

## ANIMATION OF GROUND SHAKING FOR CALIFORNIA EARTHQUAKES

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### Abstract

An animation tool for visualizing ground shaking amplitude, oscillations, and duration using existing strong-motion datasets was developed to help interpretation and understanding of strong-motion propagation and attenuation. The system uses readily available strong-motion datasets, seismic velocities, and the ShakeMap model to interpolate ground motions by time-shifting and amplitude-scaling proximal records across a study area. The animation system essentially adds a temporal dimension to the ShakeMap model. Five significant historical California earthquake animations were developed with this system (1999 Hector Mine, 1992 Landers, 1989 Loma Prieta, 1994 Northridge, and 2004 Parkfield earthquakes) and are available on the Web at [www.gmxwebsolutions.com/eq\\_animations](http://www.gmxwebsolutions.com/eq_animations).

### Introduction

Ground shaking from earthquakes varies spatially across a region based on the distance from the fault rupture (i.e. attenuation), seismic wave propagation velocities (P-Waves and S-Waves), attenuation relationships, and bedrock geology. At any snapshot in time following nucleation of an earthquake, a given location within that region will be in the midst of either strong ground shaking, no ground shaking as the seismic waves will have yet to arrive, or subsiding ground shaking as the seismic waves will have passed and ceased. The behavior of shaking during earthquakes is of interest to a broad spectrum of people from the general public to the earthquake engineering community. A ground shaking animation tool that can visualize ground shaking amplitudes, oscillations, and duration using existing strong-motion datasets from recent earthquakes can be a powerful educational tool, as well as help interpretation and understanding of strong-motion propagation and attenuation.

The prevalent and accepted standard visual representation of shaking across an entire region affected by an earthquake is the CISM Rapid Instrumental Intensity Map or ShakeMap. ShakeMap, developed by CSMIP and USGS, takes applicable records and calculates peak ground motion parameters (peak ground acceleration (PGA), peak velocity (PGV), peak displacement (PGD)) at constant grid spacing across the study area. While ShakeMap provides an excellent representation of ground motion for a specific event, it is a static view of the motion and does not describe what each of us feels or

observes during an earthquake, the time history effects of seismic wave arrival, amplitude oscillations, and shaking duration.

Digital, free-field strong-motion station records typically report values for acceleration, velocity, and displacement recorded from 3 channels (2 horizontal and 1 vertical). This produces a total of 9 variables (3 channels x 3 parameters) per time interval (commonly 0.02 seconds) to characterize earthquake ground shaking at that station. With the current network of digital strong-motion recording stations across California, we can obtain a spatially diverse set of detailed time-history records describing the ground shaking for a specific earthquake. This equates to approximately 200,000 values describing motion per station or on the order of 10,000,000 values for an entire event from every station recording. This plethora of data and the desire to temporally visualize ground shaking amplitude, oscillations and duration using existing strong-motion datasets leads the impetus for this study.

If the distribution of stations throughout the study region was dense and regularly distributed (stations on a 1km grid), then creating these animations would be simply synchronizing the records into a GIS system and extracting time-slices without interpolation. To create an animation based on the existing network of irregularly and far-spaced stations, we have developed an interpolation methodology to derive ground shaking time histories for areas away from the existing stations. The derivation of ground shaking history must take into account proximal strong-motion data, seismic velocities, geologic conditions, distance from the earthquake source and appropriate attenuation relationships. The tool uses readily available strong-motion datasets, seismic velocities, and the ShakeMap model to interpolate shaking by time-shifting and amplitude-scaling ground motions across a study area at any specified time-step. The animation system essentially adds the temporal dimension to the ShakeMap model.

Initial animations were based on available strong-motion data from the 1999 Hector Mine, 1992 Landers, 1989 Loma Prieta, 1994 Northridge, and 2004 Parkfield earthquakes. The process developed will also be used to readily produce animations of future earthquakes. These animations will help educate a broad spectrum of people, as well as aid in interpretation and understanding of strong-motion propagation on the ground surface.

### **Data Acquisition and Pre-Processing**

#### **Strong Motion Data**

Available digital, free-field strong-motion station records for all five designated earthquakes were acquired (Figures 1a, 1b, 1c). Records acquired from CSMIP generally had complete digital headers, including trigger times, and were easily parsed into the model database (Access) with an automated script. Supplemental records from other sources (e.g. USGS, USC) were acquired and integrated into the database manually where there were significant spatial gaps in the model.

Data records were processed and parsed into a database-ready format via a customized automated parsing script. The free-field records report values for acceleration, velocity, and displacement recorded from 3 channels (2 horizontal and 1 vertical). This produces a total of 9 variables (3 channels x 3 parameters) per time interval.

In addition to the strong-motion time histories, station parameters from the record header were also parsed into the model database. Station parameters include station-id, location (latitude and longitude), PGA, PGV, channel orientations, trigger time, and record time interval. The lack of consistent and complete headers (e.g., no trigger times) of the other data sources proved time-consuming to manually process. The station-to-epicenter distance was calculated using a standard GIS functionality for each record.

To simplify the visualization of ground motions, we use an absolute horizontal acceleration by taking both horizontal acceleration channels and calculating one absolute value using the square root sum of squares algorithm. The ground shaking animations presented here visualize this absolute horizontal acceleration. Future modeling efforts can isolate individual directional channels or the other ground motion parameters (velocity and displacement).

### ShakeMap Data

ShakeMap model values for all five designated earthquakes were acquired via the CSMIP Web site and imported into the model database (Figures 1a, 1b, 1c). The ShakeMap model provides peak ground motion parameters (PGA, PGV, PGD) at constant grid spacing across the study area. We use the inherent ShakeMap grid spacing to define the animation model grid. The cell-to-epicenter distance was calculated using standard GIS functionality for every model cell.

### Interpolation Methodology

We have developed an interpolation methodology that models shaking for any cell in the model using proximal strong motion records, seismic velocities, and ShakeMap to estimate ground motion time histories. The interpolation methodology can be summarized as follows:

For any model cell:

- **Search** the existing stations to find the three most appropriate records from which to extract values.
- **Shift** the time of each of the three records by a time interval derived from the difference in distance between the model cell-to-epicenter and station-to-epicenter distance divided by the characteristic seismic velocity.

- **Scale** the amplitude of each of the three records based on a ratio between the ShakeMap-derived PGA at the model cell and the station.
- **Interpolate** values from the three shifted and scaled records into one value with the Inverse Distance Weighted algorithm using the three respective cell-to-station distances.
- **Normalize** the interpolated time histories to the ShakeMap.

Details of these modeling components are discussed below.

### Search

Integral to our interpolation methodology is the selection of the three most appropriate stations from which to extract strong-motion records when estimating ground motion at any grid cell in our model. Selecting the three closest (cell-to-station distance) stations is the most simplistic solution, but it might not be the best when approximating ground motions. Ideally, the three stations should have a radial distance from the epicenter similar to the cell being modeled. This would support a better estimation of records, as attenuation and seismic wave arrival times are theoretically similar. In parts of the model where stations are sparse, this selection criterion becomes more important. For example, in the Parkfield model, grid cells 70km east of the rupture are closest to near-field stations, due to a lack of stations east of the rupture (Figure 1c). Extrapolating the shorter and stronger near-field records eastward to 70km is a greater and probably inappropriate extrapolation compared to using the stations 70km west of the rupture, even though these stations are 140km from each other and in opposite directions from the epicenter.

