Geodynamics of the southeastern Tibetan Plateau from seismic anisotropy and geodesy

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ABSTRACT

Ongoing plate convergence between India and Eurasia provides a natural laboratory for studying the dynamics of continental collision, a first-order process in the evolution of continents, regional climate, and natural hazards. In southeastern Tibet, the fast directions of seismic anisotropy determined using shear-wave splitting analysis correlate with the surficial geology including major sutures and shear zones and with the surface strain derived from the global positioning system velocity field. These observations are consistent with a clockwise rotation of material around the eastern Himalayan syntaxis and suggest coherent distributed lithospheric deformation beneath much of southeastern Tibet. At the southeastern edge of the Tibetan Plateau we observe a sharp transition in mantle anisotropy with a change in fast directions to a consistent E-W direction and a clockwise rotation of the surface velocity, surface strain field, and fault network toward Burma. Around the eastern Himalayan syntaxis, the coincidence between structural crustal features, surface strain, and mantle anisotropy suggests that the deformation in the lithosphere is mechanically coupled across the crust-mantle interface and that the lower crust is sufficiently strong to transmit stress. At the southeastern margin of the plateau in Yunnan province, a change in orientation between mantle anisotropy and surface strain suggests a change in the relationship between crustal and mantle deformation. Lateral variations in boundary conditions and rheological properties of the lithosphere play an important role in the geodynamic evolution of the Himalayan orogen and Tibetan Plateau and require the development of three-dimensional models that incorporate lateral heterogeneity.

Keywords: anisotropy, global positioning system, Tibet, syntaxis.

INTRODUCTION

In the past two decades, a number of geodetic (Chen et al., 2000; Zhang et al., 2004; Shen et al., 2005) and seismologic (e.g., Zhao et al., 1993; McNamara et al., 1994; Sandvol et al., 1997; Huang et al., 2000; Lev et al., 2006) studies have targeted parts of the Tibetan Plateau. Due to the intrinsic three-dimensional (3D) nature of the collision process, a full understanding of the dynamics of the India-Eurasia collision requires investigation of the nature of lithospheric deformation across a broader portion of the plateau. Data from two recent temporary passive-seismic array deployments and an ongoing global positioning system (GPS) field experiment provide new measurements documenting deformation of the continental lithosphere beneath two key areas: the eastern Himalayan syntaxis and adjacent plateau margins. The two surveys involved 73 broadband seismic stations and 17 geodetic sites deployed across the southeastern part of the Tibetan Plateau (Fig. 1). These new seismic data extend observations previously focused on central Tibet. The new GPS measurements fill a data gap between measurements in central and eastern Tibet. Our study, part of two large multidisciplinary research projects, focuses on assessing seismic anisotropy, which is used as a proxy for finite strain in the lithospheric mantle (Babuska and Cara, 1991), and the surface velocity field, which is used to constrain the lateral distribution of instantaneous strain.

OBSERVATIONS: GPS TRENDS AND MANTLE ANISOTROPY

The new GPS measurements (Table DR3 in the GSA Data Repository[1]) unambiguously document a gradual change in surface velocity vectors from northward convergence to eastward motion of material north of the syntaxis (Fig. 2). Combined with existing geodetic data (Chen et al., 2000; Zhang et al., 2004; Shen et al., 2005) (Fig. 2), the GPS velocity field reveals a conspicuous clockwise motion of crustal material (relative to the South China block) around the eastern Himalayan syntaxis coincident with the eastern edge of the Indian plate indentor corner. This clockwise rotation continues south to ~lat 26°N in Yunnan province, where motion of material turns to the west in western Yunnan. East of long 102°E, the GPS velocity vectors turn east, diverging around the Sichuan Basin.

