between average lithosphere/asthenosphere-scale seismic velocities found from tomography (Gao *et al.*, 2004; Sine *et al.*, 2008) and anisotropy delay times over much of the transect (Fig. 2). The observed anticorrelation between delay times and velocity beneath the CP, GP, and RGR is consistent with global shear-wave splitting observations that higher levels of anisotropy exist in the warmer/seismically slower portions of the asthenosphere (e.g., Savage and Sheehan, 2000; Gok *et al.*, 2003). However, this anticorrelation between delay time and *S*-wave velocity breaks down in the western CP-GB transition region. We hypothesize that this is the effect of edge-driven small-scale convection along this transition. Stations with small delay times of ~0.8 sec are located above the high-velocity regions just inside the CP and beneath the western edge of the GP (Fig. 2). These high-velocity regions suggest zones of lithospheric downwelling associated with edge-driven small-scale convection along the GP-CP and RGR-CP transitions (Aster, *et al.*, 2007). These smaller delay times suggest that anisotropic fast axes are dipping in these suspected mantle downwelling regions due to vertical flow.

A major change of fast direction from ~54° in central CP, subparallel to the NA plate motion, to NNE-SSW occurs near the Cenozoic Marysvale volcanic field (Steven *et al.*, 1984) in the westernmost CP (near station UT59 at 37.98° N and 111.20° W; Figs. 1 and 2). This direction is approximately parallel to the local strike of the CP-GB transition. At upper mantle depths (less than approximately 400 km), this change corresponds to the presence of very low *S*-wave velocity mantle (Sine *et al.*, 2008) (Fig. 2). Magnetotelluric study of this region also shows very low mantle resistivity beneath this region at depths below 100 km (Wannamaker *et al.*, 2001). The CP-GB transition occurs near the Neoproterozoic-rifted margin of Rodinia and is characterized by gradually thinning crust from approximately 40 to 35 km thick traveling east to west (Fig. 2; Aster *et al.*, 2007) when compared to the ~46–48-km-thick crust beneath the central CP. Gravity and topography modeling (Wilson *et al.*, 2005) combined with a receiver function study of CP-GB transition near 37° north (Zandt *et al.*, 1995) suggests a thin mantle lid in the transition zone compared to the central CP and the GB. One possibility is that the CP rim-parallel anisotropy in this region is the bow effect result of plowing of the CP mantle lithospheric root through the asthenosphere. This interpretation is consistent with a model proposed by Savage and Sheehan (2000) and with mantle flow around the continental keel explaining anisotropy measurements in large parts of eastern NA (Fouch *et al.*, 2000). Because we do not yet know the three-dimensional details of lithosphere thickness beneath the CP and GB in sufficient detail, it is premature to further evaluate detailed asthenospheric flow. However, future research in the region utilizing three-dimensional imaging capabilities, most notably using EarthScope USArray and other data currently being, or planned to be, collected, should facilitate much better constrained three-dimensional lithospheric-asthenospheric deformational models.

The fast direction of split *SKS* waves rotates notably westward and away from the NA plate motion direction for stations at the westernmost end of LR1.5, which are firmly in the eastern GB province. The NNE-SSW anisotropic fast axes are part of a remarkable circular pattern first noted by Sheehan *et al.* (1997) and Savage and Sheehan (2000). Given that the GB is a region of very thin lithosphere (e.g., Wannamaker *et al.*, 2008), underlying uppermost asthenospheric flow is likely responsible for this change. A plume origin for GB azimuthal anisotropy was hypothesized by Savage and Sheehan (2000), but subsequent geophysical and geochemical evidence has been lacking (e.g., Zandt and Humphreys, 2008). Mantle flow around the edge of the Gorda–Juan de Fuca slab has most recently been proposed to account for the observed circular fast anisotropy pattern in the central GB (Sheehan *et al.*, 1997; Badger *et al.*, 2007; Zandt and Humphreys, 2008).