We developed criteria to select the three most appropriate stations to use when modeling any grid cell. The criteria are based on both closest cell-to-station distance and similar cell-to-epicenter and station-to-epicenter radial distances. Initially the algorithm selects all stations with cell-to-station distances less than  $1/3$  of the cell-to-epicenter radial distance. If more than three cells fall within this zone, the algorithm selects the closest three. If less than three stations meet this criterion, the algorithm then selects stations with station-to-epicenter radial distances within  $1/3$  of the cell-to-epicenter radial distance (Figure 2). To remove bias in the Inverse Distance Weighting algorithm used by the interpolation methodology to equate ground motion, the stations selected by the radial distance criterion are assigned a cell-to-station distance of  $1/3$  the cell-to-epicenter distance. For earthquake animations where the spatial station distribution is sparse (i.e., Hector Mine; Figure 1a) the  $1/3$  search ratio was increased to  $1/2$ .

### Shift

To interpolate a ground shaking time-history from a station to any model cell, we must shift the selected proximal records to accommodate for travel times of seismic

waves through the geologic medium. In order to shift these ground motion records two characteristic seismic velocities are needed.

### *Calculate Seismic Velocities*

To derive the seismic velocities (P-Wave and S-Wave) for the five designated earthquakes, we plot the seismic wave arrival times versus the station-to-epicenter distance for each record. Seismic wave arrival times, for both P- and S-Waves, were manually chosen from visual inspection of the original time history. Fitting a line to the data allows us to derive the seismic velocity from the slope of the line. We assume that seismic velocities are constant within the study area for each earthquake. Figures 3a, 3b, and 3c show the distance versus arrival time for all five of the designated earthquakes.

### *Evaluate Trigger Times*

Critical to the calculation of the characteristic seismic velocities and shifting the time histories is synchronization of the records to the earthquake origin time by trigger time. Ideally, trigger times are included in the record header, but occasionally these times are either missing or erroneous. These records are problematic and must be manually evaluated. Using the arrival times versus station-to-epicenter distance plots (Figures 3a, 3b, and 3c) we can manually assign trigger times to missing records and correct erroneous ones. CSMIP records from the more recent earthquakes report correct and complete trigger times more consistently than older and non-CSMIP records.

### *Limited Record Length Adjustment*

The duration (total time) of the time histories vary from station to station. This variation does not appear to be based on station-to-epicenter distance or amplitude. For example, neighboring (<10km apart) Parkfield near-field stations have record lengths of 25 and 80 seconds. This variation in duration of recorded data is accommodated in the model to ensure that the most appropriate data for the longest time interval are used. During the estimation modeling, if an appropriate station is being used at a time-step beyond its record length, then the algorithm will step to the next appropriate station selected in the search algorithm detailed above.

### *P-Wave and S-Wave Velocity Shift*

The interpolation methodology uses the three most appropriate station records to estimate ground motion at any arbitrary grid cell in the model. Strong-motion records from these three stations are time-shifted to account for the difference in spatial distance between the grid cell and station. The time-shift is based on the distance between the grid cell and the station converted into time by the seismic velocity. To accommodate both P-Wave and S-Wave arrival components of the records, we apply different time-shifts based on the distinct arrival times of the two waves. Initially, this time-shift is based on P-Wave seismic velocity. As the model time progresses and the arrival of the S-Wave occurs, the time-shift is based on the S-Wave seismic velocity. This methodology

essentially separates the wave components to synchronize the arrival of both the P-Wave and S-Wave throughout the model.

### **Scale**

To interpolate shaking amplitude from distance records to any model cell, we scale the selected record to attenuate the shaking amplitude as the seismic waves travel through the geologic medium. The records are scaled by the ratio of ShakeMap-modeled PGA at the model cell to the recording station. ShakeMap provides a model structure where attenuation relationships and geology have been included in algorithms to estimate peak ground motion parameters (PGA, PGV, PGD). Since the ShakeMap PGA model generally decreases away from the epicenter, using this ratio will dampen or heighten amplitudes as you move away or closer to the epicenter, respectively, across a model area (Figures 1a, 1b, 1c). Using the ShakeMap model integrates these attenuation relationships into the animation tool.

### **Interpolation**

With the three most appropriate records selected, shifted, and scaled to account for attenuation and seismic velocity travel times, we calculate a new time history for every model grid. At every time interval, we take the three shifted and scaled values and use the Inverse Distance Weighting algorithm with the respective cell-to-station distances to calculate an instantaneous ground motion. Iteration of this process through the desired time duration on a cell-by-cell basis generates complete time histories for every cell in the model.

### **Normalization to ShakeMap**

To honor the ShakeMap PGA model grid, every modeled cell time history is normalized to ShakeMap PGA after the completion of the interpolation methodology. For example, if the interpolation algorithm estimates a record for a grid cell with a peak or maximum modeled acceleration of 0.70g at a location where ShakeMap models a PGA of 0.77g, the normalization algorithm will scale the record by 110 percent. The opposite also applies, where the normalization algorithm can scale down an interpolated record to match ShakeMap.

### **Model Validation**

A validation step was completed to compare the modeled strong motion time history for arbitrary grid cells versus the observed (recorded) data in proximal locations. Modeled ground motions for areas far away from stations were also examined. To check the validity of our interpolation algorithm, the modeled ground motion time histories for specific cells in the model were plotted against the actual station strong-motion recordings. Validation of the model includes comparing the amplitude, duration, and inflection points of the modeled curve to the observed curve.

The first check looks at a model cell spatially coincident with a recording station. We looked at station 47232 and model grid cell 4108, which are <1 km away from each other and both ~80km away from the epicenter (Figure 2). Comparison of the two graphs shows that their overall shape, magnitude, and duration are fairly consistent (Figure 4). The inflection points (P-Wave, S-Wave, PGA, and motion decrease) are all fairly equivalent. The similarity of these two graphs (modeled and observed) is expected, as our interpolation algorithm gives the greatest weight to the closest of the three most appropriate stations. The close spatial proximity of the station 47232 to model grid cell 4108 implies that the other two closest stations, although still included in the estimation, will have a significantly lesser weight.

Another critical check is to look at the overall wave form of a model cell far away from any stations. We looked at model grid cell 13672, which is 75km SSE of the rupture (Figure 2). While the closest stations to this cell are the Parkfield near-field cells ~50km away, the station search criteria chooses appropriate stations at a comparable epicenter radial distance. The overall wave form of model grid cell 13672 looks similar to station 47232 at similar approximate distances from the epicenter, 75km and 80km respectively. The initiation of strong ground motion begins at ~13 seconds, which corresponds to the modeled seismic velocity of 5,800 m/s ( $75,000 / 5,800 = 12.9$  seconds) (Figure 5).