Shear-wave splitting analysis was performed on teleseismic shear waves (SKS/SKKS) that pass through the Earth's core and are radially polarized upon reentry into the Earth's mantle. A majority of the 33 earthquakes (Table DR1) with good quality waveforms and magnitude m_b > 5.7 used in the analysis originated in the South Pacific, but other source regions increased azimuthal coverage (Fig. 1, inset). After bandpass filtering the data between corner frequencies of 0.06 and 0.3Hz, we estimated the splitting parameters using two comparative methods through minimization of either the transverse energy or the smallest eigenvalue of the covariance matrix between the orthogonal horizontal components (Silver and Chan, 1991). For a few noisy stations, measurements were made using the stacking technique (Restivo and Helffrich, 1999). Most of the seismic stations yield delay times between 0.5 and 1.3 s (Table DR2) and polarization directions

[1]GSA Data Repository item 2007129, Tables DR1–DR3 (events used in the splitting analysis, individual SKS splitting sorted by stations, and global positioning system data from the southeastern Tibetan Plateau), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

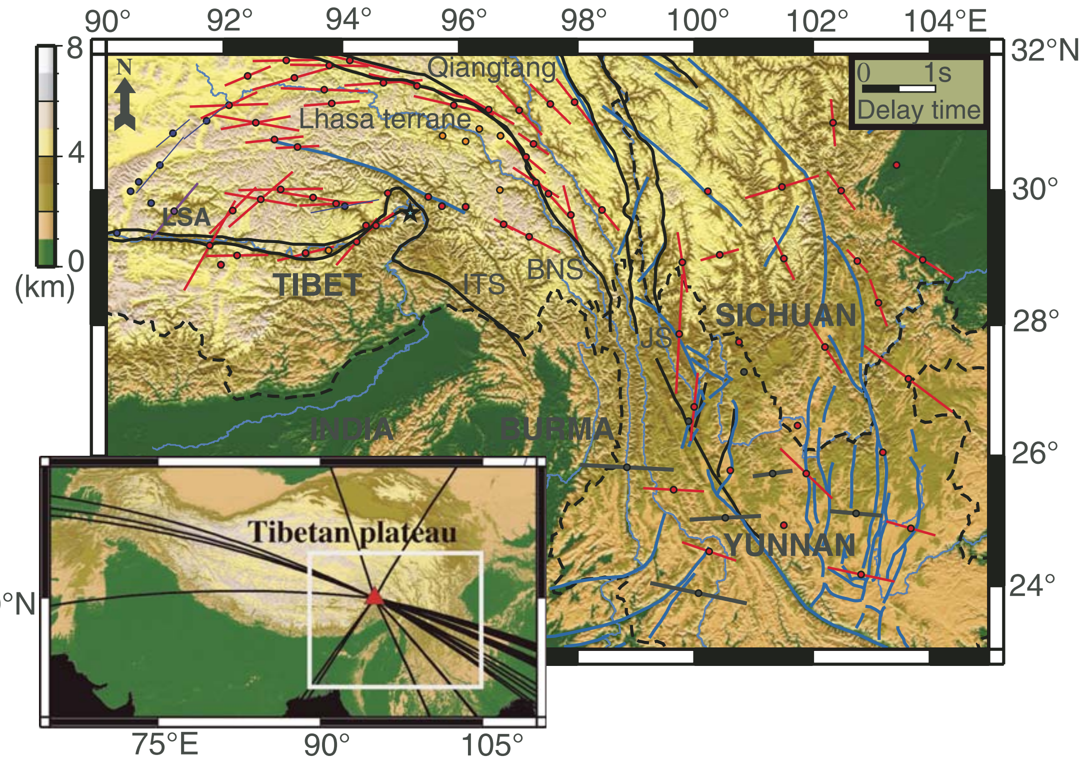

Figure 1. Topographic map displaying SKS splitting measurements from southeastern region of Tibetan Plateau. Orientation of lines represents average fast polarization direction, while their length is proportional to delay time. Red and orange circles are seismic stations deployed from our two seismic experiments, and red lines are our associated splitting measurements. Stations characterized by two lines indicate clear variation in fast direction for events coming from either west or east. Filled colored circles alone represent null anisotropy. Filled orange circles indicate that observed null anisotropy is associated with limited azimuthal coverage. Blue and black lines represent published splitting results in Tibet (McNamara et al., 1994; Sandvol et al., 1997); circles are Yunnan (Flesch et al., 2005). Permanent seismic station in Lhasa (LSA) is depicted in purple. Wider black lines show main geological sutures with Indus-Tsangpo suture (ITS), Bangong-Nujiang suture (BNS), and Jinsha suture (JS). Thin dashed black lines represent province boundaries for Tibet, Sichuan, and Yunnan, and blue lines display right- and left-lateral strike-slip faults. Bottom left inset depicts study area within entire plateau with earthquake-station SKS/SKKS paths used in splitting analysis.

