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Mantle flow in the Rivera–Cocos subduction zone

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SUMMARY

Western Mexico, where the young and small Rivera Plate and the adjacent large Cocos Plate are subducting beneath the North American Plate, is a unique region on Earth where tearing of subducting oceanic plates, as well as fragmentation of the overriding continental plate, is occurring today. Characterizing the mantle flow field that accompanies the subduction of the Rivera and adjacent Cocos plates can help to clarify the tectonics and magma genesis of this young plate boundary. Here we report observations of seismic anisotropy, as manifested by shear wave splitting derived from local S and teleseismic SKS data collected by the Mapping Rivera Subduction zone array that was deployed from 2006 January to 2007 June, in southwestern Mexico, and from data collected by two of Mexico’s Servicio Sismológico Nacional stations. SKS and local S-wave splitting parameters indicate that the fast directions of the split SKS waves for stations that lie on the central and southern Jalisco Block are approximately trench-normal, following the convergence direction between the Rivera Plate and Jalisco Block. S-wave splitting from slab events show a small averaged delay time of ∼0.2 s for the upper 60 km of the crust and mantle. Therefore, the main source of anisotropy must reside in the entrained mantle below the young and thin Rivera Plate. Trench-oblique fast SKS split directions are observed in the western edge of the Rivera Plate and the western parts of the Cocos slab. The curved pattern of fast SKS split directions in the western Jalisco block and beneath the Rivera–Cocos slab gap indicates 3-D toroidal mantle flow, around the northern edge of the Rivera slab and the Rivera–Cocos gap, which profoundly affect the finite strain field in the northeastern edge of the Rivera slab and the mantle wedge. Both the tomographic images and shear wave splitting results support the idea that the Rivera and western Cocos plates not only moved in a downdip direction but also have recently rolled back towards the trench and that the Colima rift is intimately related to the tearing between the Rivera and Cocos plates.

Key words: Mantle processes; Body waves; Seismic anisotropy; Subduction zone processes; North America.

INTRODUCTION

Understanding the plate tectonic process that controls the changing North America and Pacific plates boundary has two fundamental implications for Plate Tectonic theory. First, the process involves a change in plate stress and major reorganization of plate boundaries. Second, insight into this change provides an observational basis for quantifying fragmentation of the subducted oceanic plate into microplates with consequent effects on the geology of the overriding plate including alkaline volcanism, rifting of the overriding plate and plate capture (Stock & Lee 1994). Geological evidence clearly documents the creation of the San Andreas Fault and the addition of Baja to the Pacific Plate over late Cenozoic time (Atwater 1970), but how the process occurred and what the controlling dynamics were...
remains enigmatic. The Cascadia subduction complex will soon undergo similar changes but for now, it remains a classical subduction zone. The only place on Earth where microplate fragmentation is presently occurring is in the Rivera and Cocos subduction complex of Mexico (Fig. 1). In this region, the Rivera Plate separated from the Cocos Plate some 7–10 Ma and is presently subducting beneath the Jalisco Block (Bourgois & Michaud 1991; Bandy & Hilde 2000). The fragmentation of the proto-Cocos Plate has been attributed to pivoting subduction where the combination of trench resistance forces and slab pull forces changed the direction of convergence between the westernmost proto-Cocos Plate and the rest of the Cocos Plate and hence produced localized tension within the proto-Cocos Plate (Bandy & Hilde 2000). Consequently, if the resulting tension exceeds the strength of the lithosphere, then lateral tearing along a weak zone will occur. The effects of segmentation of the subducted proto-Cocos Plate are the formation of the Tepic-Zacoalco rift (TZR) and the Colima rift (CR) to the north and the east of the Jalisco Block, respectively (Fig. 1). The Jalisco Block appears to separate from the North American Plate along the TZR and CR. However, detailed structure mapping in the TZR by Ferrari & Rosas-Elguera (2000) indicates that it is not a single graben but rather it is a composite rift. Their work indicates that this complex rift system developed over the Late Miocene (12–9 Ma), Early Pliocene (5.5–3.5 Ma) and to a lesser extent, in the Late Pliocene to Quaternary times. Moreover, they did not find significant strike-slip deformation along the TZR in Plio-Quaternary times and indicate that the Jalisco Block is not actively separating from North America. At present the North American Plate moves with the Middle American Trench (DeMets & Traylen 2000). The trenchward migration of the volcanic arc and the slowing of the convergence rate from 8.5 to 6.5 Ma have led Ferrari et al. (2001) to postulate that the Rivera slab increased its dip and rolled back. According to this model, the rollback of the Rivera slab induced a toroidal flow of asthenosphere into the subvertically opening mantle wedge, causing mixing of mantle materials with different isotopic signatures. The observed mixed geochemical signature from extruded basalts in the western Trans Mexican Volcanic Belt (TMVB) is consistent with such an interpretation (Ferrari et al. 2001 & Ferrari 2004).

