A Simple Crustal Structure Satisfying Strong Ground Motion between Whittier and North Palm Springs

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Abstract

The October 1, 1987, Whittier Narrows M_L 5.9 earthquake produced a pattern of peak acceleration and intensity that showed a marked geographical asymmetry: the west and northwest regions had larger values than those to the east. A possible cause of this asymmetry was the earth's subsurface geological structure that managed to attenuate or defocus more severely the seismic waves that travelled east of Whittier than those travelling west or northwest. To investigate the subsurface S-wave structure we chose to consider a refraction profile generated by two natural sources, the Whittier Narrows earthquake and the July 8, 1986, North Palm Springs M_L 5.9 earthquake, 135 km due east of Whittier Narrows. After analyzing strong motion data from the mainshocks, high-gain vertical seismograms of aftershocks, and synthetic seismograms we conclude that the strong motion data are consistent with a simple layered medium with a Poisson ratio of approximately 0.25.

Introduction

The Whittier Narrows M_L 5.9 earthquake of October 1, 1987, occurred on an east-west striking thrust fault at a depth of 14.6 km [Hauksson and Jones, 1988]. The focal mechanism showed a pure thrust mechanism on a 25° north dipping plane. Given this mechanism for the earthquake there is no *a priori* reason that one would expect any asymmetry in the ground motion east or west of the source region. However, the peak accelerations [Brady et al., 1988; Shakal et al., 1988; Trifunac, 1988] and the intensity [Leyendecker et al., 1988] show comparable values of these quantities extending over much larger area west of the epicenter than east (Figure 1). One possible cause of this asymmetry could be the subsurface velocity structure. To examine this possibility we examined the data as one would if there were a reversed refraction profile. Rather than using explosions as is the case with exploration seismology, we could use naturally occurring sources, namely, the Whittier Narrows earthquake, the July 8, 1986, North Palm Springs M_L 5.9 earthquake and possibly the October 1, 1985, Redlands M_L 4.9 earthquake. Each of these earthquakes occurred within 10 km of an east-west line at 34° N latitude and all at approximately the same depth. Our concern was not with the P-wave velocity structure which has been well determined and used extensively in locating earthquakes in southern California [Hadley and Kanamori, 1977], rather our interest is in the S-wave velocity structure. S waves are generally the source of the maximum accelerations and generate the type of motion most damaging to structures.

Method

The approach we considered consisted of three parts: (1) collection of seismograms from the U.S. Geological Survey network of high-gain vertical seismometers, (2) travel time analysis of the seismograms together with the strong motion records, and (3) generation of synthetic seismograms, based on both the faulting mechanism and the velocity structure, to be compared with the recorded accelerograms. Each of these parts are discussed in detail below.

Seismogram Collection

The USGS high-gain vertical seismometers are used primarily to locate earthquakes in southern California. Consequently they invariably go offscale right after the first arriving P wave for events as large as Whittier Narrows or North Palm Springs, making the S wave unrecognizable. However, both of these mainshocks produced a large number of aftershocks, some of which would have magnitudes such that the S waves would be recognizable on these seismograms. From these seismograms we could approximate the S-wave travel time. The advantage of these stations is that they are more numerous than strong motion stations allowing for more accurate determination of the S wave. The disadvantage is that the stations generally record only the vertical component of motion which can have converted waves arriving at nearly the same time as the true S wave.

We selected those USGS stations that lay between Whittier and North Palm Springs (Figure 2). Using aftershocks of the mainshocks we plotted the seismograms on a reduced travel time plot (Figures 3 and 4). Each seismogram was scaled by the gain of the station to normalize the amplitudes to one common gain. (The gains are not always known thus limiting the use of these seismograms to travel time analysis only.) Next the amplitudes were multiplied by R, where R is the epicentral distance between the station and the source, to account for geometrical attenuation of the S wave. The seismograms are plotted versus distance. The origin time is based on a reduced travel time: the true time minus a term that is R divided by some velocity, the P-wave velocity of the medium between depths of 16 km and 32 km. The strong arrival marked by the dashed line is the presumed S wave. From the slope of the dashed line the S wave velocity can be determined, 3.64 km/s. The fact that the same velocity is determined regardless of the source being at Whittier or at North Palm Springs demonstrates that the velocity structure is basically horizontally layered. A dipping structure would have produced two different apparent velocities that could be resolved by allowing for a dipping structure. To examine the travel paths that the S wave followed from the source to the stations we analyzed the travel times.