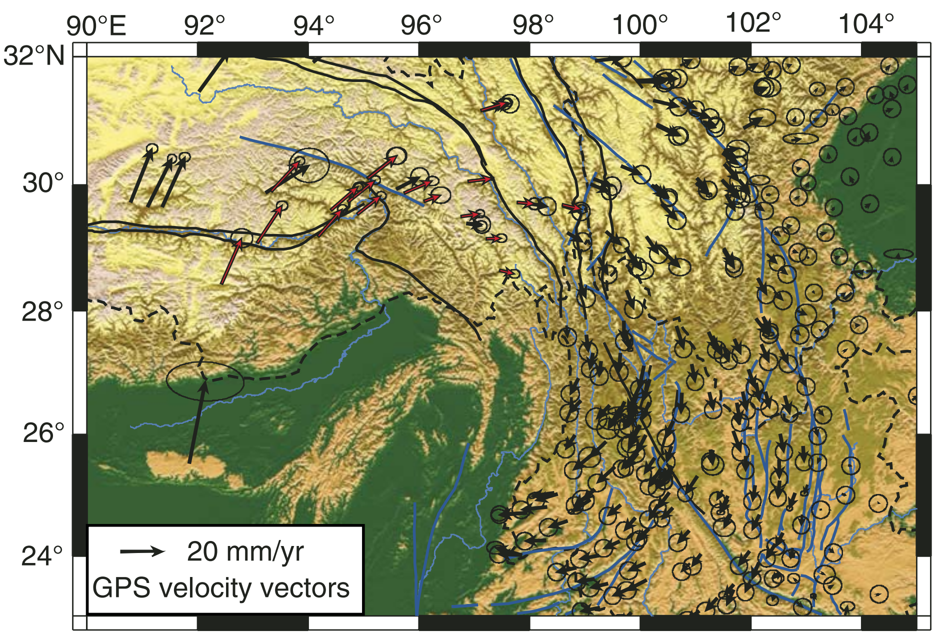

Figure 2. Topographic map displaying global positioning system (GPS) velocity vectors calculated in South China reference frame. Vectors from Indentor Corners project are depicted in red; published GPS data (Chen et al., 2000; Zhang et al., 2004; Shen et al., 2005) are in black. Left- and right-lateral strike-slip faults are represented by blue lines, sutures by black lines, and Chinese province boundaries by dashed black lines.

independent of back azimuth, suggesting that a single layer with a horizontal symmetry axis is sufficient to explain the data.

In southeastern Tibet, the fast shear-wave polarization directions wrap around the eastern Himalayan syntaxis (Fig. 1). At the western edge of our array, the fast axis of polarization is approximately parallel to Indian plate motion. At ~long 92°E, the fast axes align E-W before turning south and wrapping around the syntaxis farther east. At stations located along the Bangong Nujiang suture (BNS) and the Indus-Tsangpo suture (ITS), the fast axis of polarization parallels the sutures as they wrap around the syntaxis.

In the eastern margin of the plateau, in Sichuan province, seismic anisotropy is more complex, with fast shear-wave polarization axes oriented both parallel and oblique to surficial features. Farther south, in central Yunnan, a sharp transition in mantle anisotropy is tightly constrained across the lat 26°N line. South of lat 26°N SKS splitting exhibits a uniform pattern of E-W fast directions approximately parallel to the absolute plate motion in a no-net-rotation reference frame (Altamimi et al., 2002).

