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Data Files for Ground-Motion Simulations of the 1906 San Francisco Earthquake and Scenario Earthquakes on the Northern San Andreas Fault

Data Series 413

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By Brad Aagaard, Michael Barall, Thomas M. Brocher, David Dolenc, Douglas Dreger, Robert W. Graves, Stephen Harmsen, Stephen Hartzell, Shawn Larsen, Kathleen McCandless, Stefan Nilsson, N. Anders Petersson, Arthur Rodgers, Bjorn Sjogreen, and Mary Lou Zoback

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KEN SALAZAR, Secretary

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Suzette M. Kimball, Acting Director

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This data set contains results from ground-motion simulations of the 1906 San Francisco earthquake, seven hypothetical earthquakes on the northern San Andreas Fault, and the 1989 Loma Prieta earthquake. The bulk of the data consists of synthetic velocity time-histories. Peak ground velocity on a 1/60th degree grid and geodetic displacements from the simulations are also included. Details of the ground-motion simulations and analysis of the results are discussed in Aagaard and others (2008a,b).

1906 San Francisco Earthquake Modelers and Scenarios

Five groups participated in modeling the 1906 San Francisco earthquake (1) Aagaard, (2) Graves, (3) Harmsen and others (Harmsen and Hartzell), (4) Larsen and others (Larsen, Dreger, and Dolenc), and (5) Petersson and others (Petersson, Rodgers, McCandless, Nilsson, and Sjogreen). Each group employed a different modeling code to solve the elastic wave equation (table 1 and fig. 1).

The earthquake scenarios include two models of the 1906 earthquake (the Song scenario and the SongMod scenario) and seven models of similar-sized hypothetical earthquakes (SongModHypoN, SongModHypoC, SongModHypoS, RandomHypo06, RandomHypoN, RandomHypoC, and RandomHypoS) on the northern San Andreas Fault (table 2).

The Song scenario is based on the source model by Song and others (2008). The Song scenario specifies uniform slip on fault patches measuring 10 km along-strike and 12 km down-dip and, therefore, contains slip variations only at long scales. The hypocenter is a few kilometers offshore from San Francisco at a depth of 10 km.

The SongMod scenario is similar to the Song scenario, but it uses a source model that has been modified by adding shorter-scale variations in slip and rupture speed. This is the preferred source model for the 1906 ground motion simulations. The additional variations in slip are randomly phased and passed through a high-pass spatial filter whose amplitude falls off as the inverse square of the wavenumber for large wavenumbers. The rupture speed is modified so that the rupture propagates more quickly through regions with larger slip. The SongModHypoN, SongModHypoC, and SongModHypoS scenarios are hypothetical earthquakes that have the same slip distribution as the SongMod scenario but different hypocenters (N, north; C, center; S, south; table 3).

The RandomHypo06, RandomHypoN, RandomHypoC, and RandomHypoS scenarios use a randomly generated slip distribution. The slip distribution was produced by generating a slip distribution with random phase at all wavelengths and passing it though the wavenumber squared low-pass spatial filter mentioned above, while constraining the average slip to be the same as in the SongMod model. These four random slip scenarios are all the same, except for the location of the hypocenter. Additional information is available in the Appendix.

1989 Loma Prieta Earthquake Modelers and Scenarios

Four groups participated in modeling the 1989 Loma Prieta earthquake (1) Aagaard, (2) Dolenc and others (Dolenc, Dreger, and Larsen), (3) Graves, and (4) Harmsen and others (Harmsen and Hartzell). Each uses a different elastic wave propagation code (table 4 and fig. 2). There are two scenarios for the 1989 earthquake:

- The Beroza scenario is based on the Beroza (1991) source model.
- The Wald scenario is based on the Wald and others (1991) source model.

Additional information is available in the Appendix.

Table 1. Wave propagation codes for the 1906 San Francisco earthquake simulations.

