SCEC Report 2009

California Lithosphere Model (SCEC_CLM)

Generating Models for Lithosphere Architecture and Dynamics

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Our 2008-2009 funding supported Minoo Kosarian who worked on combining surface wave data as well as updating SKS splitting for all California broadband stations.

Abstract

We calculated SKS splitting parameters for all available data at all broadband stations in California. In southern California, where the density of stations is greatest, we calculated azimuthal anisotropy in the upper 150 km using surface waves. The results show that splitting in the mantle lithosphere is small (about 0.2 sec) compared with SKS splitting (about 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. This suggests that most of the SKS splitting is generated in the asthenosphere. SKS splitting shows a remarkable parallelism with absolute plate motion in northern and central California and east-southern California, but in west-southern California there is a notable discrepancy. We interpret the parallelism as indicating the SKS anisotropy is caused by drag of the asthenosphere imposed by the over-lying plates. The discrepancy is west-southern California is interpreted as due to asthenospheric flow westward around the drip-structure associated with the Big Bend. The results are consistent with a passive upper mantle responding to the motions of the overlying plates.

Data and Method

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 degrees 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, a stacking method in which waveforms from multiple events are concatenated, and the splitting operator applied to the composite waveform, gives more robust results than averaging widely scattered individual estimates.

The surface wave analysis is described in Prindle and Tanimoto (2006) 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 that layer times the total travel time for vertically traveling S waves. The results are shown in Figure 2.

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 3a). In northern California there is a sharp change in direction across the San Andreas fault, taken to be the plate boundary (Figure 3b).

SKS splitting parameters for the surface wave anisotropy model (Figure 2) exhibit significant differences from those obtained from SKS/SKKS splitting. First of all, the maximum delay time predicted by the surface model is 0.4 seconds, but 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 closer to the major faults also seem to be a new observation). The results suggest that at least two layers of anisotropy are required to explain the differences, the first 0-100km 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 (Figure 3a, 3b and 4). Clearly, the surface wave model has minor effects on the overall SKS pattern (Figure 4). After correction, fast directions rotate anticlockwise on average about 3 degrees and delay times decrease by on average 0.1 sec (Figure 4, 5). The overall SKS and SKKS pattern is hardly affected. Therefore we conclude anisotropic structure in the upper 100 km derived from surface waves clearly cannot explain SKS splitting. Its parallelism with the transpression suggests it is probably related to the finite strain in the lithosphere from the tectonics. We suggest that the SKS and SKKS phases are sensitive to the deeper parts of the upper mantle.

If SKS waves are sensitive to deeper parts of the upper mantle, possibly down to 300-400 km (Becker et al., 2006), the fast-axes patterns in SKS/SKKS data are dominated by anisotropy in deep structure that is not sampled by the surface wave eigenfunctions. A small crustal contribution 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 this range.

We analyzed SKS fast directions in southern California as function of distance from the plate boundary between North America plate and Pacific plate (Figure 6). We considered San Andreas Fault as a boundary layer. The data show a weak pattern of azimuthal variations with distance from San Andreas Fault. However in central and northern California the difference is clear.

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 7). Only 14 stations satisfied these criteria and the results are plotted in Figure 8. Most of the stations on the NE side 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 observed 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 (Figure 9), 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 (Gripp and Gordon, 2003). Figure 10 shows that if we mark the plate boundary as the approximate location of the San Andreas Fault, in northern and central California there is an abrupt transition from parallelism to North American absolute plate motion NAM_PM to Pacific absolute plate motion PP_APM. In southern California this correlation with NAM_PM holds well in the east, but breaks down in the west.

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, 2006). 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., 2006). Also, a pre-existing fossil anisotropy frozen in the lithosphere could be another possibility, but our surface wave analysis indicates that is small.

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. (2006) 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.

In a study of Rayleigh wave azimuthal anisotropy beneath southern California Yang and Forsythe (2006) found that the anisotropy determined from long-period surface waves extends through both lithosphere and asthenosphere. Polet and Kanamori (2002) used SKS splitting times 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. The Yang and Forsyth (2006) study 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.

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 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 splits observed (~1-1.5s) require 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 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 central and northern California and east-southern California, we suggest the 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. The barrier caused by the big bend may cause the flow to be more west directed, which could explain the anisotropy there.

Figures

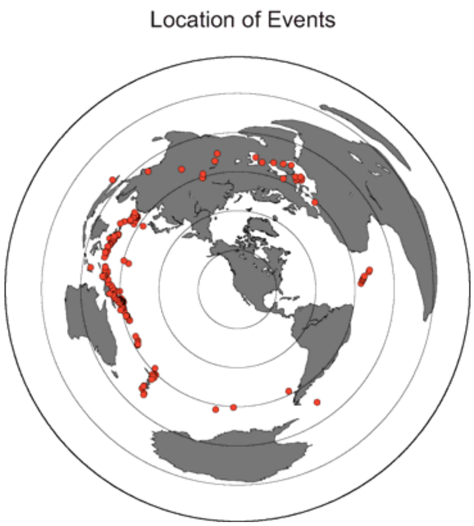

Figure 1: Location of earthquakes (red dots) used for computation in this study. Each circle shows 30-degree distance (3330 km). Magnitude of events are Mw >6.5.

