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SKS splitting beneath southern California

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Abstract. Measurements of SKS phase splitting were obtained from nineteen seismic stations in southern California. The fast polarization directions are 53° at the southern end of the Great Valley, $82 \pm 8°$ in the western Transverse Ranges and northern Peninsular Ranges, $95 \pm 4°$ in Mojave Desert, and 70° on San Clemente Island. The splitting time ranges from 0.8 to 1.8 seconds, which is consistent with an anisotropic layer of 100 to 200 km thick for 4% anisotropy.

Introduction

SKS splitting is most effective for studying upper mantle anisotropy beneath the receivers [*Kind et al*, 1985; *Silver and Chan*, 1988, 1991]. The shear wave splitting parameters consist of the polarization direction of the fast component ϕ and arrival time difference between the fast and slow components δt. The main cause for SKS splitting in the upper mantle is the preferred orientation of crystallographic axes of elastically anisotropic minerals [*Savage et al.*, 1990a; *Silver and Chan*, 1988, 1991; *Chastel et al.*, 1993]. Olivine is the most abundant and is highly anisotropic; the fast direction is along the crystallographic a–axis. Under uniaxial compression, the a–axis aligns perpendicular to the maximum compressional strain; under pure shear, it is perpendicular to the shortening direction; and under progressive simple shear, it is aligned along the flow direction.

We report measurements of SKS splitting for 19 seismic stations in southern California. The study area (Figure 1) includes the southernmost part of the Great Valley, western Transverse Ranges, Mojave Desert, and northern Peninsular Ranges. For station LAC, *Savage and Silver* [1993] used SKS and S phases from 17 events, to obtain $(\phi, \delta t) = (103 \pm 4°, 1.35 \pm 0.1\text{s})$. They explained the splitting parameters assuming a two-layer model; with $(\phi_1, \delta t_1) = (60°, 0.6s)$ for the lower layer, and $(\phi_2, \delta t_2) = (110°, 0.8s)$ for the upper layer. They observed an E-W fast feature at stations in northern and central California and Nevada and suggested this might have been generated by differential motion associated with asthenospheric flow created by the northward motion of the trailing edge of the Farallon plate. Such a flow could generate a shear zone that orients olivines E-W; this feature might extend south of the area because the Farallon plate has passed beneath southern California during the last 20 Ma. Our measurements are mostly consistent with their prediction.

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Data, Method, and Results

Twelve of the nineteen stations used are broadband TERRAscope stations and the rest are short period stations from the Southern California Seismographic Network (SCSN). Strong SKS arrivals from 37 events were recorded by at least one of the stations during the period from January 1991 to June 1994. The events chosen have $m_b \geq 5.6$ and epicentral distances between 84° and 120° from the center of the study area. Except CAL, all the broadband stations have 3 or more consistent measurements; the short period stations have one or two measurements. The broadband seismograms were bandpass filtered with corner frequencies 0.05 and 0.8 Hz, and the short period ones were low-pass filtered with corner frequency 2.0 Hz.

The optimal polarization parameters are those that most successfully remove the splitting. When more than one measurement is available, a weighted mean is obtained using the optimal parameter and the estimated uncertainties of the individual measurements [*Savage et al.*, 1990a; *Silver and Chan*, 1991]. Figure 2 shows seismograms and the particle motion patterns before and after removal of effects of splitting.

Figure 1 shows the SKS splitting in southern California. Station data and weighted means are listed in Table 1. Of the 101 measurements, about 60 have errors ranging from 0.3 to 0.5s for δt, and 10° to 20° for ϕ. The fast directions range from 53° to 99°. The simple mean for all the stations is $(\phi, \delta t) = (83 \pm 12°, 1.2 \pm 0.2\text{s})$.

Although the fast directions are mostly E-W, some consistent spatial variations can be observed. For instance, the simple mean for the 14 stations on the west side of the San Andreas Fault (SAF) is $(81 \pm 8°, 1.2 \pm 0.2\text{s})$, and for the 5 stations in the Mojave Desert is $(97 \pm 5°, 1.1 \pm 0.2\text{s})$. The 16° difference between the mean fast directions is twice the typical errors (Table 1) and may be considered significant. The three stations in the Los Angeles Basin (GSA, PAS, and USC) show almost identical fast directions. The difference between the mean ϕ of these three stations and that of the stations in the Mojave Desert is more than 20°.