Although abundant geological, palaeomagnetic and geodetic work has been conducted in the Jalisco region there have been no detailed seismic studies until the deployment of the MApping the Rivera Subduction zone (MARS) array in 2006 January. Seismic tomography images using data from the MARS array revealed the subsurface locations of the Rivera and adjacent Cocos plates as well as the boundary between them (Yang et al. 2009). Although the shallow structure of the subducting Rivera and Cocos plates are not well constrained by the tomographic images, the structures deeper than 100 km are clearly imaged. Starting at about 150 km depth a clear gap between the Rivera and Cocos slabs that increases in size at further depths is apparent. The break between the plates occurs beneath the Colima rift and may be responsible for the location of the rift and the Colima volcano. The Rivera slab reaches ∼100 km depth beneath the Colima and Mascota volcanoes. The northwestern edge of the Rivera Plate is not tightly constrained by the tomography image (Yang et al. 2009), but the location can be estimated from the western termination of the Rivera subduction zone at about 106° W. The tomographic images show that the deeper Rivera Plate is subducting more steeply than the adjacent Cocos Plate (fig. 7 of Yang...
Mantle flow and its role in the dynamics of the subduction zone can be investigated from measurement of seismic anisotropy (e.g. Savage 1999; Civello and Margheriti 2004; Long & Silver 2008). In the upper mantle, seismic anisotropy is primarily a consequence of the lattice-preferred orientation (LPO) of mantle minerals, such as olivine, often through the alignment of the fast [100] axis with the maximum elongation direction of the strained mineral although the addition of hydrous minerals can alter this relationship (e.g. Karato et al. 2008). The most unequivocal indicators of upper mantle seismic anisotropy are obtained from shear wave splitting measurements. The method measures the direction and time delay of the fast and slow waves that result when a polarized shear wave passes through an anisotropic medium. The interpretation of mantle flow often hinges on knowledge of the relationship between the fast splitting direction and the flow direction, however, the type of alignment depends on the physical and chemical properties of the mantle (Karato et al. 2008). Laboratory results for dry olivine aggregate suggest that, under low strains and low water content (less than 200 ppm H2O), the splitting fast direction tends to align with the direction of shear (A-type anisotropy), implying that fast splitting direction approximately corresponds to the mantle flow direction (Zhang & Karato 1995). Presence of high water content and high stress in the mantle wedge would align the olivine fabric with the B-axis (B-type anisotropy), yielding a fast anisotropic direction approximately perpendicular to the flow direction (Jung & Karato 2001). Such an interpretation has often been used to explain observed trench parallel fast direction seismic anisotropy in subduction mantle wedges while preserving the 2-D corner flow model of the backarc (e.g. Long and van der Hilst 2006; Kneller et al. 2008).

A variety of splitting behaviours within the mantle have been documented in subduction zones (e.g. Shi & Meyer 1991; Russo & Silver 1994; Fouch & Fisher 1996; Curie et al. 2004; Levin et al. 2004; Long & van der Hilst 2006). A trench-parallel fast direction of polarized S-wave core phases, explained by a parallel to the trench asthenospheric flow, has been observed in the forearc of South America (Russo & Silver 1994), Kamchatka (Peyton et al. 2001), Ryukyu (Long & van der Hilst), Izu-Bonin (Anglin & Fouch 2005), Mariana (Fouch & Fischer 1998), Central America (Abt & Fischer 2008; Hoernle et al. 2008) and most other forearcs (Long & Silver 2008, 2009) except in the young Cascadia subduction zone (Curie et al. 2004), the Rivera arc and in a localized part of South America (Polet et al. 2000) where the fast directions are roughly perpendicular to the strike of the trench. Since the stations used by Curie et al. (2004) to calculate SKS splitting were located about 50–100 km above the subducting slab and small local S-wave split time of 0.3 s, the main source of anisotropy is within the subwedge upper mantle and the young Juan de Fuca slab must entrain a significant amount of subslab-asthenospheric mantle.

