MODELING THREE-DIMENSIONAL WAVE PROPAGATION IN THE SAN FRANCISCO BAY AREA: ANNUAL PROJECT SUMMARY DECEMBER 20 1999.

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Investigations Undertaken

Under the current funding we have completed work on tasks 1, 2, and we have published our research results describing the simulation of Loma Prieta strong ground motions (Stidham et al., 1999a). Tasks 3 and 4 were stricken at the request of the panel and due to the reduced funding level. For tasks 1 and 2 we have conducted investigations in the following areas:

- Finalized our initial modeling of the Loma Prieta earthquake and published the results in the Bulletin of the Seismological Society (Stidham et al., 1999a).
- Performed comparison simulations for weak and strong motion events using the 3D velocity model developed by the USGS (e.g. Brocher et al., 1998).
- Explored the variation in predicted strong ground motion that results from uncertainty in assumed source parameters, particularly published kinematic source models for the 1989 Loma Prieta earthquake.
- Verification/validation of the 3D velocity model by comparing simulated ground motions for strong and weak motion events. Data and predicted ground motions were compared in terms of peak ground velocity and seismic waveform.

Results

Comparison Simulations using USGS 3D Velocity Model:

We have performed ground motion simulations using the 3D elastic finite difference code, e3d, developed by Shawn Larsen of the Lawrence Livermore National Laboratory (Larsen and Schultz, 1995). Simulations were performed for the 1989 M_W 6.9 Loma Prieta and 1998 M_W 5.1 San Juan Bautista earthquakes using a reference 1D velocity model, a 3D velocity model we developed (3D Model) in a previous contract (e.g. Stidham et al., 1999a) and the USGS 3D velocity model (USGS Model) developed by Brocher et al. (1998). For each of the events an identical source function was used in the different velocity model simulations. The results of these simulations have demonstrated that considering 3D Earth structure improves ground motion estimates compared to estimates made using 1D velocity models, and that there are substantial differences in simulated ground motions for the two 3D velocity models that need to be reconciled.

To illustrate the differences in simulated ground motions for the two 3D models we calculate the maximum of the geometric mean of the horizontal velocity components, which we refer to as the maximum peak horizontal velocity (MPGV). Figure 1 shows simulations for the UCB Model and the

USGS Model using the strong motion finite source slip model of Wald et al. (1991), herein referred to as WALDSM. The USGS model produces larger MPGV west of the San Andreas Fault (SAF), which is due to source directivity and the presence of shallow basin structure in the region. The UCB Model has no basin structure west of the San Andreas Fault and defines the Salinian block as a single unit. In addition the UCB Model has a pronounced velocity contrast across the SAF where the Salinian block is on average 10% faster at seismogenic depths. As reported in Stidham et al. (1999a) the SAF velocity discontinuity refracts energy to the east reducing amplitudes in the forward directivity region northwest along the San Francisco Peninsula and increasing, slightly, the input ground motion levels in the western Cupertino basin of the Santa Clara Valley (SCV). Both models have the largest basin amplitudes in the Cupertino basin, but the UCB model also has moderate MPGV levels in the eastern Evergreen basin whereas the USGS model produces very low MPGV levels in that area. At larger distances the level of MPGV in the Livermore Valley and San Pablo Bay are greater in the UCB Model than in the USGS Model, which is likely due to differences in the velocity gradients in the upper crust and deep crust discontinuities that may affect the amplitudes of the incident wavefield at large distances. As noted earlier we used the WALDSM slip model in these calculations, however given the different near-source seismic velocities in the two 3D structure models an identical slip model would result in different scalar seismic moment for each calculation. In fact, the scalar seismic moment of the UCB simulation is $4.2*10^{26}$ dyne-cm and in the USGS simulation it is 3.1*1026 dyne-cm. In Figure 1 we have adjusted the USGS Model MPGV values by multiplying by a factor equal to the ratio of the scalar seismic moments. Thus the amplitudes were increased by 35% and the ground motions are still much lower in the basins than in the UCB model.

