Earthquake and Seismicity Research Using TERRAscope

USGS Award No.: 1434-HQ-97-GR-02989

Final Technical Report

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Program Element: I.1

Key Words: Geophysics, Seismology, Wave Propagation

Abstract

We have determined the crustal thickness (depth to Moho) in southern California using the crustal receiver function method. We obtained an average crustal thickness of 29 ± 4 km. A thicker crust is found under the eastern Transverse Ranges, southern Sierra Nevada, and the Peninsular Range, while a thinner crust is found beneath the Salton Trough and offshore of the Los Angeles Basin.

We have determined shear wave splitting patterns for the western United States. We found that the overall pattern of fast directions agrees very well with that of the *Pn* anisotropy model. In general, the measured fast direction is orthogonal to the maximum horizontal compressive stress direction. This suggests that the pattern of anisotropy is generally uniform in the crust and lithospheric mantle, in a layer with an overall thickness of 100 to 150 km, as estimated from the *SKS* delay times. This implies that this upper mantle layer has experienced a similar stress condition and deformational history. The alignment of most fast directions can be explained by plate-tectonic, extensional and compressional events.

We have determined the site amplifications for the sites where we have digital seismic stations in southern California. The amplitude data (displacement) are band-pass filtered into three channels with frequency bands of 0.233 to 0.433 Hz (3.0 sec band), 0.7 to 1.3 Hz (1.0 sec band) and 2.0 to 4.0 Hz (0.3 sec band), and we determined the amplification factors using the events with M_L 4 which occurred during the period from 1995 to 1998. At 3 sec, the contrast between "hard rock" site and "soft rock" site is striking. The amplification factor varies by a factor of about 3, on the

average, between "hard rock" and "soft rock" sites. At 0.3 sec, it appears that even a thin surficial layer of soft material (e.g. weathered layer) is effective for amplification. The map for 1.0 sec exhibits an intermediate character.

Research

1. Determination of Crustal Thickness in Southern California Using the Receiver Functions Method

An effective technique for estimating crustal thickness is to use teleseismic receiver function. Due to the large velocity contrast across the Moho discontinuity, part of the teleseismic *P* wave energy converts to *SV* wave at the bottom of crust beneath the recording station. By measuring the time separation between the direct *P* arrival and the converted phase, the crustal thickness can be estimated. We determined the crustal thickness in southern California using this method and show the result as a map of Moho depth variation.

Wave form records of 347 teleseismic earthquakes recorded by southern California digital stations are retrieved from the data archive of the Southern California Data Center (SCEC-DC) at the Seismological Laboratory of Caltech. The actual number of events for individual stations varies from 10 to 230, depending on the length of recording period of the station. The events are selected from the global earthquakes during 1993 to 1998 with magnitudes larger than 5.5 and located in the distance range between 30° and 95° from the center of the network.

We used a time window of 150 s in length, starting 30 s before the *P* onset. The two horizontal components are rotated to the radial and tangential directions which are then deconvolved with the vertical component using the time-domain deconvolution algorithm.

We obtained an average crustal thickness of 29 ± 4 km. A thicker crust is found under the eastern Transverse Ranges, southern Sierra Nevada, and the Peninsular Range, while a thinner crust is found beneath the Salton Trough and offshore of the Los Angeles Basin. The result is summarized in a map shown in Figure 1-1.

2. Anisotropy Beneath California

Shear wave splitting determined from teleseismic *SKS* waves provides important information that can be used to examine seismic anisotropy and the related history of deformation of the strain field. Measurements of anisotropy are one of the few tools available to seismology that can tell us about the current or past dynamics of the deeper Earth, especially its upper mantle (Kind et al., 1985; Silver and Chan, 1991).

Our interest is in the lithospheric (and asthenospheric) pattern of anisotropy and its relation to the shallow and surfacial measurements of stress that have been performed over recent years. This study re-examined earlier work by Savage and Silver (1993), Ozalaybey and Savage (1995) and Liu et al. (1995), and added many more stations and more data at stations used in those papers. We also investigate lateral variations of anisotropy, as well as vertical variations (e.g., two anisotropic layer models). The previous studies found evidence for alignment of the fast direction of anisotropy in a direction parallel to the San Andreas fault (SAF-parallel anisotropy) in the crust and upper mantle, as well as a deeper EW oriented fast direction (EW-fast anisotropy). This feature was interpreted as the asthenospheric flow in the slabless window left behind the Farallon plate.