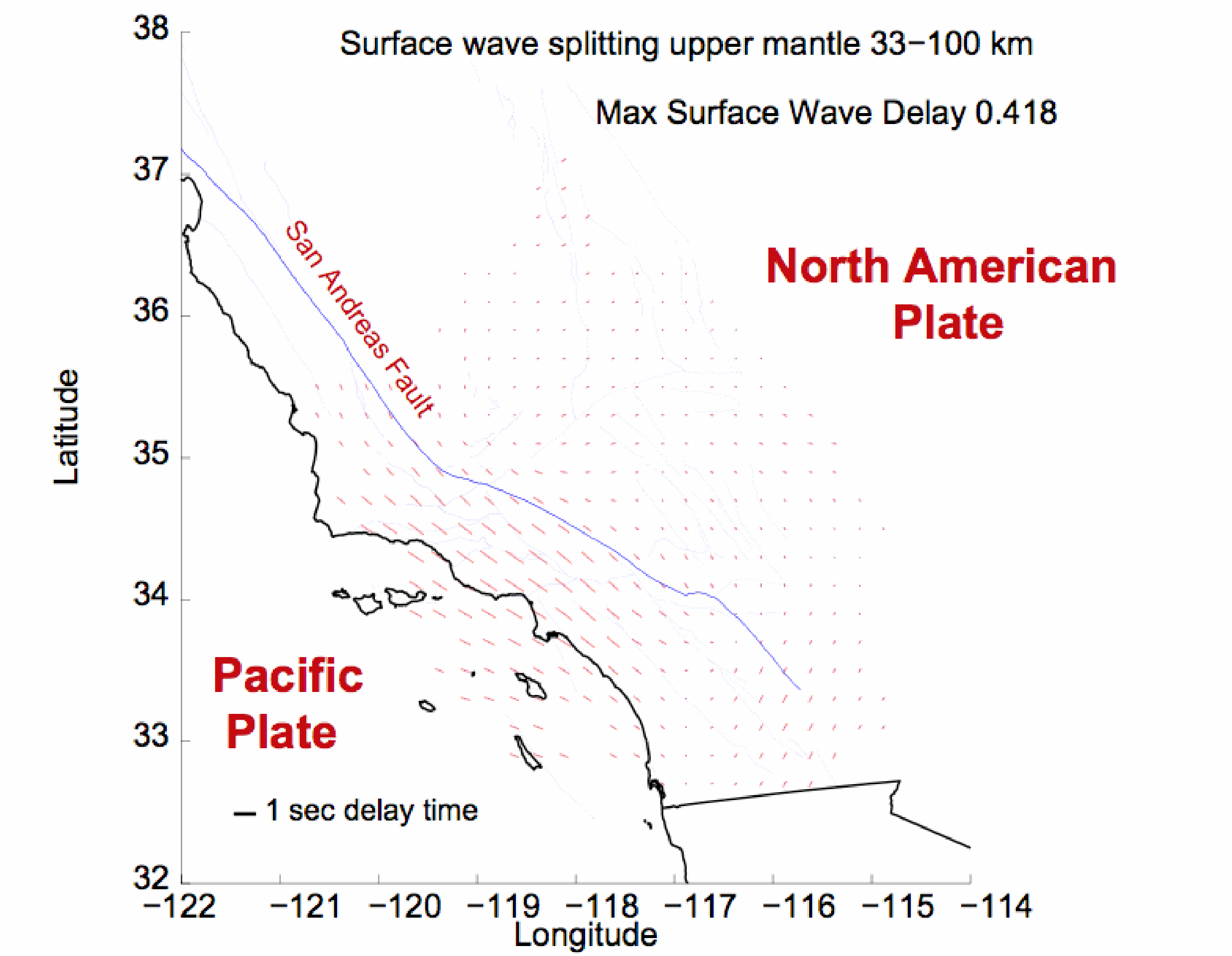

Figure 2. The predicted surface waves splitting times are much less than SKS splitting times. The surface waves fast axes directions are also different in that our results are mostly parallel to the relative plate motion direction. Larger variations closer to the major faults also seem to be a new observation.