Travel Time Analysis

The travel time analysis was based on tracing seismic rays through an assumed velocity structure (Cerveny et al., 1977). Because the S-wave velocity 3.64 km/s was 0.58 times the P-wave velocity, i.e, a Poisson solid, we initially assumed that the entire medium was a horizontally layered Poisson solid (Figure 5). With this assumption we placed a source at a depth of 14.6 km and generated a suite of rays that left the source with different takeoff angles. Figure 6 shows the ray paths and the travel time of each S wave for the distance range 0 - 100 km. This travel time is compared with the S wave on the strong motion data. (It would be circular reasoning to compare it with the data on the vertical seismograms)

In order to compare the predicted travel time with the data, the accelerogram must have absolute time, otherwise one can arbitrarily shift the accelerogram to get a perfect fit. While there are about 20 CDMG and USGS strong motion stations between Whittier and North Palm Springs near 34° North latitude, the actual number that have absolute time and have been digitized is 7 (Figure 7). Comparing the predicted travel time with the observed travel time we find that the predicted time is about 0.2 to 0.5 seconds earlier. For S waves this agreement is excellent considering that the near-surface material in the model has a high velocity compared to what is observed in this general area [Fumal and Tinsley, 1985]. Thus by allowing for a veneer of sediment cover the travel times can be brought into better agreement. An example of the predicted and observed S wave arrival time is shown in Figure 8. Although the S waves on the high-gain vertical seismometers and match between the predicted S-wave arrival time and that observed on the strong motion horizontals provide convincing evidence for a simple crustal structure, the amplitude information must be compared with predictions that are based on the source as well as the crustal structure.

Synthetic Seismograms

As mentioned above, the focal mechanism of the Whittier Narrows earthquake does not suggest any east-west asymmetry in the ground motion. The strike is east-west and the slip direction is due south with the north side of the fault overriding the south side. If there were to be asymmetry one could expect it to be stronger motion south of the epicenter compared to north of the epicenter due to directivity and interaction of seismic waves and the free surface in the hanging wall above the fault plane. This does appear to be the case as seen in the intensity data [Leyendecker et al, 1988] and peak horizontal accelerations [Trifunac, 1988]. To see if the earthquake mechanism along with the velocity structure could have produced low amplitudes east of Whittier, we generated complete synthetic seismograms [Bouchon, 1981]. Completeness refers to the fact that the seismograms contain all possible elastic waves for the given velocity structure, i.e., body waves, head waves, surface waves, and all possible overtones (reverberations within a layer or combinations of layers). The earthquake source is represented as a point source double-couple with a seismic moment of 1.0×10^{25} dyne-cm with a 90° strike and 90° slip angle on a 25° north dipping fault plane. The synthetic particle velocity time history is computed for each strong motion station and compared with the particle velocity obtained by integrating the accelerogram. The synthetics are computed for frequencies between DC and 8.0 Hz; the data have been lowpassed with a corner at 8.0 Hz for an equal comparison. As an initial comparison we look at the transverse component which should be only SH waves (Figure 9a and 9b). Using only a point source and neglecting the finiteness of the fault, we cannot expect to match more than the first cycle of the particle velocity in the data. Although the comparison between the synthetic and data is not perfect, the fit does show that the amplitudes are in fair agreement. The amplitude depends both on the source function and on the impedances of the crustal material.

Conclusions

Considering the amplitudes and arrival times are in fair agreement supports the hypothesis that the asymmetry in the observed ground motion is due to amplification west of Whittier rather than anomalous attenuation of amplitudes east of Whittier.