	Aagaard	Graves	Harmsen and others	Larsen and others	Petersson and others
Model domain					
Length, in km	250	555	128	630	550
Width, in km	110	162	52	320	200
Max. depth, in km	40	45	31	55	40
NW corner[(1)]	-123.7083, 38.2832	-125.5000, 40.2000	-122.7313, 37.6313	-126.2037, 39.6589	-125.4990, 40.0440
NE corner	-122.7002, 38.8944	-123.9482, 41.0505	-122.3116, 37.9610	-123.2940, 41.3485	-123.6000, 41.1000
SE corner	-121.0208, 37.0716	-120.2911, 36.9623	-121.2978, 37.1331	-119.0100, 36.7700	-119.9590, 37.1030
SW corner	-122.0180, 36.4894	-121.8528, 36.1118	-121.7173, 36.8069	-121.8819, 35.0804	-121.8060, 36.0470
Projection	none (3-D Earth)	spheroidal	ellipsoidal trans. Mercator	spheroidal	spheroidal
Discretization					
Method	unstructured finite element	staggered-grid finite element	staggered-grid finite difference	staggered-grid finite difference	node centered finite difference
Space accuracy	2nd order	4th order	4th order	4th order	2nd order
Time accuracy	2nd order	2nd order	2nd order	2nd order	2nd order
Resolution					
Element size, in m	variable	150	50-150	100	125
Bandwidth	T > 2.0 s	T > 1.0 s T > 0.1 s[(2)]	T > 1.0 s	T > 1.0 s	T > 1.0 s
Min. Vs, in m/s	700	760	330	500	500
Features					
Topography[(3)]	yes	bulldozed	squashed	yes	bulldozed
Water	air filled	sediment filled	excluded	included	included
Mat. properties	USGS 05.1.0	USGS 05.1.0	USGS 05.1.0	USGS 05.1.0	USGS 05.1.0
Attenuation[(4)]	none	Graves	Graves	USGS 05.1.0	none
Earthquake source					
Method	offset in mesh	point sources	point sources	point sources	point sources
Number of point sources	N/A	6,084	1,200–1,400	6,084	12,313
Fault surface	3D geol. model	3D geol. model	3D geol. model	3D geol. model	3D geol. model

[1]Domain corners are given as WGS84 longitude and latitude.

[2]Graves employs a hybrid method which combines a deterministic model for periods T > 1.0 s with a stochastic model for periods 1.0 s > T > 0.1 s.

[3]For topography, "bulldozed" means that all material above some elevation is removed, and voids below that elevation are filled with generic material. "Squashed" means that the geologic model is vertically distorted to produce a planar top surface. Squashing also eliminates bodies of water.

[4]For material properties and attenuation, "USGS 05.1.0" refers to the U.S. Geological Survey Bay Area Velocity Model 05.1.0, and "Graves" refers to a simple attenuation model developed by Graves. See the Appendix for more information.

