Fine structure of the rupture zone of the April 26 and 27, 1997, Northridge aftershocks

Anupama Venkataraman, 1 Jim Mori, 2 Hiroo Kanamori, 1 and Lupei Zhu 3

Abstract. We investigated the rupture geometry of two $M_w \sim 4.5$ earthquakes (April 26, 1997, and April 27, 1997) that occurred on the western edge of the aftershock zone of the 1994, $M_w 6.7$, Northridge earthquake. Both events have thrust mechanisms with a steep plane dipping $\sim 75^\circ$ SE and a shallow plane dipping $\sim 45^\circ$ NE. An empirical Green’s function deconvolution followed by a waveform inversion was used to determine the slip distribution of the two events. The inversion results show that the steep plane fits the data slightly better than the shallow plane. The background seismicity (aftershocks of the 1994 Northridge event) in the epicentral region shows the existence of a north dipping fault plane, similar to that of the 1971 San Fernando earthquake. However, the spatial trend of the two April 1997 events and their aftershocks reveals tightly clustered seismicity on a steep plane dipping south. Relative relocation of the April 26 and 27 events shows that the April 27 event ruptured $\sim 1.4$ km N70°E of the April 26 event and at a slightly shallower depth, i.e., almost along strike and on a steep plane dipping south. These observations suggest that the steep plane is the fault plane of both events. The two events ruptured on a plane which is almost perpendicular to the trend of the regional background seismicity. Thus the seismogenic structure beneath the Transverse Ranges exhibits complexity on scales of a few kilometers. The rupture area for both the April 26 and 27 events is $\sim 1$ km$^2$ with a stress drop of at least 20 to 30 bars.

1. Introduction

The east-west trending Transverse Ranges of southern California are undergoing active north-south shortening. The Transverse Ranges were formed as a result of the compressional stresses associated with the Big Bend in the San Andreas fault. The complex structure and tectonics of the region have been studied using plate motions [Anderson, 1971], leveling data [Thatcher, 1976], geology [Yeats, 1981; Yeats, 1983; Namson and Davis, 1988a, b], seismicity and kinematics [Corbett and Johnson, 1982; Bird and Rosenstock, 1984; Savage et al., 1986; Nicholson et al., 1986] and seismic reflection and seismicity studies [Hadley and Kanamori, 1977, 1978; Humphreys et al., 1984; Webb and Kanamori, 1985; Cheadle et al., 1986; Huang et al., 1996; Ryberg and Fuis, 1998].

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Plate 1. (a) Focal mechanisms (lower hemisphere) and location map of the April 26 and April 27, 1997, earthquakes. Triangles represent seismic stations. The location of the January 17, 1994, Northridge earthquake ($M_w 6.7$) and the February 9, 1971, San Fernando earthquake ($M_w 6.7$) are denoted by stars. (b) A cross section of all the well-located aftershocks that were recorded by the Southern California Seismic Network. The gray box in Plate 1a shows the area and orientation of the cross section. The April 1997 events and their aftershocks are shown in purple; the events that were recorded between January 1994 and April 1997 in the western edge of the Northridge aftershock zone are shown in black. The aftershocks of the San Fernando earthquake recorded from February 1971 to mid-April 1971 are shown in red. The aftershocks recorded in the year following the 1994 Northridge event are shown in blue.
the rupture planes was possible. This helps us to better understand the pattern of faulting in this region.

In sections 2 and 3 of this paper we do a relative relocation of the two April, 1997 events and use a source inversion to determine the mechanism and seismic moment of the two events. In section 4, we present the results of a Green's function deconvolution (with a positivity constraint) that we used to obtain source time functions. In section 5 we invert these source time functions to determine the slip distribution on the fault plane. In section 6 we perform an aftershock relocation of all the earthquakes that occurred in the region since the 1994 Northridge earthquake.

2. Data

The April 26 and 27, 1997, earthquakes were well recorded by the newly deployed TriNet [Mori et al., 1998] stations in southern California. The events had good azimuthal station coverage with five stations at epicentral distances of ~20 km. The data are archived at the Southern California Earthquake Center (SCEC) Data Center. In our analysis, we used velocity and acceleration records for the two mainshocks and high-gain velocity records for the smaller events which were used as empirical Green's functions. The waveforms at station NOT were corrected for a polarity reversal (the E-W and N-S components were flipped in the original data).

For both the April 26 and 27 events the displacement waveforms recorded at station SOT are much narrower than those recorded at stations NOT and SMV (Figure 1) and suggest that both events ruptured toward station SOT. The April 27 event appears to be a double event. The location of the April 27 event relative to the April 26 event provides an indication of the rupture geometry of the sequence. We measured the $P$ wave arrival times of the two events at 20 TriNet stations that had good signal to noise ratio and located them relative to each other. The April 27 event is located ~1.4 km N70°E of the April 26 event (Figure 2) and at a slightly shallower depth. As shown in Figure 2, the relative location of the two events suggests that both events are located on a steeply dipping plane. This observation, coupled with the observed directivity toward station SOT, suggests that the rupture of the whole sequence was probably on the steep nodal plane.