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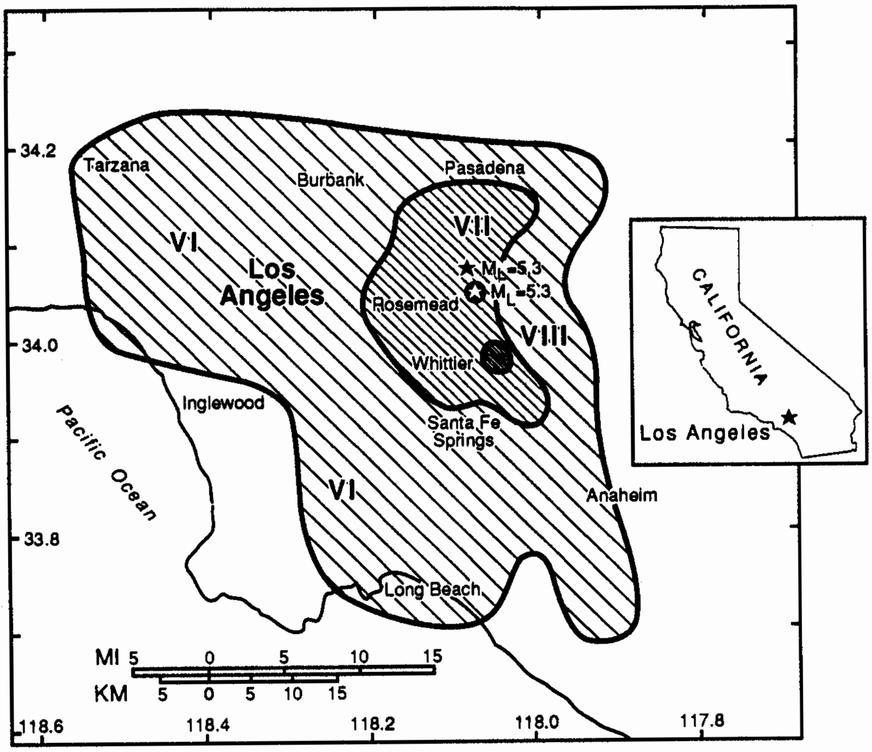

Figure 1. Modified Mercalli intensity isoseismals in the Los Angeles area for the Whittier Narrows earthquake of October 1, 1987. From Leyendecker et al., (1988).

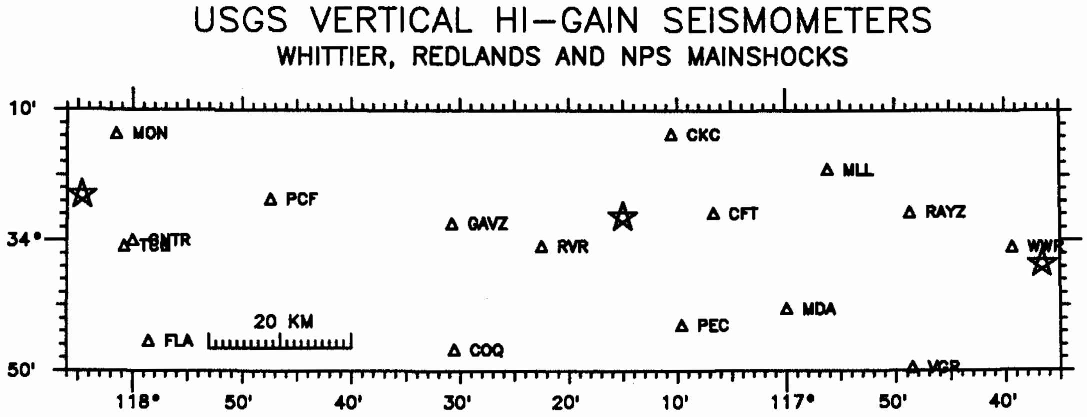

Figure 2. Plan view of U.S.G.S. high-gain vertical stations between Whittier and North Palm Springs, California. Epicenters of the Whittier Narrows, Redlands and North Palm Springs earthquakes shown by stars.