Global studies indicate that anisotropy properties of the subslab mantle wedge vary greatly. Levin et al. (2004) found that in the vicinity of the southern Kamchatka Peninsula the fast direction exhibits a change from trench-normal close to the trench to trench-parallel farther in the backarc. However, the opposite trend was observed in Japan (Nakajima & Hasegawa 2004) and in the central North Island, New Zealand (Morley et al. 2006). Both studies found that the stations further away from the trench show larger delay times and inferred that the LPO of olivine generated by the corner flow induced strain as the most likely cause for the trench-normal anisotropy. Three possible scenarios of anisotropy in the backarc side are considered: deformation of water-rich B-type olivine fabric in the cold shallow tip of the mantle wedge, trench parallel flow in the mantle wedge due to dip variations in the slabs, and crustal anisotropy.

Seismic anisotropy of the oceanic lithosphere, generally considered as a type of fossilized anisotropy, originates during mantle flow at mid-ocean ridges; viscous shear deformation imparts a structural fabric that remains in the oceanic lithosphere as it spreads and cools. For a slow-spreading (<2 cm yr⁻¹) Mid-Atlantic ridge the magnitude of the P-wave anisotropy is 3.4 ± 0.3 per cent (corresponding to S-wave anisotropy of about 2.1 ± 0.2 per cent) approximately one-half that found in lithosphere formed at faster spreading rates in the Pacific (Gaherty et al. 2004). Fossilized anisotropy has fast directions neither trench-parallel nor trench-normal and has no coherent relationship with subduction zone anisotropy observations. A slab origin would also predict an increase in delay time with increasing age of the downgoing slab, but no such correlation has been observed by Long & Silver (2008). Therefore, they propose that the source of forearc trench-parallel anisotropy comes mainly from subslab asthenospheric mantle.

Compiling shear wave splitting measurements from subduction zones worldwide, Long & Silver (2008, 2009) found that subslab regions are dominated by trench-parallel fast splitting directions. They found a positive correlation between the trench migration velocity and the strength of the subslab splitting signal. Furthermore, they suggested that shear heating formed a thin low viscosity layer that decouples the subducting slab from the asthenosphere and allows for the motion of the trench-slab system to induce trench-parallel flow. Circular patterns of anisotropy have been observed around slab edges, which generally involve a rolling back subducting slab. Both experimental (Piromallo et al. 2006) and numerical simulations (Lowman et al. 2007; Honda 2009) support the idea that a toroidal flow around the slab edge is responsible for the circular pattern of anisotropy observed in Kamchatka (Peyton et al. 2001); Calabria, Italy (Civello & Margheriti 2004); and the western United States (Zandt & Humphreys 2008).

Here we present a detailed shear wave splitting study of the Rivera and adjacent Cocos subduction zone using S waves from events within the subducted slabs and SKS waves mostly from the south Pacific recorded by the MARS temporary seismic array. We also use broad-band data collected at two of Mexico’s Servicio Sismológico Nacional Stations.

**METHODOLOGY**

When a shear wave passes through an anisotropic region, it splits into a fast and a slow phase that are polarized perpendicular to each other. The delay time between the fast and slow phase, is a measure of the thickness and strength of anisotropy and also depends on the direction and polarization of the wave propagation. Waves polarized parallel or perpendicular to the axis of symmetry do not exhibit splitting. The shear wave parameters are the direction of polarization for the fast phase and the delay time. Most shear wave splitting measurements are based upon particle motion analysis assuming that the shear wave propagates through a single or two layer anisotropic medium (e.g. Savage 1999). In this study, we use the grid search method of Silver & Chan (1991) to determine the fast splitting direction and delay time for SKS core phases.
Assuming one layer of anisotropy with a horizontal axis of symmetry, the shear wave splitting parameters were determined by minimizing the energy in the tangential components through a grid search to find those that best remove the observed splitting. Ray paths of core and local S phases are shown in Fig. 2. An S wave from a slab will often travel up-dip along the slab before it refractions towards the station. For local S waves we minimize the smaller of the two eigenvalues in the horizontal covariance matrix in order to find a combination of the delay time and fast direction that will create only one non-zero principal component of the horizontal ground motion.

