Crustal anisotropy in southern California from local earthquake data

Hanneke Paulssen

Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

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[1] Shear wave splitting measurements were made for local earthquakes in southern California at incidence angles larger than the critical incidence angle. For the region of San Bernardino Mountains, the fast polarization directions vary strongly, but are consistently fast for directions roughly perpendicular to the ray paths. This observation is most readily explained by transverse isotropy with a vertical symmetry axis, and is probably associated with horizontally foliated gneisses or schists in the upper crust. Other measurements show a predominance of north-south fast directions, while some data have fast directions that are parallel to the San Andreas fault. These observations are related to azimuthal anisotropy as found in other local shear wave splitting and SKS splitting studies. The data show that, apart from the free surface effect, shear wave splitting measurements for shear waves at shallow incidence angles can have an imprint of transverse isotropy as well as azimuthal anisotropy. *INDEX TERMS:* 7203 Seismology: Body wave propagation; 7205 Seismology: Continental crust (1242); 8015 Structural Geology: Local crustal structure. **Citation:** Paulssen, H. (2004), Crustal anisotropy in southern California from local earthquake data, *Geophys. Res. Lett.*, *31*, L01601, doi:10.1029/2003GL018654.

1. Introduction

[2] Shear wave splitting measurements are usually made for data with near vertical incidence: there is a vast amount of studies on SKS splitting and there are many investigations of local splitting measurements for incidence angles less than 35° to 45°. The reason that these studies are confined to small incidence angles is the so-called free surface effect: an S-wave with an incidence angle larger than critical produces an inhomogeneous P-wave with an associated phase change on the radial and vertical component. The resulting non-linear particle motion hampers an unambiguous interpretation of shear wave splitting caused by anisotropy along the ray path. This free surface effect is well known [*Nuttli*, 1961; *Aki and Richards*, 1980] and was examined in detail by *Booth and Crampin* [1985] for small epicentral distances.

[3] A severe limitation of near-vertical incidence is that shear wave splitting measurements are indicative only of azimuthal anisotropy. Transverse isotropy with a vertical symmetry axis will not produce shear wave splitting because the symmetry axis and the direction of wave propagation are parallel. Yet, there probably is ample crustal transverse isotropy due to fine scale layering, horizontal foliation or preferred mineral orientation.

[4] In this study, I analyzed shear wave polarizations of data in southern California to investigate whether transverse isotropy with a vertical symmetry axis can be determined from local seismograms with shallow incidence angles.

2. Data Analysis

[5] I selected broadband data of the Caltech Regional Seismic Network sampled at 100 Hz for local earthquakes with epicentral distances smaller than 200 km, and magnitudes larger than 4, in the time span from 1998 to 2002[1]. The magnitude threshold of 4 was set as a requirement for a good signal-to-noise ratio for a large number of stations. The study focussed on stations close to the San Andreas fault because of the high seismicity in this area. Seismograms with good quality S-arrivals for stations BLA, BBR, DEV, EDW, HEC, SBPX, SVD, TA2, VCS, and VTV were further analyzed. The cleanest data were obtained for seismograms with distances smaller than 60 km, where Sg arrives as a single arrival and there is no interference with other more deeply bottoming S-waves. A first inspection revealed that many seismograms had an apparently early S arrival on the tangential component, and most seismograms showed a non-linear particle motion. The data were then analyzed using particle motion diagrams, where the polarization direction of the first onset in the horizontal plane was determined. After coordinate rotation to this fast polarization direction and its perpendicular slow direction, the time difference between the arrivals on the fast and slow components was measured. After correction for this time difference, the waveforms were plotted on top of each other to confirm a good correlation and linearity of the particle motion. Uncertainties in the fast polarization direction and time difference were estimated to be less than 20° and 0.05 s, respectively.

[6] Since the analysis relies on the particle motion in the horizontal plane, I discarded data where the vertical component showed a significant signal at the time of the first arriving S-wave. Not many data were rejected for this reason, as the biggest amplitudes were usually observed in the horizontal plane. However, splitting measurements could only be made for a small fraction of the data. Many data were rejected because of emergent S-wave onsets. This was often the case for distances larger than 100 km. Other data showed a low amplitude S-wave signal on the radial component, thus inhibiting a splitting measurement. Lastly, for some of the data the travel time difference was ambiguous, having an uncertainty of half a cycle between the two components. In total 54 measurements were made on good quality data.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL018654.

