FY2003 Joint UCSD and Caltech Report

Comprehensive Application of Waveform Cross-Correlation to Southern California Seismograms

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Introduction

We continue the cooperation between Caltech and UCSD in earthquake seismology research in southern California. The ever-expanding waveform archive of over 400,000 local earthquake records provides an invaluable resource for seismology research that has only begun to be exploited. However, efficiently mining these data requires the development of new analysis methods, an effort that goes beyond the limited resources of individual scientists. We are coordinating these efforts and developing common tools and data products that can be used by us and other researchers to accomplish some of the goals of SCEC.

This project has several purposes. These include enhancing our understanding of the clustering of earthquakes and their possibly overlapping spatial and temporal source processes. We also seek to improve the earthquake hypocenters to explore the relationship between seismicity and late Quaternary faults. Because the bulk of the background seismicity does not appear to be located on these faults, more accurate relative locations may make it possible to identify foreshocks as they happen and possibly infer the potential of a larger magnitude earthquake.

In 2003, we completed computing waveform cross-correlation functions for the whole dataset. The cross-correlation functions provide the differential travel times needed to improve the hypocenters. Waveform cross-correlation is also an increasingly important tool for characterizing event similarity and studying source properties (e.g., *Poupinet*, 1983; *Got*, 1994; *Dodge et al*., 1995; *Rubin et al*., 1999).

Below we present some of our exciting new results. The catalogs of relocated events are still preliminary but will be released to the SCEC community by the end of the year. Future work will concentrate on comparisons between the methods and detailed assessments of location accuracy and strategies for further improvements. In addition, we plan to use the waveform archive to determine other parameters such as spectra and amplitude measurements.

Data and Data Processing

We continued joint Caltech and UCSD analyses of the vast waveform archives of the Southern California Seismic Network (SCSN/CISN) to perform waveform cross-correlation on southern California seismograms for over 380,000 events between 1984 and 2002.

Waveforms recorded by the SCSN are first extracted from the SCEDC data center and trimmed into 50 s windows that include both P and S waves. The resulting online waveform archive uses about 0.5 TB on a RAID system. To simplify the computation, we divided southern California into five polygons, such that there are ~100,000 events or less in each region. Polygon boundaries are chosen to lie in regions of sparse seismicity (Figure 1).