ORIGIN OF MANTLE ANISOTROPY

Seismic anisotropy has previously been inferred in the central Tibetan Plateau from analyses of surface waves (Yu et al., 1995), Pn traveltimes (McNamara et al., 1997; Liang et al., 2004), and shear-wave splitting (McNamara et al., 1994; Sandvol et al., 1997; Huang et al., 2000). The splitting technique relies on the propagation of an upgoing shear wave traveling through an anisotropic medium. Similar to birefringence, a shear wave will split into two orthogonally polarized fast and slow components. The splitting analysis solves for both the delay time, δt, that separates the fast- and slow-polarized waves, and the fast shear-wave polarization direction ϕ. The delay time provides information on the thickness of the anisotropic layer and the strength of its anisotropy, whereas ϕ is typically interpreted as diagnostic of the strain-induced lattice-preferred orientation of olivine crystals in the mantle (Silver and Chan, 1991). Under tectonic deformation, ϕ tends to orient parallel to the fast a-axis of olivine crystals. Under simple shear and small strain (<75%), ϕ tends to align along the direction of maximum extension (Ribe, 1992), while under high strain (to 150%) and during recrystallization it rotates toward the flow or shear direction (Zhang and Karato, 1995). Estimates of ϕ thus offer insight into the directions of flow, extension, or shear at depth.

In southeastern Tibet, the fast shear-wave polarization directions can be interpreted as either asthenospheric flow around the eastern Himalayan syntaxis or as strain in the lithospheric crust and/or mantle. The crust in the region is very thick (Chen and Molnar, 1981; Zurek et al., 2005), but birefringence of Moho P-to-S converted phases indicates average crustal splitting times of only a few tenths of a second (McNamara et al., 1994; Sherrington et al., 2004; Ozacar and Zandt, 2004), representing at most a small component of our measured delay times. Assuming anisotropy of 4%, typical of olivine-rich mantle material (Mainprice and Silver, 1993), the magnitude of our delay times requires an anisotropic layer with a thickness ranging from 50 to 140 km. Together with the Fresnel zones of the waves considered (Alsina and Snieder, 1995), the inferred anisotropic layer thickness suggests that the source of anisotropy resides primarily in the upper mantle between a depth of 60 and 160 km. The parallelism between crustal and mantle deformation together with an observed small-scale variation in splitting parameters and the inconsistency between the regional pattern of anisotropy with the predicted directions of absolute plate motion of India relative to Eurasia suggest that the dominant source of anisotropy in southeastern Tibet is lithospheric (Davis et al., 1997; Holt, 2000; Flesch et al., 2005), rather than flow induced in the asthenosphere. If the main source of anisotropy is in the lithospheric mantle, then this suggests the presence of an intact mantle lithosphere beneath southeastern Tibet.

DISCUSSION: LITHOSPHERIC DEFORMATION

In southeastern Tibet, the observed curvature of the fast axis of polarization reflecting anisotropy in the mantle correlates with trends in structural geology, crustal markers, topography, surface velocity, and shear strain inferred from GPS (Chen et al., 2000; Zhang et al., 2004) (Figs. 2 and 3). Seismic anisotropy has been observed along major, possibly lithospheric scale, strike-slip faults that are thought to accommodate the eastward extrusion of the plateau (e.g., Altyn Tagh, Kunlun; Huang et al., 2000; Herquel et al., 1995). A similar alignment occurs at stations located along the BNS and the ITS, suggesting that simple shear is likely the source of the anisotropy. However, observed anisotropy at stations located in the interior of tectonic blocks, away from the major faults, indicates that mantle deformation is distributed and not restricted to block-bounding faults. These observations are consistent with a clockwise rotation of material around the eastern Himalayan syntaxis and suggest coherent distributed lithospheric deformation beneath much of southeastern Tibet. At the southeastern edge of the Tibetan Plateau, we observe a sharp transition in mantle anisotropy with a change in fast directions to a consistent E-W direction and a clockwise rotation of the surface velocity field and fault network toward Burma. The E-W orientation of the fast axis of polarization is trending almost 90° to the topographic grain dominated by the deeply incised Salween, Mekong, and Yangzi Rivers draining Tibet.