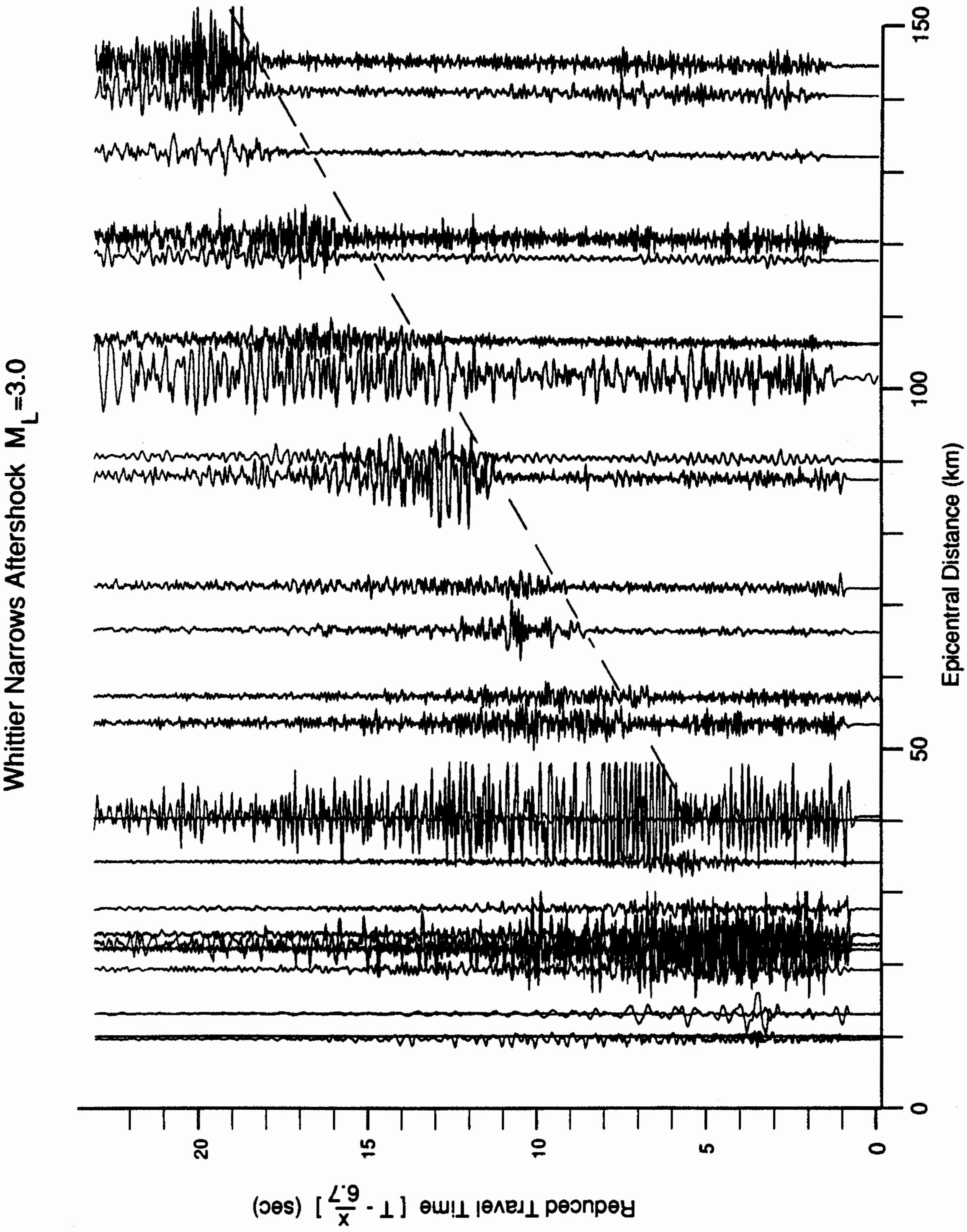

Figure 3. Reduced travel time plot for an aftershock of the Whittier earthquake (10/1/87 at 15:05, 11.5 km depth, $M_L3.0$) recorded by USGS high gain vertical stations. Reduction velocity is 6.7 km/sec. Seismograms have been scaled by station gain (where known) and for geometrical spreading.