Method and Data

The method we used for measuring the anisotropic parameters of fast polarization direction and delay time has been described in detail in Silver and Chan (1991). Our data set consists of TriNet, Anza, Berkeley and United States Seismic Network broad-band recordings of *SKS* and *SKKS* phases, mainly from deep events along the western Pacific rim. Previous authors (Savage and Silver, 1993; Ozalaybey and Savage, 1995; Liu et al., 1995) have examined a small subset of this data. We have re-analyzed (and re-interpreted) some of these data, and added a substantial new data-set, consisting of more events and newly installed stations. The combined stations of these four networks form a dense seismic array that is ideally suited for the investigation of lateral variations of anisotropy. Also, this large data-set provides convincing evidence for the interpretation of shear wave splitting as being caused by anisotropy and not lateral structural inhomogeneities, if consistent splitting parameters are found over a wide geographic area.

To illustrate the quality and coverage of the data, Figures 2-1(a) and (b) show the transverse component of the data collected for a recent (September 1997) deep event near Fiji, before and after correction for anisotropy, using our measurements of fast direction and delay time. These traces were filtered with a very broad-band Butterworth band-pass filter between 1 and 100 sec to eliminate the long-period noise present in the records of some stations.

Interpretation

In Figure 2-2 we first plot all determined fast directions and delay times for the western U.S. The delay times are indicated by the length of the arrows and the fast direction by the direction of the arrows. In general, these results are consistent for almost all stations.

In the southern California region west of the San Andreas, all stations show a consistent EW fast direction, with delay times varying between 1 and 1.5 seconds. This range of delay times implies a layer of anisotropic material of

100 to 150 km thick with 4% anisotropy, a value thought typical for sheared mantle rock. A small crustal contribution may be included; studies of crustal anisotropy in this region suggest delay times smaller than 0.1 to 0.3 sec (Li et al., 1994).

To investigate the relationship between these anisotropic splitting parameters and the crust further, we show in Figure 2-2 the maximum compressive stress directions from the World Stress Map (1997). These directions were determined mostly from borehole break-outs and crustal focal mechanisms, and thus give an indication of the very shallow, crustal stress regime in the area. We only used those measurements which were given an A or B quality rating. Many studies of transpressional collision zones have found that the measured fast splitting direction is aligned with the transpressional zone (e.g., McNamara et al. 1994; Silver et al., 1993 and see Silver, 1996, for an overview). Thus, the fast direction is orthogonal to the maximum compressive stress in these regions. Overall, we find that there is a correlation between the World Stress Map (WSM) vectors and our determined fast directions, in that most seem to be close to orthogonal to each other in the central and southern California regions. This agrees with the observations in transpressional regions described earlier, and suggests that the upper mantle deformation is consistent with the shallow stress indicators. This interpretation implies that the fast direction reflects deformation of the mechanical lithospheric mantle and thus suggests that 100-150 km of anisotropic material has experienced stress conditions coherent with the surface.

In central California we find fast directions of about N60°. The measurements for stations HOPS, BRIB, BKS, MHC, JRSC, SAO and PKD are all very consistent with each other, and show some variation with back-azimuth. Interpretation of the splitting parameters for these stations is more difficult. Previous authors have focused on the proximity of these stations to the SAF to explain these results; however, stations at similar distances from the SAF in southern California do not show this amount of complexity, suggesting that it is more likely a regional problem.

In southern California as well as the Basin and Range and the Mojave Desert, we find mostly EW directed fast direction and delay times varying between 1 and 1.5 seconds. In the case of simple shear, a mineral will align its principal slip system with the direction of shear (Ribe, 1989; Zhang and Karato, 1995), which requires the least energy. For olivine the principal slip direction coincides with the a-axis and thus also with the fast splitting direction. In the case of California and the San Andreas Fault system, this mechanism would predict alignment of the fast direction with the SAF. The measured EW fast direction thus indicates that shear at the plate boundary does not dominate the deformation in this area. This EW anisotropic orientation is perpendicular to the late Cenozoic north-south compression in southern California (Liu et al., 1995). Alternatively, this direction could be due to subduction of the Farallon plate, either because of the EW directed shear induced on the asthenosphere beneath the continent, or remnant frozen in anisotropy in the remnants of the Farallon plate under the North American plate.