As discussed in Stidham et al. (1991a) the predicted MPGV obtained using the WALDSM source and the UCB Model agree well with observations. Four stations located in the SCV, namely ASH, SAR, SJI, and SUN, match observed MPGV quite well (compare Figure 2A and 2B). Station SJI located just south of the SCV is significantly over predicted. The UCB Model also slightly over predicts MPGV in San Francisco and in the east bay, however we are pleased with the performance of the model given the fact that it was derived independently of the Loma Prieta strong motion data. The ratio plot Figure 2C highlights problem sites such as HOA where we significantly under-predict MPGV, and sites near San Lorenzo where we significantly over-predict MPGV. Sites in the SCV are found to have ratios fairly close to 1. The under-prediction at HOA may be due to the lack of basin structure representing the Salinas Valley. The USGS Model on the other hand includes the Salinas Valley and the fit to HOA is significantly better. Two of the SCV sites are significantly under-predicted by the USGS Model, and station COR, closest to the epicenter of the earthquake, is greatly over-predicted. Generally the USGS Model MPGV in San Francisco are under-predicted. Adjusting the scalar seismic moment of the calculation would improve the under-predictions to a degree, but would worsen the misfit at sites that are being over-predicted. These simulations have proven very useful for several reasons. First, they demonstrate the level of variability that can arise given two 3D velocity structures that attempt to approximate the same crustal structure. Second, both models are found to better-fit subsets of the total data set therefore it is possible to attempt to combine the successful parts of each model to arrive at a comprehensive structure that can be used in simulations of future earthquake scenarios. Our current modeling is focusing on the SCV where there is a more extensive and growing data set with the type of coverage needed to calibrate the basin structure.

Several small to moderate events were recorded by the Santa Clara Valley Seismic Experiment (SCVSE, June-December 1998) dense array. The largest local event recorded by the array occurred approximately 55 km to the south on August 12, 1998. A number of the short-period stations in the SCVSE clipped, however the remaining stations provide a superior data set to investigate SCV structure than is available from the Loma Prieta strong motion data set. In Figure 3 we compare observed MPGV with those calculated using the UCB Model, the reference 1D velocity model and the

USGS Model. In these simulations a point-source model was assumed to adequately represent the source of the earthquake, and the seismic moment tensor solution reported in Uhrhammer et al. (1999) was used. Thus all of the simulations had an identical scalar seismic moment. As was the case for the Loma Prieta earthquake we find that the UCB Model best predicts the observed MPGV. The observations (Figure 3A) show that both deep basins in the SCV produce elevated ground motions, and the UCB Model (Figure 3B) generally reproduces the observed pattern. There are discrepancies at individual stations that may be due to incorrect basin structure or also unaccounted for site response. For the 1D model (Figure 3C) we find that the MPGV decrease with distance from the source, under-predict sites over the deep basins, and that they significantly over predict ground motions south of the SCV. In this region the surface velocities of the 1D Model are less than they are in either of the 3D models. The USGS Model provides the best fit to the southern SCV stations (identified by the asterix on Figure 3A), whereas the UCB Model tends to under-predict MPGV at these stations indicating that either the basin structure and/or the surface velocity structure needs to be adjusted. Neither of the 3D models reproduce the detailed patterns observed at sites over the deepest parts of the SCV basin, however the UCB model does tend to describe the relative excitation of the two deep basins relatively well.

A problem with the San Juan Bautista data set is the number of clipped stations. Several smaller events were recorded and those with adequate signal-to-noise levels will be incorporated into our study. Future work will focus on combining aspects of the two models that appear to best fit the data. For example we will attempt to refine our deep basin structure to improve the fits to stations within the basins, and incorporate the southern basin boundary structure of the USGS model that fits those stations so well. We will focus our attention on the general (large-scale) patterns in the ground motions and lower frequency waveforms as individual stations may also be due to unaccounted for site response. The smaller events recorded by the SCVSE, located at different azimuths from the SCV, are expected to produce different excitation of basin generated waves and amplification patterns that will help in the modeling. Finally, we are also integrating teleseismic P-wave data recorded by the SCVSE, which clearly shows basin generated traveltime delays, primary wave amplification, and coda development (Stidham et al., 1999b).

