Experiments in improving Southern California earthquake locations, focal mechanisms, and inferred stress orientations

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Progress Report

Introduction

We have worked on improving earthquake locations and focal mechanisms in southern California using a variety of different approaches. These include: (1) Application of the L1-norm, source-specific station terms, and waveform cross-correlation to improve earthquake location accuracy, (2) Development of new methods for computing focal mechanisms from P-polarity data including more realistic error estimates, (3) Experiments in increasing the reliability of stress field inversions through the use of improved location and focal mechanism catalogs and development of new analysis techniques.

Results

Here we summarize results from several different studies which we have completed during the last year, including Hardebeck and Shearer (2002), Shearer et al. (2002) and Shearer (2002) to which the reader is referred for additional details.

New focal mechanism method

Measuring the orientation and state of stress of subsurface faults is an important part of seismic hazard estimation in California and other seismically active regions. Earthquake focal mechanisms play a key role in these studies, because they describe both fault-plane orientation and the slip direction, thus providing information about the geometry and kinematics of faults at depth. Focal mechanism observations are also used in many studies of the mechanics of crustal faulting and provide one of the few ways to infer the stress orientation at seismogenic depths. The accuracy of these stress inversions is limited, however, by the uncertain reliability of many of the focal mechanism estimates and the fault plane ambiguity inherent in the double-couple source.

We have developed a new method for determining earthquake focal mechanisms from P-wave first-motion polarities (*Hardebeck and Shearer*, 2002), which differs from previous methods by accounting for possible errors in the assumed earthquake location and seismic velocity model. Focal mechanism solutions can be sensitive to these parameters because they affect the computed takeoff angles to the stations. Our technique identifies a set of acceptable mechanisms for each event, allowing for the expected errors in polarities and takeoff angles. Multiple trials are performed with different possible source locations and velocity models, and all mechanisms with up to a specified fraction of misfit polarities are included in the set of acceptable mechanisms. Only those mechanisms for which the set of acceptable solutions is tightly clustered are considered adequately stable.

The similar event clusters identified by cross-correlation are useful in implementing and testing the focal mechanism method. Similar waveforms imply similar mechanisms, so the observed polarity at a given station should be the same for each event in a cluster. The fraction of anomalous polarity picks for the similar event clusters can be used to estimate the polarity error rate for the entire data set. We have also demonstrated that the computed focal mechanisms for events in a similar event cluster are identical (within their estimated errors) and may be characterized by a single composite mechanism for the cluster.

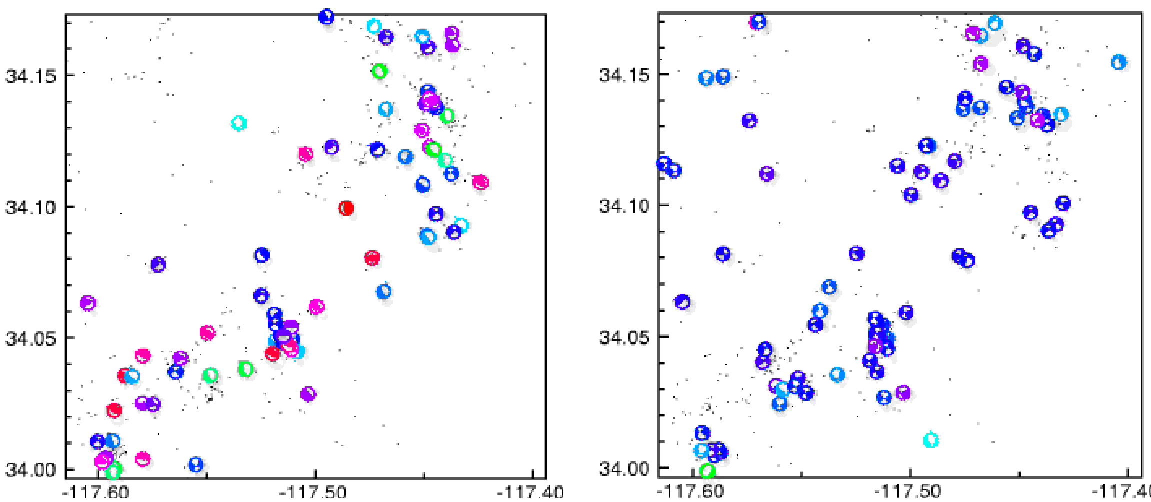

Figure 1. A comparison between focal mechanisms computed, (left), using FPFIT (*Reasenberg and Oppenheimer*, 1985) and, (right), using the method of *Hardebeck and Shearer* (2002). The map view shows focal spheres for events southwest of the junction of the San Jacinto and Cucamonga faults. The methods use the same event locations and polarity data; we plot only those solutions with relatively small estimated errors. Mechanisms are color-coded by faulting style: red for thrust, blue for strike-slip, and green for normal faulting. Note the greater spatial coherence in the Hardebeck and Shearer mechanisms.

