Final Technical Report

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Abstract

We have undertaken investigations to improve our ability to determine earthquake finite source parameters and to estimate near-source *ShakeMaps* using regionally recorded seismic data. The first step in estimating a *ShakeMap* is to determine the fault slip distribution. To do this we have developed two procedures. The first utilizes empirical Green's functions (eGf) to obtain a clear estimate of the earthquake's seismic moment rate function (MRF). These MRFs are then inverted for slip distribution on the fault plane. The second method utilizes theoretical Green's functions and a direct inversion of the regional three component waveform data for the distribution of fault slip. We found that it was possible to obtain a reasonable estimate of the slip distribution for the Northridge earthquake using either method. Our slip maps for the Northridge earthquake are found to compare well with those obtained using near-field strong motion recordings (e.g. Zeng and Anderson, 1996; Wald and Heaton, 1994, 1996). Using either of our methods we are able to resolve the fault plane ambiguity and characterize the directivity of the earthquake. We have also tested our theoretical Green's function approach on the 1992 Landers earthquake and have obtained results that compare remarkably well with those of Cohee and Beroza (1994ab) even though we use only the four closest TERRAscope stations in our analysis. Regional broadband data is continuously recorded and near-realtime telemetered both of which allow for very rapid analysis of the finite nature of earthquake sources. These rapidly determined slip maps may then be used to predict the distribution of strong shaking (*ShakeMaps)* in the near-source region. Our preliminary comparisons of our predicted *ShakeMaps* with actual strong motion observations indicates that it should be possible to obtain estimates of near-source shaking level for earthquakes in all areas of broadband station coverage not just areas that have dense strong motion instrument deployments.

Investigations Undertaken

1. Refine eGf inverse procedures and assess the resolution and uncertainty of the methodology.

2. Refine existing automated moment tensor algorithms such that rapid quantification of point-source properties and identification of potential eGfs becomes a robust and routine practice.

3. Test both empirical and theoretical Green's function methods of estimating finite fault parameters on several recent earthquake sequences.

Reports Published and Meeting Presentations

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Results

At the time of our application for a no cost extension we had completed the first two phases of the project. The no cost extension was to complete work on the development of a waveform inversion code for earthquake finite source parameters utilizing theoretical Green's functions, and to test the code on several recent earthquakes. This work has been completed and is described below in section 3.

1. Refinement of eGf Inverse Procedure: We have developed both frequency domain and time domain code to perform eGf deconvolution. When applied to our data sets both deconvolution codes yield essentially the same MRFs, however the time domain code affords greater flexibility by allowing for the addition of causality and positivity constraints. Furthermore, using the time domain code we are able to invert three-component data simultaneously to determine the common MRF. In addition, we completed an analysis of the sensitivity of the MRF inverse procedure using the Northridge station geometry. The following outlines the primary results of the sensitivity analysis:

1. The optimal location of the eGf used to estimate a representative far field moment rate function (MRF) is near the slip centroid of the mainshock and not the high frequency hypocentral location.

2. The method of estimating whole waveform deconvolutions and then stacking the three-component results yields stable and robust MRFs at regional distances.

3. The deconvolution results are more sensitive to the relative depth of the eGf then they are to the eGf's lateral position on the fault. The apparent reason for this is that large

differences in depth between the eGf and the main event result in different excitation of seismic depth phases.

4. The regional application of Mori and Hartzell's (1990) inverse procedure is capable of recovering the gross distribution of fault slip. The results obtained for the Northridge mainshock using this method (Dreger, 1994) compare favorably with the strong motion results of Wald and Heaton (1994, 1996) and Zeng and Anderson (1996).

5. It is not possible to resolve slip below the level of 5-10% of the peak slip using the MRF technique.

Figure 1ab shows the input and inversion derived slip distribution for a synthetic test case. Figure 1c shows the geometry of the sensitivity test. Figure 2a illustrates the three-component deconvolution at station GSC. Figure 2b illustrates the stacked deconvolutions that are obtained for PFO using each of the eGf locations defined on Figure 1a. Figure 3 compares the synthetic moment rate data with synthetics computed from the model in Figure 1b. This inversion was performed with the MRF derived from the eGf located at the center of the fault. As Figure 1ab shows it is possible to recover the gross distribution of slip and the locations of principal asperities quite well. The multiple phases in the MRF shown on Figure 3 result from radiation from each of the asperities in the slip model. The area of low slip amplitude extending to the left of the hypocenter in the input model is not well recovered and in fact it is not possible to resolve slip in this region of the fault. The small asperity near the hypocenter is recovered fairly well however.

