The Relationship Between Upper Mantle Anisotropic Structures Beneath California, Transpression and Absolute Plate Motions

Minoo Kosarian[1], Paul M Davis[1], Toshiro Tanimoto[2] and Robert Clayton[3]

Submitted JGR 2010

[1.] Department of Earth and Space Sciences UCLA

[2.] Department of Geological Sciences, UCSB

[3.] Seismology Laboratory, California Institute of Technology

Abstract

We calculated SKS splitting parameters for all available data from the California Integrated Seismic Network. In southern California, where the density of stations is greatest, we also estimated azimuthal anisotropy in the upper 100 km using surface waves. The inferred splitting from surface waves in the mantle lithosphere is small (on average 0.2 sec) compared with SKS splitting (1.5 sec) and obtains a maximum value (0.4 sec) in the transpressive region of the Big Bend, south of, and aligned with, the San Andreas Fault. In contrast, the SKS splitting is approximately E-W and is relatively uniform spatially either side of the Big Bend. These differences suggest that most of the SKS splitting is generated deeper, perhaps in the asthenosphere. Fast SKS directions align with absolute plate motions (APM) in northern and southeastern California but not in southwestern California. We interpret the parallelism with APM as indicating the SKS anisotropy is caused by cumulative drag of the asthenosphere by the over-lying plates. The discrepancy in southwestern California is

interpreted as arising from the diffuse boundary there compared to the north, where relative plate motion has been concentrated near the SAF system. In southern California the relative motion originated offshore in the Borderlands and gradually transitioned onshore to the SAF system. This has given rise to smaller displacement across the SAF (160-180 km) compared with central and northern California (400-500 km). Thus in southwestern California the inherited anisotropy from prior North American plate motion has not yet been overprinted by Pacific plate motion.

Introduction

One of the effective methods to infer finite strain in the deep lithosphere-asthenosphere is the measurement of seismic anisotropy thought to be associated with the alignment of olivine crystals [e.g Vinnik et al., 1984; Silver, 1996; Silver and Holt, 2002; Savage, 1999; Silver and Chan, 1991; Becker at el., 2006a,b, 2007a,b;]. The study of seismic anisotropy has several applications [Montagner, 1998]. It helps (1) to define the roots of continents and to investigate if there is ~~a~~ coupling between the lithosphere and the rest of mantle [Montagner and Tanimoto, 1991; Silver, 1996; Silver and Holt, 2002; Becker et al., 2006a,b; 2007a,b], (2) to gain information on strain, and effects of large-scale tectonics in the upper mantle [Savage, 1999], (3) to understand the dynamics of mantle convection [Becker, 2006], and (4) to detect internal boundary layers, as seismic anisotropy is closely related to the large-strain deformation [Montagner, 1998; Nicolas and Christensen, 1987; Karato, 1989].

For the oceanic upper mantle, anisotropy reveals a relatively simple structure, with the fast axis aligned with plate motion [Montagner and Guillot, 2000]. However, for continental regions, due to their complex geodynamic development and deformation, it is not as simple. The two main methods for observing anisotropy are shear wave splitting of seismic phases SKS and SKKS, and travel time variations of surface wave data [Yang and Forsyth, 2006; Prindle and Tanimoto, 2006]. SKS and SKKS waves are Earth's core phases that emerge with radial polarization, and arrive at the receiver along a near vertical path. Azimuthal anisotropy underneath the receiver temporally splits the waves depending on their polarization. Resolving anisotropy using surface wave data requires path coverage in all directions. In contrast with seismic anisotropy obtained from SKS/SKKS splitting, anisotropy derived from surface waves can be localized at depth. Both measurements can be integrated to understand tectonic processes prevailing in a given tectonic context [Yang and Forsyth, 2006]. Patterns for fast velocity axes derived from these datasets (shear wave splitting and surface wave data) may appear inconsistent as the two types of data have different depth sensitivities.