Three $M_w$ ~ 2.7 aftershocks (origin times April 26, 1997, 1054 UT; April 26, 1997, 0017, 1431 UT and April 26, 1997, 1109 UT) of the April 1997 sequence with high signal to noise ratio are shown in Figure 1c. We observe that these aftershocks also exhibit an azimuthal varia-

Figure 1. Transverse (T), radial (R), and vertical (Z) displacement waveforms at three stations SMV, SOT, and NOT for the two events studied and the aftershock used as the empirical Green’s function are shown; (a) April 26, 1997, event, (b) April 27, 1997, event, and (c) the aftershock that occurred at 1110 UT on April 26, 1997. Observe that the waveforms at station SOT are narrower than those at stations NOT and SMV for the two events as well as for the aftershock. This directivity effect is especially noticeable on the transverse (T) component and suggests that the events ruptured toward station SOT.
Figure 2. Location of the April 27 event relative to the April 26 event on the stereographic plot (upper hemisphere projection of the April 26 event), with the April 26 event at the center. The location of station SOT, which is at an azimuth of N75°E is marked.

Figure 3 shows the STFs obtained from P and SH waves by deconvolution with a positivity constraint. The positivity constraint is desirable because it yields nonnegative STFs. However, the method has a drawback in that any noise in the data tends to produce a long tail thereby broadening the STF. We believe that the STFs obtained using the deconvolution with a positivity constraint represent the overall time function, but the long tail is an artifact of the deconvolution.

4.2. Waveform Inversion

As mentioned earlier, the STFs at some stations have long tails which are probably artifacts of deconvolution. To minimize the effects of the tail on the inversion, we cut off the tails. As illustrated in Figure 4, we fit a function \(1-(\cos(2\pi t/T))/2\) near the peak of the STF and truncate the STF at \(t=0\) and \(T\). We used the truncated STFs for the inversion.

To remove the effects of radiation pattern, we normalized the area of the truncated source time functions.

### Table 1. Velocity Model Used

<table>
<thead>
<tr>
<th>P Wave Velocity, km/s</th>
<th>Depth, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>0 - 5.5</td>
</tr>
<tr>
<td>6.3</td>
<td>5.5 - 17.5</td>
</tr>
<tr>
<td>6.7</td>
<td>17.5 - ∞</td>
</tr>
</tbody>
</table>

Modified from Hadley and Kanamori [1977].
at each station and used these to determine the slip distributions on both fault planes for each of the events. The method used here assumes a circular rupture propagating with a constant velocity across the fault. The fault plane is divided into triangular subfaults 0.5 km wide and 0.8 km high. Synthetic STFs for each subfault are calculated at each station [Spudich and Frazer, 1984], and the observed STF at each station is matched to the weighted sum of these sub-fault synthetics. The weights, which correspond to the slip distribution on the fault plane, are determined by a least squares inversion method with a positivity constraint [Lawson and Hanson, 1974], such that the error between the observed and synthetic STFs is minimized. The details of the method are described by Mori and Hartzell [1990]. The absolute values of slip are calculated by equating the moment obtained from the slip distribution to the moment obtained from the source inversion.

To compute the takeoff angles from each subfault to the stations, we used a modified Hadley-Kanamori velocity model (Table 2). To avoid complications in the source model, the discontinuity at a depth of 16 km is moved to a depth of 17.5 km so that the rupture plane lies within a single velocity layer. We performed the inversion for a range of rupture velocities from 2.7 to 3.6 km/s for both nodal planes. These rupture velocities correspond to 0.74 to 0.99 times the shear velocity of 3.64 km/s at the source depth of the model.

5. Results

The results of the waveform inversion for the April 26 and 27 events are shown in Figure 5. At each station, a set of three seismograms representing the observed displacement data and displacement synthetics for the shallowly dipping and steeply dipping planes is shown.

By comparing the data and synthetics we observe that for the April 27 event the steep plane fits the data marginally better than the shallow plane (e.g., the shallow plane is unable to fit the P pulses at SOT and CALB, while the steep plane yields a better fit). For the April 26 event, though the steep plane fits the data slightly better, the difference in fit between the steep and shallow planes is not significant (Figure 5). We calculated the root mean square (rms) values of the misfit between the data and synthetics and normalized them by the average peak amplitude of the data. For the April 26 event these values are 123 for the steep plane and 143 for the shallow plane; for the April 27 event we obtained values of 133 for the steep plane and 93.
Table 2. Focal Mechanism Solutions

<table>
<thead>
<tr>
<th>Event</th>
<th>Depth, km</th>
<th>Steeply Dipping Plane</th>
<th>Shallowly Dipping Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>Dip</td>
</tr>
<tr>
<td>970426103731</td>
<td>17.2</td>
<td>73°</td>
<td>72°SE</td>
</tr>
<tr>
<td>970427110920</td>
<td>16.9</td>
<td>65°</td>
<td>78°SE</td>
</tr>
</tbody>
</table>

The locations of the April 26, and 27 1997, events are 34.367°N, 118.674°W and 34.372°N, 118.650°W, respectively.

for the shallow plane. The difference between the values for the shallow and steep planes is not large enough to allow determination of the slip plane. Thus the results of the waveform inversion alone cannot be used to determine the rupture plane. A rupture velocity of 3.0 km/s on the steeply dipping plane yields the best fitting solution for both the April 26 and 27 events.