Recently, *Savage and Silver* [1993] presented a method to invert the parameters for two anisotropic layers using the splitting parameters obtained under the assumption of a single layer. We fit the measurements using their two-layer model at three stations(GSC, PAS, and PFO) (see Figure 3 for station PFO), and found that the extra

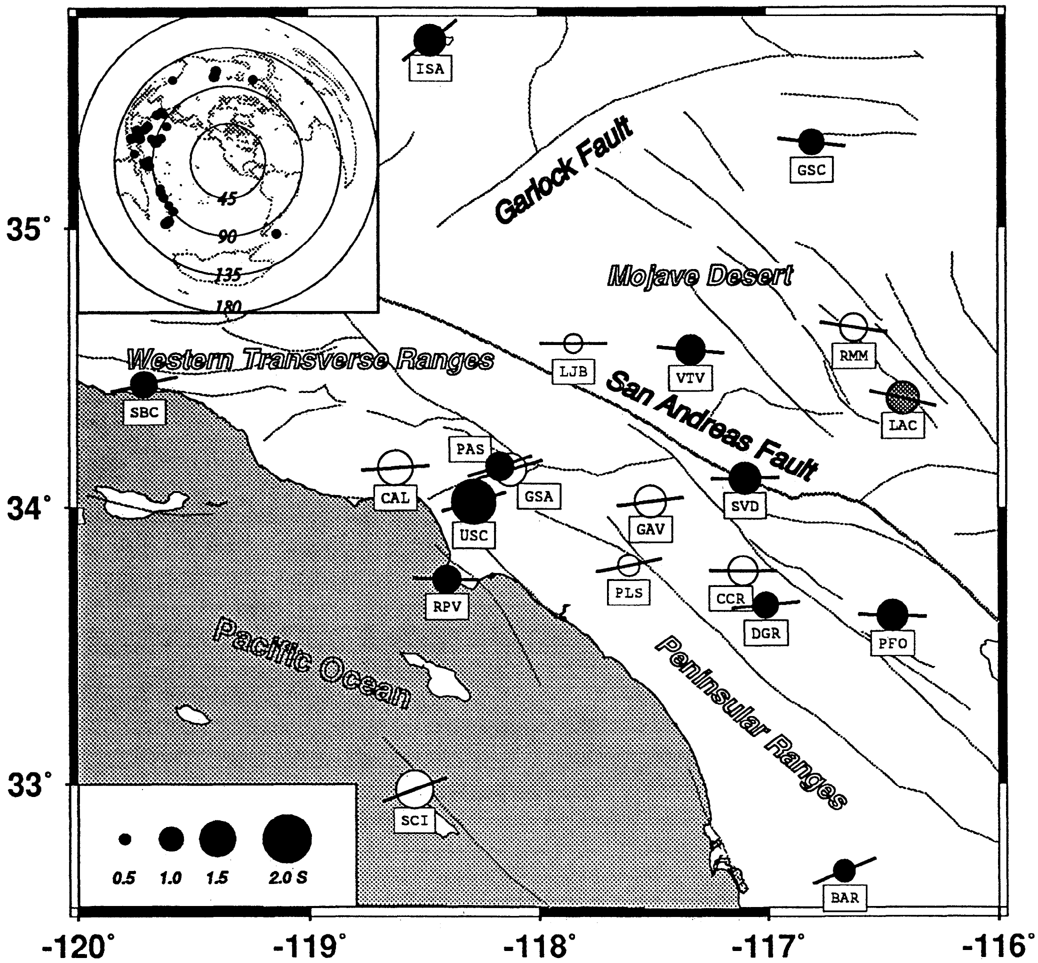

Figure 1. Map showing splitting and fast polarization direction of SKS phases in southern California. The size of the dots is related to the size of the travel time difference between the fast and slow SKS arrivals; the orientation of the bars represents the fast polarization direction. Dark dots represent stations with three or more consistent measurements, and bright dots are those with one or two measurements. Results for LAC (grey dot) are by *Savage and Silver* [1993]. The upper left insert (azimuthal equidistant projection) shows epicenters and their distances from the center of the study area.

parameters were not justified according to the F-test. The values obtained for the lower layer are $(\phi_1, \delta t_1) = (74 \pm 6.4°, 0.43 \pm 0.13s)$, $(84 \pm 5.8°, 0.44 \pm 0.14s)$, and $(79 \pm 4.5°, 0.51 \pm 0.14s)$, for station GSC, PAS, and PFO, respectively; and for the upper layer are $(\phi_2, \delta t_2) = (101 \pm 3.9°, 0.60 \pm 0.15s)$, $(96 \pm 3.1°, 0.65 \pm 0.16s)$, and $(98 \pm 3.0°, 0.70 \pm 0.15s)$. At PAS, the difference between the fast directions of the upper and lower layers is 12° , which is smaller than most of the errors from individual measurements and indicates that a one-layer model is sufficient to interpret the data. We will assume that the observed splitting is due to one anisotropic layer, or due to multiple layers with similar fast directions.