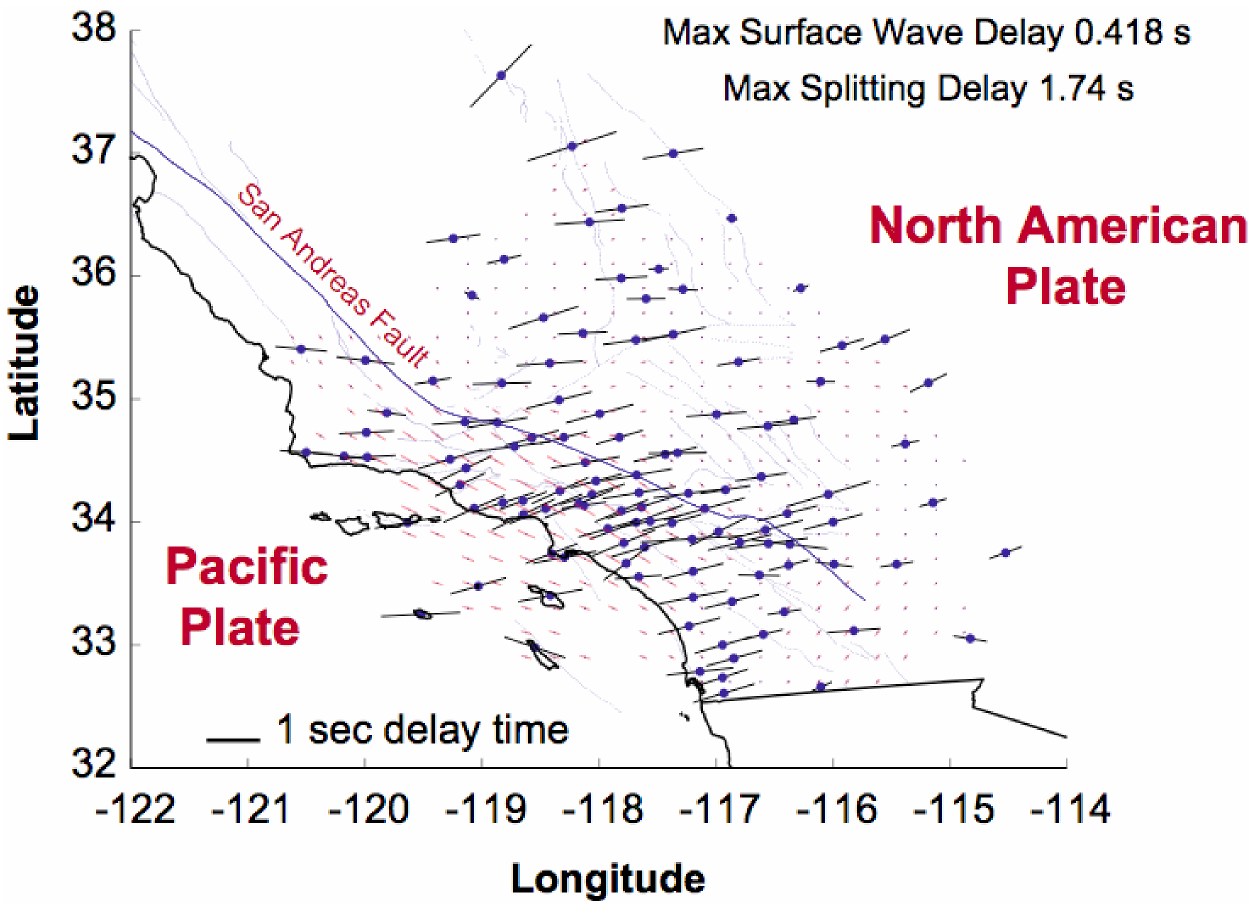

Figure 3a. Results of the inversion for the 2θ type variations (red lines) of splitting from fabric in the upper 100 km as determined from the surface wave data compared with the SKS splitting results (black lines). The splitting results have been corrected for the effects of the upper 100 km and show a general parallelism WSW-ENE. One of the features that stands out is that the anisotropy is strong in the transverse ranges. It also hints that anisotropy is stronger on the Pacific plate side of the San Andreas Fault.

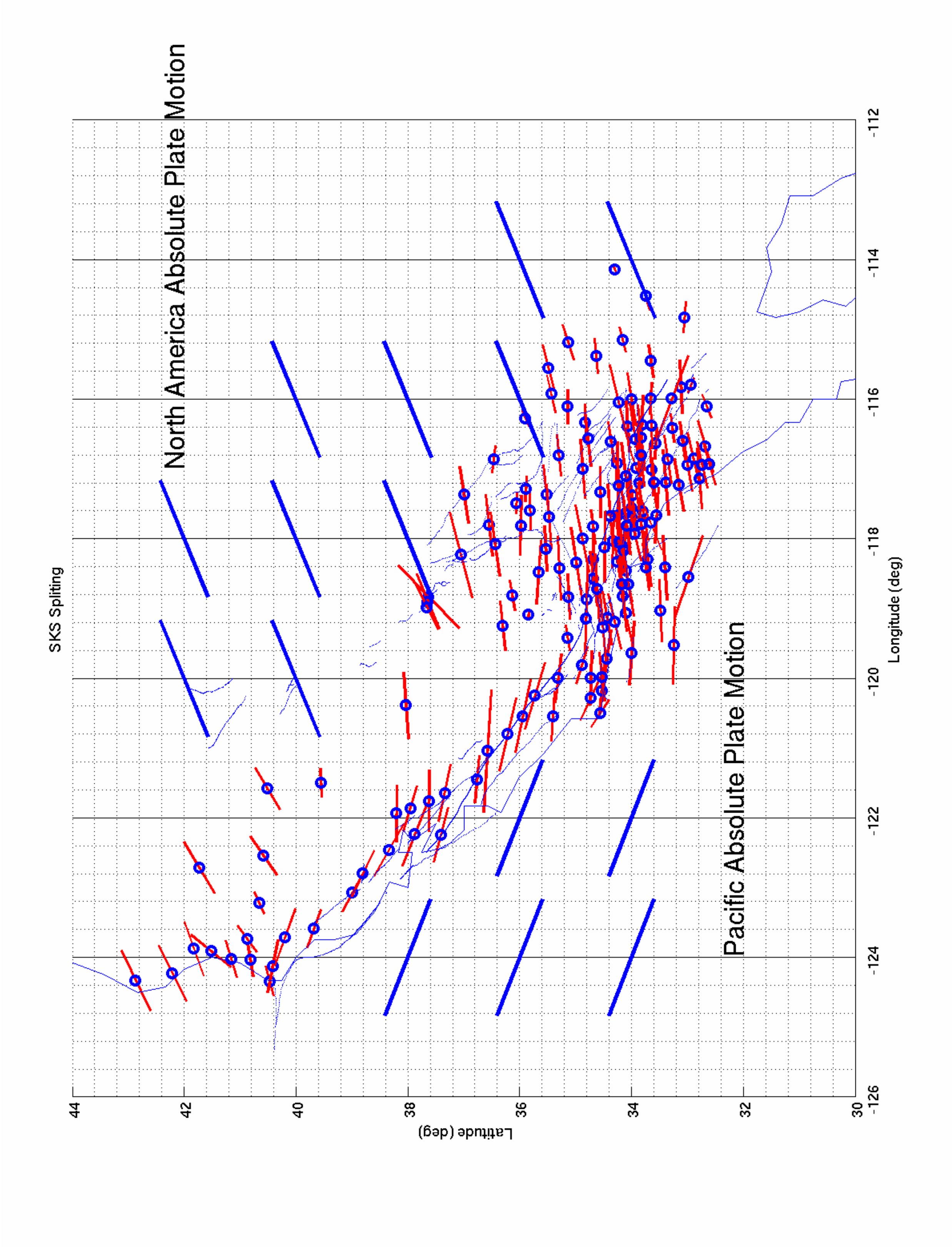
SKS Spliting
North America Absolute Plate Motion
Pacific Absolute Plate Motion
Longitude (deg)
Latitude (deg)
-126
-124
-122
-120
-118
-116
-114
-112
30
32
34
36
38
40
42
44

Figure 3b New SKS splitting calculations for California showing an abrupt change to absolute parallel plate motion as the San Andreas fault is crossed in the north, but not in the south. The difference between northern and southern California is interpreted as indicating that the relative plate motion at the boundary in northern California is much more concentrated than that in southern California, a finding that is in agreement with the geodesy.