### Animations

Once the complete ground shaking time histories are interpolated for each model cell, we extract instantaneous values from these time histories and use the GIS (ArcGIS) to create a gridded surface of ground motion at that specific time. The gridded surface of instantaneous acceleration is visualized with a color scheme consistent with the ShakeMap ground shaking legend. This gridded surface is layered onto the GIS basemap (digital terrain model, roads, and station locations) to provide a spatial reference frame and then saved as an individual map still-frame. Iterating this process at a desired time interval creates a series of map still-frames. The sequential compilation of these map still-frames within an commercial animation generator (i.e. QuickTime) creates a Web-ready animation of ground shaking duration and amplitude radiating away from the epicenter (Figure 6).

Animations for all five designated earthquakes, at an interval of 0.5 seconds, were produced and can be found on the web at [www.gmxwebsolutions.com/eq\\_animations](http://www.gmxwebsolutions.com/eq_animations).

### Discussion and Future Goals

This animation tool begins to take the copious amounts of digital free-field strong motion data and visualize the ground shaking amplitude, oscillation, and duration using existing strong-motion datasets in a temporal sense. The animation tool takes seismic velocities and existing time-histories to interpolate ground motion records across the study area. The tool also integrates attenuation and geologic conditions by using the ShakeMap model to scale ground shaking amplitudes. Validation of our interpolation methodology, by comparison of observed to modeled time-history curves, shows that we

can successfully create a ground motion time-history at any arbitrary location in the model.

The overall dynamics of the ground shaking animation captures the behavior of seismic waves traveling through the geologic medium. The earthquake animations show strong-motions proximal to the epicenter at the nucleation of the event and decreasing motions emanating away from the source with time. Both P-Wave and S-Wave can be recognized and tracked at their respective velocities in the animations. Attenuation relationships, integrated from ShakeMap, can also be recognized as well as the interaction between rock/alluvium surface geology and the shaking.

The animation model as currently implemented is limited to the amount and spatial distribution of existing CSMIP strong motion records and occasional supplemental records from other sources. While we have tried to include all readily available substantial datasets there are other datasets that exist for some of the earthquakes in this study (e.g. USGS, universities, utilities, private owners), which were not presently included in these models due to the time necessary to manually prepare individual recording to incorporate into the model.

With the completion of the animation system and interpolation methodology, future goals will include:

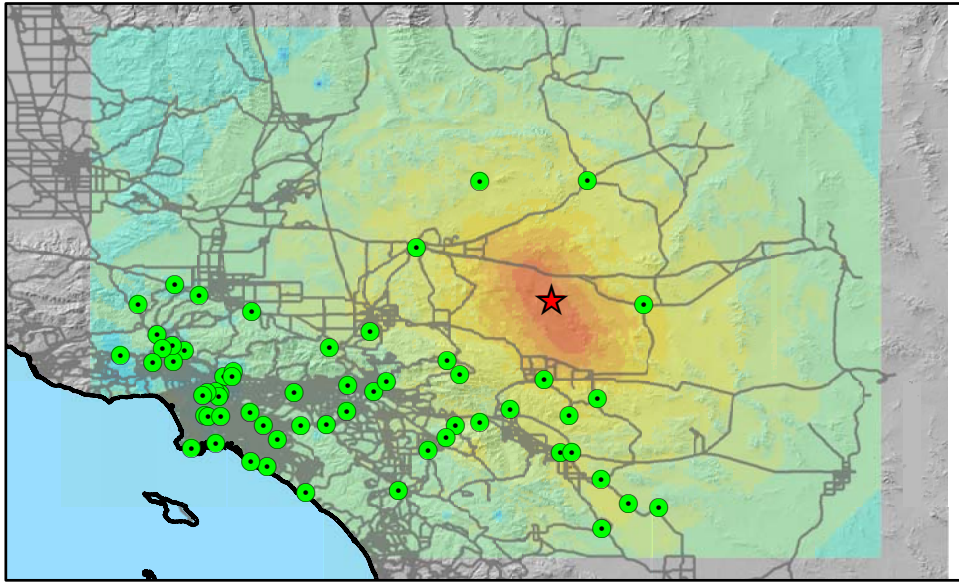
- Focusing the animation on isolating the nine other ground motion parameters.
- Focusing on near field-effects of the Parkfield dataset.
- Extending out beyond the existing ShakeMap grid and looking at far-field effects.
- Attempting to include a more robust geologic model.
- Modeling historic earthquakes such as the 1906 San Francisco earthquake that pre-date recording of strong ground motion.

### **Acknowledgements**

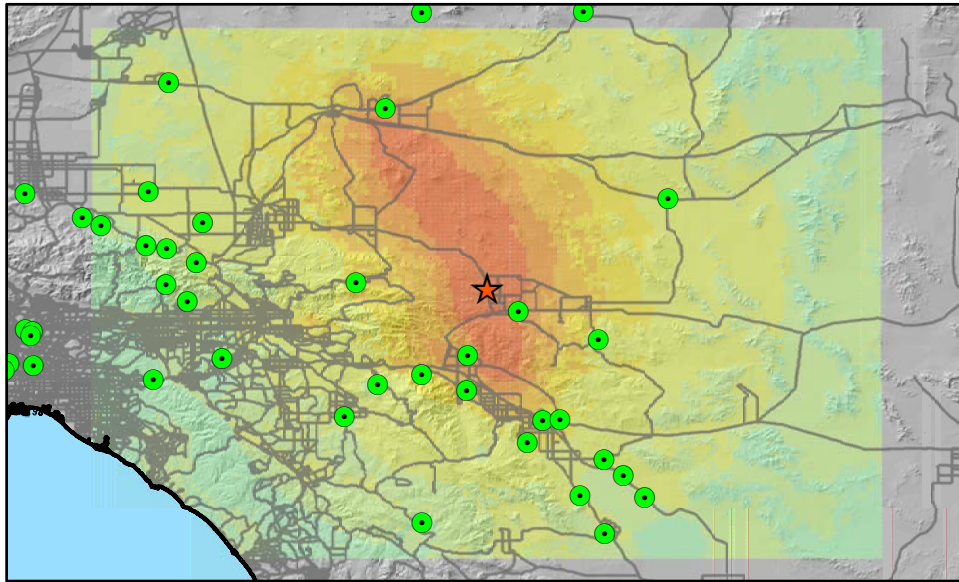
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1999 Hector Mine



1992 Landers



Legend

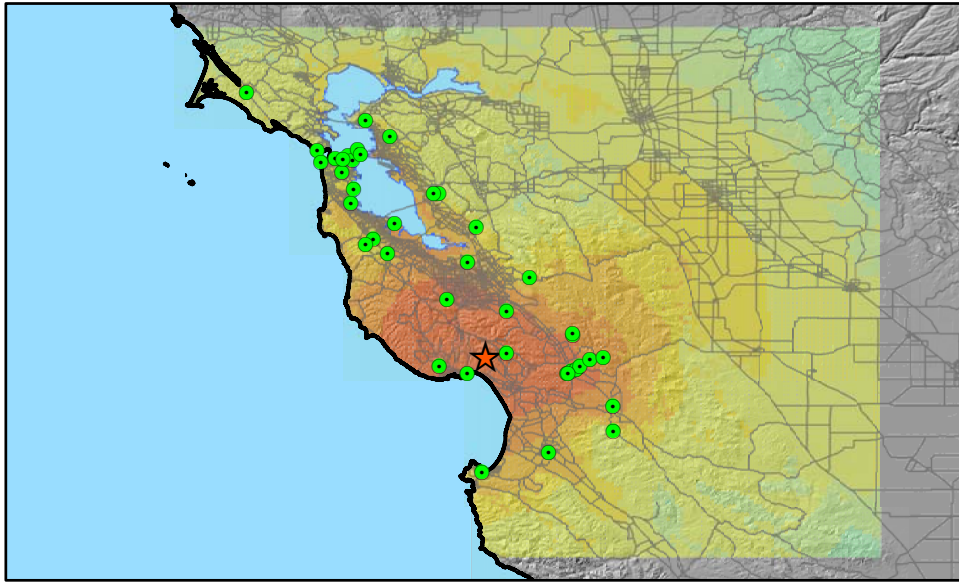
- ★ Earthquake
- Stations

ShakeMap PGA (%g)