One of the challenges in interpreting anisotropy is evaluation of how much is caused by lithospheric, asthenospheric and lower mantle sources [Savage 1999] and the time scales of anisotropic fabric formation and subsequent preservation. Inferring the origin of seismic anisotropy is non-unique [Montagner, 1998, 2000] and further considerations are required for its interpretation such as tectonic history. For the crust, the distribution of cracks and fractures located in the vicinity of active faults may play a major role [Crampin and Booth, 1985]. In the deep continental lithosphere, anisotropy may be due to fossil features of past tectonic events, whereas in the asthenosphere it is more likely due to recent strain. In the upper mantle, seismic anisotropy arises primarily from strain-induced lattice-preferred orientation (LPO) of the dominant mantle minerals, primarily olivine [Montagner 1994]. The fast polarization (ϕ) tends to align parallel to the olivine a-axes, and mantle Xenoliths show anisotropy of up to 7% [Savage, 1999]. Often it is possible to distinguish different sources (crust, mantle, fracture or else) of anisotropy by using different kinds (e.g., frequencies) of data, such as surface waves and body waves, or teleseismic waves and local/regional waves [Becker et al., 2007a,b]. Also, there is a trade-off between homogeneous anisotropic models and heterogeneous isotropic models, and there is no way to distinguish between them from long wavelength seismological observation alone [Becker et al., 2007b). It has been long-recognized that most parts of the earth are not only laterally heterogeneous but also anisotropic [Montagner, 1998].

Makeyeva et al. [1992] discussed the concept of "frozen" anisotropy in the lithosphere, noting that the mobility of olivine crystals at temperatures below ~1100 K is low. Thus a preferred orientation of olivine can be created by deformation only at temperatures higher than ~1100 K. This threshold occurs near the thermal boundary between the lithosphere and asthenosphere, and therefore anisotropy in the lithosphere is most probably "frozen in" from the past.

There has been considerable controversy as to how much of SKS splitting is due to absolute plate motions (APM) and how much to finite strain of the lithosphere [Silver 1996] and whether an additional effect due to mantle flow unrelated to plate motions occurs. For example, for southern California, Silver and Holt [2002] have suggested that an east-west directed mantle flow might explain discrepancies between splitting directions and WSW plate motion, perhaps associated with the sinking Farallon slab. In contrast, Polet and Kanamori [2002] have suggested fast directions are related to compressive stress.

In this paper, we present new shear-wave splitting observations from 126 broadband seismograph stations in southern California and 35 in central and northern California for the 53 events shown in Figure 1. We examine the relationship between anisotropic structures within the lithosphere and asthenosphere, and the tectonic deformation process and plate motions associated with the California transform boundary, and compare the results with splitting inferred from surface waves.

Data and Method

Surface Wave Analysis

The surface wave analysis is described in Prindle and Tanimoto [2006] and Tanimoto and Prindle [2007] in which they estimated azimuthal anisotropy in several layers including upper and lower crustal layers, a mantle lithosphere layer (33-100 km) and an asthenospheric layer (100-150 km). The most significant splitting occurs in the mantle lithosphere layer. In order to convert to SKS splitting values we used the fractional perturbation in travel time in a layer times the total travel time for vertically traveling S waves. The results are shown in Figure 2. The largest signal comes from the 33-100 km layer. Fast directions are found parallel to the SAF and reach maximum values to the south where the topography associated with the Transverse Ranges and Big Bend is largest. This appears be an example of finite lithospheric strain, as it has the right direction and spatial distribution to associate it with lithospheric root effects caused by the mountain building, but the directions and small amplitudes cannot explain the SKS splitting.

SKS Splitting

For the SKS splitting we analyzed all the data between 1990 and 2008. For each of the 235 seismic stations, all events (190 earthquakes, producing more than 33,000 seismograms) were visually inspected. We considered events with magnitude greater than 6.5 and epicentral distance greater than 90 and less than 120 degrees in order to avoid contamination by other S wave phases. For various reasons, such as noisy data, non-reporting of stations, we found 53 events at 161 stations suitable for splitting analysis (Figure 1). The data were bandpass filtered with corner frequencies of 0.01 Hz and 1 Hz to improve signal to noise ratio. For estimates of splitting parameters of individual events we used the method of Silver and Chan [1991]. For station averages we used the method of Davis [2003], simultaneously minimizing the energy of the transverse component of all suitable seismograms at a given station. Because splitting parameters from individual events are scattered, especially if they are polarized near null-directions, waveforms from multiple events are stacked, and the splitting operator applied to the composite waveform. This gives more robust results than averaging widely scattered individual estimates.