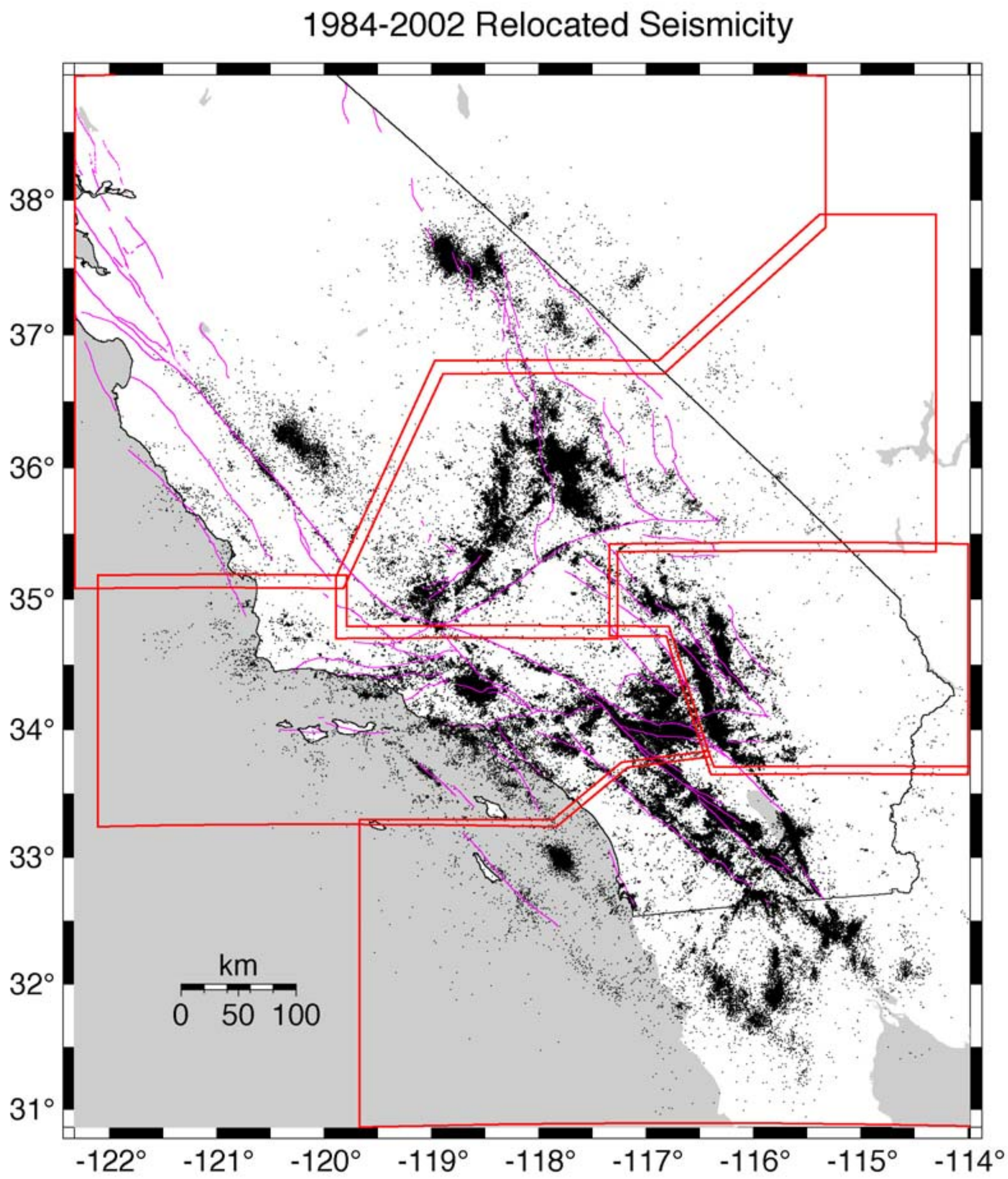

Figure 1. Southern California seismicity and the five selected processing boxes.

The waveforms are re-sampled to a uniform 100 Hz sample rate and band-pass filtered to between 1 and 10 Hz. Next, time domain waveform cross-correlation times are computed for P and S waves between each event and 100 neighboring events (identified from the catalog based on a 3-D velocity model of *Hauksson*, 2000). The algorithm identifies and saves differential times from the peaks in the cross-correlation functions and uses a spline interpolation method to achieve a nominal timing precision of 0.001 s. The Caltech/UCSD group used these differential times as input to two different relocation methods: (1) the double-difference program (HypoDD) of *Waldhauser and Ellsworth* (2000, 2002), and (2) the cluster analysis approach of *Shearer et al*., (2003a).

Results: Southern California

We have completed preliminary relocations for the entire southern California catalog and are in the process of comparing and verifying our results. We presented plots of these locations at the 2003 SCEC meeting and plan to release initial versions of these catalogs by year's end. The following is a brief summary of some of the main features that we have observed so far.

Double-difference method

At Caltech we have been using the double difference algorithm of *Waldhauser and Ellsworth* (2000, 2002) to relocate hypocenters using both phase picks and the cross-correlation differential times. The resulting HypoDD hypocenters show improved clustering both horizontally and vertically, creating a more focused picture of the previously identified, spatially complex distributions of seismicity. In many cases, the late Quaternary faults, such as the Elsinore and Hollywood-Santa Monica faults appear to bracket the seismicity distributions; in other cases, the faults trace the median within a symmetric distribution of hypocenters. The depth distribution of the seismicity shows sudden changes across some of the major strike-slip faults, while regions of dip-slip faulting are often bound by dipping surfaces that are clearly defined by the deepest hypocenters.