Discussion

We assume that the SKS splitting (1) reflects strain in the upper mantle; (2) is an integrated effect over all the ray path from the CMB to the surface, unless the depth is constrained by other data; and (3) represents an integrated effect over geological time.

For southern California, the crust contributes a negligible portion to the anisotropy for the following reasons: 1) the time separation δt ranges from 0.8 to 1.8s, which implies a layer of 100 to 200 km thick for 4% anisotropy, a value thought typical for sheared mantle rocks, [most studies of crustal anisotropy suggest measurements of δt less than 0.1 to 0.3 s, e.g. *Savage et al.*, 1990b; *Li et al.*, 1994]. 2) The fast direction obtained from shear wave splitting using local crustal events is usually parallel to surface fracture directions [*Savage et al.*,,1990b; *Li et al.*, 1994]. Therefore the source of the SKS anisotropy is likely to be in the mantle. The thickness of the lithosphere here is about 80 km [*Humphreys and Hager*, 1990], the sub-crustal part of this together with about 100 km of sub-lithosphere upper mantle contributes to the splitting.

The E-W fast feature may be related to the passage of the trailing edge of the Farallon plate as it moved northward over the last 20 Ma [*Savage and Silver*, 1993]. Although our measurements support this interpretation in general, some other aspects of the data must be ex-

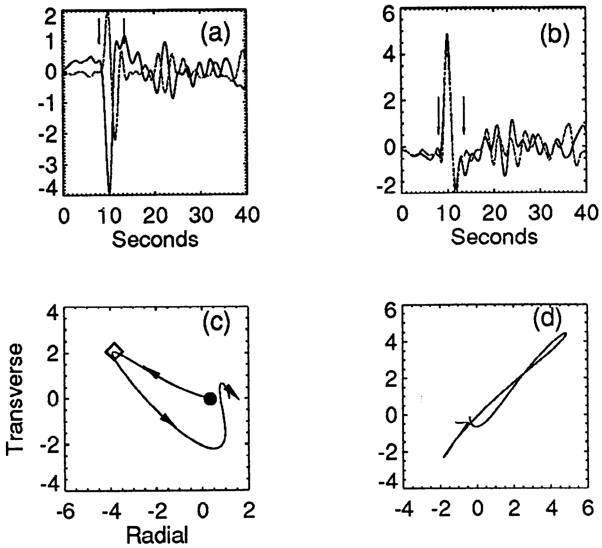

Figure 2. Example SKS arrivals on the original and corrected radial and transverse components and their particle motions for station VTV for event 1993-138(May 18):10:19. The seismograms on the left are the original radial (solid line) and transverse (dotted line) components, and on the right are corrected seismograms by removing the anisotropy. The particle motions are plotted using the parts of the seismograms between the two arrows. On the polarization diagrams of the original seismograms, the arrival of the fast wave is labeled by a dot and that of the slow wave by a diamond.

plained. The first is the fast directions at the two stations at the northern and southern ends of the study area (ISA and BAR). These are more NE-SW than those in the central part. More measurements in central California and Mexico are needed to judge whether the E-W fast feature in southern California is connected to those observed in the Basin and Range province, or is a localized feature. The second is the subtle yet consistent difference between the fast directions on the eastern and western side of the SAF. The trailing edge of the Farallon plate should have created the same fast feature on both sides, unless the anisotropy has been disturbed by some later effects.

Another cause of the E-W fast feature might be it is related to the recently documented late Cenozoic N-S contraction in southern California. (1) geological mapping reveals the entire Mojave Desert may have experienced substantial late Cenozoic N-S contraction [*Bartley et al.*, 1990], the structures of early Miocene and younger rocks generally trending E-W; (2) in the western transverse ranges, Cenozoic N-S shortening is significant along E-W faults such as the Santa Monica fault [*Wright*, 1991]; and (3) a curtain-like high-velocity anomaly beneath the Transverse Ranges was resolved using high-resolution seismic imaging [*Humphreys and Clayton*, 1990]. The vertical extension of the anomaly is about 250 km and was thought as being formed by N-S convergence and sinking of the entire thickness of the subcrustal lithosphere [*Humphreys and Hager*, 1990].