To compare the pattern of seismic anisotropy, a proxy for finite strain in the mantle, with upper-crustal deformation, we derive the continuous upper-crustal strain field (Shen et al., 1996) represented by the left-lateral maximum shear directions (Fig. 3) using the South China referenced velocity field (Fig. 2). On the plateau proper, the GPS-derived shear strain displays a rotational pattern that is spatially consistent with our measured mantle anisotropy fast directions around the Himalayan syntaxis. The striking parallelism between structural crustal features, the surface strain field, and fast shear-wave polarization directions beneath southeastern Tibet argues for vertically coherent deformation reflecting either mechanical coupling between crust and mantle, or that the crust and the mantle are subjected to similar velocity boundary conditions (Holt, 2000).

Across the southeastern flank of the plateau south of ~lat 26°N in central Yunnan, upper-crustal deformation characterized by both the continuous crustal strain field and the orientation of the main active faults gradually diverge westward toward Burma (Figs. 2 and 3). In contrast, fast directions of mantle anisotropy are consistently oriented E-W approximately parallel to plate motion, indicating that anisotropy may have developed in the asthenosphere. The sudden change in mantle strain when moving away from the plateau into central Yunnan may also reflect the influence of two additional boundary conditions, the subduction along the Indo-Burmese arc to the west and the motion of the South China block to the east.

In southeastern Tibet, the GPS data, the interpolated surface shear strain field, and the new, dense set of fast shear-wave directions are consistent with the directions of maximum shear in

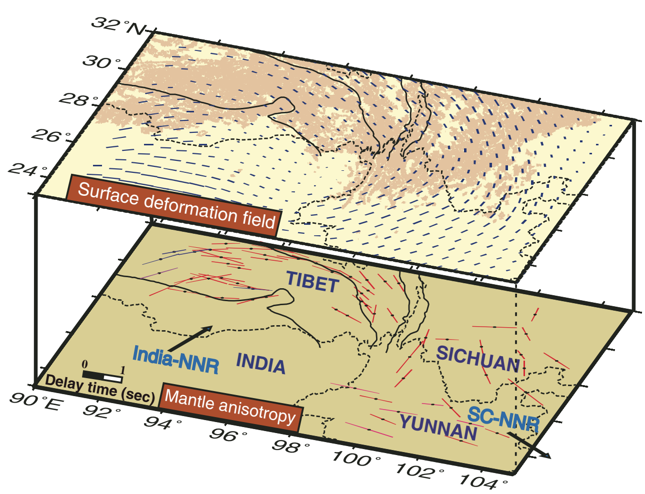

Figure 3. Three-dimensional block diagram: top is surface deformation field plotted as left-lateral shear directions (in blue) and bottom is slice through upper-mantle layer displaying seismic anisotropy. Surface layer includes global positioning system–derived left-lateral shear strain, geological sutures, and province boundaries. Elevations above 5000 m are embedded in background in light brown. Mantle layer includes splitting measurements from our study, and vectors displaying absolute plate motion of Indian plate and of South China block (SC) calculated using ITRF2000-No-Net-Rotation (NNR) frame (Altimimi et al., 2002). Figure shows similar pattern between surface strain field and mantle anisotropy wrapping around eastern Himalayan syntaxis. Sharp transition in splitting pattern is observed when moving south away from Plateau at ~lat 26°N. Province boundaries are plotted as black dotted lines.

the mantle predicted by a "hybrid" thin viscous sheet geodynamic model (Flesch et al., 2005) incorporating boundary forces and gravitational potential. The geodynamic model of Flesch et al. (2005) requires mechanical coupling between the mantle and the crust beneath the plateau. Our data are also consistent with first-order predictions from a 3D model driven by northward motion of India and rollback of the Indian slab beneath Burma (Koons et al., 2006). While our observations do not rule out ductile flow in the lower crust (Royden et al., 1997; Beaumont et al., 2001), they place constraints on the strength of the crust and suggest that the lower crust must be sufficiently strong to transmit stress, an observation that is consistent with the general absence of high Poisson's ratios within the crust beneath southeastern Tibet (Zurek et al., 2005).