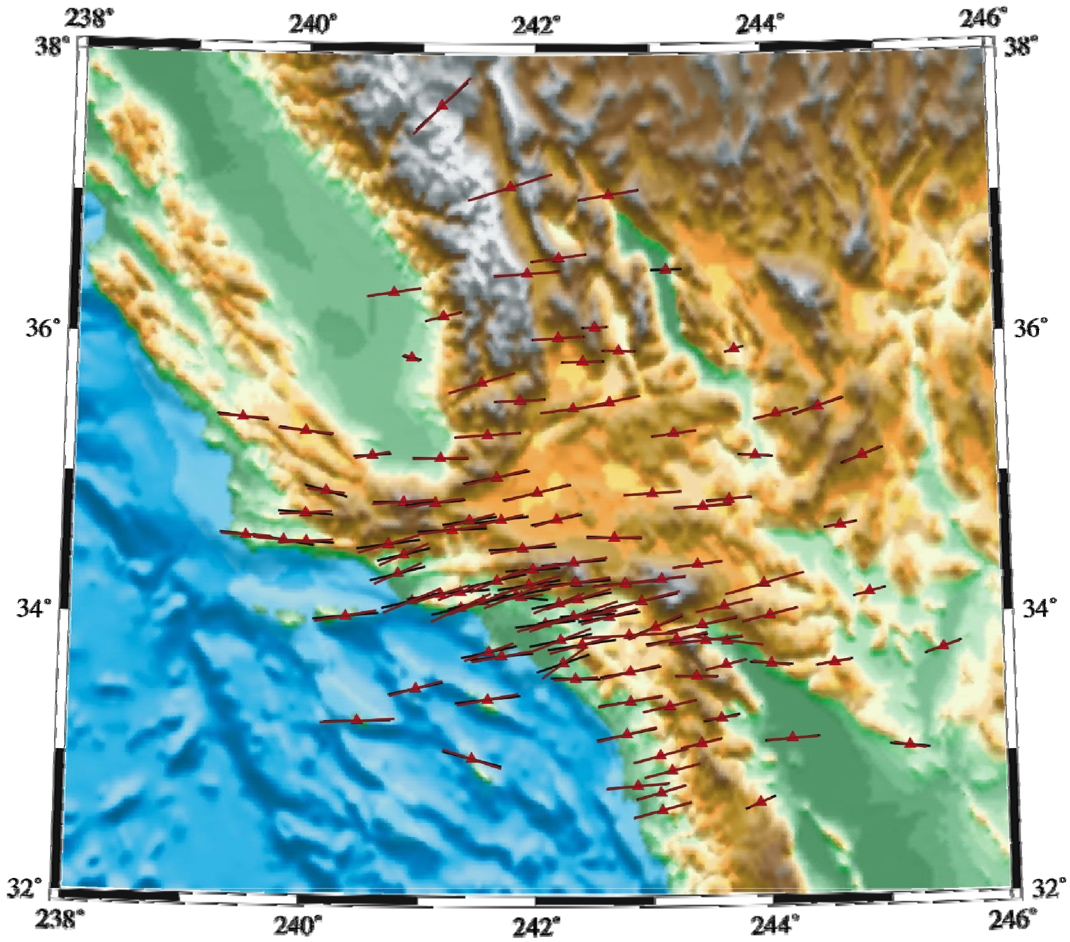

Figure 4. SKS splitting for stacked data 1990-2008. Black and red lines give fast directions before and after correction for splitting in the upper 100 km as determined from surface waves. Apart form some anticlockwise rotations in the Transverse Ranges the differences are very small suggesting the largest splitting occurs at greater depths.

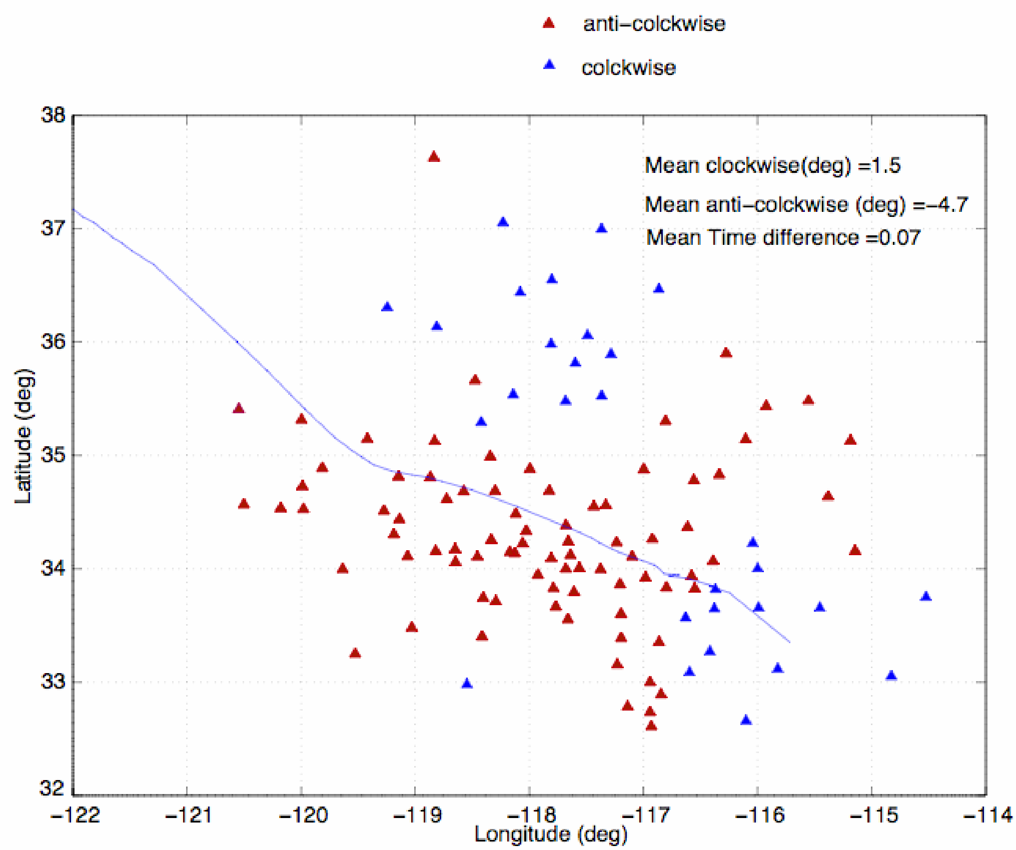

Figure 5. This plots shows the difference between fast directions before and after correction for splitting in the upper 100 km as determined from surface waves. Red triangles represent the location of stations that have anticlockwise rotation after correction and blue triangles show the location of stations that show clockwise rotation after the correction.