In other words, if we can find a fast direction and lag time that gives us a perfectly linear particle motion then we have completely removed the effect of the splitting and this must be the correct fast direction–lag time pair. We chose windows beginning ~10 s before the SKS and local S phase arrival and ending immediately after one period of the phase and analyzed each phase that displayed elliptical horizontal particle motion indicative of shear wave splitting. After determining parameters that minimized tangential component energy, we checked the fast and slow components visually and made sure that corrected seismograms had linear particle motion. Null measurements, in which no splitting is inferred, are here defined if the estimated delay time is less than 0.4 s, and 0.05 s for the core and local S phases, respectively.

Our error analysis utilizes the inverse F-test, as implemented by Silver & 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 per cent confidence region. Only seismograms with variance reduction contours exhibiting clear minima were selected as reliable solutions of splitting parameters. We also obtained error estimates using the bootstrap technique of Sandvol & Hearn (1994) with similar results.

### RESULTS

Analysis of SKS and phases yielded 122 sets of shear wave splitting parameters (Fig. 3, Table S3). Fast direction and delay time estimates have typical 95 per cent confidence intervals of ±12° and ±0.3 s, respectively. Fast directions with errors (two standard deviations) greater than 27° or delay time errors larger than 62 per cent of the corresponding delay time estimate were discarded. We filtered SKS data from a 535 km deep event (057/2006, Table S1) to 4–5 s and 2–3 s periods and then re-analysed these filtered data. Results of filtered data have nearly identical splitting parameters when compared with results from the longer period data (~6 s), except the resolution in the delay time is improved (±0.1 s). Therefore, we do not expect significant frequency dependence of our splitting results. Analysis of local S phases produced 60 sets of shear wave splitting parameters (Fig. 4, Table S4). Fast directions of split S wave and delay time estimates have typical 95 per cent confidence intervals of ±10° and ±0.04 s, respectively. Fast S-wave directions with errors greater than 18° or delay time errors larger than 50 per cent of the delay time are eliminated.

The SKS wave splitting parameters of the MARS array and two of Mexico’s Servicio Sismológico Nacional stations (CJIG and COIG) (van Benthem 2005; van Benthem & Valenzuela 2007) are shown in Fig. 3, where the black bars indicate the weighted average of the fast directions of polarization and their lengths are proportional to the delay times. Thin red bars indicate the event backazimuths for null measurements. Null measurements are consistent with two possible fast directions; one along the event backazimuth and the other perpendicular to this azimuth. The stations with larger delay times are generally located east of the Colima Rift. On the Jalisco Block the fast directions of split SKS phases show a gentle curved pattern that approximately is collinear with Rivera Plate motion relative to North America shown by small circles drawn from the pole.
Figure 3. SKS and SKKS shear wave splitting measurements from MARS array and two of Mexico’s Servicio Sismológico Nacional stations (CJIG and COIG). Black bars indicate the weighted average of the fast directions of polarization and their lengths are proportional to the delay time according to the legend. Red bars represent the backazimuths for the null measurements. Black solid triangles represent recent volcanoes. 20, 40, 60 and 80 km Benioff contours are shown by thin black dotted lines (Pardo & Suárez 1995). Deeper contours, 100, 150, 200 and 257 km are from Yang et al. (2009). TZR, Tepic Zacoalco Rift; CTR, Chapula Tula Rift; EGG, El Gordo Graben; MV, Mascota Volcano; CV, Colima Volcano.

of rotation between the Rivera Plate and North America (DeMets & Traylen 2000; Figs 1 and 3).

Stations 32, 35, 38, 45 and adjacent stations located within the middle of the Jalisco block show approximately N–S to NNE–SSW fast SKS directions that are approximately perpendicular to the Middle American Trench and parallel to the convergence direction (Fig. 3). Stations CJIG, 37, 55, 43 and 42 located above the northwestern edge of the Rivera slab, show a curved fast direction pattern around the western Rivera slab edge with delay times of slightly less than 1.0 s. In the central backarc of the Rivera subduction complex (e.g. station 54 and the adjacent station) the fast direction is approximately trench-normal. Along the Colima rift, the fast SKS directions are approximately parallel to the rift axis. For stations (16 and the one north of it) that lie north of the Colima Volcano and above the gap between the Rivera and Cocos plates (stations 49 and 50), the fast directions of polarized SKS phases are oriented NE–SW with a mean delay time of about 1.3 s. Stations located on the westernmost Michoacan block, which is underlain by the Cocos Plate are characterized by trench-normal fast directions except for station 17 where the fast direction of the split SKS phase is oblique to the trench. Many stations on the Michoacan block show null measurements because of the lack of a wide azimuthal distribution of teleseismic events. Null measurements do not always mean there is no seismic anisotropy beneath these stations; rather it may be that the fast or slow directions are along the backazimuth.