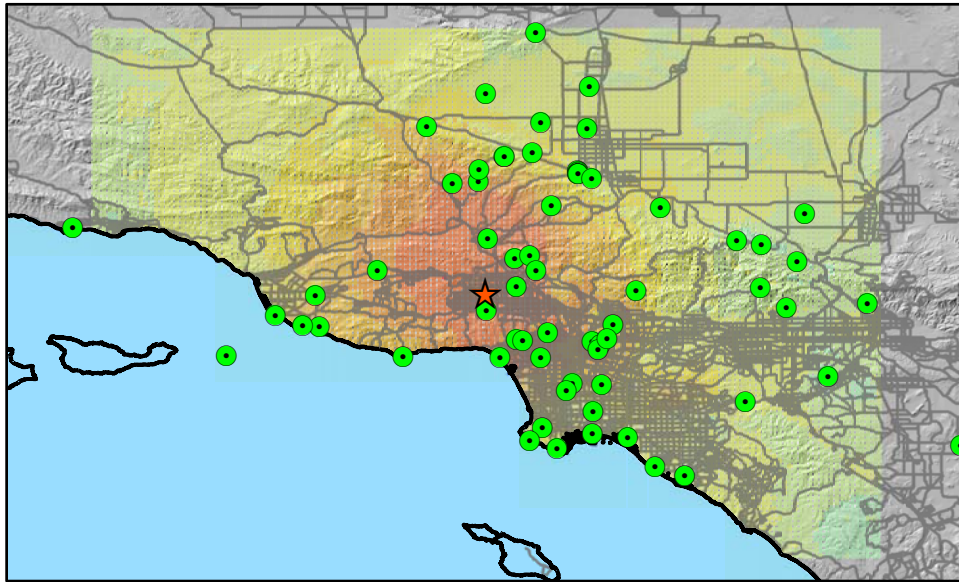
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●	0.61%	●	8.2%	●	86.0%
●	1.2%	●	13.0%	●	100%
●	2.4%	●	17.0%		
●	3.5%	●	24.0%		

**Figure 1a.** Location of available strong motion recording stations and ShakeMap PGA models for the 1992 Hector Mine (top) and 1992 Landers (bottom) earthquakes.

1989 Loma Prieta



1994 Northridge



Legend

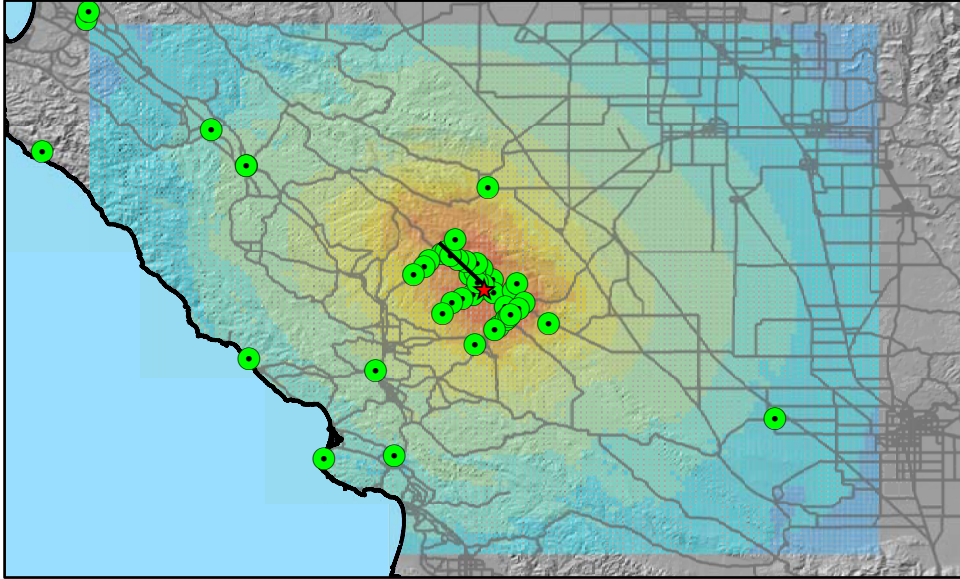
- ★ Earthquake
- Stations

ShakeMap PGA (%g)

● 0.11%	● 6.1%	● 32.0%
● 0.61%	● 8.2%	● 86.0%
● 1.2%	● 13.0%	● 100%
● 2.4%	● 17.0%	
● 3.5%	● 24.0%	

**Figure 1b.** Location of available strong motion recording stations and ShakeMap PGA models for the 1989 Loma Prieta (top) and 1992 Northridge (bottom) earthquakes.