Conclusions

Shear-wave anisotropic fast directions in the central CP are subparallel to the absolute plate motion of NA. Local variations of fast direction within the CP suggest that a component of lithospheric anisotropy must exist, particularly in the central CP regions where thick lithosphere is present. The overall pattern of fast directions and their association with absolute plate motion is broadly consistent with shearing between overriding NA lithosphere and asthenosphere, despite the traversal of the RGR province. Within the RGR province, delay times increase but fast direction is unaltered, suggesting a greater thickness and/or greater degree of strained asthenospheric mantle, but showing no evidence for lateral perturbations in mantle strain due to RGR-centered convection or other localized effects. This pattern across the RGR also supports the contention that lithospheric fabric has a second-order effect on anisotropy in the transitional provinces bridging dormant and active tectonics between the Great Plains and the Great Basin. Anisotropic delay times are reduced along the edge of the CP where mantle downwellings have recently been hypothesized. Exiting the CP to the west, the fast direction rotates smoothly toward north–south, and then NNW-SSE orientations, for stations in the western GB. This westward rotation in seismic anisotropic fast direction marks a profound transition from a Couette (channel) flow regime (e.g., Podolefsky *et al.*, 2004) dominated by anisotropy controlled by absolute NA plate motion to one dominated by regional mantle flow arising from other processes.

Data and Resources

The results published in this article were derived from seismograms recorded by the LA RISTRA 1.0 and 1.5 experiments conducted between 1999 and 2001, and 2004 and 2006, respectively. Both deployments utilized the equipment and data resources of the Incorporated Research Institutions for Seismology Program for Array Seismic Studies of the Continental Lithosphere (IRIS PASSCAL). These data are openly available from the IRIS Data Management System under experiment codes XM 99-01 (RISTRA 1.0) and XK 04-06 (RISTRA 1.5).

Acknowledgments

This research was supported by National Science Foundation Grants Number EAR 9706094, Number 9707188, Number 9707190, and Number 0207812, and by the Los Alamos National Laboratory Institute of Geophysics and Planetary Physics. Instruments and critical field and data assistance were provided by the PASSCAL facility of the Incorporated Research Institutions for Seismology (IRIS) through the PASSCAL Instrument Center at New Mexico Tech. IRIS facilities are supported by National Science Foundation Cooperative Agreement Number EAR-000430 and the Department of Energy National Nuclear Security Administration. We thank George Zandt and Gene Humphreys for providing a preprint of Zandt and Humphreys (2008).

References

Aster, R., C. Sine, X. Wang, D. Wilson, J. Ni, S. Grand, and W. S. Baldridge (2007). Mantle structure of the Colorado Plateau and its margins revealed by LA RISTRA, in *Proceedings of the Geological Society of America*, Denver, Colorado, 28–31 October 2007, Paper No. 101-2.

Badger, N., I. Bastow, T. Owens, G. Zandt, C. Jones, and H. Gilbert (2007). Shear wave anisotropy beneath the Sierra Nevada range: implications for lithospheric foundering and upper mantle flow (Abstract T33A-1149), *Eos Trans. AGU*, **88,** no. 52 (Fall Meet. Suppl.), T33A-1149.

Cather, S., S. Connell, R. Chamberlin, W. McIntosh, G. Jones, A. Potochnik, S. Lucas, and P. Johnson (2008). The Chuska erg: paleogeomorphic and paleoclimatic implications of an Oligocene sand sea on the Colorado Plateau, *Geol. Soc. Am. Bull.* **120,** 12–33.

Condie, K. C. (1982). Plate-tectonics model for Proterozoic continental accretion in the southwestern United States, *Geology* **10,** 37–42.

DeCelles, P., and J. Coogan (2006). Regional structure and kinematic history of the Sevier fold-and-thrust belt, central Utah, *Geol. Soc. Am. Bull.* **118,** 841–864.

Demets, C., R. G. Gordon, D. F. Argus, and S. Stein (1994). Effect of recent revisions to geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.* **21,** 2191–2194.

Dickinson, W. R., and W. S. Snyder (1978). Plate tectonics of the Laramide orogeny, *Mem. Geol. Soc. Am.* **151,** 355–366.

Fouch, M., and S. Rondenay (2006). Seismic anisotropy beneath stable continental interiors, *Phys. Earth Planet. Interiors* **158,** 292–320.

Fouch, M. J., K. Fisher, E. Parmentier, M. Wysession, and T. Clarke (2000). Shear wave splitting, continental keels, and patterns of mantle flow, *J. Geophys. Res.* **105,** 6255–6275.

Gao, W., S. Grand, W. S. Baldridge, D. Wilson, M. West, J. Ni, and R. Aster (2004). Upper mantle convection beneath the central Rio Grande rift imaged by *P* and *S* wave tomography, *J. Geophys. Res.* **109,** B03305, doi 10.1029/2003JB002743.