Our slip map obtained for the Northridge mainshock using the eGf approach (Figure 4) was found to compare favorably with those obtained from local (<30 km) strong-motion data (e.g. Wald and Heaton, 1994, 1996; Zeng and Anderson, 1996). This is an important result because in contrast to the strong-motion studies our results were obtained at regional distances (100 to 430 km) using telemetered broadband data. The rapid telemetry of such data affords the possibility of obtaining finite source parameters of the detail shown for events throughout California in a timely manner provided that a suitable eGf can be found. In section 3 we illustrate that it is possible to obtain comparable results using theoretical Green's functions.

In addition, Figure 4 illustrates that with the tools developed under this contract it is possible to characterize the source processes of large aftershocks as well as the mainshocks. In this way we are able to map out the distribution of slip for earthquake sequences rather than events. As was shown for Northridge (Dreger, 1997) this enables a greater understanding of fault segmentation and the related restraints on earthquake rupture. Briefly, in Dreger (1997), it was found that small aftershocks were clustered near the edges of maximum slip, and that the mainshock and the Mw 6 aftershock 11 hours later (Jan 17, 1994; 23:33UTC) were arrested by a pronounced bend in the fault plane. This bend was also observed in the aftershock seismicity (Hauksson et al., 1995) and is called the Gilibrand Canyon Lateral Ramp.

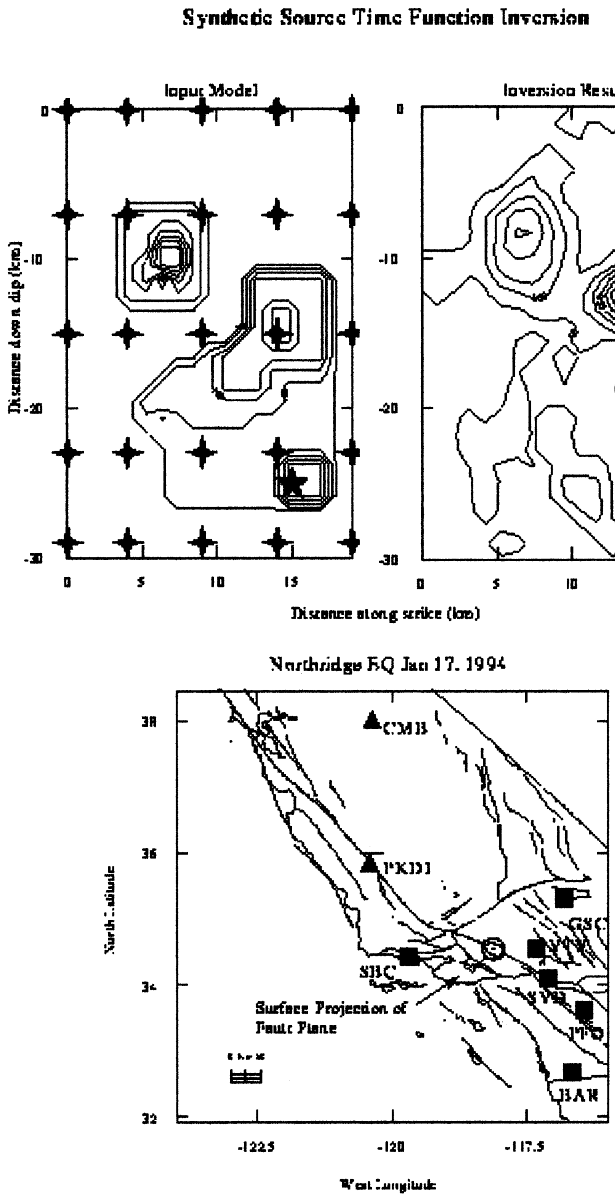

Figure 1. a) Input slip model. The slip level is in centimeters. Star denotes the hypocenter and the plusses denote the test eGf locations. b) Slip map obtained from the inversion of MRF derived from synthetic mainshock and eGf data. Note the correct positioning of asperities and the lack of resolution of low slip regions. c) Map showing location of stations used in the synthetic test inversion.