Results

SKS splitting from Surface wave anisotropy

In southern California the SKS splitting fast directions exhibit a general WSW-ENE trend with apparent deflection at stations in the Transverse Ranges region (Figure 3). As we shall see, in northern California there is a change in direction across the SAF, taken to be the plate boundary (Figure 7) but this is much more gradual in southern California.

SKS splitting parameters for the surface wave anisotropy model exhibit significant differences from those obtained from SKS/SKKS splitting (Figure 4). First of all, even the maximum delay time predicted by the surface model is 0.4 seconds, and on average 0.2 sec, much smaller than >1 second SKS splitting in this region. The fast axes directions are also different in that surface wave results are mostly parallel to the relative plate motion direction. Larger variations are observed closer to the SAF. The results suggest that at least two layers of anisotropy are required to explain the two data sets, the first in the depth range 33-100km and the second deeper.

We corrected the SKS and SKKS seismograms for anisotropy effects in the mantle lithosphere using the results from the surface wave analysis by rotating the east and west components into fast and slow directions, and advancing the phase of the slow component by the surface wave splitting time, and then rotating back to east and west. Then we invert the corrected data for SKS and SKKS splitting parameters. As can be seen in Figure 3 the anisotropy from the surface wave model has minor effects on the overall SKS pattern. After correction, fast directions rotate anticlockwise on average about 3 degrees, and delay times decrease by an average 0.1 sec. We therefore conclude that the anisotropic structure in the uppermost mantle 33-100 km derived from surface waves cannot explain SKS splitting. The correspondence of the surface wave fast directions with the strike and elevations of the Transverse Ranges suggests it is probably related to the finite strain in the lithosphere from the transpression associated with the Big bend. We also conclude that the SKS and SKKS phases are sensitive to the deeper parts of the upper mantle that are not sampled by the surface wave eigenfunctions, possibly down to 300-400 km [Becker et al., 2006a,b]. We note a small crustal contribution of about 0.1-0.3 sec could be part of the total delay time [Li et al., 1994] but the surface wave analysis of crustal layers indicates it is at the low end of that range.

Azimuthal Dependence of Splitting

We also carried out a systematic analysis of splitting parameters as a function of back azimuth. Splitting parameters from different events agreed in general, but we observed significant variations in splitting parameters at individual stations depending on event-back azimuth. Such behavior suggests a departure from the simplest model of a single anisotropic layer. Again, because a limited numbers of events gave rise to scattered signals, we restricted the analysis to stations that had multiple events (#>3) in a given azimuth range (Figure 5a). Only 14 stations satisfied these criteria, and the results are plotted in Figure 5b. Most of the stations on the northeast side of the SAF exhibit a systematic clockwise rotation (blue to red) of the fast directions by about 40^{o} as azimuth rotates clockwise by 100^{o}. However stations in the west and northwest have variable rotations. Silver and Savage [1994] suggested that apparent splitting parameters are expected to show characteristic $\pi/4$ periodicity for two-layer anisotropy, but we did not observe this pattern in our data. Other possible explanations for azimuth-dependent splitting, are noise in the data, a layer with dipping symmetry axis, or anisotropy caused by an inhomogeneous medium [Fouch & Rondenay, 2006]. Regional tomography [Kohler et al., 2003] indicates the upper mantle is heterogeneous and rays from different azimuths may sample lateral variations in anisotropy. We tested whether anisotropy was dependent on event depth but found no correlation.