The slip distributions on the steep planes of the April 26 and 27 events obtained from the inversion are shown in Figure 6. The hypocenter (marked X) is at the cen-

Figure 5. The top trace (thick line) at each station representing the displacement data for the mainshock at each station. The bottom two traces are synthetics for the shallow (thin line) and steep planes (shaded line) respectively computed by convolving the synthetic source time functions (obtained from the slip distribution on the fault planes) with the aftershock data. (a) Waveforms for April 26, 1997, event; (b) Waveforms for the April 27 event.
Figure 6. (a) The slip distribution on the steeply dipping fault plane for the April 26, 1997, event. (b) The slip distribution on steeply dipping fault plane for the April 27, 1997, event. Each square corresponds to a triangular subfault 0.5 km wide and 0.83 km tall. X denotes the location of the hypocenter on the fault plane. The downdip direction is marked by DD, and the strike of the plane is indicated.

For both events, most of the slip is concentrated in a small area around the hypocenter with very small amounts of slip in the rest of the fault plane. For the April 27 event, if we take the five sub-faults where the slip is largest, the average slip, $D$, is $\sim 12$ cm, and the rupture area is 1.04 km$^2$. For a circular rupture the stress drop, $\Delta \sigma$ is given by [Eshelby, 1957; Keilis Borok, 1959]

$$\Delta \sigma = \frac{7}{16} \mu \frac{D}{(\text{area}/\pi)^{1/2}},$$

where $\mu = 3 \times 10^{11}$ dyn cm$^{-2}$. Using $D = 12$ cm, and area is 1.04 km$^2$, we obtain $\Delta \sigma = 30$ bars. For the April 26 event, if we consider the four sub-faults where the slip is largest, the average slip, $D$, is $\sim 10$ cm, the rupture area is 0.83 km$^2$, and the calculated stress drop, $\Delta \sigma$ is 25 bars. The inversion cannot resolve the distinct pulses of the double event of the April 27 event. Hence the calculated stress drops are lower limits; the actual stress drops could be higher.

6. Aftershock Relocations

Distributions of hypocenters of aftershocks can often be used to determine the orientation of rupture planes. In the Northridge aftershock region, however, the pattern of aftershocks is quite complicated and does not
clearly indicate a strong regional trend. Plate 1b shows a cross section of all the well-located aftershocks in the region that were recorded by the Southern California Seismic Network from January 1994 through April 1997. The gray box in the Plate 1a shows the area and orientation of the cross section. The events were relocated using a local three-dimensional velocity model that was derived by simultaneously relocating a subset of 748 events and solving for the velocity structure. We used the program SIMULPS by Eberhart-Phillips [1993] with a 7x4 horizontal grid of 1 km spacing and eight depth layers.

In this western region of the Northridge aftershock zone, the events prior to April 1997 generally show a broad pattern dipping toward the north (black dots), while the events of April 1997 sequence (purple dots) show a trend dipping steeply to the south, similar to the trend shown by the aftershocks of the 1971 San Fernando earthquake (shown in red). Several smaller seismicity clusters illuminate other structures in the region.

7. Discussion and Conclusions

Although the waveform data cannot distinguish the rupture plane from the auxiliary plane, the relative relocation of the April 26 and April 27 events, the trend of the aftershocks of these events, and the directivity toward station SOT suggest that the whole sequence ruptured on a south dipping steep plane that coincides with the steep nodal plane of the April 26 and the April 27 events. It is interesting to note that Plate 1 shows no obvious south dipping plane of seismicity in the epicentral region prior to the April 1997 sequence. The seismicity pattern of the events that occurred between January 1994 and April 1997 (black dots) suggests the existence of a north dipping rupture plane, similar to that of the 1971 San Fernando earthquake. However, the April 1997 sequence ruptured on a plane that is almost perpendicular to the plane of background seismicity in the region. It is important to note that the north dipping plane of background seismicity (black dots) is opposite to the trend of the Northridge mainshock (blue dots). We also observe smaller clusters of seismicity, which suggest the presence of other structures with different orientations in the region. Thus this study shows that the deformation beneath the Transverse Ranges occurs on a complex array of rupture planes. The complexity of the seismogenic structure in this region has been suggested previously, e.g., the fault plane of the 1971 San Fernando earthquake is nearly perpendicular to that of the 1994 Northridge earthquake [Hauksson et al., 1995; Mori et al., 1995]. Our study provides evidence that shows that the complex seismogenic structure at depth beneath the Transverse Ranges exists on much smaller scales too, i.e., at scales of a few kilometers. The rupture area for both the April 26 and 27 events is ~1 km² with a stress drop of at least 20 to 30 bars.

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