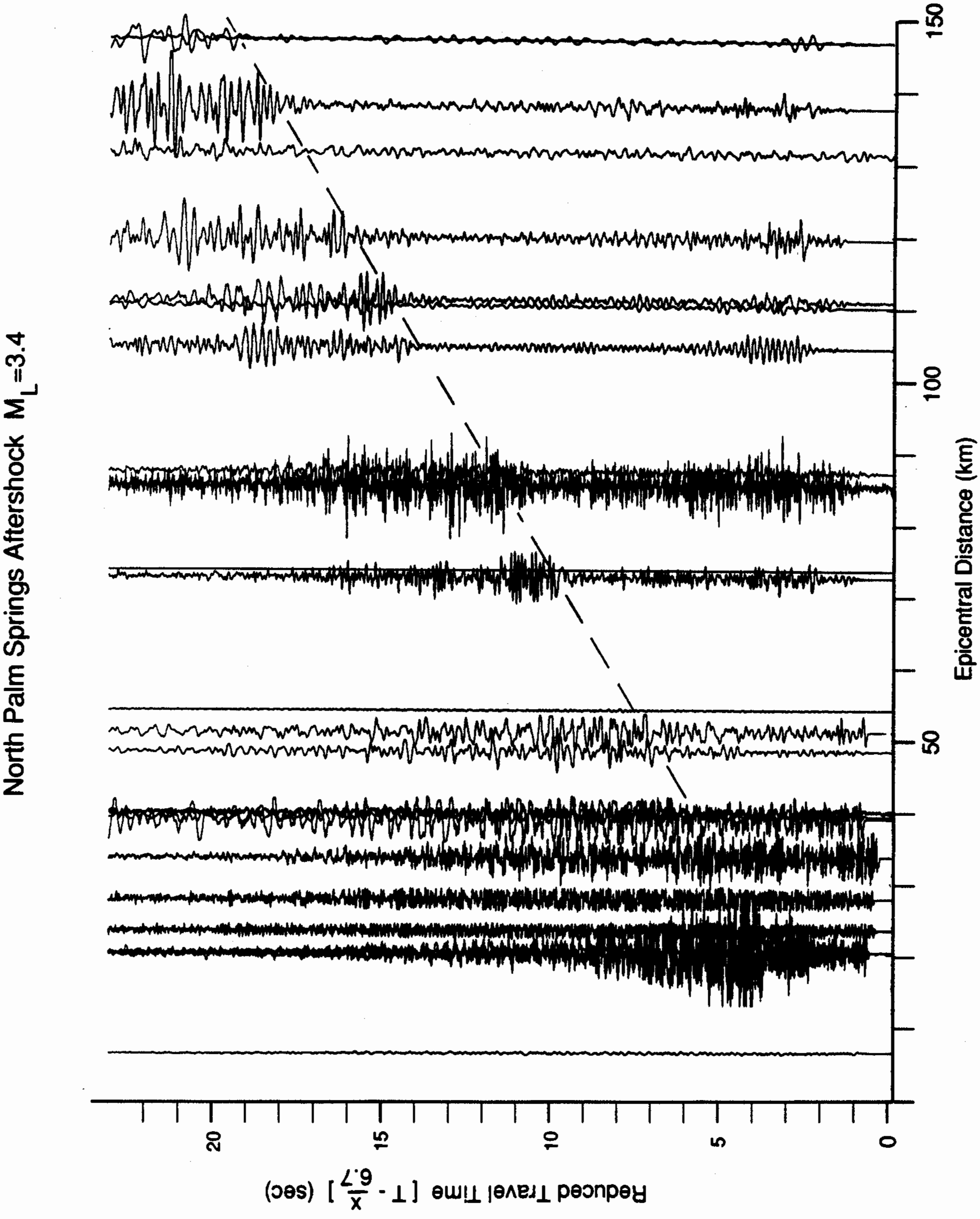

Figure 4. Reduced travel time plot for an aftershock of the North Palm Springs earthquake (7/14/86 at 01:43, 12 km depth, M_L3.4) recorded by USGS high gain vertical stations. Reduction velocity is 6.7 km/sec. Seismograms scaled for station gain (where known) and for geometrical spreading.

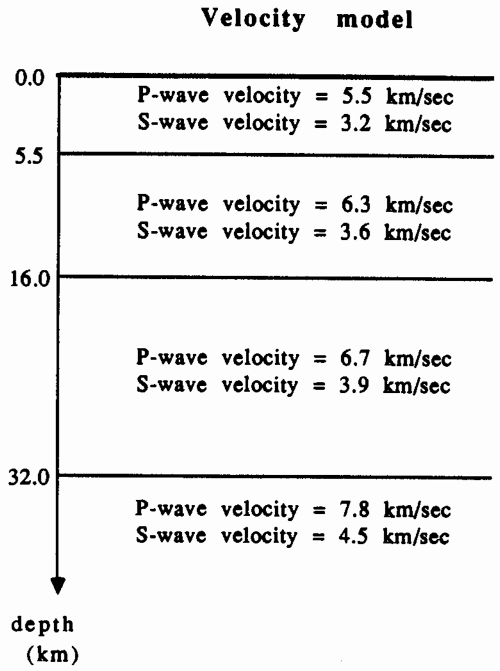

Figure 5. P and S-wave velocity structure used in our study. P-wave velocity structure is from Hadley and Kanamori (1977). S-wave velocity structure is result of analysis of high gain vertical data, which gives a P to S wave velocity ratio of 1.732.