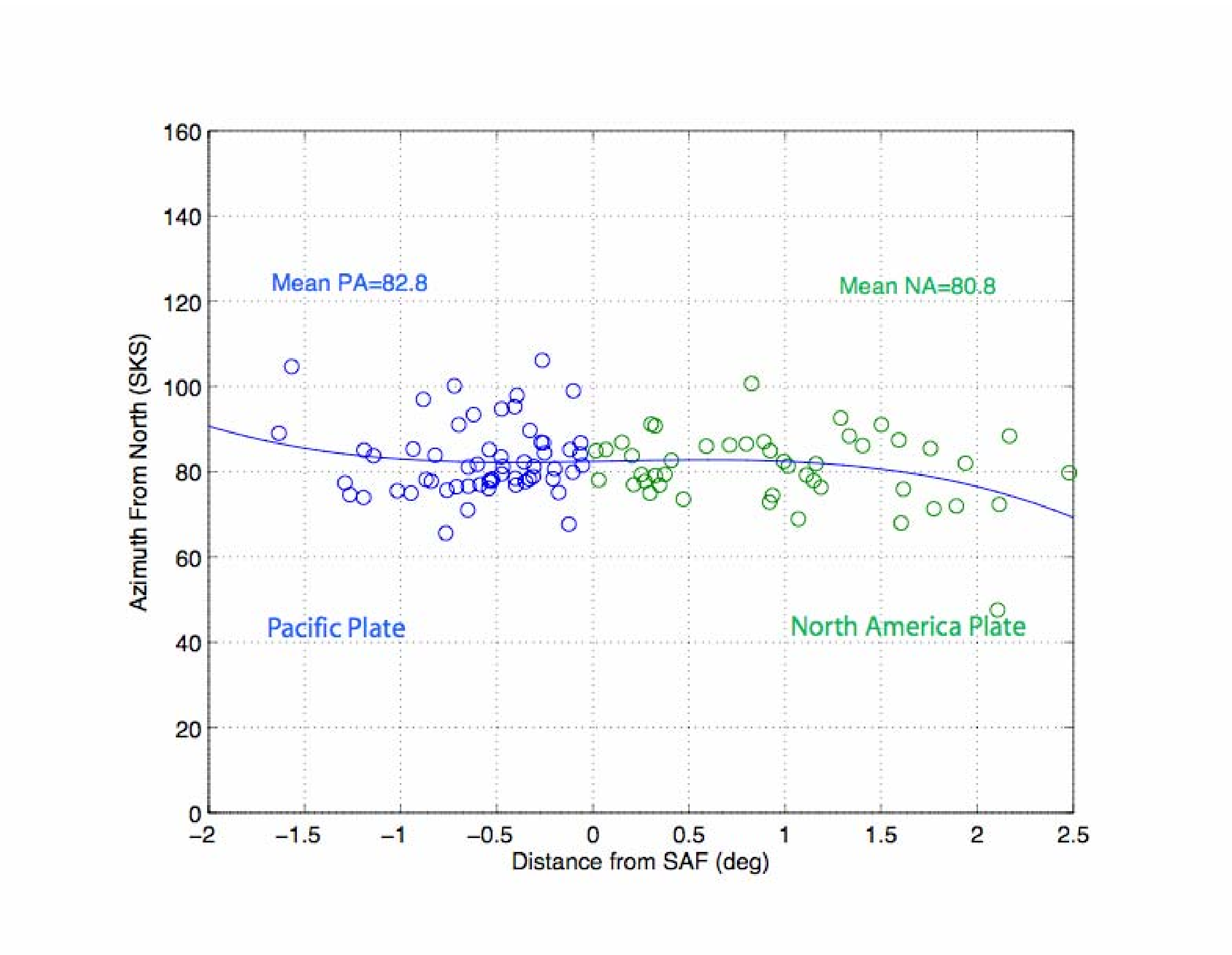

Figure 6: Variations of SKS azimuth as function of distance from San Andreas Fault (ref. plate boundary between North America plate and Pacific plate)