Ground Motion Sensitivity to input Finite Source Model:

We have made progress in our effort to characterize ground motion variability due to differences in the input finite source model. We have simulated Loma Prieta ground motions for several point-source and multiple point-source models, as well as, the WALDSM, teleseismic (WALDTS) and combined (WALDCB), and Beroza (1991) (BEROZAMS) finite fault slip models. The best agreement to observed MPGV was obtained using the WALDSM source as presented in Figure 2B. We find considerable variability in the predicted MPGV due to the different finite fault models, which underscores the need to focus on smaller earthquakes with simpler sources, and well-recorded teleseisms in which all SCVSE stations “see” the same source time function, in the calibration of 3D structure. Figure 4AB illustrates the variability in predicted MPGV for the WALDSM and the BEROZASM finite fault slip models. The Wald model produces a MPGV pattern, which suggests a unilateral rupture. Although the WALDSM is bilateral most of the slip in the northwestern asperity and therefore the MPGV has a unilateral pattern. The BEROZASM model has the largest slip in the southeastern asperity and the distribution of slip is more symmetrical about the hypocenter resulting in a bilateral MPGV pattern. The ratio plot (Figure 4D) highlights the differences between the two models and shows that the ratios range between 0.25 to 4.0. The different Wald et al. (1991) models are more similar, however the ratio plot comparing his strong motion and teleseismic models (Figure 4C) shows a range of 0.5 to 1.8. In either case these are significant differences that need to be

reconciled if possible with the Loma Prieta strong motion data. In the least they demonstrate that in the simulation of ground motions for future earthquake scenarios a large number of finite source model realizations will be needed to account for the variability. To further document the variability in estimated ground motions due to input source model we plan to perform the same calculations using the USGS Model, and if time permits we may perform simulations using one of the other published finite source models.