2004 Parkfield



**Legend**

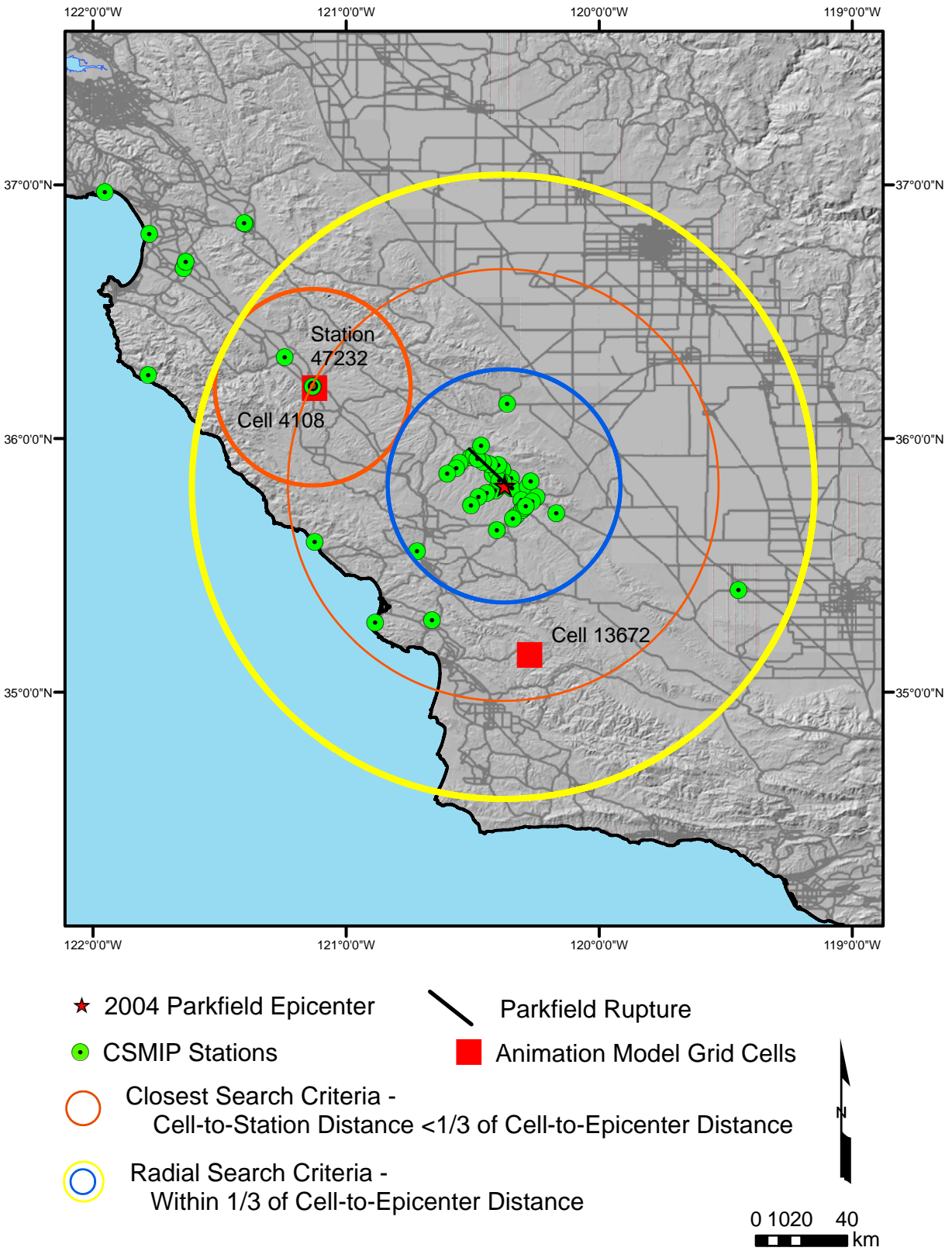
- ★ Earthquake
- Stations

**ShakeMap PGA (%g)**

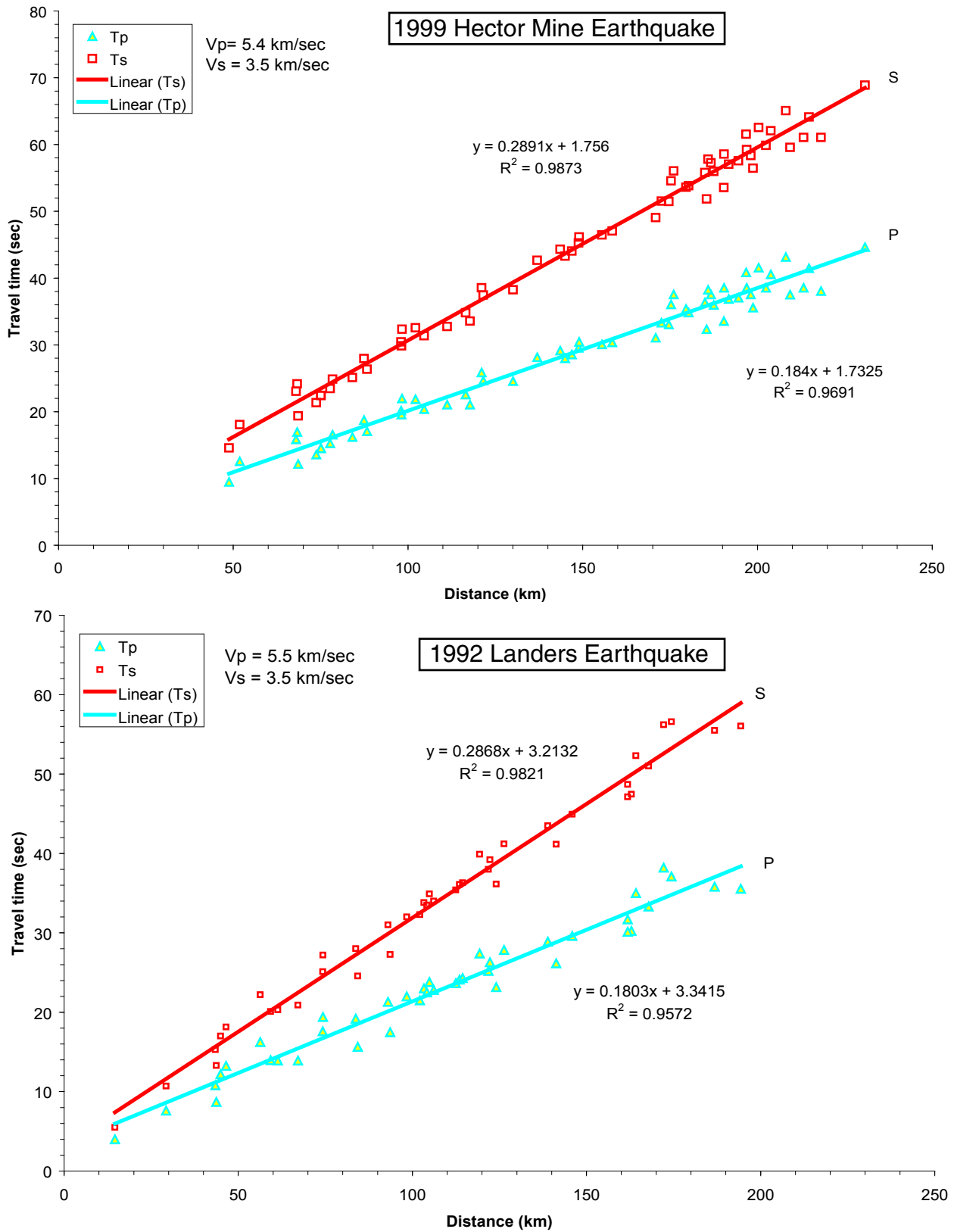
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● 0.61%	● 8.2%	● 86.0%
● 1.2%	● 13.0%	● 100%
● 2.4%	● 17.0%	
● 3.5%	● 24.0%	

**Figure 1c.** Location of available strong motion recording stations and ShakeMap PGA models for the 2004 Parkfield earthquake.