The orientation of the fast direction in northern California is parallel to the northeast subduction direction of the Gorda plate, which suggests that subduction-related deformation (NE-SW directed internal shearing of the Gorda plate) is responsible for the anisotropy observed at stations YBH, WDC and ARC.

The western Nevada stations show ENE-WSW fast directions, consistent with observations made by Savage et al. (1990). This direction is inconsistent with both present-day extension (-60° to -80°) and the absolute plate motion (+55°). However, this fast direction can be interpreted as fossil anisotropy associated with pre-Miocene extension, of which the direction is about 68° (Savage et al, 1990) under the assumption that the a-axis of olivine aligns with the extension direction (Silver, 1996).

3. Determination of Frequency Dependent Ground-Motion Amplification Factors in Southern California

We have determined the site amplification factors for the sites where we have digital seismic stations in southern California. As the number of broad-band and strong-motion stations increases in southern California, we can cover a fairly large area. The amplitude data (displacement) are band-pass filtered into three channels with frequency bands of 0.233 to 0.433 Hz (3.0 sec band), 0.7 to 1.3 Hz (1.0 sec band) and 2.0 to 4.0 Hz (0.3 sec band), and we determined the amplification factors using the events with M_L 4 which occurred during the period from 1995 to 1998 shown in Figure 3-1. For some areas many events occurred at about the same location, and we used only a few selected events from these areas. For stations with both vbb (broad-band) and fba (accelerograph), only vbb channels are used, and for those with fba only, lg (low gain) channels are used. Events with $M_L<4$ are not used because lg channels are often noisy at periods longer than 3 sec for these events.

In the traditional method, the site amplification factor is determined by solving

$$a_{ij} = a_{0j} s_i r_{ij}^{-n} \exp(-k r_{ij}) \tag{1}$$

where a_{ij} is the amplitude at station i (i=1, 2, 3, ⋯, N) for event j (j=1, 2, 3, ⋯, M), r_{ij} is the hypocentral distance between station i and event j, s_i is the station amplification factor for station i, and a_{0j} is the amplitude factor for event j. The constants n and k determine the amplitude attenuation function in the form $r^{-n}\exp(-kr)$. Usually a reference station i_0 is chosen for which s_{i0} is set equal to 1. Then

$$(a_{ij} / a_{i_0 j}) = s_i (r_{ij} / r_{i_0 j})^{-n} \exp[-k(r_{ij} - r_{i_0 j})] \quad (2)$$

which is solved for k, n, and s_i (i=1,2, 3, ···, N-1). However, as the number of stations increases, the number of unknowns becomes very large (i.e. large N), and this method becomes impractical. We thus used an alternative method as follows. For event j, from equation (1), we absorb s_i in a_{ij}, and write

$$\log a_{ij} = \log a_{0j} - n \log r_{ij} + \log e(-kr_{ij}) \quad (3)$$

and determine $\log a_{0j}$, n, and k by solving a least-square problem for (3). Then, we compute the reduced amplitude by

$$a'_{ij} = a_{ij} / a_{0j} \quad (4)$$

Having computed all a'_{ij} for all the events, we re-determine n and k by solving a least-square problem for

$$\log\left(a_{ij} / a_{0j}\right) = -n \log r_{ij} + \log e(-kr_{ij}) \quad (5)$$

for the entire data set. This procedure is essentially equivalent to stacking the data for all the events with different magnitudes after normalizing the amplitudes to those with a reference magnitude. We compared the results obtained by this method with those determined by the traditional method (equation 1) for N 40, and found that both methods yield essentially the same results.

Because of the particular functional form of (1), considerable trade-off exists between n and k. The values of n and k for each frequency band, thus determined are

	n	k (km^{-1})
3.0 sec band	0.956	0.00179
1.0 sec band	0.793	0.00531
0.3 sec band	0.830	0.00852

and the distance attenuation curves (5) are shown in Figures 2, 3, and 4 for each period range. Because of the trade-off between n and k , the actual values of n and k may change as more data become available, but the trends shown in Figures 2, 3, and 4 will remain essentially the same. The amplitude for the 0.3 sec band decays rapidly with distance, as expected.