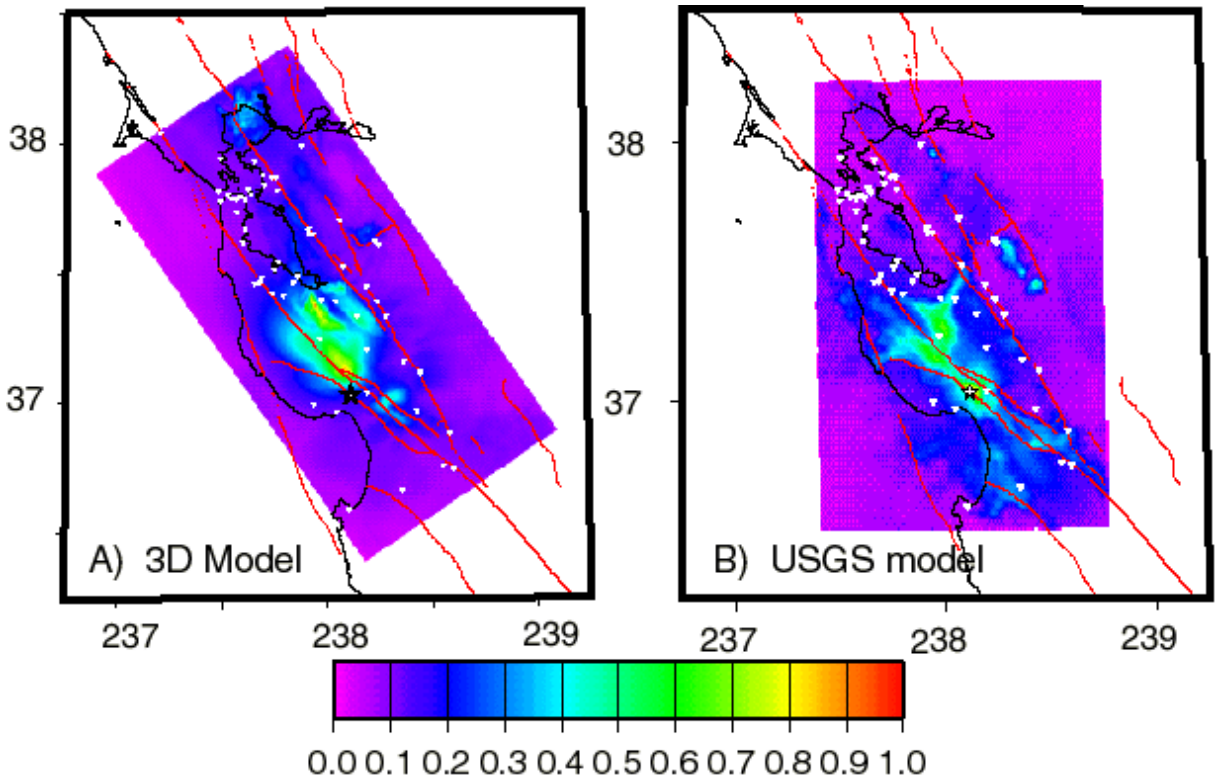

Figure 1. A) MPGV simulation using the UCB Model and the strong motion finite source model of Wald et al. (1991). The color bar shows MPGV in units of m/s. B) Same as (A) using the USGS Model. The values shown have been increased by 35% to equalize the scalar seismic moment in the two runs. The small white triangles show the locations of CDMG and USGS strong motions stations used in our analysis.