Comparison of Fast Directions with Absolute Plate Motions relative to the Hot Spot Reference Frame

Splitting directions are found to correlate well with absolute plate motions relative to the hot spot reference frame [NUVAL 1A model, Gripp and Gordon, 2002] for most stations. Figure 6 shows splitting directions in southern California plotted with North American absolute plate motion (APM) vectors. The correlation is excellent, suggesting the stacking method used has produced spatially robust directions, and that APM provides a good explanation for the fast-axes directions. However, on crossing the SAF we expect a rotation to Pacific plate motion, but other than at a few stations off the coast, the direction remains relatively constant.

We therefore extended the analysis to all stations of the California Integrated Seisimic Network (Figure 7). Figure 7 shows that if we take the plate boundary as the approximate location of the SAF, in northern and central California there is indeed a transition in the fast-axes directions from parallel to the North American APM to the Pacific Plate APM. In southern California this correlation with North American APM agrees well in the east, but breaks down to the west. This difference is illustrated in Figure 8 where we plot fast directions as a function of distance measured at right angles to the plate boundary (taken as a line along the azimuth of relative plate motion (NUVEL1A model, , N37^{o}W) passing through (-119^o, 35^o) in southern (Figure 8a) and central-northern California (Figure 8b). This notional plate-boundary line lies east of the SAF. Since most of the rays are from the east deep anisotropy effects would project to the eastern side of the SAF.

Discussion

For southern California most studies have found that fast directions in SKS splitting measurements are dominantly ENE-WSW [Savage and Silver, 1993, Ozalaybey and Savage, 1995; Liu et al., 1995; Polet and Kanamori, 2002, Silver and Holt, 2002]. The fast direction in SKS splitting is most likely due to the strain-induced lattice-preferred orientation (LPO) of olivine. SKS splitting is usually associated with regions shallower than ~400 km, where most anisotropy seems to reside [Becker et al., 2006a,b]. A pre-existing fossil anisotropy frozen in the lithosphere could be another possibility, but our surface wave analysis indicates that while evidence for lithospheric anisotropy exists in the Big Bend region, it is small and negligible elsewhere.

Since the lithospheric effects appear to be too small to explain the shear-wave splitting, we examine the effects of sub-lithospheric mantle flow. There are two different views of the dynamics of mantle flow for Western America. Silver and Holt [2002] argue that the mantle flows due east in a hot spot reference frame, nearly opposite to the direction of North American plate motion (west-southwest). They suggest that the mantle flow in western North America is weakly coupled to the motion of the surface plate, producing small drag force, and that this flow field is probably due to heterogeneity in mantle density that is produced by the sinking Farallon slab. On the other hand, Becker et al. [2006b] suggest that coupling exists between the mantle flow and the North America plate. They conclude that the interaction between mantle and lithospheric motions need not be weak to explain splitting, implying potentially strong plate driving forces associated with mantle flow. Further to the north of our study area Zandt and Humphreys [2007] suggest a circular pattern of fast directions seen in West North America is related to toroidal flow around the Juan de Fuca Slab as it retreats west. While this may affect some our northern stations its affect is probably small in the Big Bend area.

In a study of Rayleigh wave azimuthal anisotropy beneath southern California, Yang and Forsyth [2006] found that the anisotropy determined from long-period surface waves extends through both lithosphere and asthenosphere. They found that the strength of azimuthal anisotropy is ~1.7% at periods shorter than 100 s and less than 1% at longer periods. They find that the fast direction is nearly E-W and the anisotropic layer is more than 300 km thick. Polet and Kanamori [2002] used SKS splitting time to estimate an anisotropic layer about 100-200 km thick with assumption of 4% anisotropy for upper mantle material. Using estimates of long period P wave polarization, Pn times [Hearn, 1996], and Rayleigh and Love wave velocities, Davis [2003] concluded that anisotropy is distributed throughout the upper 200 km of the mantle up to the base of the crust.