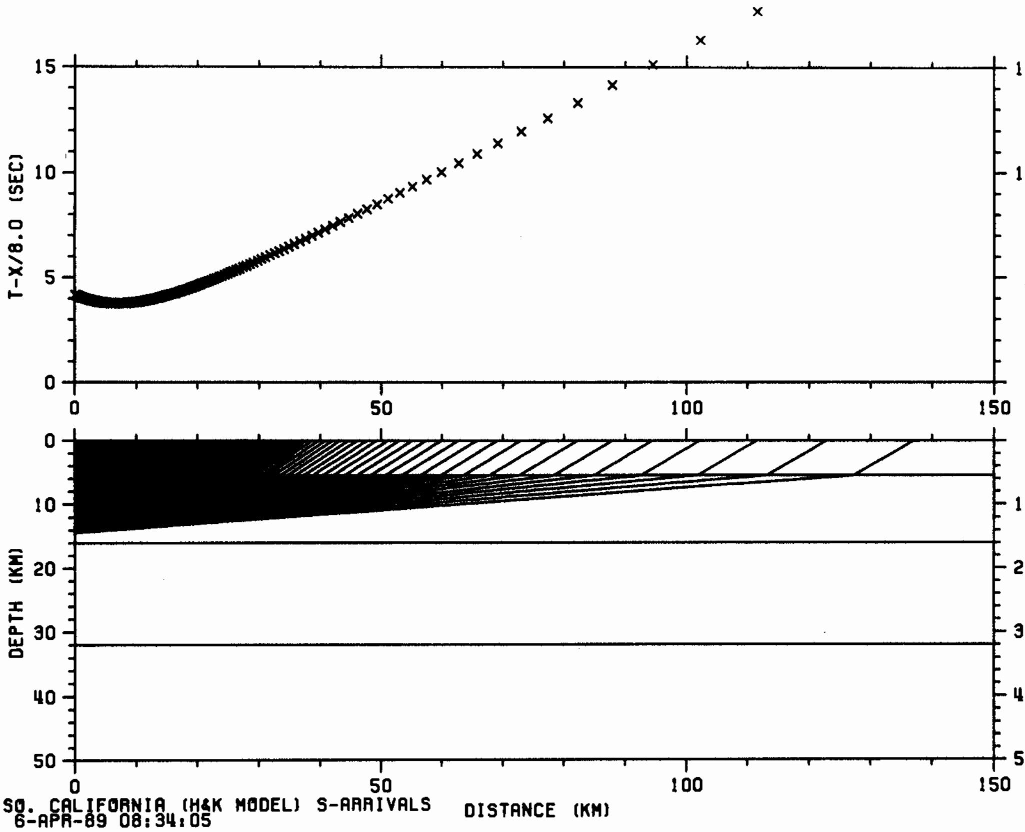

Figure 6. Plot of S-wave arrival times versus distance from the Whittier epicenter for rays traced through the S-wave velocity model shown in Figure 5.

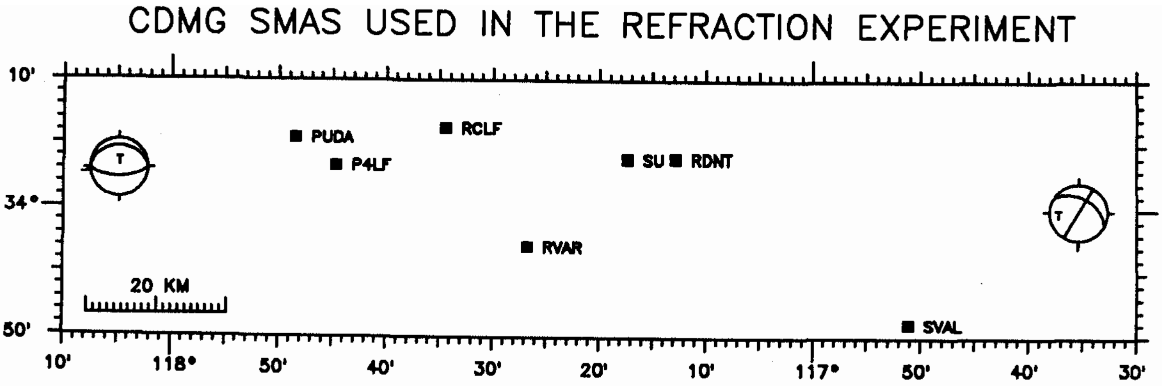

Figure 7. CDMG strong-motion stations used in our study. These stations were the only free-field or in building basements that have both absolute time and have been digitized.