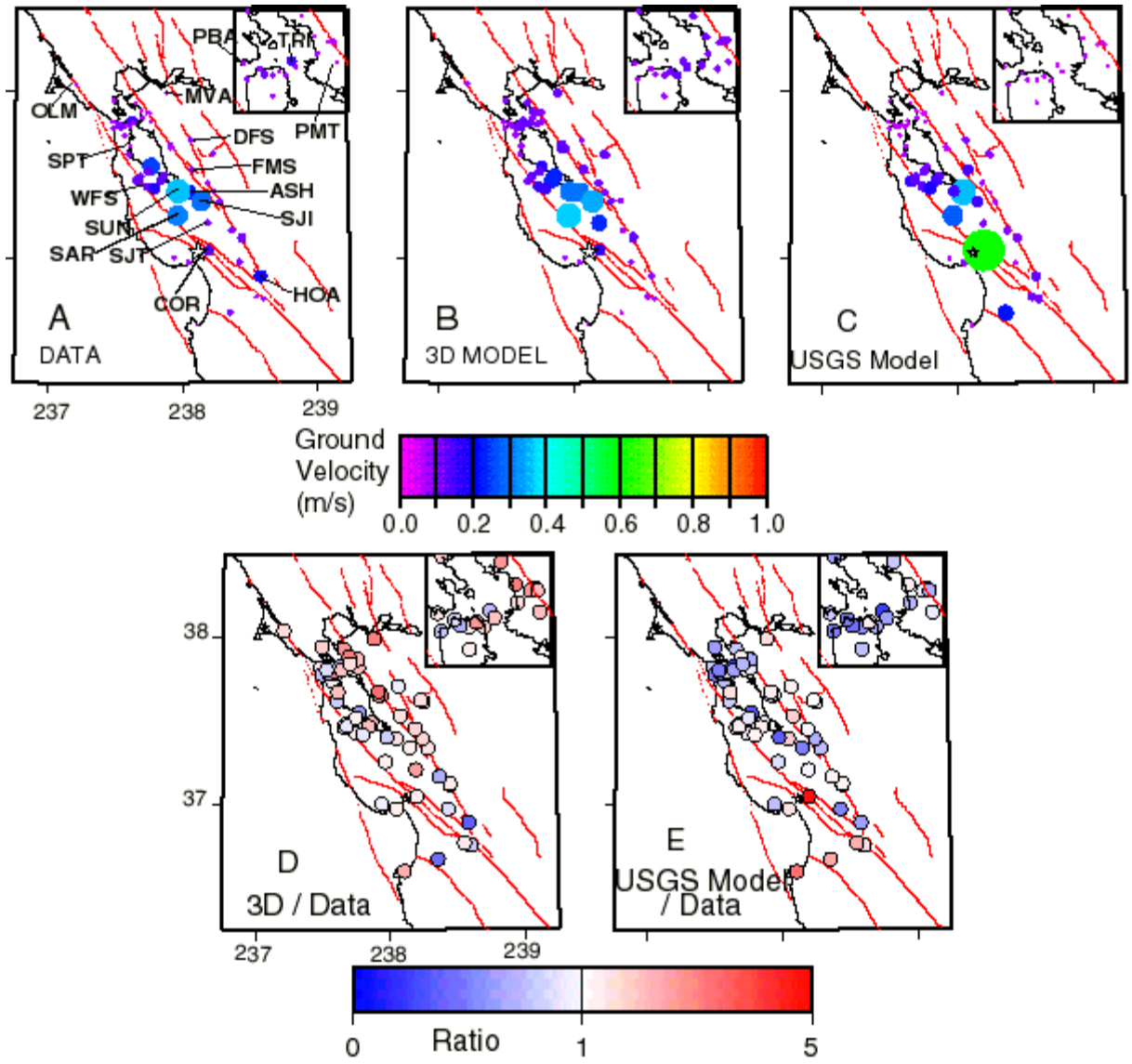

Figure 2. MPGV for the 1989 Loma Prieta earthquake calculated after low pass filtering observed and synthetic velocity seismograms at a corner frequency of 0.8 Hz. A) Observed MPGV. Symbol size is scaled to the peak ground motion and the color bar gives the ground motion level in units of m/s. B) MPGV calculated using the UCB Model and WALDSM. C) Same as (B) using the USGS velocity model. D) Ratio of UCB Model predictions to observations. Red colors indicate over prediction. E) Ratio of USGS Model predictions to observations. Red colors indicate over prediction.