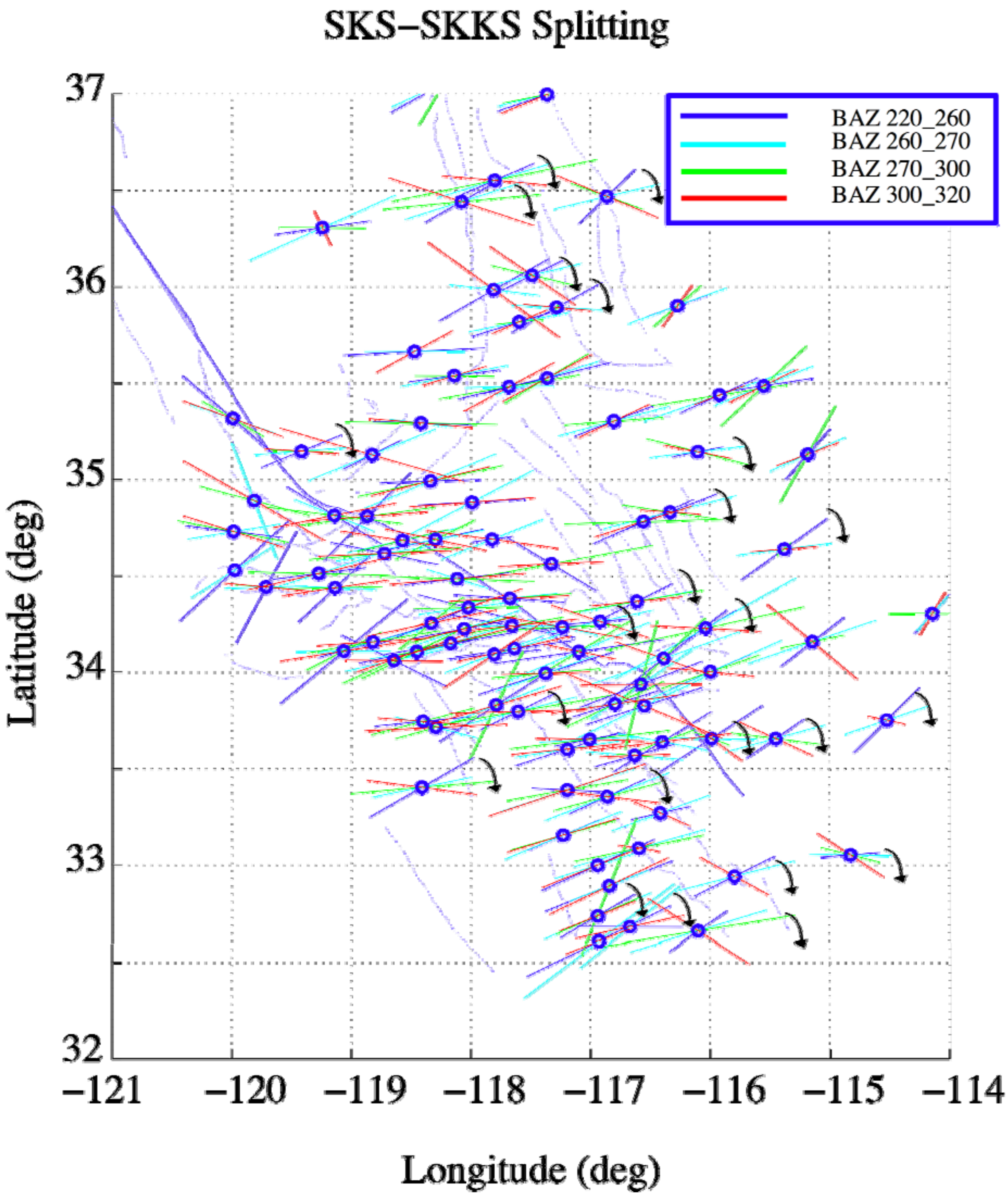

Figure 7. SKS splitting times and fast directions as a function of back azimuth of arriving waves. Rotation of the easternmost stations may be due to variable anisotropy with depth. It is not explained by the upper 100 km anisotropy as determined from surface waves (Figures 2 and 3).

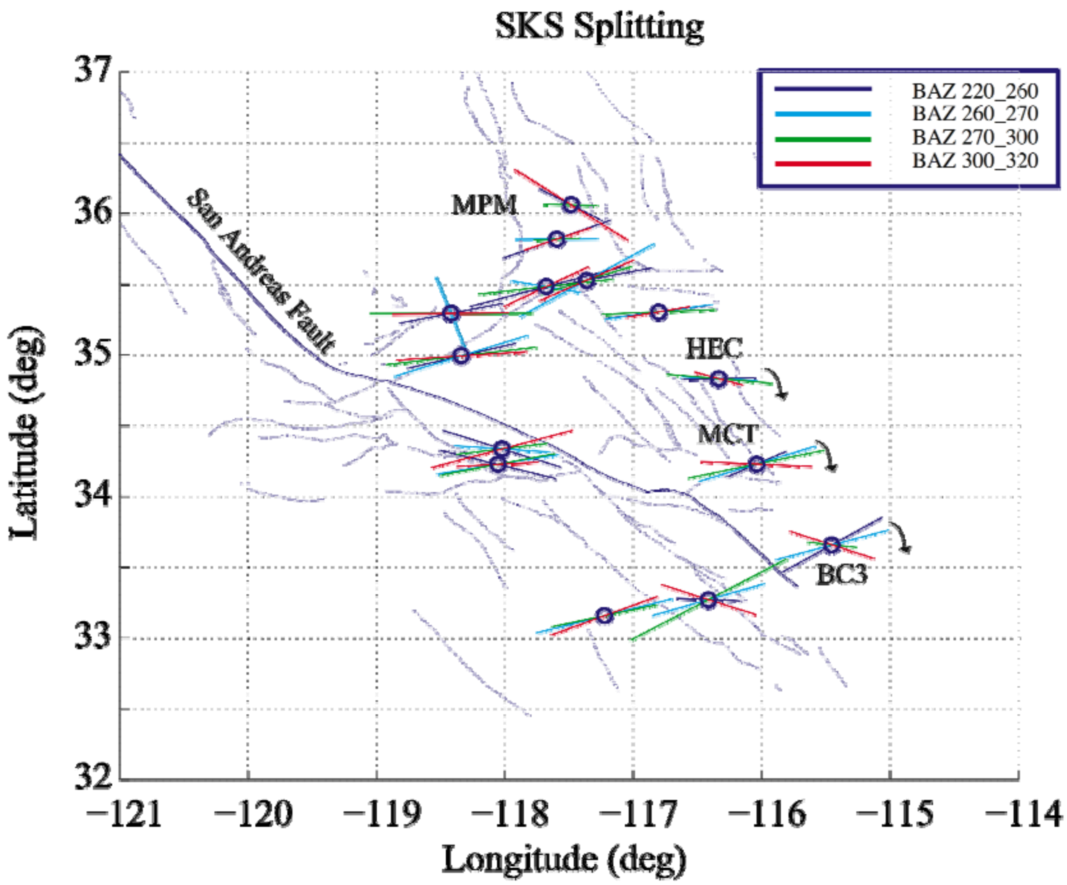

Figure 8. Stations that have multiple events (#>3) in a given azimuth range. SKS splitting times and fast directions as a function of back azimuth of arriving waves for 14 stations.