In central Yunnan, the misfit between the surface deformation field and the directions of fast shear-wave polarization can be explained by several different interpretations: (1) the crust and the mantle are decoupled, compatible with the predicted mantle shear directions of Flesch et al. (2005); (2) the 3D deformation of the mantle is not dominated by simple shear in the horizontal plane, but is influenced by boundary conditions associated with rollback of the lithosphere beneath Burma; or (3) the observed anisotropy is dominated by asthenospheric flow.

CONCLUSIONS

Our new geodetic and seismologic measurements document a correlation and clockwise rotation of surface and mantle strain around the eastern syntaxis of Tibet. Patterns of strain derived from mantle anisotropy and the GPS velocity field diverge at the southeastern margin of the Tibetan Plateau. The data suggest that lateral heterogeneities play an important role in the geodynamic evolution of the region and that models extrapolated to explain all of Tibetan dynamics may be overly simple. Fully 3D geodynamic models incorporating lateral heterogeneity in boundary conditions and lithospheric properties are required to more accurately describe the development of collisional orogens.

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REFERENCES CITED

Alsina, D., and Snieder, R., 1995, Small-scale sublithospheric continental mantle deformation: Constraints from SKS splitting observations: Geophysical Journal International, v. 123, p. 431–448.

Altamimi, Z., Sillard, P., and Boucher, C., 2002, ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications: Journal of Geophysical Research, v. 107, p. 2214, doi: 10.1029/2001JB000561.

Babuska, V., and Cara, M., 1991, Seismic anisotropy in the Earth: Dordrecht, Netherlands, Kluwer Academic Publishers, 217 p.

Beaumont, C., Jamieson, R.A., Nguyen, M.H., and Lee, B., 2001, Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation: Nature, v. 414, p. 738–742.

Chen, W.P., and Molnar, P., 1981, Constraints on the seismic wave velocity structure beneath the Tibetan Plateau and their tectonic implications: Journal of Geophysical Research, v. 86, p. 5937–5962.

Chen, Z., Burchfiel, B.C., Liu, Y., King, R.W., Royden, L.H., Tang, W., Wang, E., Zhao, J., and Zhang, W., 2000, GPS measurements from eastern Tibet and their implications for India/Eurasia intracontinental deformation: Journal of Geophysical Research, v. 105, p. 16,215–16,227.

Davis, P., England, P., and Houseman, G., 1997, Comparison of shear wave splitting and finite strain from the India-Asia collision zone: Journal of Geophysical Research, v. 102, p. 27,511–27,522.

Flesch, L.M., Holt, W.E., Silver, P.G., Stephenson, M., Wang, C.Y., and Chan, W.W., 2005, Constraining the extent of crust-mantle coupling in Central Asia using GPS, geologic, and shear-wave splitting data: Earth and Planetary Science Letters, v. 238, p. 248–268.

Herquel, G., Wittlinger, G., and Guilbert, J., 1995, Anisotropy and crustal thickness of northern Tibet. New constraints for tectonic modeling: Geophysical Research Letters, v. 22, p. 1925–1928.

Holt, W.E., 2000, Correlated crust and mantle strain fields in Tibet: Geology, v. 28, p. 67–70.

Huang, W.C., Ni, J.F., Tilmann, F., Nelson, D., Guo, J., Zhao, W., Mechie, J., Kind, R., Saul, J., Rapine, R., and Hearn, T.M., 2000, Seismic polarization anisotropy beneath the central Tibetan Plateau: Journal of Geophysical Research, v. 105, p. 27,979–27,989.

Koons, P.O., Barker, A., Pavlis, T.L., Liu, Y., Sol, S., Zeitler, P.K., and Meltzer, A., 2006, Vorticity, erosion, and crust:mantle coupling at plate corners in south east Alaska and south east Tibet [abs.]: Eos (Transactions, American Geophysical Union), v. 87, abstract T32B–07.

Lev, E., Long, M.D., and van der Hilst, R.D., 2006, Seismic anisotropy from shear-wave splitting in Eastern Tibet reveals changes in lithospheric deformation: Earth and Planetary Science Letters, v. 251, p. 293–304.