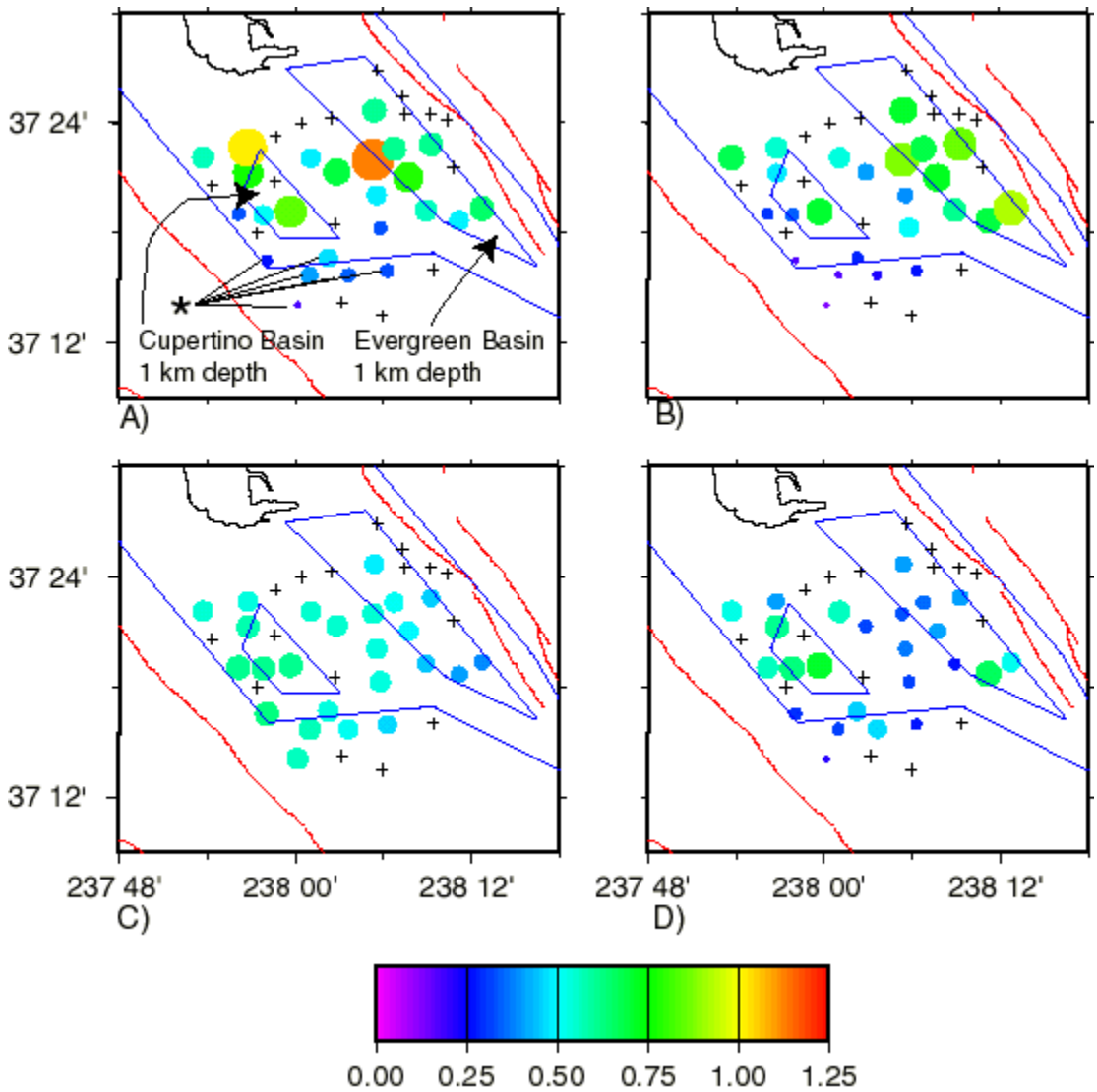

Figure 3. MPGV for the August 12, 1998 San Juan Bautista earthquake calculated after low pass filtering observed and synthetic velocity seismograms at a corner frequency of 0.5 Hz. A) Observed MPGV. Symbol size is scaled to the peak ground motion and the color bar gives the ground motion level in units of cm/s. Plusses show clipped stations. B) Predicted peak horizontal ground velocity calculated using the UCB velocity model and point-source parameters reported in Uhrhammer et al. (1999). The synthetic seismograms were processed the same way as in (A). C) Same as (B) for the 1D velocity model. D) Same as (B) for the USGS velocity model. Blue lines show the outline of alluvium (Vs=1 km/s) and the 1 km isopachs of the basin structure in the UCB Model.