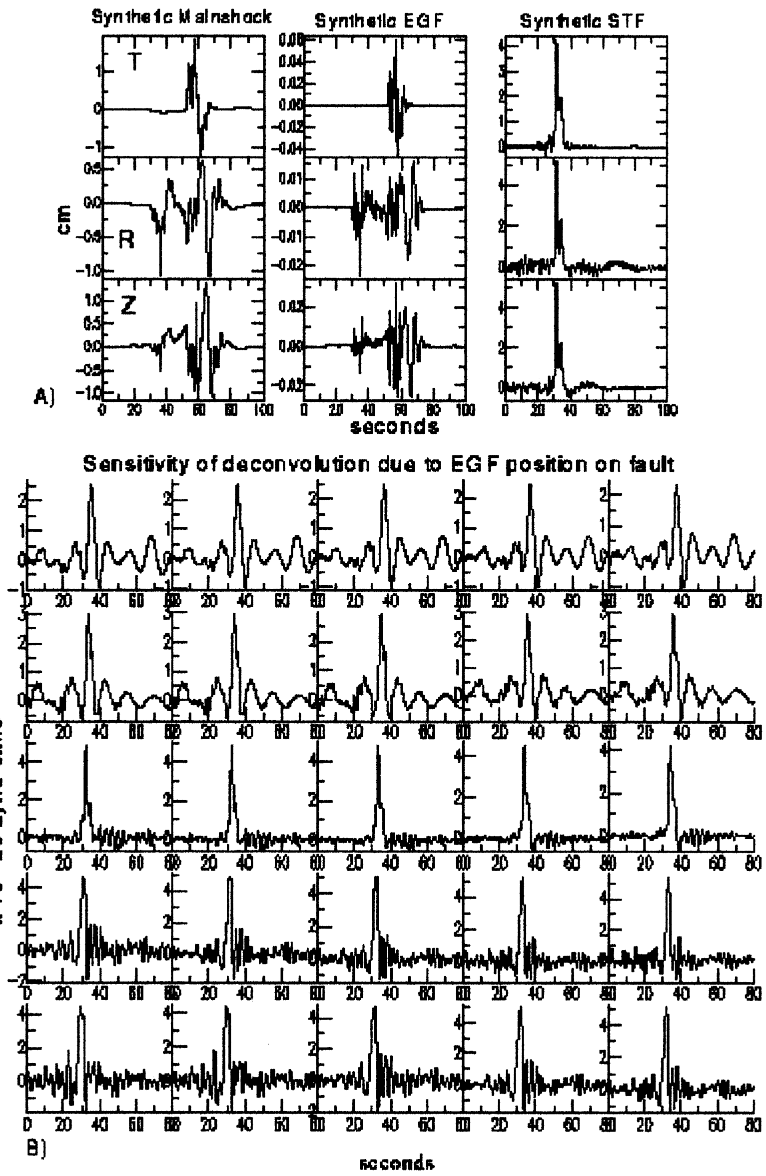

Figure 2. a) Example of a three-component deconvolution of complete regional seismograms. The synthetic data was computed by summing point-sources distributed across the model shown in Figure 1a. The synthetic mainshock thus incorporates waveform distortion due to lateral distance changes and differences in relative source depth. The use of a single eGf is therefore considered a source of noise in this test and in real applications. b) Three-component deconvolutions computed using eGf at each of the locations shown on Figure 1a. Note that the most stable deconvolutions result when the eGf is located close to the slip centroid. This figure demonstrates that the deconvolution procedure is less sensitive to lateral position of the eGf and more sensitive to the relative depth of the eGf.

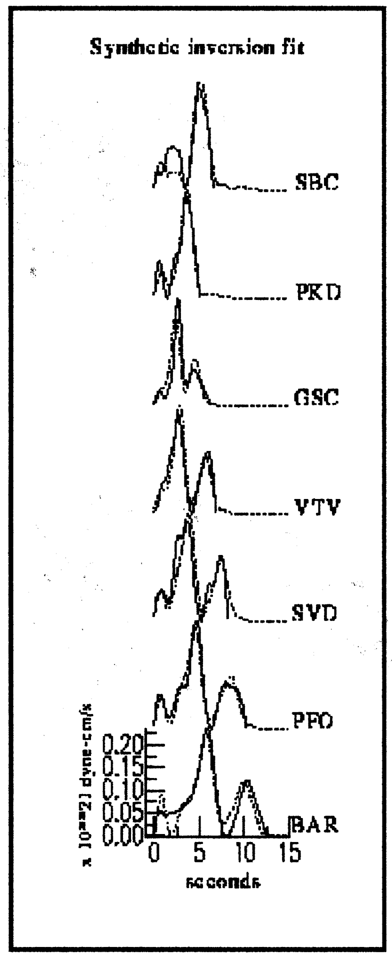

Figure 3. MRF data (solid) are compared to synthetic MRF (dashed) computed from the model shown in Figure 1b.

