# FINAL TECHNICAL REPORT
## Grant Number 01HQGR0098

# BROADBAND MODELING LOCAL AND REGIONAL SEISMOGRAMS; SOUTHERN CALIFORNIA

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## Investigations

In recent years, geologists and geophysicists have witnessed a revolution in the development and implementation of an array of new tools for measuring motions of the earth, including global positioning (CSIGN), interferometric synthetic aperture radar, and broadband digital systems (TriNet), allowing tremendous advances in motion detection. We have also developed analytical tools involving wavelet transforms, modified annealing methods, Pseudo-Green's functions, and theoretical transfer functions to explode these new data. Initial results from applying these tools to the Hector Mine data are very encouraging where we can recover kinematic models containing the details of slip, rise-time, and rupture velocities compatible with GPS, ground-breakage, and broadband seismic data. A complex pattern of rupture, results displaying a Y-shaped pattern of faulting apparently caused by the misalignment of the stress-field with the older fault system. The model predicts the InSAR data well and also agrees nicely with the developing aftershock patterns, see *Abstracts I and II*. Application of these methods to the Chi-Chi dataset is also producing some breakthroughs in understanding the details of rupture properties. The static solution is discussed in *Abstract III*. The papers recently published titled "Basin Structure Estimation by Waveform Modeling: Forward and Inverse Methods" by Chen Ji, Don Helmberger, and David Wald, and "Crustal complexity from regional waveform tomography; Aftershocks of the 1992 Landers earthquake, California" by Don Helmberger, X. J. Song, and L. Zhu are included in the references.

## Results

### 1. Source description of the 1999 Hector Mine, California earthquake; Part I: Wavelet Domain Inversion Theory and Resolution Analysis

**Chen Ji, David J. Wald, and Donald V. Helmberger**
**(*BSSA*, in press)**
(NOW published) *Bull. Seismol. Soc. Am.,* **92**, No. 4, 1192-1207 (2002)

*Short title*: Wavelet Domain Inversion Theory

**Abstract.** We present a new procedure for the determination of rupture complexity from a joint inversion of static and seismic data. Our fault parameterization involves multiple fault segments, variable local slip, rake angle, rise time and rupture velocity. To separate the spatial and temporal slip history, we introduce a wavelet transform which proves effective at studying the time and frequency characteristics of the seismic waveforms. Both data and synthetic seismograms are transformed into wavelets that are then separated into several groups based on their frequency content. For each group, we use error functions to compare the wavelet amplitude variation with time between data and synthetic seismograms. The function can be L1+L2 norm or correlative function based on the amplitude and scale of wavelet functions. The objective function is defined as the weighted sum of these functions. Subsequently, we developed a finite-fault inversion routine in the wavelet domain. A simulated annealing algorithm is used to determine the finite-fault model, which minimizes the objective function, described in terms of wavelet coefficients. With this approach, we can simultaneously invert for the slip amplitude, slip direction, rise time and rupture velocity efficiently. Extensive experiments conducted on synthetic data are used to assess the ability to recover rupture slip details. We also explore slip-model stability for different choices of layered earth models assuming the geometry encountered in the 1999 Hector Mine, California earthquake.

## 2. Source description of the 1999 Hector Mine, California earthquake; Part II: Complexity of slip history

**Chen Ji, David J. Wald, and Donald V. Helmberger**
**(*BSSA*, in press)**
(NOW published) *Bull. Seismol. Soc. Am.,* **92**, No. 4, 1208-1226 (2002)

*Short title*: Complexity Slip History

**Abstract.** We present a rupture model of the Hector Mine earthquake (M 7.1), determined from the joint inversion of strong motion records, P and SH teleseismic body waves, Global Positioning System (GPS) displacement vectors, and measured surface offset. We solve for variable local slip, rake angle, rise time and rupture velocity of a finite fault model involving multiple segments. The inversion methodology developed in (**Part I**) combines a wavelet transform approach with a nonlinear (simulated annealing) algorithm. The final model is checked by forward simulating the Interferometric Satellite Aperture Radar (InSAR) data with remarkable agreement. Our estimation to the seismic moment is 6.28 x $10^{26}$ dyne-cm, which is distributed along three segments from north to the south, releasing 37%, 41%, and 22% of the total moment, respectively. The average slip is 1.5 m with peak amplitudes as high as 7 m. The fault rupture has an average rise time of 3.5 sec and a relatively slow average rupture velocity (1.9 km/sec) resulting in a 14 s rupture propagation history. Our approach permits large variation in rupture velocity and rise time, and indicates that rise time appears to be roughly proportional to slip and shorter rise times are associated with the initiation of asperity rupture. We also find evidence for nearly simultaneous rupture of the two northern branches. Results obtained from extensive tests using various combinations of data are presented. A particularly attractive

combination for resolving fault complexity is the use of static and teleseismic waveforms, which implies that the slip history can be recovered well independent of local observations.

## 3. Slip distribution and tectonic implication of the 1999 Chi-Chi, Taiwan Earthquake

**Chen Ji, Donald V. Helmberger, Teh-Ru Song, Kuo-Fong Ma, and David J. Wald**
**(*GRL* in press)**
(NOW published) *Geophys.Res. Lett.,* **28**, No. 23, 4379-4382 (2001)

**Abstract.** We report on the fault complexity of the large (Magnitude 7.6) Chi-Chi earthquake obtained by inverting densely and well-distributed static measurements consisting of 119 GPS and 23 doubly integrated strong motion records. We show that the slip of the Chi-Chi earthquake was concentrated on the surface of a "wedge shaped" bloc. The inferred geometric complexity explains the difference between the strike of the fault plane determined by long period seismic data and surface break observations. When combined with other geophysical and geological observations, the result provides a unique snapshot of tectonic deformation taking place in the form of very large (>10m) displacements of a massive wedge-shaped crustal block, which may relate to the changeover from over-thrusting to subducting motion between the Philippine Sea and the Eurasian plates.

## References

Helmberger, Donald V., X. J. Song, and L. Zhu, Crustal complexity from regional waveform tomography: Aftershocks of the 1992 Landers earthquake, California, *J. Geophys. Res.*, **106**, No. B1, 609-620, 2001.

Ji, Chen, Don V. Helmberger, and David J. Wald, Basin Structure Estimation by Waveform Modeling: Forward and Inverse Methods, *Bull. Seismol. Soc. Am.*, **90** (4), 964-976, 2000.

Ji, Chen, David J. Wald, and Donald V. Helmberger, Source description of the 1999 Hector Mine, California earthquake; **Part I:** Wavelet Domain Inversion Theory and Resolution Analysis, *Bull. Seismol. Soc. Am.*, **92**, No. 4, 1192-1207 (2002).

Ji, Chen, David J. Wald, and Donald V. Helmberger, Source description of the 1999 Hector Mine, California earthquake; **Part II:** Complexity of slip history, *Bull. Seismol. Soc. Am.*, **92**, No. 4, 1208-1226 (2002).

Ji, Chen, Donald V. Helmberger, Teh-Ru Alex Song, Kuo-Fong Ma, and David J. Wald, Slip distribution and tectonic implication of the 1999 Chi-Chi, Taiwan Earthquake, *Geophys. Res. Lett.*, **28**, No. 23, 4379-4382 (2001).