Gok, R., J. Ni, M. West, E. Sandvol, D. Wilson, R. Aster, W. S. Baldridge, S. Grand, W. Gao, F. Tillman, and S. Semken (2003). Shear wave splitting and mantle flow beneath LA RISTRA, *Geophys. Res. Lett.* **30,** 1614 doi 10.1029/2002GL016616.

Gripp, A. E., and R. Gordon (1990). Current plate velocities relative to the hotspots incorporating the NUVEL-1 global plate motion model, *Geophys. Res. Lett.* **17,** 1109–1112.

Humphreys, E. D. (1995). Post-Laramide removal of the Farallon slab, western United States, *Geology* **23,** 987–990.

Karlstrom, K. E., K.-I. Åhäll, S. S. Harlan, M. L. Williams, J. McLelland, and J. Geissman (2001). Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia, *Precambrian Res.* **111,** 5–30.

Karlstrom, K. E., S. Harlan, M. Williams, J. McLelland, J. Geissman, and K. Ahall (1999). Refining Rodinia: geologic evidence for the Australia-western U.S. connection in the Proterozoic, *GSA Today* **9,** 1–17.

Kennett, B., and E. Engdahl (1991). Traveltimes for global earthquake location and phase identification, *Geophys. J. Int.* **105,** 429–465.

Magnani, M., K. Miller, A. Levander, and K. Karlstron (2004). The Yavapai-Mazatzal boundary: a long-lived tectonic element in the lithosphere of southwestern North America, *GSA Bull.* **116,** 1137–1142 doi 10.1130/B25414.1.

Ni, J., J. van Wijk, D. Wilson, C. Sine, S. Grand, R. Aster, W. S. Baldridge, and D. Coblentz (2007). Edge-driven convection along the Colorado Plateau–Great Basin transition: implications for the morphology and dynamics of the plateau (Abstract T31E-07), *Eos Trans. AGU* **88,** no. 52 (Fall Meet. Suppl.), T31E-07.

Podolefsky, N., S. Zhong, and A. McNamara (2004). The anisotropic and rheological structure of the oceanic upper mantle from a simple model of plate shear, *Geophys. J. Int.* **158,** 287–296.

Riter, J., and D. Smith (1996). Xenolith constraints on the thermal history of the mantle below the Colorado Plateau, *Geology* **24,** 267–270.

Roden, M. F., and N. Shimizu (1993). Ion microprobe analyses bearing on the composition of the upper mantle beneath the Basin and Range and Colorado Plateau provinces, *J. Geophys. Res.* **98,** 14,091–14,108.

Sandvol, E., and T. Hearn (1994). Bootstrapping shear-wave splitting errors, *Bull. Seismol. Soc. Am.* **84,** 1971–1977.

Sandvol, E., J. Ni, S. Ozalaybey, and J. Schlue (1992). Shear-wave splitting in the Rio Grande Rift, *Geophys. Res. Lett.* **19,** 2337–2340.

Savage, M. (1999). Seismic anisotropy and mantle deformation: what have we learned from shear wave splitting?, *Rev. Geophys.* **37,** 65–106.

Savage, M. K., and A. Sheehan (2000). Seismic anisotropy and mantle from the Great Basin to the Great Plains, western United States, *J. Geophys. Res.* **105,** 13,715–13,7347.

Savage, M. K., and P. Silver (1993). Mantle deformation and tectonics: constraints from seismic anisotropy in western United States, *Phys. Earth Planet. Interiors* **78,** 207–228.

Sheehan, A., C. Jones, M. Savage, S. Ozalaybey, and J. Schneider (1997). Contrasting lithospheric structure between the Colorado Plateau and Great Basin: initial results from Colorado Plateau—Great Basin PASSCAL experiment, *Geophys. Res. Lett.* **24,** 2609–2612.

Silver, P., and W. Chan (1991). Shear-wave splitting and mantle deformation, *J. Geophys Res.* **96,** 16,429–16,454.

Silver, P. G., and W. Holt (2002). The mantle flow field beneath western North America, *Science* 1054–1057.

Silver, P. G., and M. Savage (1994). The interpretation of shear wave splitting parameters in the presence of two anisotropic layers, *Geophys. J. Int.* **119,** 949–963.