In this study, which uses shorter periods than the Yang and Forsyth [2006] study, we find that predicted surface wave splitting times obtain their largest values in the mantle lithosphere (velocity variations up to 1.5%), but are much less than SKS and SKKS splitting times. The surface wave fast axes directions are also different from SKS and are mostly parallel to the relative plate motion direction and major faults. The largest variations occur just south of the big bend where transpression has been greatest. We correct the SKS and SKKS seismograms for anisotropy effects in the mantle lithosphere using the results from the surface wave analysis. After correction, fast directions only rotate anticlockwise on average about 3 degrees and delay times decrease by on average 0.1 sec. The overall SKS and SKKS pattern is hardly affected. Also, the larger splitting observed (~1-1.5s) requires an anisotropic layer that is thicker than the mantle lithosphere. Therefore we conclude anisotropic structure derived from surface waves clearly cannot explain SKS splitting data, but is probably related to the finite strain from the plate tectonics. We suggest that the SKS and SKKS phases are sensitive to the deeper parts of the upper mantle, and given the correlation with APM it is probably located in the asthenosphere.

Polet and Kanamori [2002] plotted the fast directions of anisotropy and the maximum compressive stress directions from the world Stress Map together for southern California. They found that the fast direction is nearly orthogonal to the maximum compressive stress, and argued that this perpendicularity is consistent with the alignment of the a–axis of olivine perpendicular to the direction of lithospheric shortening. This mechanism, however, does not explain the larger contribution to splitting from the asthenosphere, which is unlikely to be directly coupled to any lithospheric shortening.

Given the good correlation between absolute plate motion in the central and northern California, and on the eastern side of southern California, we suggest the shear-wave splitting is due to drag on the asthenosphere by the absolute plate motion of the over-riding plates. However, in west-southern California the effect of the big bend causes the plate margin to be much more diffuse than further north. This contrast south to north, across the Big Bend extends to Baja California where splitting analyses have obtained similar E-W fast directions to those in southern California [Obrebski and Castro, 2008; Obrebski et al., 2006]. We suggest that the mantle flow models [e.g., Silver and Holt, 2002; Becker 2007b] are unlikely to have a sudden change across the Big Bend, and that the difference is due to the history of the plate tectonic interactions. Prior to 30 Ma, when the east Pacific rise collided with North America, most of the region west of the SAF had North American plate motion. With the collision, and development of the transpressive plate boundary, parts of North America were captured and have taken on Pacific plate motion [Atwater, 1970]. North of the Big Bend the relative motion across the plate boundary has concentrated near the SAF and nearby offshore faults such as the San Gregorio and Hosgri Faults. Over the last 12 Ma the relative plate displacement is as much as 400-500 km [Powell et al., 1994] across a narrow boundary region that GPS measurements show continues narrow to the present.

South of the Big Bend the relative displacement has been, and continues to be, broadly distributed. Over the past 12 Ma the transform motion has stepped east from offshore to the San Gabriel Fault, and then at 5 Ma to the SAF, which has an offset of just 160-180 km [Powell et al., 2004]. The plate capture has involved microplate capture in the continental borderland with significant motion offshore. Thus the underlying asthenosphere beneath onshore stations has seen less accumulated Pacific plate APM.

It takes more than 40% finite strain to overprint a previous anisotropy [Ribe, 1992]. We explain the Big Bend contrast in southern California as due to fact that the Pacific Plate motion for captured North America, southwest of the Big Bend, has been insufficient to overprint North American APM. This has been more successful in central and northern California where the finite strain is estimated to be more than a factor of two larger. We expect that offshore, both southern and northern California, the anisotropy will rotate to be fully parallel to Pacific plate APM, some indication of which is apparent in global surface wave anisotropy maps [Montagner and Guillot, 2000].