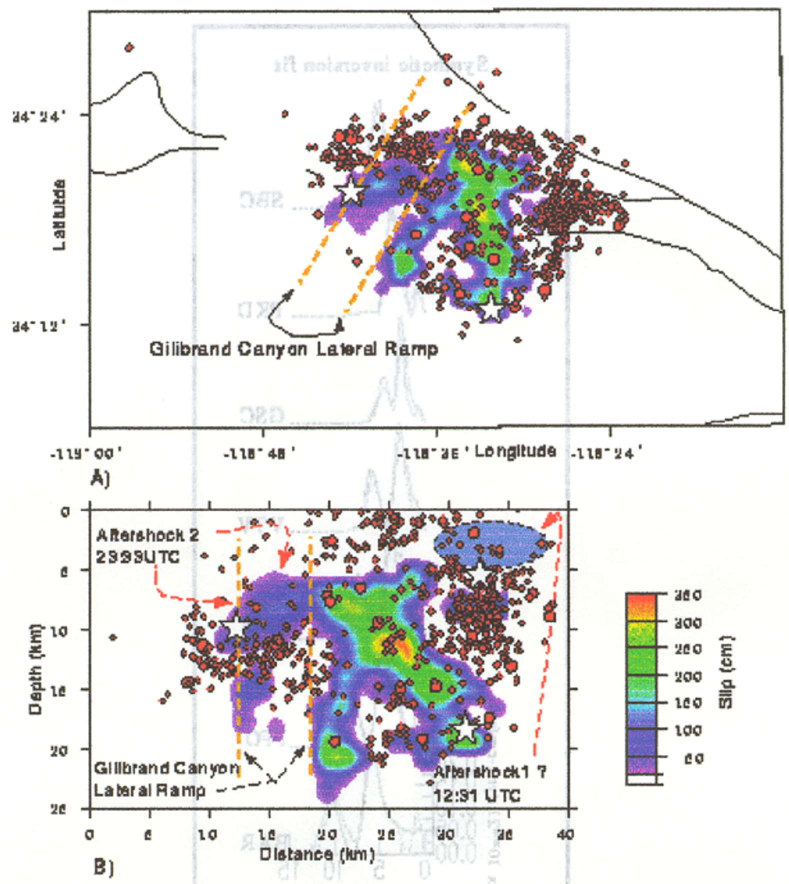

Figure 4. a) Map view of in-plane M≥2.5 aftershocks (circles) and fault slip for the mainshock and an aftershock that occurred 11 hours after the mainshock (aftershock2). The aftershock slip is confined to the region between the orange dashed lines marking the position of the Gilibrand Canyon Lateral Ramp (e.g. Hauksson et al., 1995). Hypocenters of Mw>6 events are plotted as stars. b) West-east cross-sectional view of fault slip and the M≥2.5 aftershocks. The rupture area of aftershock1 (a Mw 6 event that occurred 60s after the main event) is inferred from the lack of mainshock slip and small aftershocks in the region updip from the mainshock hypocenter. This slip map was obtained from MRF derived from eGf deconvolution. See Dreger (1997) for a complete discussion.

2. Refinement of the Moment Tensor Codes. We have refined the moment tensor codes to perform a more exhaustive search of the depth parameter space. The catalog of Green's functions has been extended to include sources between 5 to 39 km depth at 3 km intervals. Other refinements focused on reducing run time and increasing the stability of the program. Both the time domain and surface wave amplitude and phase spectra inverse codes (e.g. Pasyanos et al., 1996) have been fully integrated into the automated processing of the Rapid Earthquake Data Integration (REDI) system (Gee et al., 1996). The redesigned codes utilize UNIX environment variables that enable on the fly control of the operating environment, such as station lists, data streams, and Green's function lists, without the need to recompile code or maintain fixed path links. This modification was an essential step in the integration of the codes into the REDI processing stream. The Berkeley Seismological Laboratory moment tensor results are also reported on the worldwide web at:

http://www.seismo.berkeley.edu/~dreger/mtindex.html

Development of Waveform Inversion Method for Fault Slip. We have developed an inverse routine that fits theoretical Green's functions to regional data to determine finite source parameters. We have applied this code to both the 1992 Landers and 1994 Northridge earthquakes. For both events we have compared the solutions we obtain from a sparse regional network with solutions obtained using local strong motion data with excellent results. For example, Figure 4 shows a slip map obtained for the Northridge mainshock and large aftershock using the eGf approach (Dreger, 1994, 1997). Figure 5b compares the slip map obtained using only the TERRAscope stations shown and Green's functions computed using the SoCal (Dreger and Helmberger, 1993) velocity model appropriate for southern California. The degree of similarity in the slip maps, notably in the overall extent of rupture both along strike and updip and also in terms of the asperity located at 20 km depth on the western edge of the slip map is clear. Correlation of the maps in Figures 4b and 5b together with the correlation with the strong motion studies mentioned previously suggest that we can use these slip maps to predict strong shaking in the near-source region. This is the premise of continued work in which we are comparing our predicted *ShakeMaps* with observed strong motions for the 1994 Northridge and 1992 Landers Earthquakes. Preliminary results are shown in Figure 6 in which the slip shown in Figure 5b is projected to the surface using hard rock Green's functions (e.g. Wald and Heaton, 1996). Our *ShakeMap* does a reasonable job explaining the observations however it is necessary to investigate the effects of different near-source velocity models, site specific amplification factors, and additional complexity in the source process. This work is being continued.

Finally, we have performed the slip map inversions for the 1992 Landers earthquake. For this event we were able to determine the fault plane and a gross slip distribution which clearly shows unilateral northward directivity. In this study we used only the four closest TERRAscope stations that were operating at the time. Even though we used a sparse network of stations located at distances beyond 60 km we were able to determine a slip map that compares well with results obtained using TERRAscope and many additional strong motion stations (e.g. Cohee and Beroza, 1994ab). Figure 7 compares our slip map solution with the solution reported by Cohee and Beroza (1994ab). There is a striking similarity in the two slip maps, particularly in the amplitude and extent of slip, suggesting that our map could be used to determine a near-source *ShakeMap* that would fit the strong motion data reasonably well.