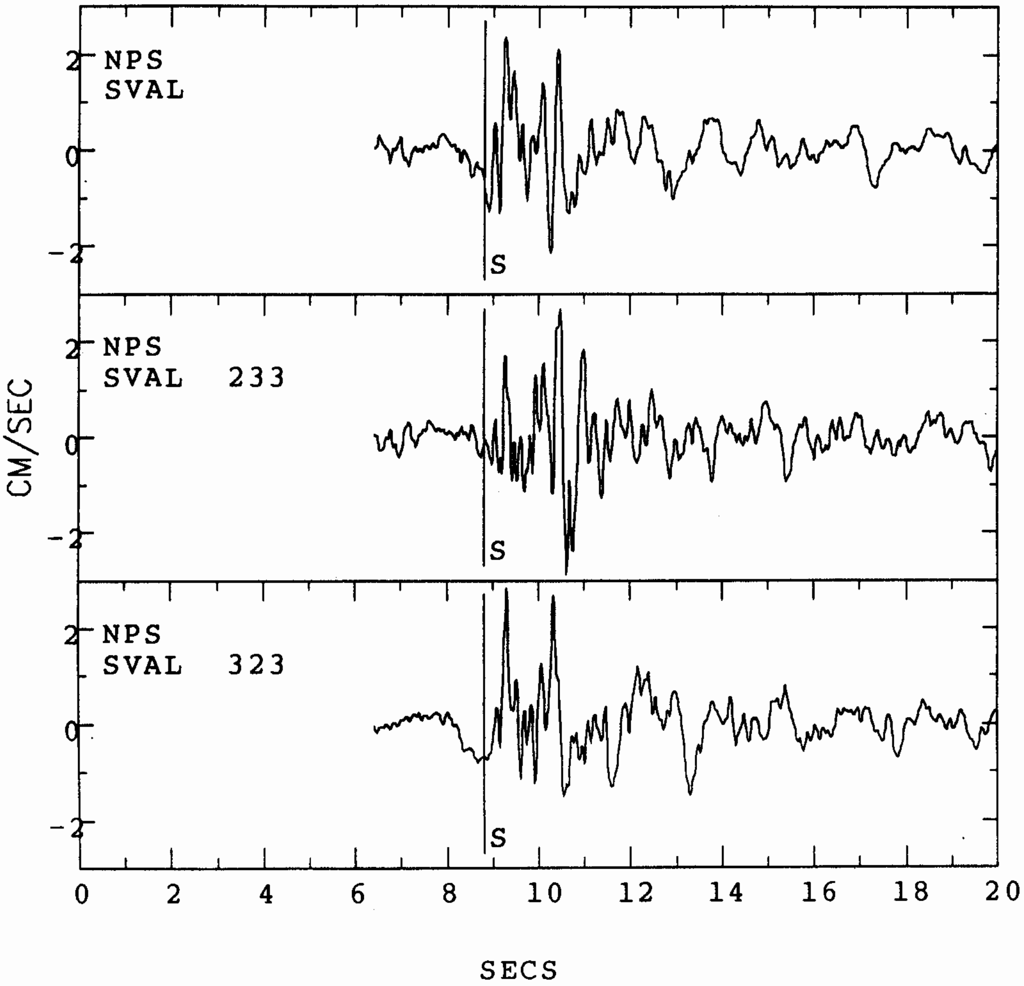

Figure 8. Actual and predicted S-wave arrival time at the Silent Valley station which recorded the North Palm Springs earthquake (epicentral distance, 28 km). Zero time is the origin time of the earthquake. Prediction of S-wave arrival is denoted by the vertical line. Components shown are vertical (down motion is positive), radial, transverse particle velocity obtained by integrating acceleration.