Then, for each frequency band, we determined the station amplification factors from the distribution of the amplification factors for each station; the results are shown in Figures 5, 6, 7, 8, 9, and 10. Figures 5, 7, and 9 show the results for the entire network, and Figures 6, 8, and 10 show the results for the greater Los Angeles Basin. The amplitude of the N-S component of PAS is used as a reference, and all the amplification factors are given relative to it. The results are shown for N-S component, but the pattern for E-W components is essentially the same. The solid and open circles indicate amplification and attenuation on a logarithmic scale, respectively. At 3 sec, the contrast between "hard rock" site and "soft rock" site is striking. At 0.3 sec, it appears that even a thin surficial layer of soft material (e.g. weathered layer) is effective for amplification. The map for 1.0 sec exhibits an intermediate character.

Although these amplification factors are for relatively weak motions, they provide an important baseline information for frequency dependence of site amplification factors.

Publications

Polet, J., 1998, Ph.D. Thesis, I. Seismological observations of upper mantle anisotropy
II. Source spectra of shallow subducion zone earthquakes and their tsunamigenic potential, Calif. Institute of Technology.

Zhu L. and H. Kanamori, Estimates of crustal thickness and Vp/Vs ratio of southern California using the TERRAscope/Southern California Digital Seismic Network, abstract, IRIS'97 Workshop, Berckridge, Colorado, 1997.

Non-Technical Summary

We conducted three independent research projects using the newly installed digital seismic stations in southern California. In the first project we determined the thickness of the crust in southern California using the wave forms of distant earthquakes. We found that the average crustal thickness is 29 ± 4 km. A thicker crust is found under the eastern Transverse Ranges, southern Sierra Nevada, and the Peninsular Range, while a thinner crust is found beneath the Salton Trough and offshore of the Los Angeles Basin. In the second project, we determined the pattern of crustal anisotropy (difference in wave speed in different directions) using *S* wave forms recorded at stations in California. The pattern of anisotropy thus found is generally uniform in the crust and upper mantle, in a layer with an overall thickness of 100 to 150 km. In general, the *S* wave fast direction is perpendicular to the maximum horizontal compressive stress direction determined with other methods. The results from these studies provide important information on the state of stress in southern California. In the third project, we determined the variation of wave amplification pattern in southern California. In general, seismic waves at sites located on soft rock are amplified by a factor of 3 compared with those at sites located on hard rock. However, this pattern depends on the period of the waves. The results provide important information on the spatial variation of seismic shaking during a large earthquake.

Figure 1-1.

The depth to Moho discontinuity in southern California determined with the receiver function method.

Figure 2-1.

(a, left) Record section of the original transverse components for a deep event near Fiji, recorded with TriNet. (b, right) Record section corrected for splitting due to anisotropy.

Figure 2-2.

The direction of dark lines indicates fast direction, and their lengths are proportional to delay time. The direction of maximum horizontal compressive stress is shown by white arrows.

Figure 3-1.

Epicenters of M_L 4 earthquakes in southern California (Jan. 1995 to 1998) used for the determination of the frequency dependent site amplification factors.

Figure 3-2.

Amplitude attenuation curve for the period of 3.0 sec. The amplitude is set at 0.1 at a distance of 100 km.

Figure 3-3.

Amplitude attenuation curve for the period of 1.0 sec. The amplitude is set at 0.1 at a distance of 100 km.

Figure 3-4.

Amplitude attenuation curve for the period of 0.3 sec. The amplitude is set at 0.1 at a distance of 100 km.

Figure 3-5.

Site amplification factor at the period of 3.0 sec for southern California.

Figure 3-6.

Site amplification factor at the period of 3.0 sec for greater Los Angeles basin.

Figure 3-7.

Site amplification factor at the period of 1.0 sec for southern California.

Figure 3-8.

Site amplification factor at the period of 1.0 sec for greater Los Angeles basin.

Figure 3-9.

Site amplification factor at the period of 0.3 sec for southern California.

Figure 3-10.

Site amplification factor at the period of 0.3 sec for greater Los Angeles basin.

Technical Abstract

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