Conclusions

The combined SKS and surface wave splitting results can explain earlier estimates of azimuthal anisotropy from P_n that found SAF-aligned directions [Hearn, 1984, Sung and Jackson, 1992, Smith and Ekstrom, 1999] in southern California. In this region, the Rayleigh wave fast directions N112^{o}W are in agreement with previous studies of P_n anisotropy which vary from N115E [Sung and Jackson, 1992] to ~N120^{o}E [Smith and Ekstrom, 1999]. Both surface waves and P_n are sensitive to uppermost mantle structures. But surface wave and P_n results are in stark contrast with the fast SKS splitting directions N80^{o}E suggesting anisotropy twists anticlockwise with depth. SKS Splitting values, which have been corrected for mantle lithosphere effects, are remarkably parallel to plate motions. This suggests that transpression that has given rise to the San Gabriel Mts in the Big Bend region has generated anisotropy in the mantle lithosphere, but deeper down, absolute plate motion aligns olivines in the asthenosphere.

Acknowledgements:

This research was supported by the Southern California Earthquake Center. SCEC is funded by NSF Cooperative Agreement EAR-8920136 and USGS Cooperative Agreements 14-08-0001-A0899 and 1434-HQ-97AG01718. SCEC contribution 1711.

References

Atwater, T., and H. W. Menard (1970), Magnetic Lineations in Northeast Pacific, Earth Planet. Sci. Lett., 7(5), 445-450.

Becker, T. W. (2006), On the effect of temperature and strain-rate dependent viscosity on global mantle flow, net rotation, and plate-driving forces, Geophysical Journal International, 167(2), 943-957.

Becker, T. W., Becker, T. W., S. Chevrot, V. Schulte-Pelkum, and D. K. Blackman, (2006a), Statistical properties of seismic anisotropy predicted by upper mantle geodynamic models, Journal of Geophysical Research-Solid Earth, *111,* B08309, doi:10.1029/2005JB004095.

Becker, T. W., V. Schulte-Pelkum, D. K. Blackman, J. B. Kellogg, J. B., and R. J. O'Connell (2006b), Mantle flow under the western United States from shear wave splitting, *Earth Planet. Sci. Lett., 247*, 235-251.

Becker, T. W., J. T. Browaeys, and T. H. Jordan, (2007a), Stochastic analysis of shear wave splitting length scales. *Earth Planet. Sci. Lett., 259*, 526-540.

Becker, T. W., G. Ekström,L. Boschi, L., and J. WoodhousW (2007b), Length scales, patterns, and origin of azimuthal seismic anisotropy in the upper mantle as mapped by Rayleigh waves. *Geophysical J. Int., 171*, 451-462.

Crampin, S., and D. C. Booth (1985), Shear-Wave Polarizations near the North Anatolian Fault .2. Interpretation in Terms of Crack-Induced Anisotropy, Geophysical Journal of the Royal Astronomical Society, 83(1), 75-92.

Davis, P. M. (2003), Azimuthal variation in seismic anisotropy of the southern California uppermost mantle, Journal of Geophysical Research-Solid Earth, 108, NO. B1, 2052, doi:10.1029/2001JB000637.

Fouch, M., and S. Rondenay (2006), Seismic anisotropy beneath stable continental interiors, Physics of the Earth and Planetary Interiors, 158, 292-320.

Gripp, A. E., and R. G. Gordon (2002), Young tracks of hotspots and current plate velocities, Geophysical Journal International, 150(2), 321-361.

Hearn, T. M. (1984), Pn Travel Times in Southern California, *J. Geophys. Res.* 89, 1843–1855.

Hearn, T. M. (1996), Anisotropic Pn tomography in the western United States, Journal of Geophysical Research-Solid Earth, 101(B4), 8403-8414.

Karato, S., et al. (1989), Seismic anisotropy; mechanisms and tectonic implications, in Rheology of solids and of the Earth., edited, pp. 393-422.

Kohler, M. D., et al. (2003), Mantle heterogeneities and the SCEC reference three-dimensional seismic velocity model version 3, Bulletin of the Seismological Society of America, 93(2), 757-774.

Li, Y. G., et al. (1994), Shear-Wave Splitting Observations in the Northern Los-Angeles Basin, Southern California, Bulletin of the Seismological Society of America, 84(2), 307-323.

Liu, H., et al. (1995), Sks Splitting beneath Southern California, Geophysical Research Letters, 22(7), 767-770.