Sine, C. (2007). Tomographic investigation of the upper mantle velocity structure beneath the transition from the western Colorado Plateau to the Great Basin, *Master's Thesis*, University of Texas at Austin, 112 pp.

Sine, C. R., D. Wilson, W. Gao, S. P. Grand, R. Aster, J. Ni, and W. S. Baldridge (2008). Mantle structure and dynamics beneath the Colorado Plateau and its margins, *Geophys. Res. Lett.* **35,** L10303, doi 10.1029/2008GL033391.

Spencer, J. E. (1996). Uplift of the Colorado Plateau due to lithosphere attenuation during Laramide low-angle subduction, *J. Geophys. Res.* **101,** 13,595–13,609.

Steven, T., P. Rowley, and C. Cunningham (1984). Calderas of the Marysvale volcanic field, west central Utah, *J. Geophys. Res.* **89,** 8751–8764.

Vinnik, L. P., L. J. Makeyeva, A. Milev, and A. Y. Usenko (1992). Global patterns of azimuthal anisotropy and deformations in the continental mantle, *Geophys. J. Int.* **111,** 433–447.

Wannamaker, P., D. Hasterok, J. M. Johnson, J. Stodt, D. Hall, T. Sodergren, L. Pellerin, V. Maris, W. Doerner, K. Groenewold, and M. Unsworth (2008). Lithospheric dismemberment and magmatic processes of the Great Basin–Colorado Plateau transition, Utah, implied from magnetotellurics, *Geochem. Geophys. Geosys.* **9,** Q05019, doi 10.1029/2007GC001886.

Wannamaker, P. E., J. Bartley, A. Sheehan, C. Jones, A. Lowry, T. Dumitru, T. Ehlers, W. S. Holbrook, G. L. Farmer, M. Unsworth, D. Hall, D. Chapman, D. Okaya, B. John, and J. Wolfe (2001). Great Basin–Colorado Plateau transition in central Utah: an interface between active extension and stable interior, in *The Geological Transition: Colorado Plateau to Basin and Range*, in *Proceedings of the J. Hoover Mackin Symposium*, Cedar City, Utah, 20–23 September 2001, in *UGA/AAPG Guidebook*, 30/GB78, M. C. Erskine, J. E. Faulds, J. M. Bartley and P. Rowley (Editors), Utah Geological Survey, Salt Lake City, 1–38.

West, M., J. Ni, W. S. Baldridge, D. Wilson, R. Aster, W. Gao, and S. Grand (2004). Crust and upper mantle shear wave structure of the southwest United States: implications for rifting and support for high elevation, *J. Geophys. Res.* **109,** B03309, doi 10.1029/2003JB002575.

Willis, G. C. (1999). The Utah thrust system—an overview, in *Geology of Northern Utah and Vicinity*, L. W. Spangler and J. C. Allen (Editors), Utah Geological Association, Salt Lake City, Utah, Vol. **27**, 1–9.

Wilson, D., S. Grand, R. Aster, and J. Ni (2005). Colorado plateau crust and upper mantle structure and implications for uplift mechanisms, *Proceedings of the Geological Society of America*, Salt Lake City, Utah, 16–19 October 2005.

Zandt, G., and G. Humphreys (2008). Toroidal mantle flow through the western U.S. slab window, *Geology* **36,** no. 4, 295–298, doi 10.1130/G24611A.1.

Zandt, G., S. Myers, and T. Wallace (1995). Crust and mantle structure across the Basin and Range—Colorado Plateau boundary at 37N latitude and implications for Cenozoic extensional mechanism, *J. Geophys. Res.* **100,** 10,529–10,548.

Department of Physics
MSC 3D
New Mexico State University
Las Cruces, New Mexico 88003
jni@nmsu.edu
(X.W., J.F.N.)

Department of Earth and Environmental Science
and Geophysical Research Center
New Mexico Institute of Mining and Technology
Socorro, New Mexico 87801
(R.A.)

Department of Geological Sciences
University of Missouri
Columbia, Missouri 65211
(E.S.)

Department of Geological Sciences
The University of Texas at Austin
Austin, Texas 78712
(D.W., C.S., S.P.G.)

Earth and Environmental Sciences Division
MS D462
Los Alamos National Laboratory
Los Alamos, New Mexico 87545
(W.S.B.)

Manuscript received 6 February 2008