0094-8276/04/2003GL018654$05.00

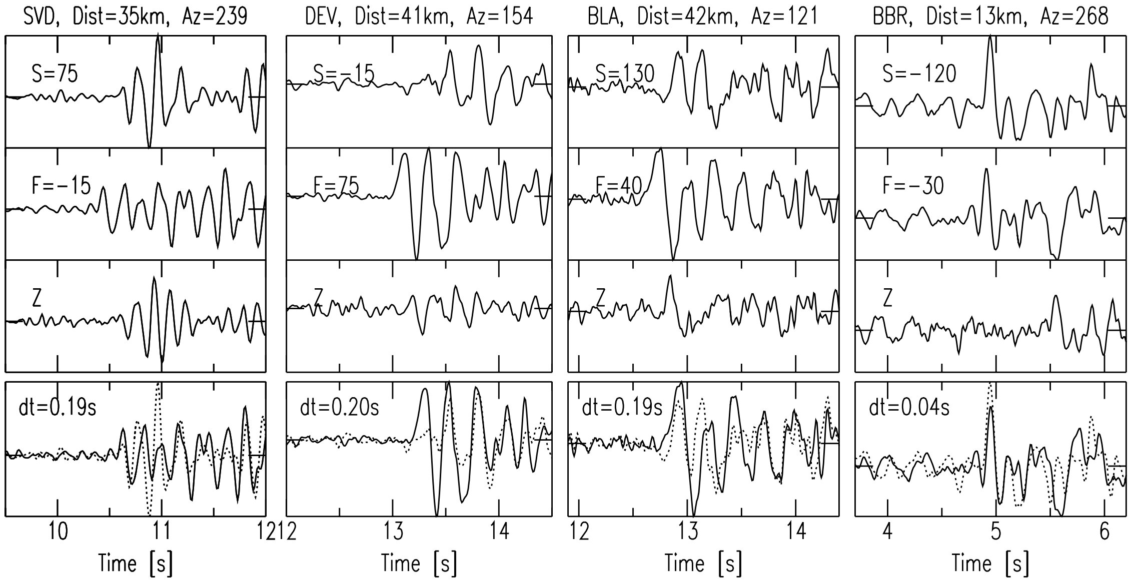

Figure 1. Shear wave arrivals of a magnitude 4.1 event on Dec 2, 2000 (8:28:07.4, 34.267N 116.775E, 3 km depth) recorded by stations SVD, DEV, BLA, and BBR. Epicentral distance and source azimuth are indicated at the top. Top three panels show the slow (S), fast (F), and vertical (Z) components; the azimuths of F and S are indicated. Lowest panel shows S (dashed) and F with a delay of dt (solid).

[7] Figure 1 shows the data for an event near San Bernadino Mountains on Dec. 2, 2000, recorded by stations SVD, DEV, BLA, and BBR. The top three panels show the slow (S), fast (F), and vertical (Z) components, and the lowest panel shows the slow component (dashed) together with the fast component (solid) delayed by the indicated time difference. Note that the fast polarization directions vary strongly from seismogram to seismogram over a small distance (<60 km). The time differences for the first three stations with an epicentral distance of roughly 40 km is approximately 0.2 s. Since this is more than half the dominant period of most of the data (T 0.3 s), the time difference cannot be explained by a phase change from the free surface effect, and must be attributed to another cause.