Liang, C., Song, X., and Huang, J., 2004, Tomographic inversion of Pn traveltimes in China: Journal of Geophysical Research, v. 109, B11304, doi: 10.1029/2003JB002789.

Mainprice, D., and Silver, P.G., 1993, Interpretation of SKS-waves using samples from the subcontinental lithosphere: Physics of the Earth and Planetary Interiors, v. 78, p. 257–280.

McNamara, D.E., Owens, T.J., Silver, P.G., and Wu, F.T., 1994, Shear wave anisotropy beneath the Tibetan Plateau: Journal of Geophysical Research, v. 99, p. 13,655–13,665.

McNamara, D.E., Walter, W.R., Owens, T.J., and Ammon, C.J., 1997, Upper mantle structure beneath the Tibetan Plateau from Pn travel time tomography: Journal of Geophysical Research, v. 102, p. 493–505.

Ozacar, A.A., and Zandt, G., 2004, Crustal seismic anisotropy in central Tibet: Implications for deformational style and flow in the crust: Geophysical Research Letters, v. 31, L23601, doi: 10.1029/2004GL021096.

Restivo, A., and Helffrich, G., 1999, Teleseismic shear wave splitting measurements in noisy environments: Geophysical Journal International, v. 137, p. 821–830.

Ribe, N.M., 1992, On the relation between seismic anisotropy and finite strain: Journal of Geophysical Research, v. 97, p. 8737–8747.

Royden, L.H., Burchfiel, B.C., King, R., Chen, Z., Shen, F., and Liu, Y., 1997, Surface deformation and lower crustal flow in eastern Tibet: Science, v. 276, p. 788–790.

Sandvol, E., Ni, J., Kind, R., and Zhao, W., 1997, Azimuthal seismic anisotropy beneath the southern Himalayas-Tibet collision zone: Journal of Geophysical Research, v. 102, p. 17,813–17,823.

Shen, Z.K., Jackson, D.D., and Ge, X.B., 1996, Crustal deformation across and beyond the Los Angeles basin from geodetic measurements: Journal of Geophysical Research, v. 101, p. 27,957–27,980.

Shen, Z.K., Lu, J.N., Wang, M., and Bürgmann, R., 2005, Contemporary crustal deformation around the southeast borderland of the Tibetan Plateau: Journal of Geophysical Research, v. 110, p. 1–17.

Sherrington, H.F., Zandt, G., and Frederickson, A., 2004, Crustal fabric in the Tibetan Plateau based on wave form inversions: Journal of Geophysical Research, v. 109, B02312, doi: 10.1029/2002JB002345.

Silver, P.G., and Chan, W.W., 1991, Shear wave splitting and subcontinental mantle deformation: Journal of Geophysical Research, v. 96, p. 16,429–16,454.

Yu, Y., Park, J., and Wu, F., 1995, Mantle anisotropy beneath the Tibetan Plateau: Evidence from long-period surface waves: Physics of the Earth and Planetary Interiors, v. 87, p. 231–246.

Zhang, P., Shen, Z., Wang, M., Gan, W., Bürgmann, R., Molnar, P., Wang, Q., Niu, Z., Sun, J., Wu, J., Sun, H., and You, X., 2004, Continuous deformation of the Tibetan Plateau from global positioning system data: Geology, v. 32, p. 809–812.

Zhang, S., and Karato, S., 1995, Lattice preferred orientation of olivine aggregates deformed in simple shear: Nature, v. 375, p. 774–777.

Zhao, W.B., Nelson, K.D., and the Project INDEPTH Team, 1993, Deep seismic-reflection evidence for continental underthrusting beneath southern Tibet: Nature, v. 366, p. 557–559.

Zurek, B., Meltzer, A., Sol, S., Zhang, X., and Zhang, J., 2005, Measurements of crustal thickness and Poisson's ratio in southeastern Tibet from receiver functions [abs.]: Eos (Transactions, American Geophysical Union), v. 86, abstract T41A–1283.

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