If the NW-SE shear strain related to the SAF is dominant, the observed fast direction would be parallel to the faults as observed in the San Francisco Bay area [*Savage and Silver*, 1993]. In the Mojave block, the total slip across major NW-SE dextral faults is estimated to be 27 to 38 km [*Dokka*, 1983] and the bulk shear strain 0.24 to 0.33 [*Garfunkel*, 1974]. Since the observed fast directions are mostly E-W rather than NW-SE, the strain related to the N-S contraction must be much larger than the present NW-SE bulk shear strain.

The observed fast direction at ISA is perpendicular to the axis of the Great Valley and may be related to the formation of the Valley. It is also consistent with the modern absolute plate motion direction [*Minster and Jordan*, 1978]. More measurements are needed to distinguish between the two possibilities.

We have measured SKS splitting beneath 19 stations in southern California and found that the area is highly anisotropic with fast polarization directions nearly E-W. The observed splitting can be explained by a layer of 100 to 200 km thick with 4% anisotropy. The E-W fast direction could be related to E-W extension and flow associated with the northward movement of the trailing edge of the Farallon plate, or to late Cenozoic N-S contraction.

Table 1. SKS Splitting of Southern California

Station Name	ϕ (Deg.)	δt (Sec.)	Coordinates Lat.	Coordinates Long.	$n^{\star}$
BAR†	68±6	0.9±0.1	32.680	-116.672	4
CAL†	86±17	1.4±0.6	34.143	-118.628	2
CCR‡	90±13	1.2±0.4	33.776	-117.106	1
DGR†	85±10	1.0±0.2	33.650	-117.009	3
GAV‡	83±13	1.3±0.4	34.022	-117.512	1
GSA‡	75±7	1.3±0.1	34.137	-118.127	2
GSC†	97±2	1.0±0.1	35.302	-116.805	23
ISA†	53±4	1.3±0.2	35.663	-118.473	6
LJB‡	90±11	0.8±0.3	34.591	-117.848	1
PAS†	72±4	1.2±0.1	34.149	-118.172	12
PFO†	92±2	1.2±0.1	33.612	-116.459	18
PLS‡	79±7	0.9±0.2	33.796	-117.608	2
RMM‡	99±9	1.1±0.3	34.643	-116.624	2
RPV†	92±6	1.2±0.2	33.744	-118.404	5
SBC†	77±9	1.1±0.2	34.442	-119.713	4
SCI‡	70±7	1.5±0.2	32.980	-118.547	2
SVD†	89±4	1.3±0.1	34.105	-117.098	6
USC†	74±5	1.8±0.2	34.019	-118.285	3
VTV†	95±2	1.2±0.1	34.567	-117.333	4

* Number of events
† TERRAscope broadband stations
‡ SCSN short period stations

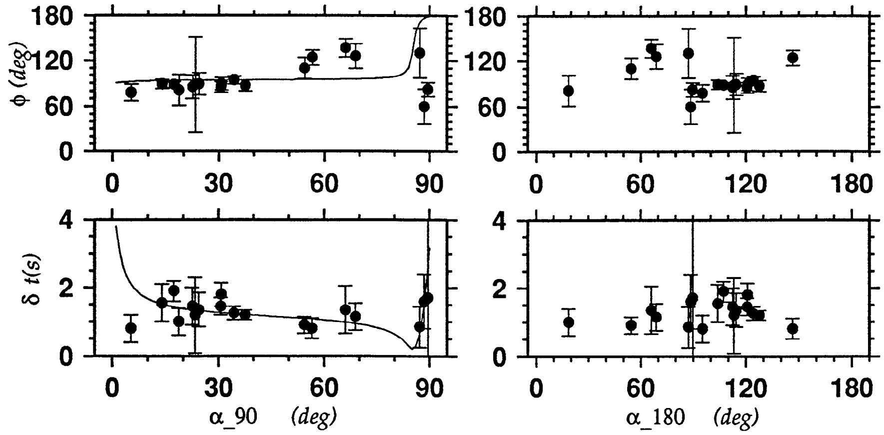

Figure 3. Diagrams showing individual measurements with errors of ϕ and δt as functions of incoming azimuth α modulo 90° (left diagrams) and α modulo 180° (right diagrams) for station PFO. The solid curves on the left diagrams were calculated using best-fit parameters from a two-layer model.

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