Fig. 4 shows a synoptic view of S-wave splitting measurements above the Rivera and Cocos plates. We have plotted the fast S-wave direction of polarization at the midpoint between the event and the receiver. Black bars indicate fast directions of polarization for event-station-pairs. Crosses represent the midpoint position for null measurements. In the forearc region most fast-directions of split S waves are oriented in an E–W to NW–SE direction, with an average delay time of 0.2 s that is parallel to the strike of major faults. In the central Colima rift and in the slab gap region between the Rivera and Cocos plates, the fast-directions of the split S waves are oriented N–S to NE–SW with an average delay time of about 0.3 s. Although the orientation of fast split S-wave directions in the westernmost Michoacan block (adjacent to the Colima rift) is similar to the fast direction of the split SKS waves, the delay time is much smaller probably because the path lengths are less than 60 km.

DISCUSSION

Anisotropy observed in the Rivera–Cocos subduction complex is an integrated effect of finite strain accumulated in the subslab mantle, the slab (fossil anisotropy developed by corner flow at the ridge), the mantle wedge and the overlying plate. The complexity makes it difficult to resolve where the anisotropy is originating. The argument against a primary contribution from the overlying plate is that in the forearc region the overlying plate consists of mostly crustal material (up to ~45 km thick crust; Suhardja et al. 2007). It is unlikely that crustal material could contribute more than 0.2 to 0.3 s lag time. S-wave polarizations from local events from 60 to 106 km depth
were utilized to map the seismic anisotropy of the overlying plate and a small portion of the overlying mantle wedge. $S$-wave splitting results (Fig. 4) show mostly weak overlying crustal anisotropy with a fast direction that is trench-parallel with a mean delay time of about 0.2 s. We did not find any significant depth dependence in the delay times. The lack of depth dependence in local $S$-wave delay times together with the alignment of the fast direction polarizations with the major faults on the southern Jalisco block makes it plausible that the origin of the anisotropy resides in the continental crust. Our interpretation is consistent with the general idea that crustal anisotropy is caused by stress-aligned fluid-saturated microcracks in the upper 15 km of the crust (Crampin & Peacock 2008). The lack of seismicity deeper than 106 km prevented us from mapping the anisotropy properties throughout the mantle wedge. In contrast, to the local $S$ data, splitting parameters of $SKS$ phases in the central and southern Jalisco Block show trench-normal fast splitting directions with delay times of about 1.0 s. Thus at least 0.8 s of delay time must come from anisotropy in the slab and subslab mantle which would be the case for two anisotropic layers with parallel fast polarizations (for those stations further away from the trench) In the other extreme case, for layers with a perpendicular fast orientation (stations on the forearc), the $SKS$ splitting times would imply a delay time of 1.2 s through the slab and underlying mantle. During mantle flow at the East Pacific ridges, viscous shear deformation imparts a structural fabric that remains in the lithosphere as it cools, preserving an fossilized anisotropic fabric. (e.g. Nicolas & Christensen 1987). Near the ridge the A-type crystal-preferred orientation is perpendicular to the ridge, while away from the ridge it is perpendicular to the magnetic lineation. Based on plate reconstructions the part of the Rivera Plate (DeMets & Traylen 2000) that lies beneath the Jalisco Block is about 8 Ma and lithosphere fast anisotropy direction should be approximately trench-normal. An 8 Ma oceanic lithosphere has a thickness of $\sim$35 km. Assuming the averaged anisotropy of the slab is 2–4 per cent in the downdip direction and the slab dip is 42° as measured from the seismicity in the Benioff zone, the slab anisotropy would only account for $\sim$0.15–0.3 s of the observed $SKS$ delay time. Therefore, the primary contribution (60–80 per cent) of $SKS$ seismic anisotropy beneath the central and southern Jalisco Block originates in the entrained subslab mantle as illustrated in Fig. 5. The subslab-entrained flow below the Rivera Plate would produce trench-normal fast $SKS$ direction as well as a fast direction pattern that is collinear with the convergence direction between the Rivera Plate and Jalisco Block (Figs 1 and 3). In most subduction complexes, trench-parallel subslab anisotropy is observed with the exception of the Cascadia subduction zone (Long & Silver 2008, 2009). They argued that Cascadia is a young subduction zone where the asthenosphere channel is not well developed yet and slab-entrained flow accompanies the subduction process. Since the Rivera Plate also involves oceanic lithosphere less than 10 Ma, the observed trench-normal fast direction is consistent with subslab mantle flow in a young and narrow ($\sim$400 km) subduction zone. Schellart (2004) demonstrated that poloidal flow occurred in the mantle wedge and beneath the slab. This flow results from shearing between the sinking slab and the mantle due to a slab-dip parallel component of displacement. The entrained mantle is just a part of the poloidal flow.