The seismicity around the southern San Andreas fault shows clear alignment along the Carrizo Plain segment while both the Mojave and Coachella Valley segments are dominated by off-fault hypocenters. A prominent horizontal boundary striking a few degrees north of west with a prominent depth change in the seismicity cuts across Banning Pass towards San Bernardino. Earthquake swarms in the Salton Sea at the south end of the San Andreas fault suggest the presence of two north-northwest striking seismic zones at the south end of the San Andreas fault.

In the Los Angeles basin, the major aftershock sequences appear as densely focused clusters within a cloud of scattered background seismicity. The seismicity along the Newport-Inglewood fault forms a sharp alignment to the north and a diffuse distribution to the south, where the 1933 Long Beach earthquake occurred. Similarly, several clusters as well as scattered background seismicity extending from east to west across the basin illuminate the blind thrusts beneath the north edge of the basin.

The major aftershock sequences such as 1992 Landers, 1994 Northridge, and 1999 Hector Mine form clusters, with distinct internal structures, illuminating secondary faults and a heterogeneous main fault rupture surface. Some of these alignments suggest that high angle cross-faults were activated by the mainshock.

Cluster analysis approach

The cluster analysis approach obtains precise relative locations for the earthquakes by applying the source-specific station term (SSST) method to existing P and S phase picks and a differential location method to over 200,000 events within similar event clusters identified using waveform cross-correlation. The entire catalog is first relocated using existing phase picks and the SSST method of *Richards-Dinger and Shearer* (2000). Next, cluster analysis is applied to the waveform cross-correlation output in order to identify similar event clusters (*Shearer et al.,* 2003b). Because cross-correlation results are obtained for only some of all possible event pairs, some modifications to standard cluster analysis algorithms were necessary to achieve a suitable method. Earthquakes are then relocated within each similar event cluster using the differential times alone (e.g., *Got et al.*, 1994; *Shearer et al.*, 2003a), keeping the cluster centroid fixed to its initial SSST location. Standard errors are obtained for the relative locations from the internal consistency of differential locations between individual event pairs; these errors are often as small as tens of meters. In many cases the relocated events within each similar event cluster align in planar features suggestive of faults. There are a surprising number of conjugate faults at small scales that strike nearly perpendicular to the main seismicity trends. In general, the fine-scale details of the seismicity reveal a great deal of structural complexity in southern California fault systems. One prominent example is the events within the Brawley seismic zone in the Imperial Valley, which are organized into a series of parallel faults that are nearly perpendicular to the south-southeast trend of the zone itself.