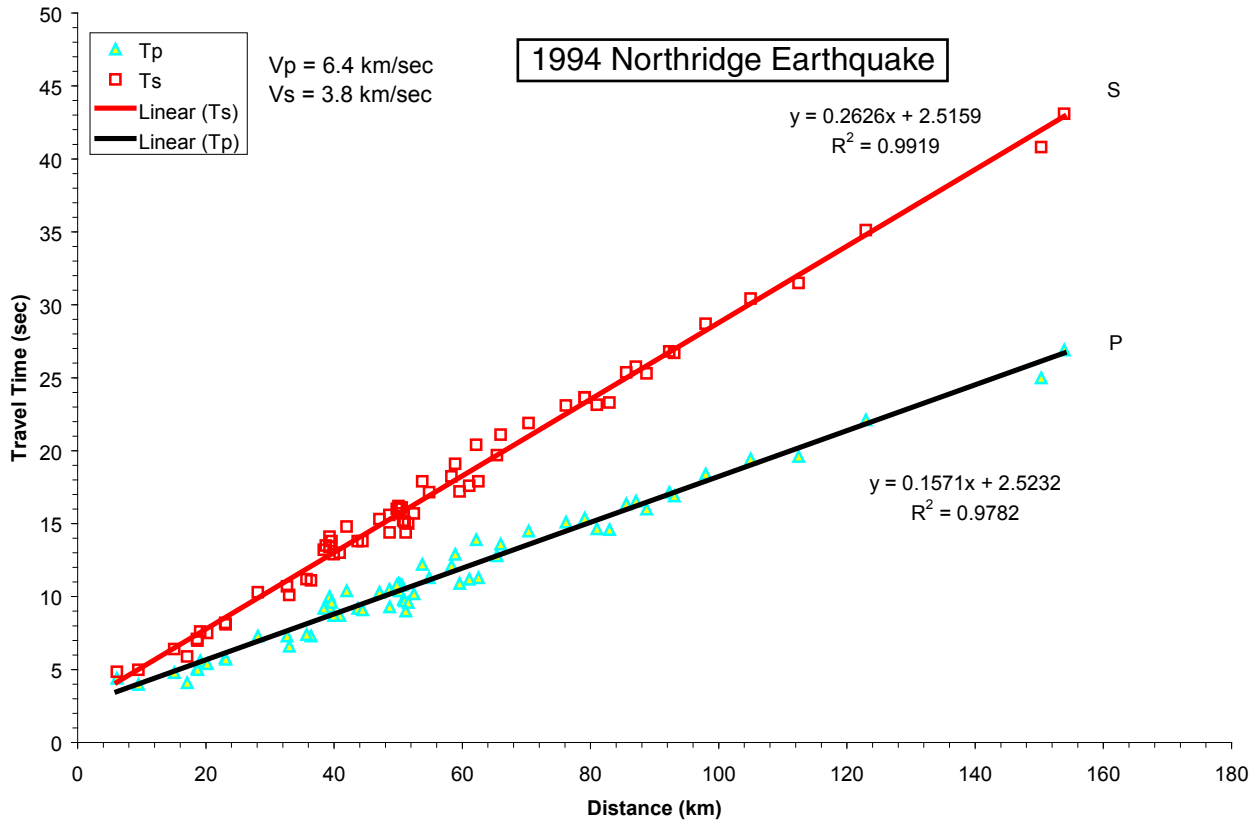
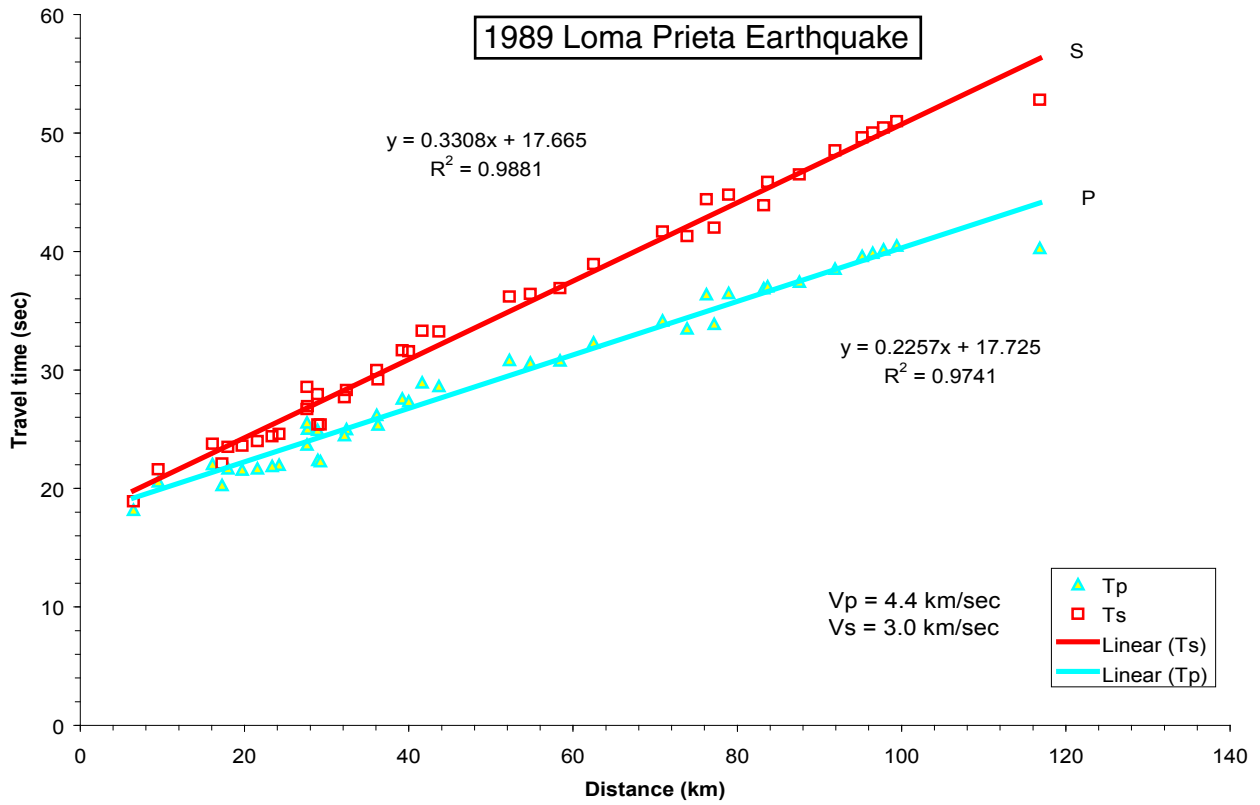




**Figure 2.** Schematic of 'Most Appropriate' Station Search Criteria



**Figure 3a.** P-wave and S-wave seismicity velocity travel times for the 1999 Hector Mine and 1992 Landers earthquakes



**Figure 3b.** P-wave and S-wave seismicity velocity travel times for the 1989 Loma Prieta and 1994 Northridge earthquakes