In the backarc of the Rivera subduction zone, above the mantle wedge, $SKS$ splitting beneath station 47 and adjacent stations...
shows predominantly subduction-parallel fast direction, which is consistent with a simple 2-D corner flow regime, which is a result of shear coupling between the downgoing slab and the overlying mantle wedge. However, stations 42 and 43 above the western Rivera backarc show subduction-oblique fast directions. SKS splitting fast directions (stations CJIG, 37 and 55) show a semi-circular pattern around the western edge of the Rivera slab (Figs 3 and 5). The pattern of fast split SKS phases indicates that the flow of subslab mantle beneath the forearc is forced around the edge of the slab as the Rivera Plate rolled back (Fig. 5). The perspective view illustrates that the rollback induced flow is not strictly toroidal because the rotation axis of the flow cell is tilted from vertical (Schellart 2004). We suggest that 3-D toroidal flows around the northwestern edge of the Rivera slab are complicating the 2-D corner flow as well as 3-D toroidal flows around the northwestern edge of the Rivera plate (Fig. 5). Toroidal flow through the gap between the Rivera and Cocos Plate is also revealed by the curved pattern of fast split SKS waves. Geologic and seismic data indicate that the subducting Rivera and Cocos slabs not only move in a downdip slab-parallel direction, but also in a slab-perpendicular backward direction. Mantle flow induced by such a subduction process is predominantly responsible for the observed seismic anisotropy, the formation and migration of melt, volcanic production, seismic hazard and tectonic processes on the western edge of the North American Plate.

CONCLUSION

We have presented shear wave splitting results from the Rivera and adjacent Cocos subduction zones. The seismic anisotropy measurements, mainly trench-normal fast directions, confirm that in the middle of the Rivera Plate poloidal flow occurs in the mantle wedge and underneath the slab. These flows result from shearing between the downgoing Rivera slab and the surrounding mantle. On the western edge of the Rivera Plate, the SKS fast directions show a circular pattern and the observed LPO induced seismic anisotropy is associated with 3-D toroidal flow (Fig. 5). Toroidal flow through the gap between the Rivera and Cocos Plate is also revealed by the curved pattern of fast split SKS waves. Geologic and seismic data indicate that the subducting Rivera and Cocos slabs not only move in a downdip slab-parallel direction, but also in a slab-perpendicular backward direction. Mantle flow induced by such a subduction process is predominantly responsible for the observed seismic anisotropy, the formation and migration of melt, volcanic production, seismic hazard and tectonic processes on the western edge of the North American Plate.

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longitude 167.799° E, at a depth of 140 km and magnitude 6.0. The backazimuth was 254.66° and a distance of 93.67°. The splitting parameters are: $\phi = 12^\circ \pm 8^\circ$ and $\delta t = 1.1 \pm 0.2$ s. The figure shows the seismogram with the corresponding particle motion to the right. (a) original radial and tangential components; (b) components rotated to the fast and slow coordinate system; (c) fast and shifted slow components and (d) radial and tangential components with splitting removed.

Figure S2. Example of a local S wave recorded by station 47 from an event occurred on event 295, 2006, at latitude 19.396° N, longitude 103.584° E, at a depth of 90.3 km and magnitude 1.8. The backazimuth was 140.03° and the distance 0.404°. The splitting parameters are: $\phi = 41^\circ \pm 18^\circ$ and $\delta t = 0.28 \pm 0.03$ s. The figure shows the seismogram with the corresponding particle motion to the right. (a) fast and slow components and (b) corrected components with splitting removed.

Table S1. SKS event list.
Table S2. Local S event list.
Table 3. SKS Splitting parameters for MARS stations.
Table 4. S splitting parameters for MARS stations.

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