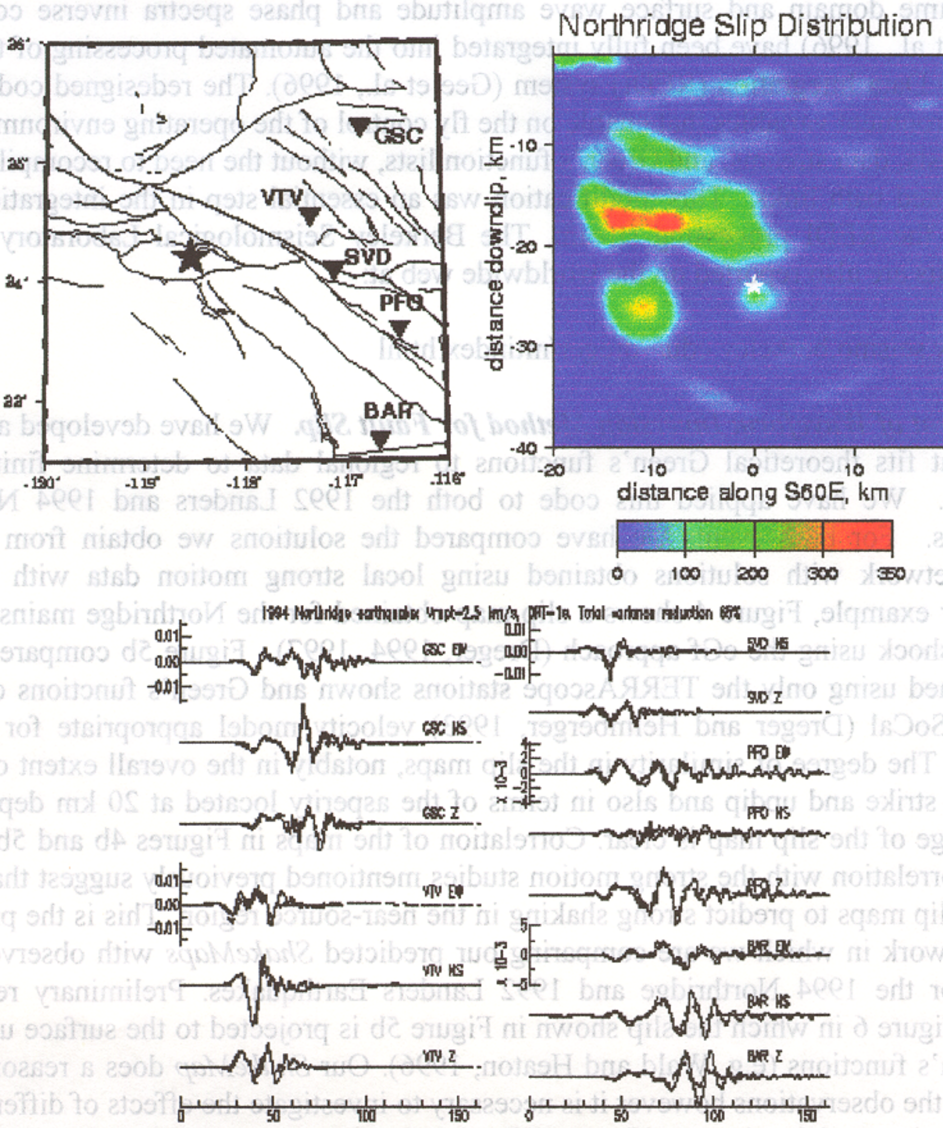

Figure 5. a) Map showing the locations of TERRAscope stations used in the inversion for slip distribution of the Northridge earthquake. b) Slip distribution for the Northridge earthquake. Slip amplitude is in cm. c) Comparison of displacement data (solid) and synthetic seismograms computed using the slip map shown in (b). Note that the agreement is very good considering whole, three-component displacement waveforms were used in the inversion.

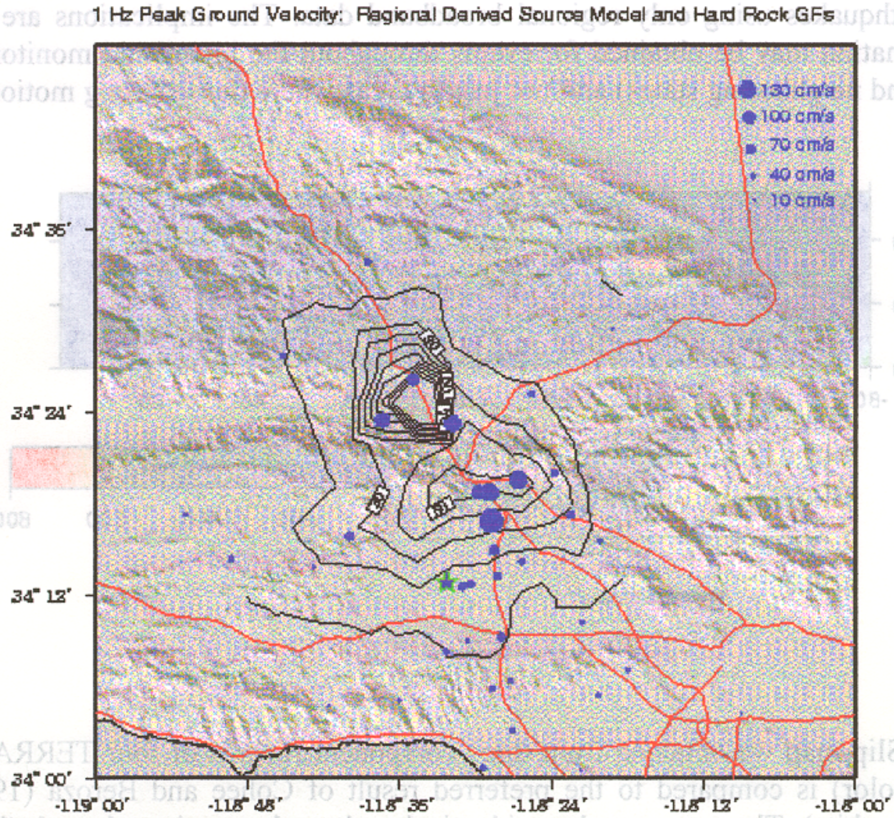

Figure 6. Predicted *ShakeMap* generated from the slip model shown in Figure 5b and hard rock Green's functions computed from a model reported on by Wald and Heaton (1996). The contours represent 20 cm/s increments in peak horizontal ground velocity and they clearly show the northward directivity focussing of energy. The blue circles are scaled to peak horizontal ground velocity and show the actual values recorded at CDMG and USGS strong motion sites.