We have begun applying this new technique to the SCSN catalog, and have found that our well-constrained focal mechanisms are quite spatially homogeneous. For example, the mechanisms for a NE-trending zone of seismicity near the junction of the San Jacinto and Cucamonga faults are predominately strike-slip and consistent with left-lateral motion along the trend (Fig. 1). In contrast, previous results for this region (obtained with the FPFIT program of *Reasenberg and Oppenheimer*, 1985) exhibit much greater diversity, even when equivalent error cutoffs are applied. This diversity is likely not real and reflects instabilities in the focal mechanism inversion method that could lead to false inferences regarding the stress state of the region. In general, our new results suggest that the mechanisms of small earthquakes are much more strongly correlated in space than previously thought. Our focal mechanism catalog will be useful in tectonic studies to infer structure and kinematics and should result in more reliable inversions for stress orientations.

Waveform cross-correlation

We have continued over efforts to systematically apply waveform cross-correlation across southern California and Figure 2 shows areas covered to date. We have progressed from analyzing aftershock sequences of 500 to 3000 events (Whittier Narrows, Upland, Oceanside) to the Northridge group of over 15,000 events (*Shearer et al*., 2002). Most recently, we have begun examining the entire southern portion of the catalog and have processed SCSN waveforms for over 45,000 events. In contrast to the limited duration of most aftershock sequences, this region includes many areas of ongoing seismicity along the active parts of the San Jacinto and Elsinore faults. Preliminary analyses of these data suggest higher fractions of similar events than are seen in the aftershocks, but lower fractions than those seen along active faults in northern California.