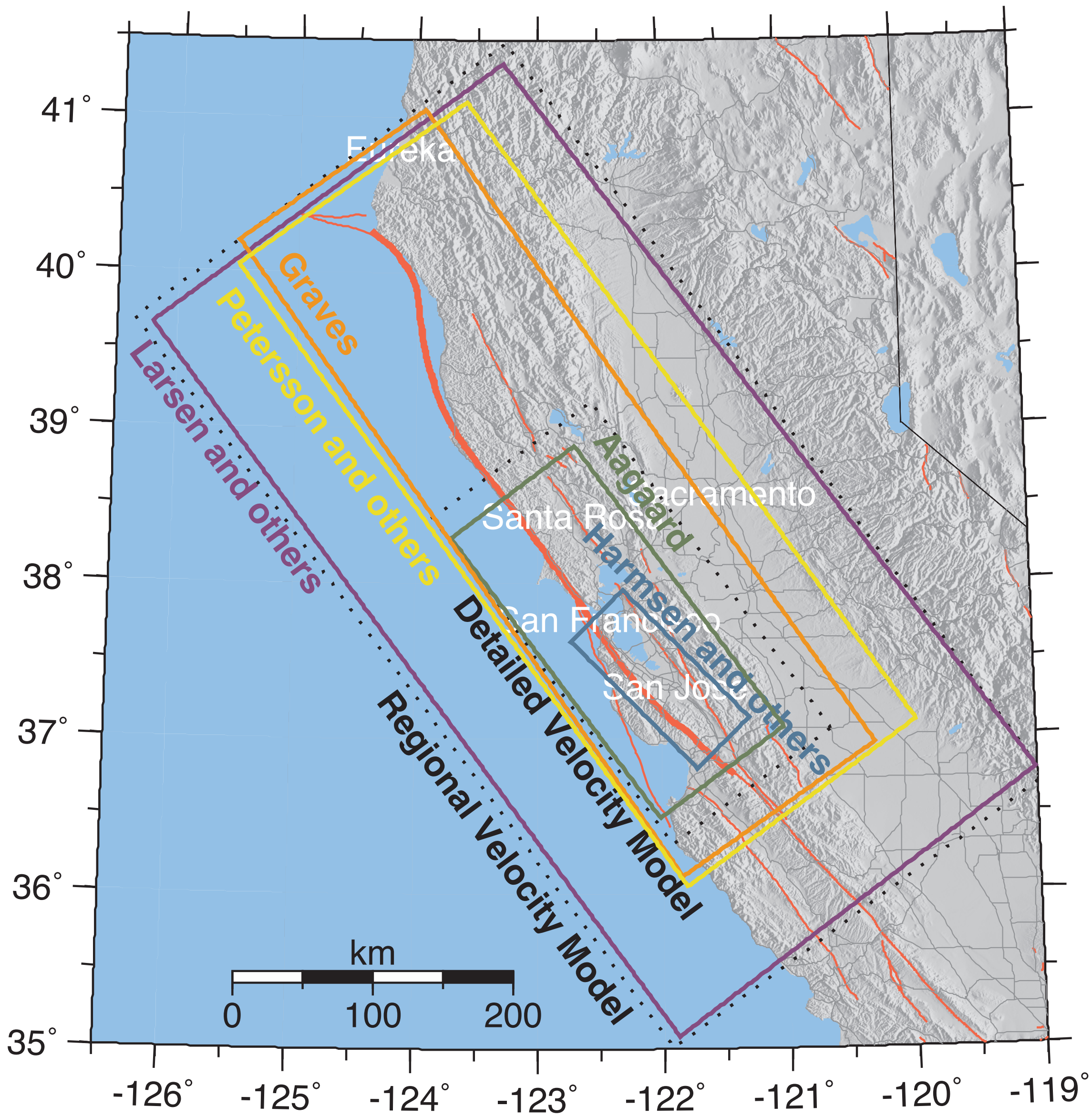

Figure 1. Model domains for the 1906 San Francisco earthquake simulations. Solid lines are the bounding boxes of the domains used by the five modeling groups. Dotted lines are the bounding boxes of the US Geological Survey Bay Area Velocity Model 05.1.0. The thick red curve is the portion of the San Andreas Fault that ruptured in 1906. Thin red curves are the surface traces of major faults in the region.