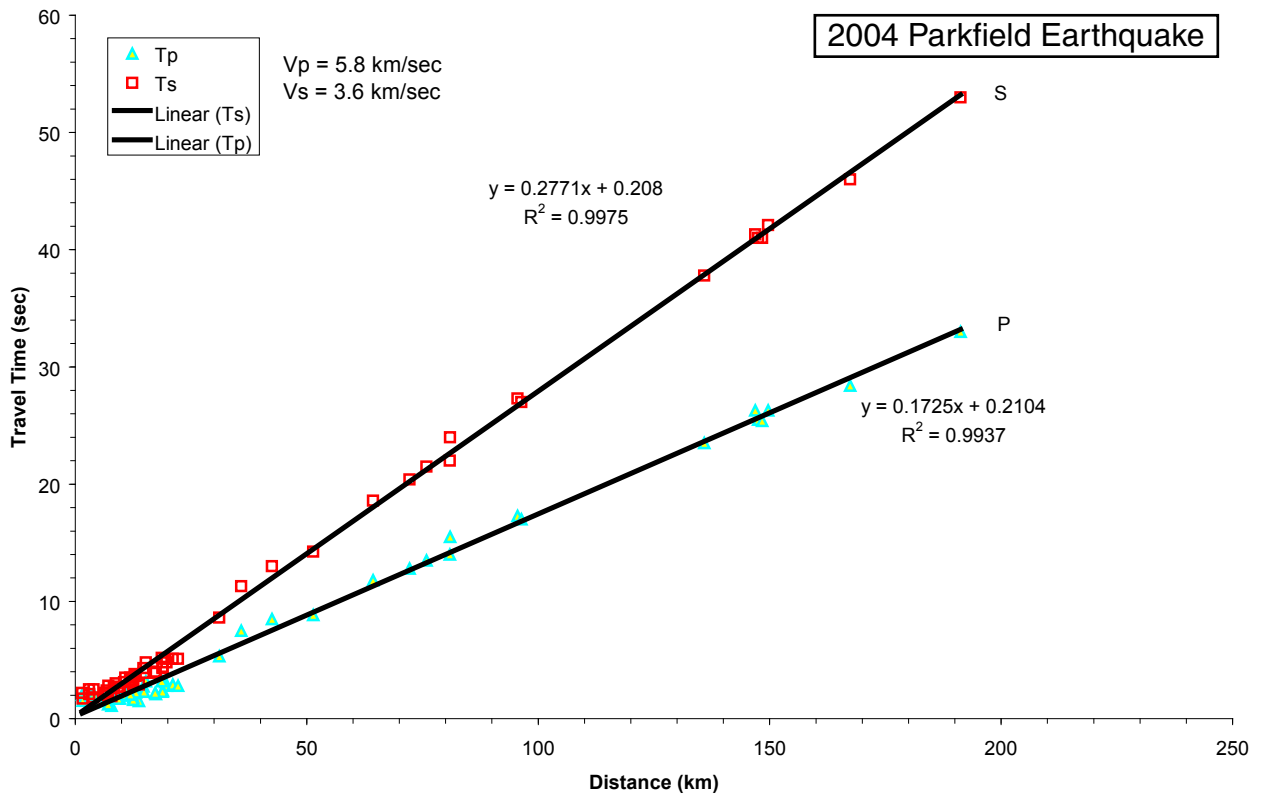
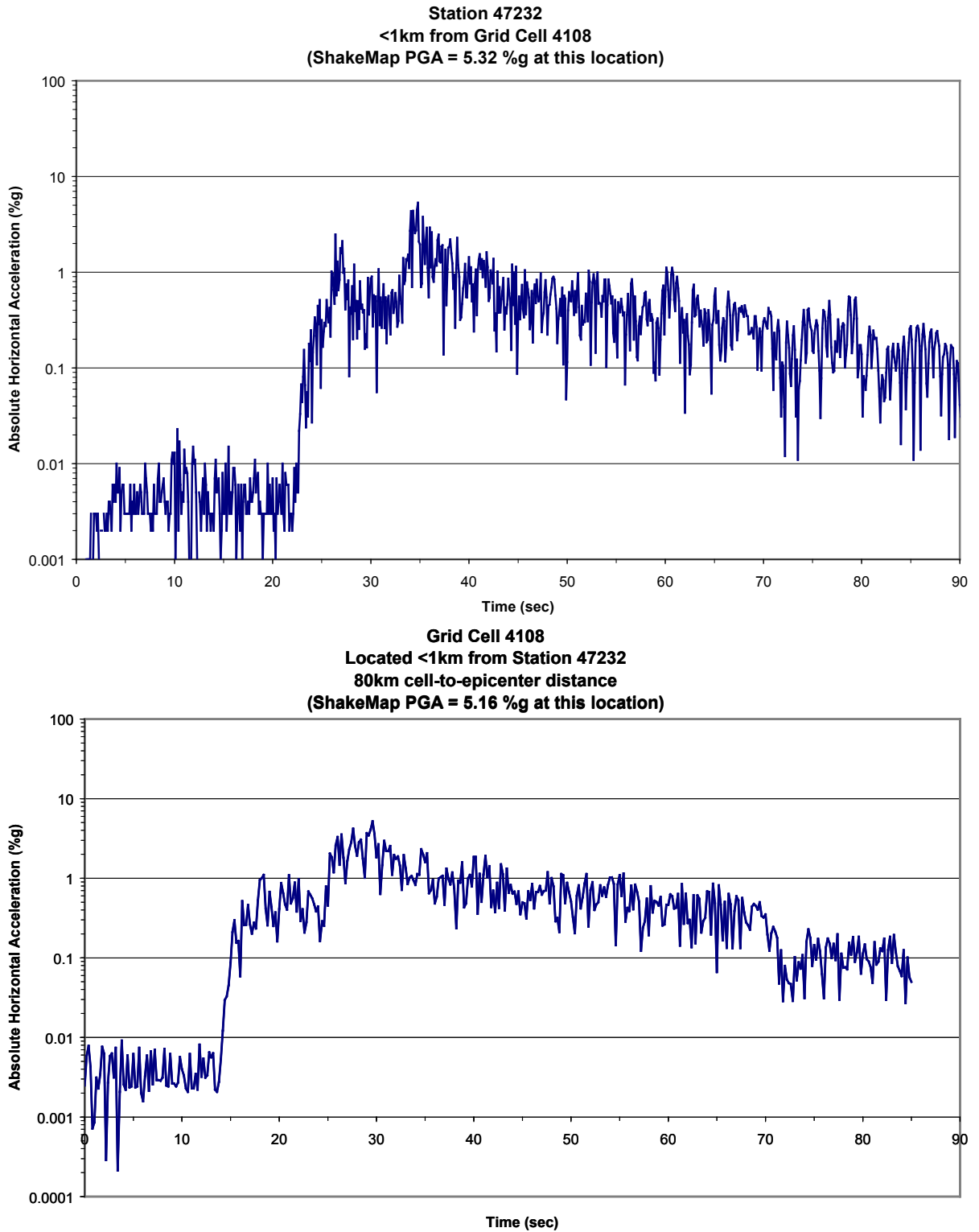
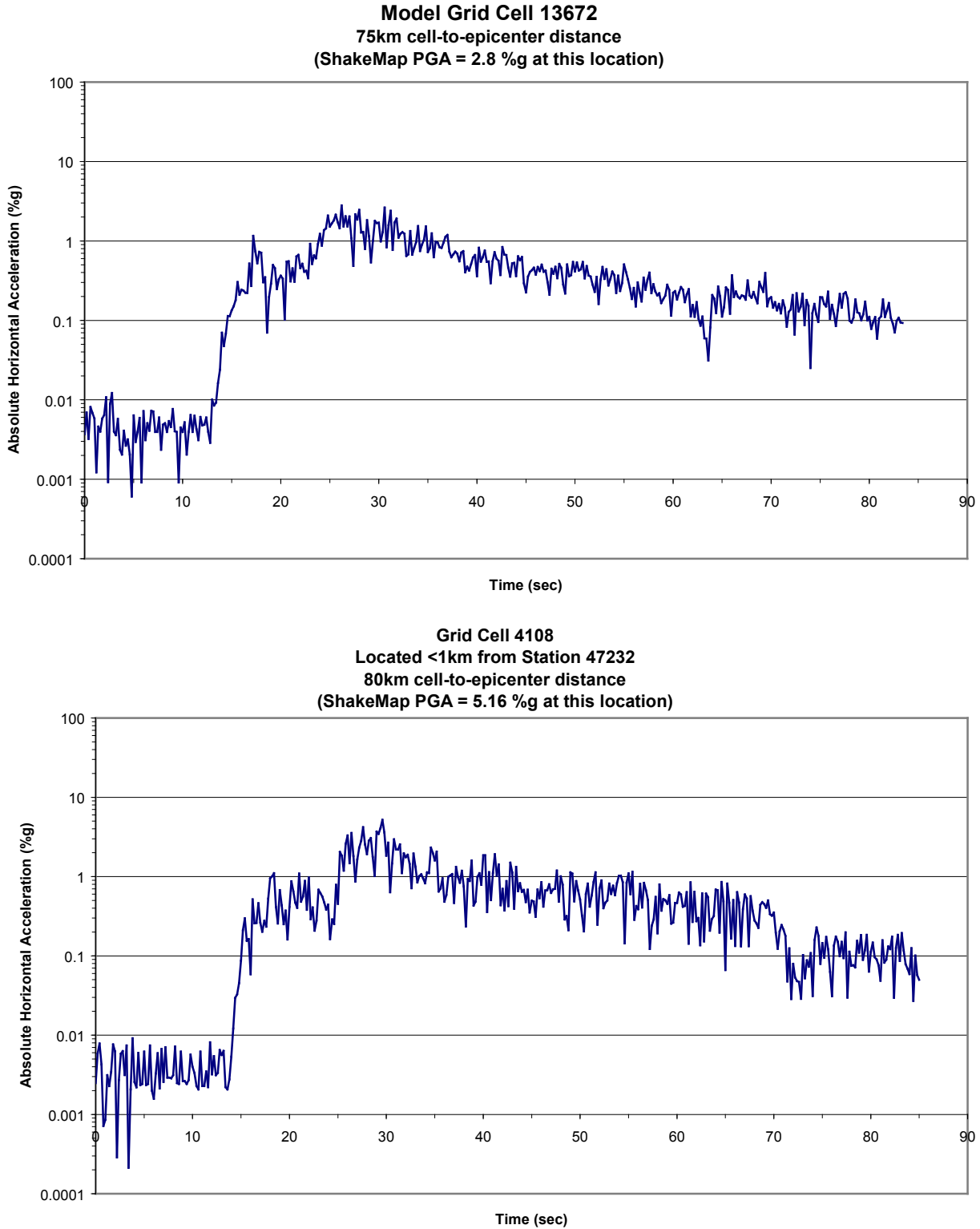