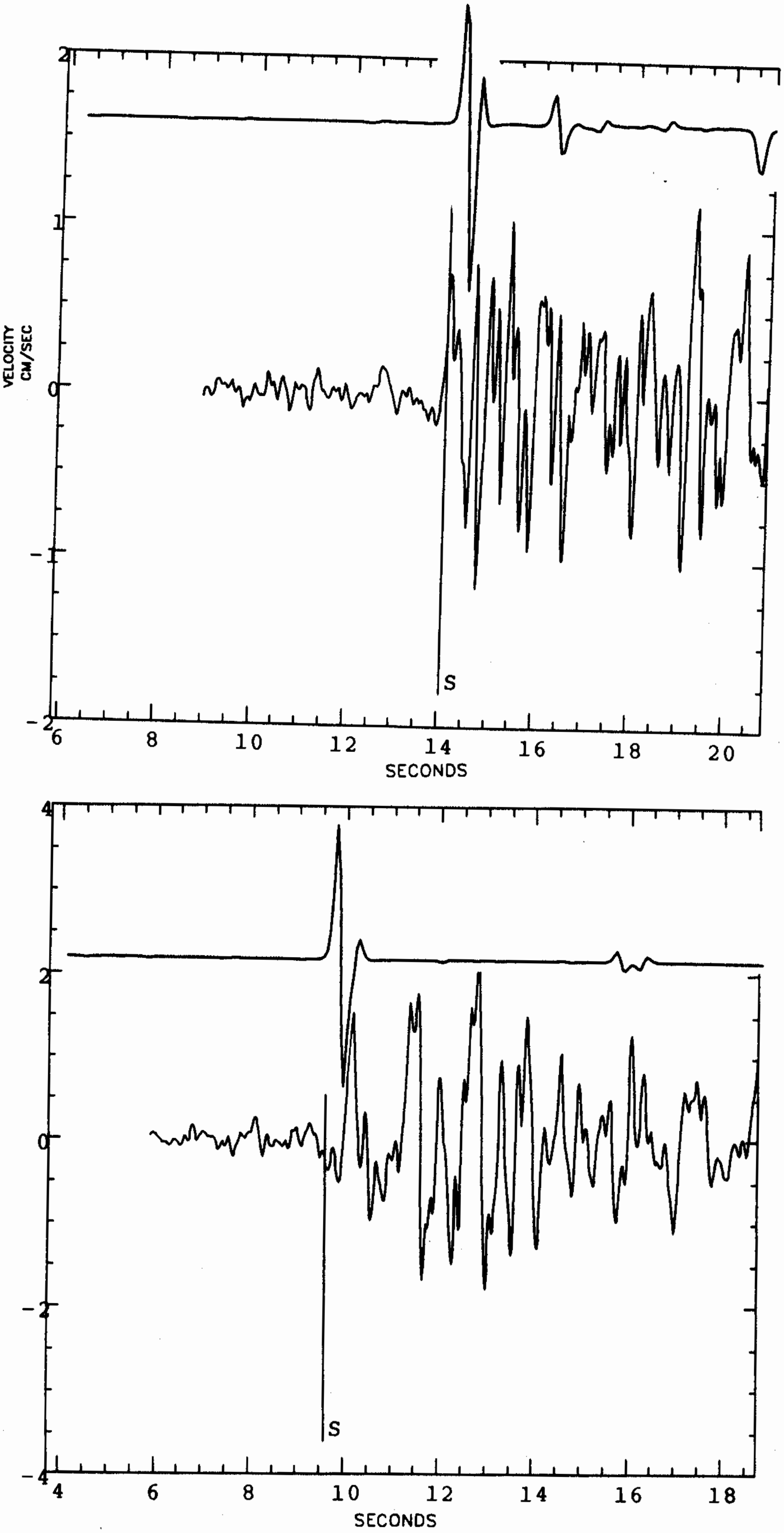

Figure 9. Predicted and observed transverse components of particle velocity. Synthetics include both the focal mechanism of the Whittier Narrows earthquake and the horizontally layered medium. Stations are (a) Rancho Cucamonga Law and Justice Center Free Field at 47 km epicentral distance and (b) Pomona 4th and Locust Free Field at 30 km epicentral distance.