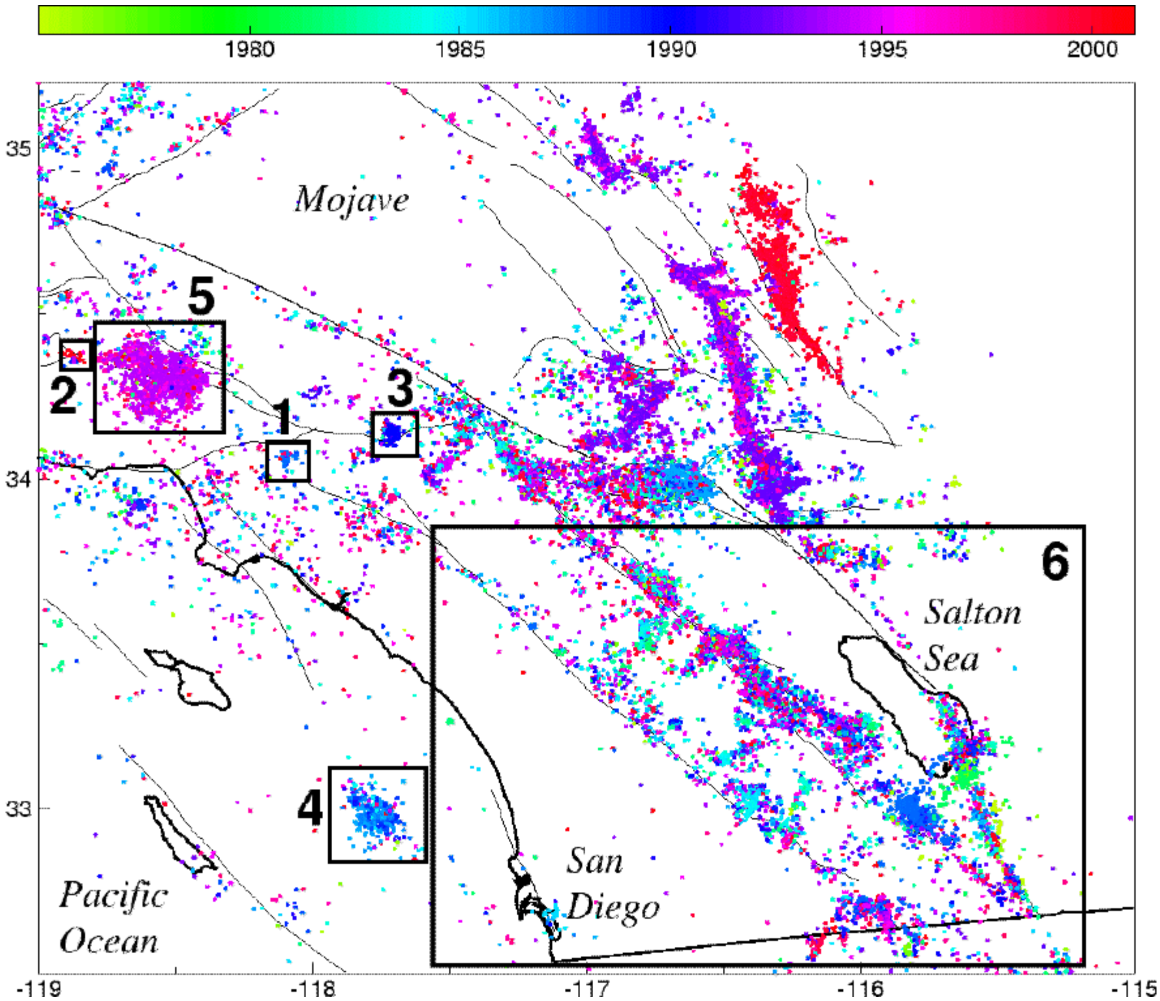

Figure 2. A map of southern California seismicity colored by year showing the areas of our waveform cross-correlation studies. Regions include (1) Whittier Narrows, (2) Oak Ridge, (3) Upland, (4) Oceanside, (5) Northridge, and (6) southernmost CA (*Shearer*, 1997, 1998; *Astiz and Shearer*, 2000; *Astiz et al*., 2000; *Shearer et al*., 2002).

Northridge aftershocks

We performed waveform cross-correlation on nearly 15,000 aftershocks of the 1994 Northridge M=6.7 earthquake in southern California as recorded by short-period stations of the Southern California Seismic Network (SCSN). Approximately 10 to 30% of the events belong to similar event clusters, depending upon the similarity criteria that are applied. We relocate events within 218 of these clusters to a relative location accuracy of about 30 m using the differential times obtained from the cross-correlation. These relocated event clusters often show planar features suggestive of faults at depth and we apply principal parameter analysis to characterize the shape of each cluster and to compute best fitting planes. In several cases these planes are parallel to the mainshock fault plane; however, more generally the seismicity planes exhibit a wide range of orientations suggesting complexity in the aftershock faulting. Composite focal mechanisms can be obtained for each cluster by combining the P polarity data from individual events (see Figure 3). A comparison of polarity measurement differences within similar event clusters provides constraints on the error rate in the individual focal mechanisms. For some clusters, we are able to resolve the primary versus auxiliary fault plane ambiguity by comparing the computed focal mechanisms with the best fitting seismicity planes. Individual event focal mechanisms are in general agreement with the composite focal mechanisms for the similar event clusters. Events occurring along the mainshock rupture plane are mainly thrust whereas events in the hanging wall are predominately strike-slip.