Figure 3c. P-wave and S-wave seismicity velocity travel times for the 2004 Parkfield earthquake



**Figure 4.** Comparison of recorded time history from Station 47232 to modeled time history for model grid cell 4108. (Refer to Figure 2 for locations)





**Figure 5.** Comparison of modeled time histories for model grid cels 4108 and 13672. (Refer to Figure 2 for locations)

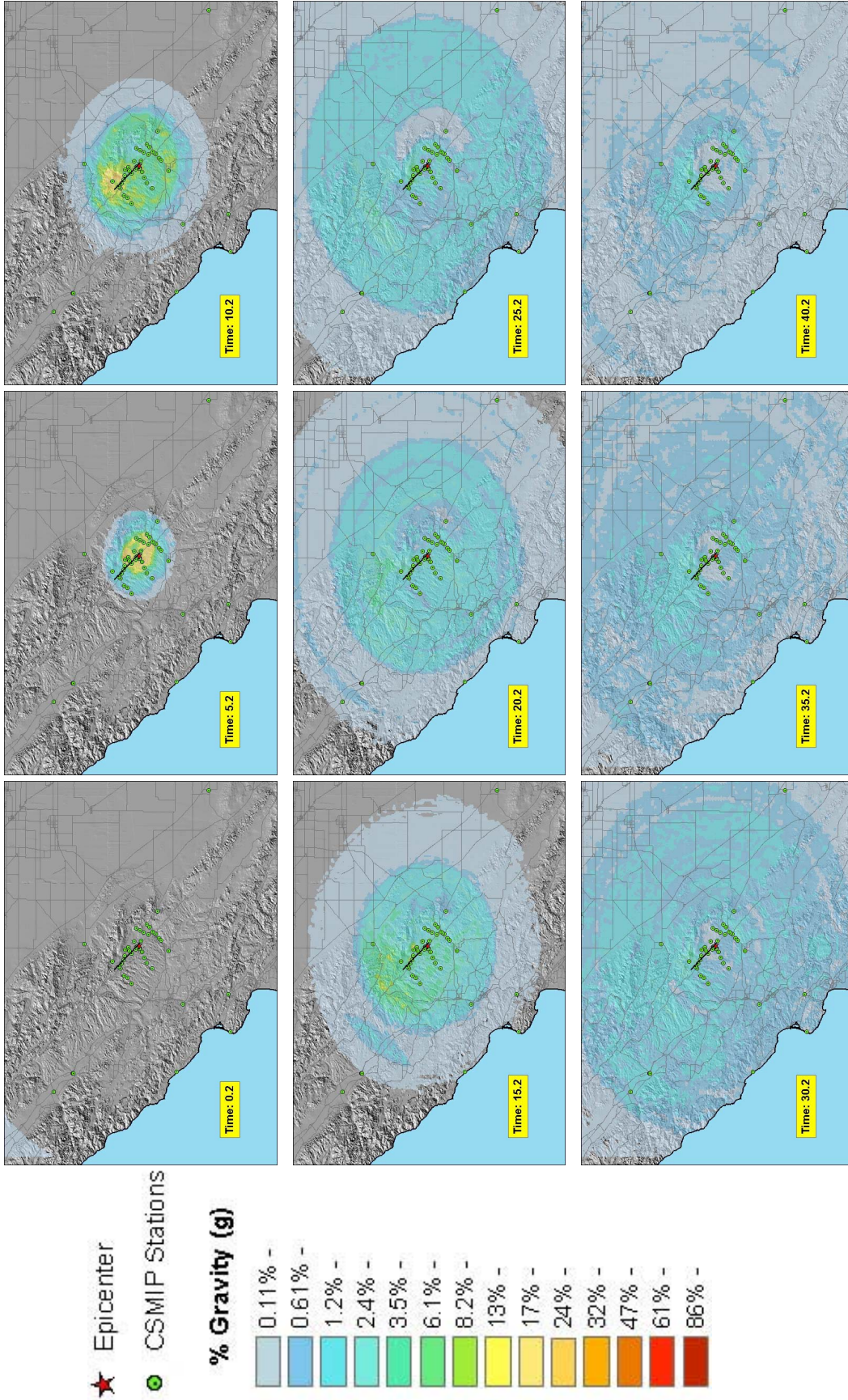


Figure 6. Time series of sequential map-still frames used to create the 2004 Parkfield animation.