Makeyeva, L. I., et al. (1992), Shear-Wave Splitting and Small-Scale Convection in the Continental Upper Mantle, Nature, 358(6382), 144-147.

Montagner J. P., and L. Guillot (2000), Seismic anisotropy tomography. *In* Problems in Geophysics for the Next Millennium. E Boschi, G Ekström, A Morelli (eds) Editrice Compositori, Bologna, Italy, p 217-254.

Montagner, J. P., and T. Tanimoto (1991), Global Upper Mantle Tomography of Seismic Velocities and Anisotropies, Journal of Geophysical Research-Solid Earth, 96(B12), 20337-20351.

Montagner, J. P. (1994), Can Seismology Tell Us Anything About Convection in the Mantle, Reviews of Geophysics, 32(2), 115-137.

Montagner, J. P. (1998), Where can seismic anisotropy be detected in the earth's mantle? In boundary layers, Pure and Applied Geophysics, 151(2-4), 223-256.

Montagner, J. P., D.-A. Griot-Pommera and J. Lave, (2000), How to relate body wave and surface wave anisotropy?, Journal of Geophysical Research-Solid Earth, 105(B8), 19015-19027.

Nicolas, A. and N. I., Christensen, (1987), Formation of anisotropy in upper mantle peridotites: A review, in Composition, Structure, and Dynamics of the Lithosphere-Asthenosphere System, Geodyn. Ser., edited, pp. 111-123.

Obrebski, M. and R. Castro, (2008), Seismic anistropy in northern and central Gulf and California region, Mexico, from teleseismic receiver function and new evidence of possible plate capture, JGR, 113, B03301, doi:10.1029/2007JB005156.

Obrebski, M., R. Castro, R. Valenzuela, S. Van Benthem, and C.Rebollar (2006), Shear-wave splitting observations at the regions ofnorthern Baja California and southern Basin and Range in Mexico,Geophys. Res. Lett., 33, L05302, doi:10.1029/2005GL024720,2006.

Ozalaybey, S., and M. K. Savage (1995), Shear-Wave Splitting beneath Western United-States in Relation to Plate-Tectonics, Journal of Geophysical Research-Solid Earth, 100(B9), 18135-18149.

Polet, J., and H. Kanamori (2002), Anisotropy beneath California: shear wave splitting measurements using a dense broadband array, Geophysical Journal International, 149(2), 313-327.

Powell, R.E., Weldon, II, R. J., and Matti J. C., (1994), The San Andreas fault: A balance palinspastic reconstruction and geologic evolution, Geol Soc. Amer. Mem., 178.

Prindle, K., and T. Tanimoto (2006), Teleseismic surface wave study for S-wave velocity structure under an array: Southern California, Geophysical Journal International, 166(2), 601-621.

Ribe, N. M. (1992), On the Relation between Seismic Anisotropy and Finite Strain, Journal of Geophysical Research-Solid Earth, 97(B6), 8737-8747.

Savage, M. K., and P. G. Silver (1993), Mantle Deformation and Tectonics - Constraints from Seismic Anisotropy in the Western United-States, Physics of the Earth and Planetary Interiors, 78(3-4), 207-227.

Savage, M. K. (1999), Seismic anisotropy and mantle deformation: What have we learned from shear wave splitting?, Reviews of Geophysics, 37(1), 65-106.

Silver, P., and M. Savage (1994), The interpretation of shear-wave splitting parameters in the presence of two anisotropic layers, Geophys. J. Int., 119(3), 949-963.

Silver, P. G., and W. W. Chan (1991), Shear-Wave Splitting And Subcontinental Mantle Deformation, Journal Of Geophysical Research-Solid Earth, 96(B10), 16429-16454.

Silver, P. G. (1996), Seismic anisotropy beneath the continents: Probing the depths of geology, Annual Review of Earth and Planetary Sciences, 24, 385-&.

Silver, P. G., and W. E. Holt (2002), The mantle flow field beneath western North America, Science, 295(5557), 1054-1057.