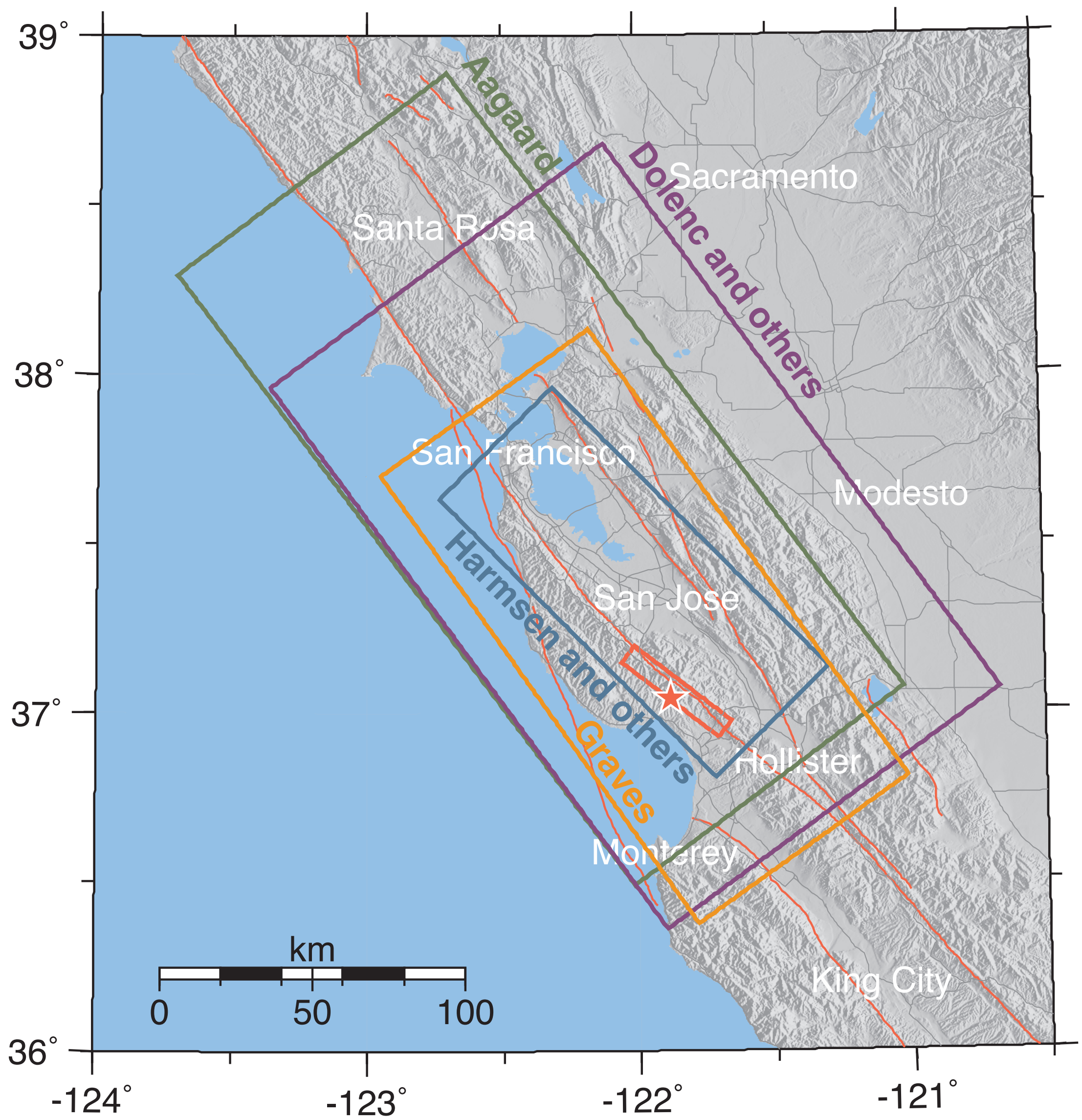

Figure 2. Model domains and epicenter for the 1989 Loma Prieta earthquake simulations. Large rectangles are the bounding boxes of the domains used by the four modeling groups. The small red rectangle is the projection of the fault plane in the Wald model, and the star is the epicenter. Thin red curves are the surface traces of major faults in the region.

Table 2. Scenarios for the 1906 San Francisco earthquake simulations. The table lists the names of the nine scenarios, along with the slip distribution and hypocenter location used for each scenario.

Scenario name	Slip distribution and rise time	Hypocenter
Song	Song	1906
SongMod	SongMod	1906
SongModHypoN	SongMod	Rockport
SongModHypoC	SongMod	Bodega Bay
SongModHypoS	SongMod	San Juan Bautista
RandomHypo06	Random	1906
RandomHypoN	Random	Rockport
RandomHypoC	Random	Bodega Bay
RandomHypoS	Random	San Juan Bautista

The Song distribution produces a moment magnitude 7.9 event (average slip is 4.3 m). The SongMod and Random slip distributions produce moment magnitude 7.8 events (average slip is 3.0 m).

Table 3. Coordinates of the earthquake scenario hypocenters, all of which are at an elevation of -10 km.

Hypocenter	Longitude	Latitude
1906	-122.55	37.75
Rockport	-124.000	39.800
Bodega Bay	-123.016	38.300
San Juan Bautista	-121.615	36.872

Coordinates are WGS84 longitude and latitude.