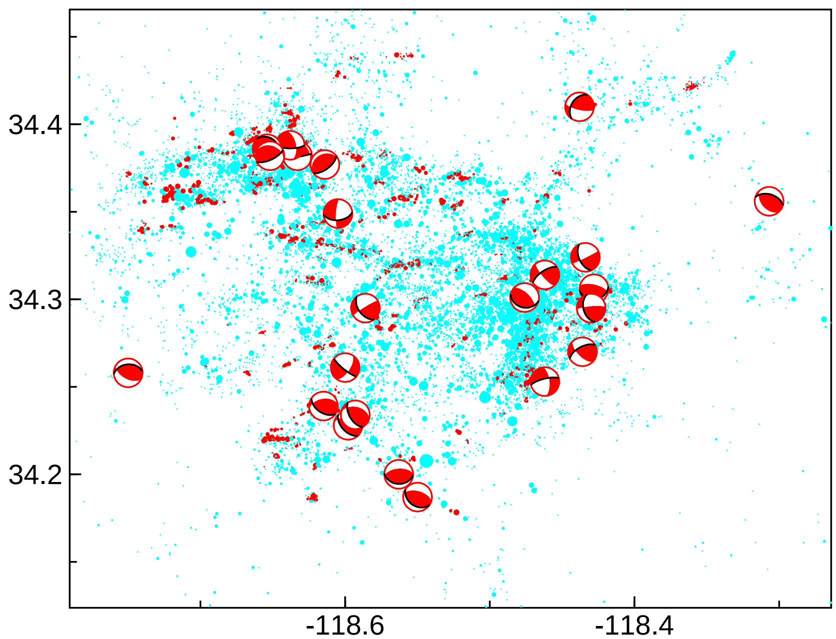

Figure 3. Relocated aftershocks of the 1994 Northridge earthquake. Similar event clusters are shown in red. Composite focal mechanisms for selected similar event clusters are also plotted. The true slip plane is indicated on these mechanisms as a solid line; this plane is inferred from principal component analysis of the seismicity distribution within each cluster.

Imperial Fault Seismicity

We have relocated earthquakes along the Imperial Fault in southernmost California. The Imperial Fault, just north of the Mexican border, was the site of major strike-slip earthquakes in 1940 ($M_W = 7.1$) and 1979 ($M_W = 6.6$), with geodetic results indicating that the fault accommodates 70% to 80% of the relative motion between the Pacific and North American plates. Since the 1979 rupture, seismicity has mostly occurred at depths of about 7 to 11 km between the near-surface locked part of the fault and aseismic creep or distributed shear at depth. Our results are shown in Fig. 4, which compares the original catalog locations with those obtained using the source-specific station term (SSST) method and waveform cross-correlation. The cross-correlation results for events during the last two decades reveal reveals parallel steaks of seismicity at 9-km depth. These strands are spaced about 0.5 km apart within a 2 km wide zone of earthquakes near the brittle-ductile transition between the shallow locked part of the fault and a creeping zone at depth. These results suggest that the lower crustal shear zone below the Imperial Fault, site of major earthquakes in 1940 and 1979, must be at least two kilometers wide (Shearer, 2002).

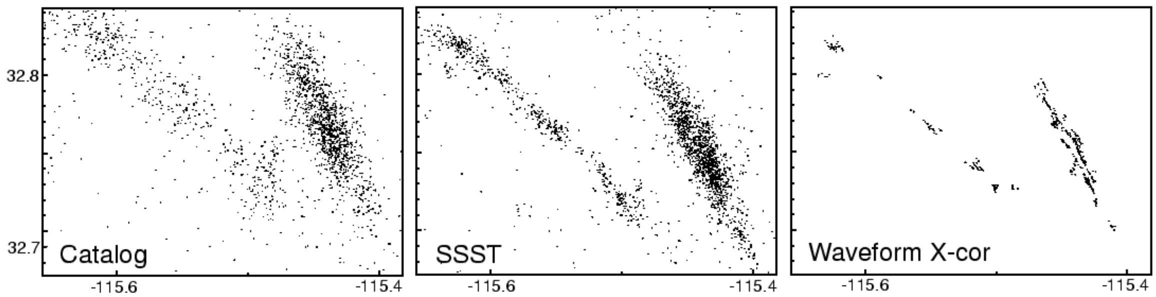

Figure 4. Closeup of the Superstition Hills and Imperial Faults, showing a comparison between the SCSN catalog locations, source-specific station term (SSST) results, and relocated similar event clusters analyzed with waveform cross-correlation.

Budget Statement

We have now spent $20,790.63 of the $70,000 allocated for the second year. This includes $12,828.96 of support for postdoc Jeanne Hardebeck, $146.52 in telecommunications and general supplies, $753.21 in travel (mainly for the Fall 2001 AGU meeting), and $7061.94 in overhead.

References

Hardebeck, J.L. and P.M. Shearer, A new method for determining first-motion focal mechanisms, *Bull. Seismol. Soc. Am.*, in press, 2002.

Shearer, P.M., J.L. Hardebeck and L. Astiz, Analysis of similar event clusters in aftershocks of the 1994 Northridge, California, earthquake, *J. Geophys. Res.*, in press, 2002.

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