Smith, G. P., and G. Ekström (1999), A global study of Pn anisotropy beneath continents, *J. Geophys. Res.,* 104, 963–980.

Sung L-Y., and d. D. Jackson (1992), Crustal and uppermost mantle structure under southern California, Bulletin of the Seismological Society of America, April 1, 82(2): 934 – 961.

Tanimoto, T., K. Prindle-Sheldrake, Three-dimensional S-wave Velocity Structure in Southern California, Geophys. Res. Lett., 29, No. 8, 64-1, 2002.

Tanimoto, T. and K. Prindle, Surface wave analysis with beamforming, Earth Planets and Space, 59, 453-458, 2007.

Vinnik, L. P., G. L. Kosarev, and L. I. Makeyeva (1994), Anizotropiya litosfery po nablyudeniyam voln SKS and SKKS, Dokl. Akad. Nauk USSR, 278, 1335– 1339.

Yang, Y., and D. W. Forsyth (2006a), Regional tomographic inversion of amplitude and phase of Rayleigh waves with 2-D sensitivity kernels, Geophys. J. Int., 166, 1148-1160.

Yang, Y.,and D.W. Forsyth, (2006b) Rayleigh wave phase velocities, small-scale convection and azimuthal anisotropy beneath southern California, J. Geophys. Res., 111, 7, B07306, doi:10.1029/2005JB004180, 2006.

Zandt, G., and E. Humphreys (2008), Toroidal mantle flow through the western US slab window, *Geology*, *36*(4), 295-298.

Figures

Figure 1: Location of earthquakes (red dots) used for analysis in this study. Each circle shows 30-degree distance. Magnitude of events are Mw >6.5.

Figure 2. (Lower panel) Predicted splitting times from surface wave analyses from mantle lithosphere (33 -100 km). The other layers give negligible effects. The surface waves fast axes are parallel to the San Andreas Fault (curved dark line) and obtain maximum values in the region of high topography associated with the Big Bend south of the fault. A cross-section illustrating this is shown in the upper panel along the line in the lower panel.

Figure 3. SKS splitting for stacked data 1990-2008. Black and red lines give fast directions before and after correction for splitting in the upper 100 km of the mantle as determined from surface waves. Apart form some anticlockwise rotations in the Transverse Ranges the differences are very small, suggesting the largest splitting occurs at greater depths.

iFgure 4. Contrast between splitting determined from the surface wave data (red lines) with the SKS splitting results (black lines). The splitting results have been corrected for the effects of the upper 33-100 km of the mantle and show a general parallelism WSW-ENE. The plot shows that the surface wave anisotropy neither matches the direction or amplitudes of the SKS data.

Figure 5a. SKS splitting times and fast directions as a function of back azimuth of arriving waves. Rotation of the easternmost stations may be due to variable anisotropy with depth. It is not explained by the upper 100 km anisotropy as determined from surface waves (Figures 2 and 4).

Figure 5b. Stations that have multiple events (#>3) in a given azimuth range. SKS splitting times and fast directions as a function of back azimuth of arriving waves for 14 stations.

Figure 6. Comparison between the direction of absolute plate motion (APM) of the North American plate (red lines) and the splitting variations of the SKS phase (black lines). Except for a few stations in the west the correlation with APM is excellent.

Figure 7. Comparison between APM and splitting variations of the SKS phase for California Stations. Yellow lines give Pacific plate APM from the Nuvel 1A model (Gripp and Gordon, 2002). Red lines denote North American APM and black lines are SKS splitting fast directions. The brown box shows stations that have splitting directions that are rotated towards Pacific plate APM consistent with the 400-500 km of relative motion across the San Andreas Fault system that has occurred after plate capture. In southwestern California the onshore relative motion west of the SAF has been less than half this amount, insufficient to rotate the fast directions.

Figure 8a: Central and Northern California variations of SKS azimuth as function of distance from ref. plate boundary between North America plate and Pacific plate.

Figure 8b: Southern California variations of SKS azimuth as function of distance from ref. plate boundary between North America plate and Pacific plate.