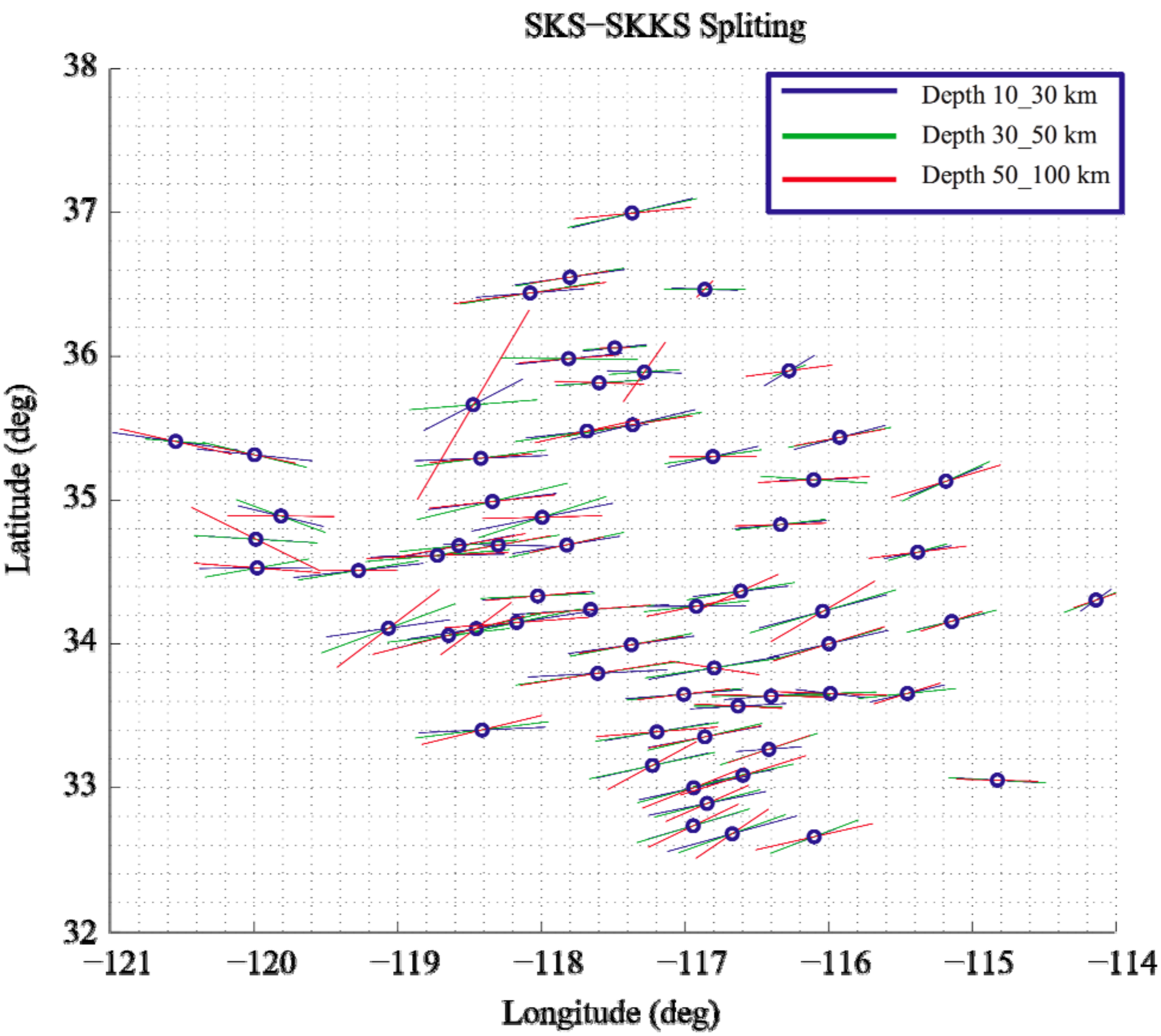

Figure 9. Variation of SKS splitting parameters in terms of depth distribution of events.