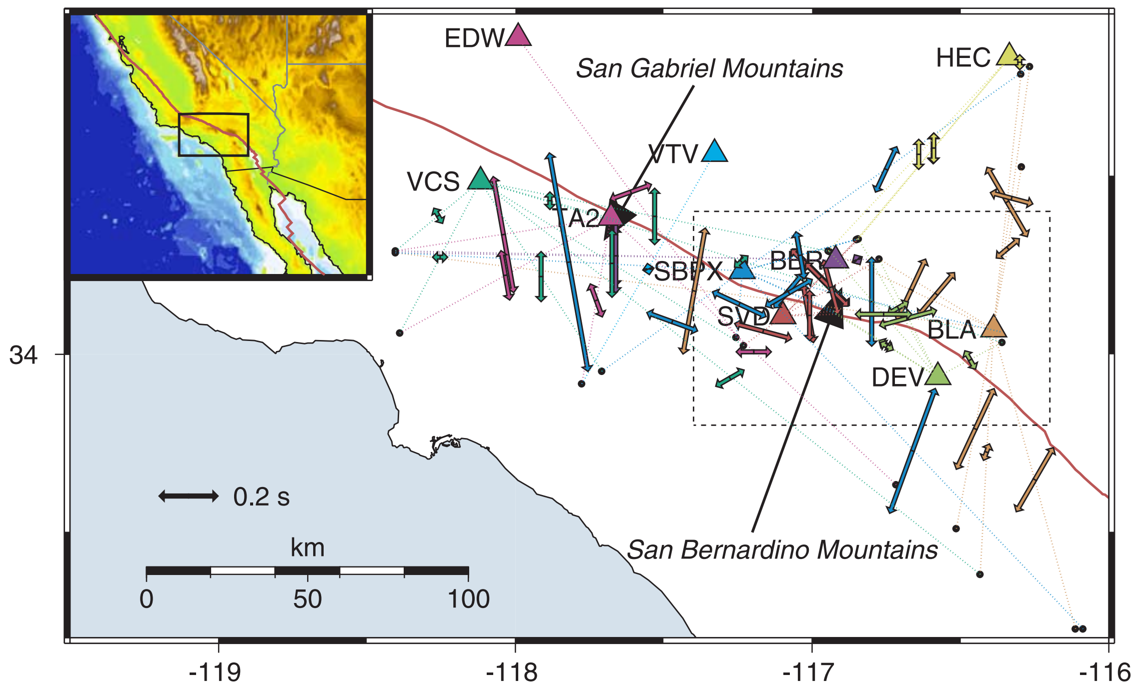

Figure 2. Shear wave splitting measurements (arrows) in the color of the recorded stations plotted midway between epicenters (small black dots) and stations (colored triangles). The raypaths are indicated by dotted colored lines. The thick red line represents the San Andreas Fault. The dashed box shows the area of San Bernardino Mountains of Figure 3. The inset shows an enlarged area with the location of the figure.

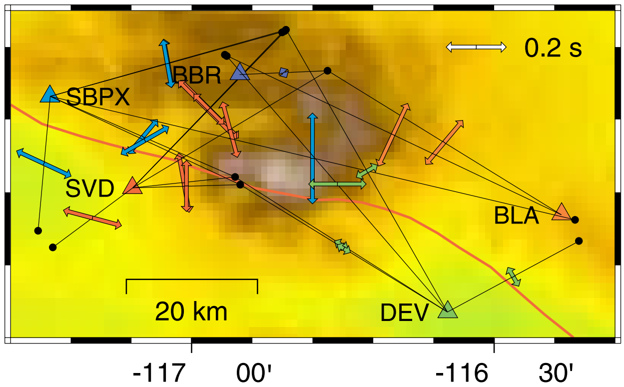

Figure 3. Shear wave splitting measurements for the region of San Bernardino Mountains with topography. See Figure 2 for further explanation.

[8] Figure 2 shows the results for all 54 measurements. It is obvious that there is not a very consistent pattern of fast directions over the entire area, although there are a few regions with more or less consistent measurements. In the area of San Bernardino Mountains, the fast directions appear to be randomly oriented. Figure 3 zooms in on this region, and shows that closely spaced earthquakes produce similar measurements. Furthermore, this figure shows that the measurements are not random, but that most of the fast directions are roughly perpendicular to the raypaths. This implies that the SH polarization is consistently leading SV particle motion. These data cannot be explained by the free surface effect because (1) the time difference is too large for a phase shift, and (2) the inhomogeneous P-wave would arrive prior to the S-wave, producing an early 'P-SV' motion rather than an early SH particle motion as is observed here [see *Booth and Crampin*, 1985]. The focal mechanisms of the events are unknown, but are unlikely to have had an effect on the splitting measurements, since I was careful to select seismograms with large SH and SV amplitudes only. An explanation in terms of scattering (from SH to SV) is therefore not plausible.

3. Interpretation

[9] The data for San Bernardino Mountains must be explained by a fast shear wave speed for horizontally polarized S-waves (β_H) compared to the speed of vertically polarized S-waves (β_V). This corresponds to transverse isotropy with $\beta_H > \beta_V$, as is obtained for a horizontally layered structure with layer thicknesses much smaller than the wavelength [*Backus*, 1962]. Alternatively, the data can be explained by preferred mineral orientation. *Barruol and Mainprice* [1993], amongst others, have shown that shear wave splitting is maximum for waves propagating parallel to the foliation of the rock with the fast shear wave polarized parallel to the foliation plane. Thus, (sub)horizontally foliated rock could also explain the observations. A third explanation is the presence of microcracks: oriented microcracks often appear to be the dominant cause of seismic anisotropy in the upper crust up to a pressure of 200 MPa [e.g., *Crampin*, 1985; *Kern*, 1990].