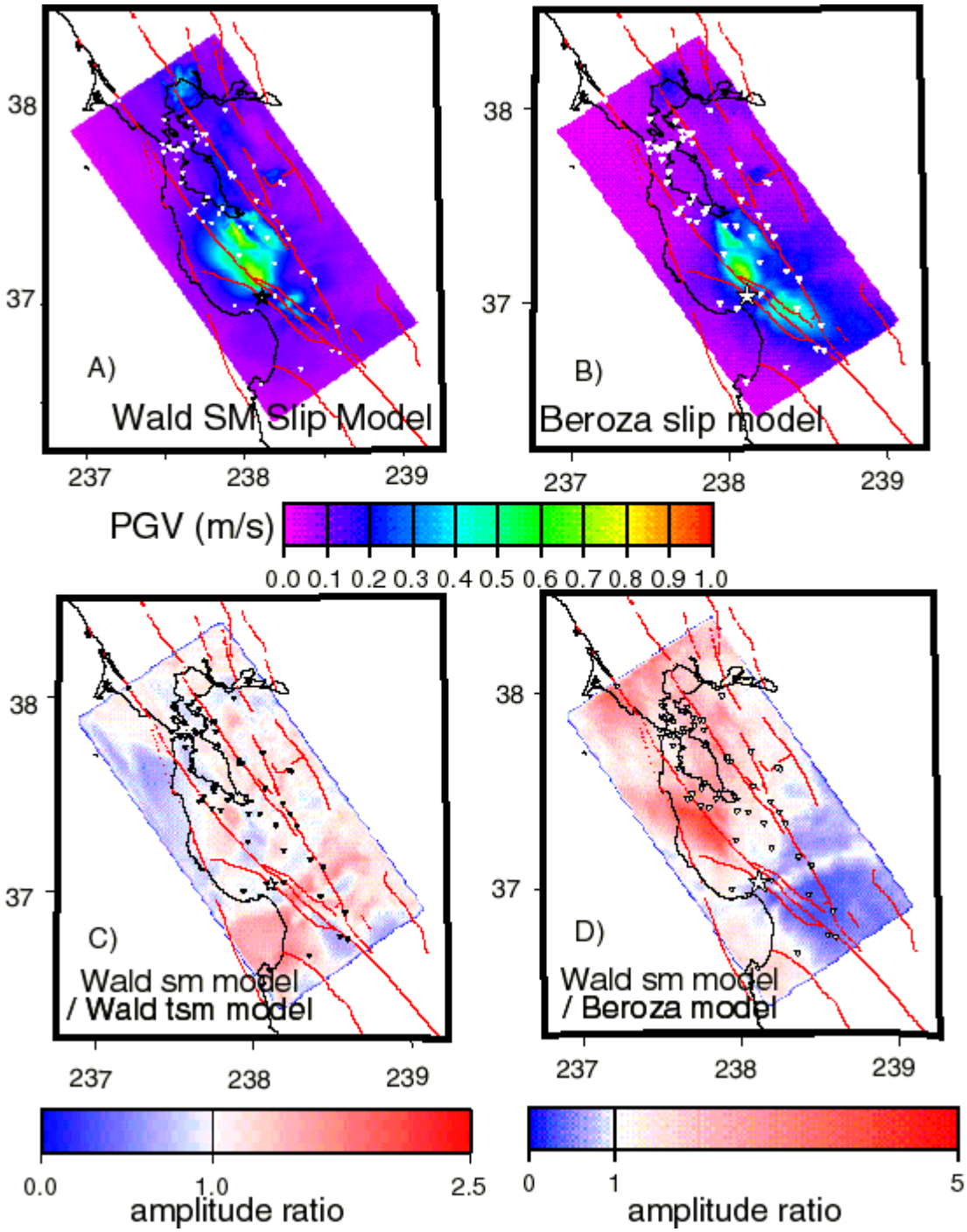

Figure 4. A) Same as Figure 1A. B) Peak ground velocity calculated using the UCB Model and the BEROZASM source model. C) Ratio of the WALDSM simulation to one using WALDTS. D) Ratio of the WALDSM simulation to one using the BEROZASM model. Triangles show the locations of strong motion stations.

Non-Technical Summary

The focus of this project is to test compiled 3D Earth structure models in the prediction of earthquake ground shaking patterns. Additionally, this project investigates the variability in estimated ground shaking due to assumptions made in the construction of the 3D structure models and in terms of input earthquake source models. The results of this study will be useful in the development of methodology to predict ground-shaking patterns for future earthquakes.

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Data Availability

Data and modeling results of this project may be acquired by contacting the PI, Douglas Dreger (dreger@seismo.berkeley.edu).