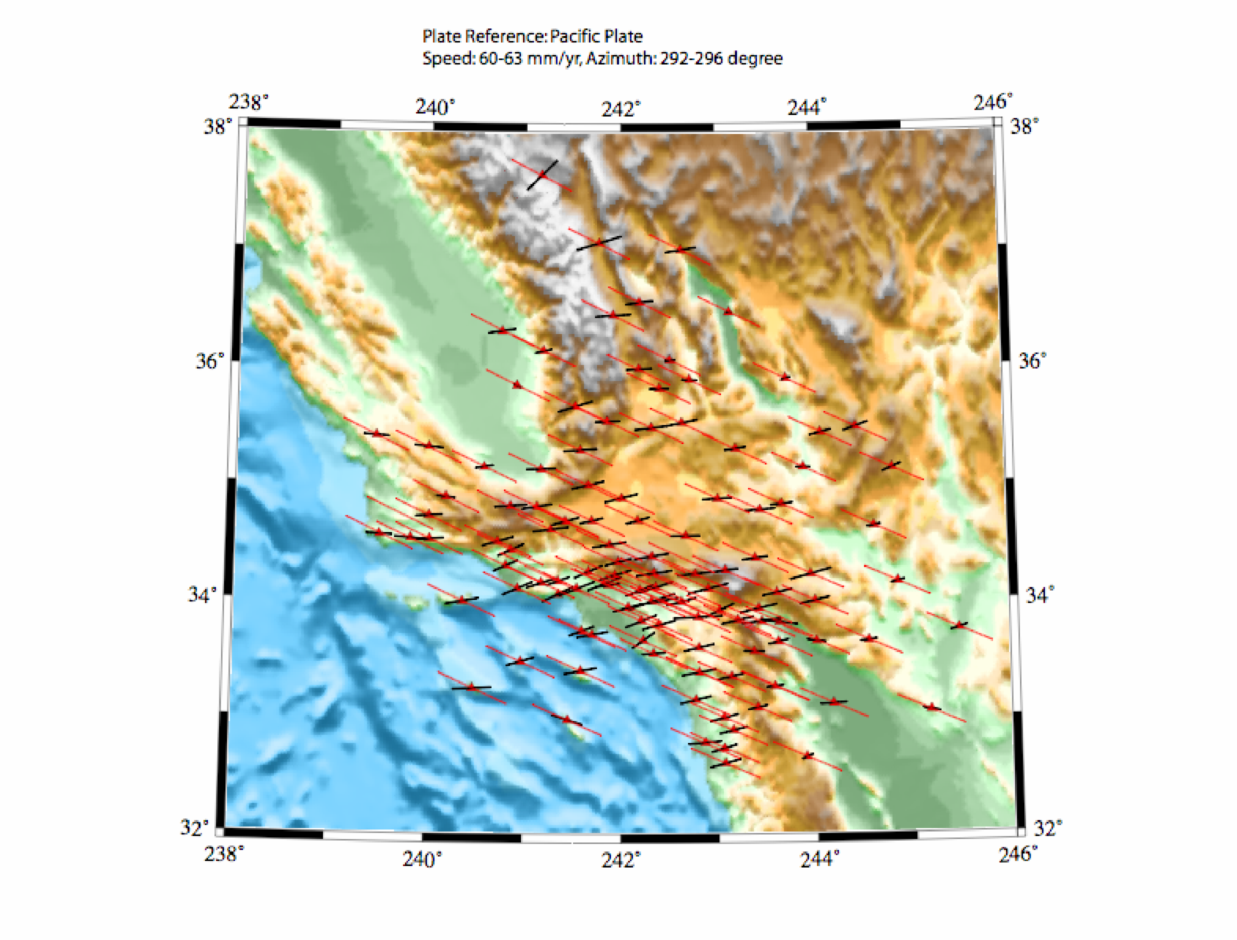

Figure 10a. Comparison between the direction of absolute plate velocity if the Pacific plate and the splitting variations of the SKS phase.

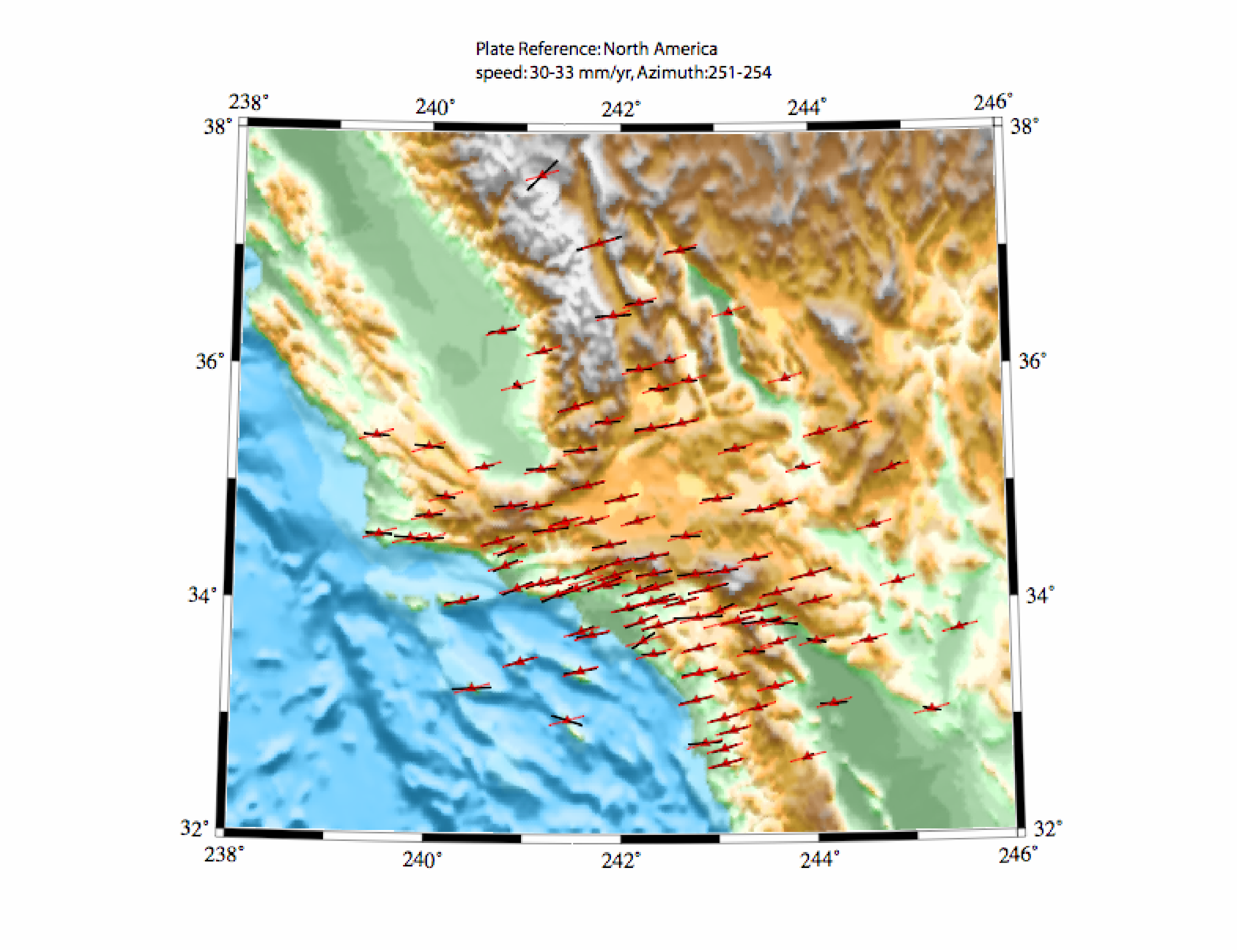

Figure 10b. Comparison between the direction of absolute plate velocity if the North American plate and the splitting variations of the SKS phase.

5. References

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