[10] For the area of San Bernardino Mountains we find typical travel time differences of 0.2 s for epicentral distances of approximately 40 km. This corresponds to an anisotropy of roughly 1.5% when averaged over the entire raypath assuming that maximum polarization anisotropy is observed in the direction of propagation, and the value is therefore a minimum estimate. Furthermore, since the rays are bottoming at depths less than 10 km, the observations imply that the anisotropy must be present in the upper crust.

[11] Mechanisms to explain the observations are (sub)-horizontally oriented cracks or other rock fabric with a horizontal orientation. There are no deep seismic reflection or refraction lines traversing the San Bernardino Mountains, but seismic lines have been shot in the Mojave Desert [*Cheadle et al.*, 1986], across San Gabriel Mountains [*Fuis et al.*, 2001] and from San Fernando Valley through the Transverse Ranges [*Fuis et al.*, 2003] The data show bright subhorizontal crustal reflectors associated with fault zones surfacing south of the San Andreas fault, but most of them are at mid- and lower-crustal depths close to the San Andreas fault. Thus, it is not very likely that mylonitic fault zones produce the observed shear wave splitting.

[12] *McCaffree Pellerin and Christensen* [1998] measured shear wave velocities for rock samples from the Mojave Desert and San Gabriel Mountains. They showed that the upper crust is dominated by gneisses and schists and southwest of the San Andreas fault also by granitic intrusives. The gneisses and schists are strongly birefringent, in particular the Pelona schist which has a horizontal foliation in the Mojave Desert. If this material is also present in the upper crust of San Bernardino Mountains, it could easily explain the data: a 1 km thick layer produces a maximum time difference of 0.4 s between the split shear waves. Although this interpretation is not certain, the shear wave splitting measurements definitely point to a medium with transverse isotropy in the upper crust of San Bernardino Mountains.

[13] Other factors, such as azimuthal anisotropy and the free surface effect also contribute to the data. The measurements south of the San Andreas fault, for instance, show more coherent patterns that are related to the presence of azimuthal anisotropy. The north-northwesterly fast directions for the western part of Figure 2 and the northeasterly fast directions in the southeast are consistent with local shear wave splitting studies for the Los Angeles basin [*Li et al.*, 1994; *Li*, 1996] and for stations of the Anza seismic network [*Peacock et al.*, 1988; *Crampin et al.*, 1990; *Aster et al.*, 1990] that show a predominance of north-south fast directions. These data are generally interpreted by vertical microcracks in the upper crust which are aligned in the north-south direction, consistent with the local north-south direction of maximum horizontal compressive stress.

[14] A patch south-southwest of San Bernardino Mountains shows fast directions that are parallel to the San Andreas fault. There are no local splitting studies for this area, but SKS splitting measurements for stations close to the San Andreas fault indicate that these data are best explained by a layer of fault-parallel anisotropy overlying a deeper and more general layer of fast east-west polarization [*Özalaybey and Savage*, 1995; *Polet and Kanamori*, 2002]. Such an upper layer with a fault parallel fast polarization direction is consistent with the measurements close to station SVD (indicated by the red triangle in Figures 2 and 3), and suggests that the measurements

presented here are best explained by a combination of azimuthal anisotropy and transverse isotropy.

4. Conclusions

[15] Shear wave splitting measurements were made for local S-waves with large incidence angles. It was shown that the large variations in the fast polarization direction for San Bernardino Mountains can be explained by transverse isotropy with a fast shear wave speed for horizontally polarized S-waves (β_H). However, azimuthal anisotropy also contributes to the data as is evident from the other measurements. Thus, it is concluded that both types of anisotropy contribute to the data, and that both types of anisotropy can be investigated using local shear waves with incidence angles outside the 'shear wave window'. The free surface effect also gives a contribution, but this effect is smaller than the time differences observed here, which are often of the order of half a wavelength.

[16] The observations imply that one has to be careful to interpret the local shear wave measurements solely in terms of azimuthal anisotropy or transverse isotropy. A study by *Park et al.* [2002, Figure 8] shows shear wave splitting observations from local S-waves for 2 stations above the Kamchatka subduction zone. The time differences are of the same order as observed here, and the pattern of fast directions seems inconsistent at first sight, but is easily explained by a combination of strike parallel azimuthal anisotropy and transverse isotropy. In general, it will be difficult to unravel the relative contributions of both types of anisotropy, but this study has shown that shear wave splitting measurements obtained for shallow incidence angles provide information about the orientation of the minerals or rock fabric that may not easily be obtained otherwise.

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H. Paulssen, Department of Earth Sciences, Utrecht University, P.O. Box 80021, 3508TA Utrecht, The Netherlands. (paulssen@geo.uu.nl)