Organization of the Data Files

The simulation data files are stored under two top-level directories, `sf1906` and `lomaprieta`, which contain simulation results for the 1906 San Francisco and 1989 Loma Prieta earthquakes, respectively. The names of the files and directories use the following conventions. The names of the modeling groups are abbreviated with `aagaard` for Aagaard, `dolenc` for Dolenc and others, `graves` for Graves, `harmsen` for Harmsen and others, `larsen` for Larsen and others, and `petersson` for Petersson. In some cases we append the bandwidth to the name of the modeler with `bb` for T > 0.1 s, `t1` for T > 1.0 s, and `t2` for T > 2.0 s. We also include the type of data in the filename for geodetic displacements (`geodeticdisp`) and peak ground velocity (`pgvgrid`). In the case of the grid files, the data spans either the entire rupture length (indicated by `cenca` in the filename) or the San Francisco Bay area (indicated by `bayarea` in the filename). The directory trees are shown in figures (figures 3 through 12 follow the references).

The `sf1906` directory contains three subdirectories and two files:

- `geodetic` —Calculated geodetic displacements. For comparison purposes, this subdirectory also contains displacements calculated from geodetic models and triangulation data from Song and others (2008). These files are listed in figure 4, and the file format is described in figure 7.
- `pgvpgagrid` — Calculated peak ground velocity (PGV). Broadband simulations in this subdirectory (`gravesbb`) also include peak ground acceleration (PGA). This data can be used to construct maps of PGV or Modified Mercalli Intensity (MMI). These files are listed in figure 5, and the file format is described in figure 8.
- `rupturetrace.txt` — Coordinates of rupture trace for the 1906 San Francisco earthquake simulations. The file format is described in figure 9.
- `stations.txt` — List of stations used for the 1906 San Francisco earthquake simulations. The file format is described in figure 10.
- `waveforms` — Calculated velocity time histories. Within this subdirectory are five subdirectories corresponding to the five participating modeling groups. Each of these subdirectories contains a zip archive file with the waveforms for each scenario. The zip archive contains a file for each site, in which the name of the file matches the site; for example, the waveforms for site SF003 are in a file called `sf003.txt`. The waveform file format is described in figure 11. Most modern operating systems include utilities for extracting all or a selected subset of files from zip archives.

The `lomaprieta` directory contains two subdirectories and one file:

- `pgvpgagrid` — Calculated PGV. The data in this subdirectory can be used to construct maps of PGV or MMI. These files are listed in figure 6, and the file format is described in figure 8.
- `stations.txt` — List of stations used for the 1989 Loma Prieta earthquake simulations. The file format is described in figure 10.
- `waveforms` — Calculated velocity time histories. There are four subdirectories corresponding to the four participating modeling groups. Each of these contains a zip archive file with waveforms for the an earthquake source model. The zip archive contains a file for each station, in which the name of the file matches the station; for example, the waveforms for station AGNW would be in a file called `agnw.txt`. The waveform file format is described in figure 11

Table 4. Wave propagation codes for the 1989 Loma Prieta earthquate simulations.

	Aagaard	Dolenc and others	Graves	Harmsen and others
Model domain				
Length, in km	250	220	180	128
Width, in km	110	135	84	52
Max. depth, in km	40	50	45	31
NW corner[1]	-123.7083, 38.2832	-123.3610, 37.9610	-122.9500, 37.7000	-122.7313, 37.6313
NE corner	-122.7002, 38.8944	-122.1150, 38.6800	-122.1748, 38.1326	-122.3116, 37.9610
SE corner	-121.0208, 37.0716	-120.6670, 37.0640	-121.0106, 36.8075	-121.2978, 37.1331
SW corner	-122.0180, 36.4894	-121.9000, 36.3600	-121.7858, 36.3749	-121.7173, 36.8069
Projection	none (3-D Earth)	ellipsoidal trans. Mercator	spheroidal	ellipsoidal trans. Mercator
Discretization				
Method	unstructured finite element	staggered-grid finite difference	staggered-grid finite difference	staggered-grid finite difference
Space accuracy	2nd order	4th order	4th order	4th order
Time accuracy	2nd order	2nd order	2nd order	2nd order
Resolution				
Element size, in m	variable	125	150	50-150
Bandwidth	T > 2.0 s	T > 1.2 s	T > 1.0 s, T > 0.1 s [2]	T > 1.0 s
Min. Vs, in m/s	700	500	760	330
Features				
Topography[3]	yes	bulldozed	bulldozed	squashed
Water	air filled	included	sediment filled	excluded
Mat. properties	USGS 05.1.0	USGS 05.1.0	USGS 05.1.0	USGS 05.1.0
Attenuation[4]	none	none	Graves	USGS 05.1.0 (Beroza) Graves (Wald)
Earthquake source				
Method	offset in mesh	point sources	point sources	point sources
Number of point sources[5]	N/A	34,020 (Beroza) 47,424 (Wald)	1,215 (Beroza) 2,400 (Wald)	1,099 (Beroza) 316 (Wald)
Fault surface	3D geol. model	plane	Plane	Plane