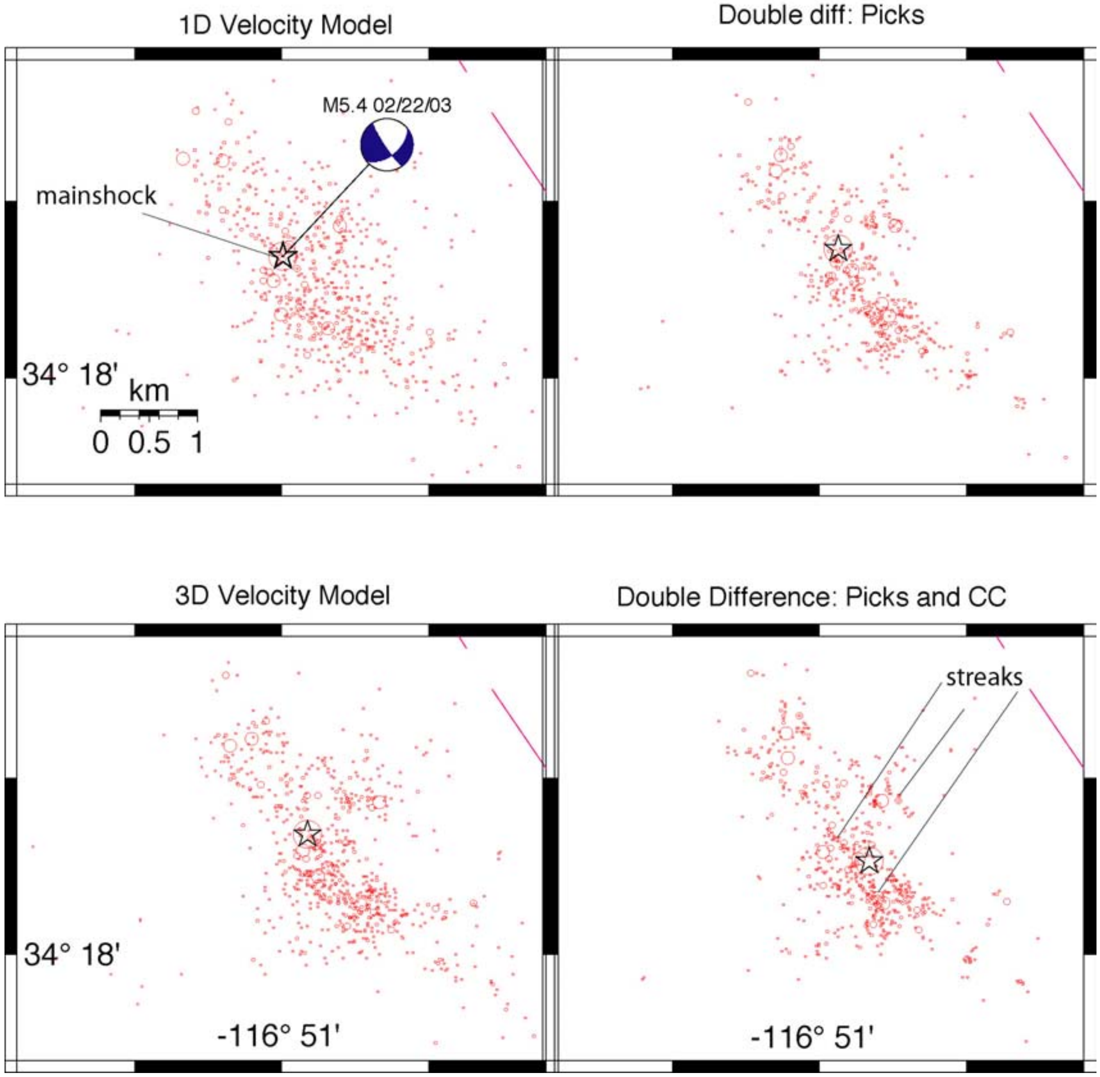

Figure 2. The 2003 ML5.4 Big Bear earthquake sequence. Comparison of hypocenters from 1-D and 3-D models as well as hypoDD using picks and cross-correlation differential times. The mainshock is shown as a star.

Results: The 2003 M_L5.4 Big Bear Earthquake

The M_L5.4 mainshock occurred at 04:19 am on 22 February 2003, located 2 miles north of Big Bear City in San Bernardino County at a depth of 3.7 miles. It was not preceded by foreshocks. It was followed by strong aftershock activity of 700 aftershocks during the first four months.

The mainshock exhibited strike-slip faulting on a steeply dipping (80°) plane striking N40°W, sub-parallel to the local strike of the Helendale fault. This mechanism is consistent with the mainshock being near the Helendale fault, a more than 40 mile long, late Quaternary fault in the Mojave Desert. Accurate locations of the aftershocks form a 3-km-long northwest-striking trend, located 2.5 km to the west of the main surface trace of the Helendale fault. Hence, this sequence may be occurring on a small sub-parallel fault, adjacent to the Helendale fault.

The relocations in Figure 2 show the comparison between hypocenters obtained with a 1-D model using hypoinverse and a 3-D model using simulps. We also show the results from hypoDD using picks only and picks and differential travel times from cross-correlation measurements. The use of the differential travel times is clearly necessary to bring the linear distributions of hypocenters, often called streaks, into focus.

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