Because we are proposing that this analysis may eventually be coded into an automated processing stream we need to provide a model with sufficient dimension to allow for all possible rupture scenarios. Most importantly we must allow for unilateral rupture in any direction from the hypocenter confined to the two possible fault planes. We need to independently determine the fault plane, as this analysis will be done before aftershocks have occurred in sufficient numbers to map it out. As a consequence, our model space is nearly four times larger than Cohee and Beroza's (1994ab). This is compensated for by considering simpler source models in which rupture velocity and dislocation rise time are constant during the entire rupture. Nevertheless, the four TERRAscope stations were found to be sufficient to determine that the Landers earthquake ruptured unilaterally to the north, at shallow depth (less than 15 km). This example clearly shows that it is possible to resolve the fault plane ambiguity, rupture directivity, gross slip distribution, and potentially near-source *ShakeMaps* for large earthquakes using only regional broadband data. The implications are that finite source information may be obtained for events throughout the broadband monitoring region (California and neighboring states) and not just in areas where dense strong motion networks exist.

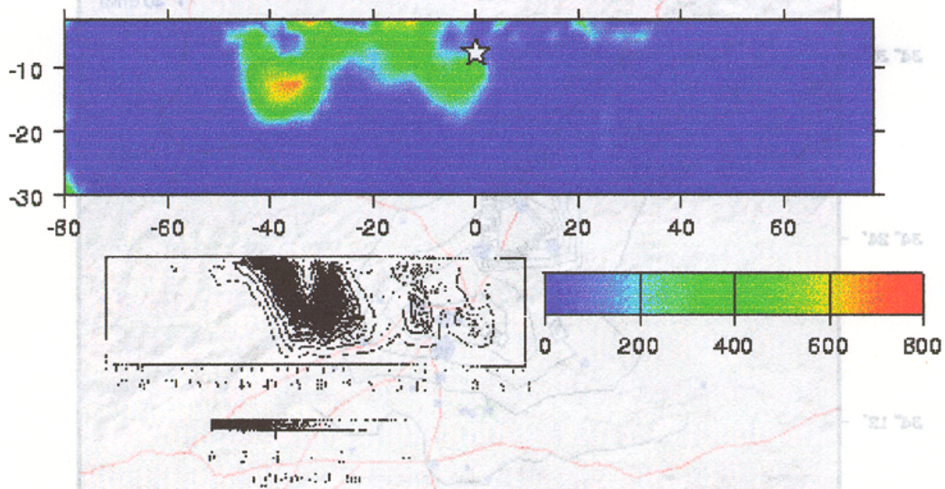

Figure 7. Slip map we obtained from three-component records of four TERRAscope stations (color) is compared to the preferred result of Cohee and Beroza (1994ab) (black and white). The two maps have identical scale and are oriented north (left) to south (right). The slip contours shown are in cm. The peak slip in the Cohee and Beroza (1994a) model is 6m. Unfortunately the scanned image of the Cohee and Beroza (1994a) model is bitmapped and not well reproduced however the overall dimension, peak slip, and slip partitioning are clearly very similar in the two models.

Conclusions

In the conclusion of this project we have accomplished the necessary steps to integrate our moment tensor algorithms into the Berkeley Seismological Laboratory automated processing stream. At the writing of this final report this automatic information is provided to the Menlo Park office of the US Geological Survey. We "broadcast," via internet email, human reviewed moment tensor information routinely and often within 30 minutes of the occurrence of an earthquake in the northern California region and vicinity. We have refined the tools necessary for the estimation of finite source parameters (fault slip maps) of earthquakes utilizing regional distance seismograms, and we have begun to reconcile predicted near-source *ShakeMaps* obtained using our derived fault slip maps with the observations. This of course is a continuing project, however from our analysis thus far, it appears that it is entirely possible that this predicted *ShakeMap* information may be rapidly and automatically determined after large earthquakes occurring throughout the recording region of the Berkeley Digital Seismic Network. This next step is the focus of continued study and it is our goal to develop automated software to provide this information within 30 minutes following large and potentially damaging earthquakes.

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