[1]Domain corners are given as WGS84 longitude and latitude.

[2]Graves employs a hybrid method which combines a deterministic model for frequencies T > 1.0 s with a stochastic model for frequencies 1.0 s > T > 0.1 s.

[3]For topography, "bulldozed" means that all material above some elevation is removed, and voids below that elevation are filled with generic material. "Squashed" means that the geologic model is vertically distorted to produce a planar top surface. (Squashing also eliminates bodies of water.)

[4]For material properties and attenuation, "USGS 05.1.0" refers to the U.S. Geological Survey Bay Area Velocity Model 05.1.0, and "Graves" refers to a simple attenuation model developed by Graves. See the Appendix for more information.

[5]"Beroza" and "Wald" refers to the source model.

File Formats

All files are ASCII text files in standard UNIX format (each lines ends with a single line-feed character, hexadecimal value 0A). Each file contains a header, followed by a data table. In the header each line begins with a # character. In the data each lines contains a series of numbers separated by spaces and/or tabs. Figures 7 through 12 describe the file formats. The files ending in .zip are zip archives. Most modern operating systems include utilities for extracting one or more files from a zip archive.

References Cited

Aagaard, B.T., Brocher, T.M., Dolenc, D., Dreger, D., Graves, R.W., Harmsen, S., Hartzell, S., Larsen, S., McCandless, K., Nilsson, S., Petersson, N.A., Rodgers, A., Sjogreen, B., and Zoback, M.L., 2008a, Ground motion modeling of the 1906 San Francisco earthquake II: Ground motion estimates for the 1906 earthquake and scenario events, Bulletin of the Seismological Society of America, v. 98, no. 2, p. 1012-1065.

Aagaard, B.T., Brocher, T.M., Dolenc, D., Dreger, D., Graves, R.W., Harmsen, S., Hartzell, S., Larsen, S., and Zoback, M.L., 2008b, Ground motion modeling of the 1906 San Francisco earthquake I: Validation using the 1989 Loma Prieta earthquake, Bulletin of the Seismological Society of America, v. 98, no 2, p. 989-1011.

Beroza, G.C., 1991, Near-source modeling of the Loma Prieta earthquake: Evidence for heterogeneous slip and implications for earthquake hazard, Bulletin of the Seismological Society of America, v. 81, no. 5. P. 1603-1621.

Boatwright, J. and Bundock, H., 2005, Modified Mercalli Intensity maps for the 1906 San Francisco earthquake plotted in ShakeMap format; U.S. Geological Survey Open-File Report 2005-1135.

Brocher, T., Aagaard, B., Simpson, R., and Jachens, R., 2006, The new USGS 3D seismic velocity model for Northern California (abstract), Seismological Research Letters, v. 77, no. 2, p. 271.

Brune, J.N., 1970, Tectonic stress and spectra of seismic shear waves from earthquakes, Journal of Geophysical Research, v. 75, p. 4997-5009.

Song, S.G., Beroza, G.C., and Segall, P., 2008, A unified source model for the 1906 San Francisco earthquake, Bulletin of the Seismological Society of America, v. 98, no. 2, p. 823-831.

Wald, D.J., Helmberger, D.V., and Heaton, T.H., 1991, Rupture model of the 1989 Loma Prieta earthquake from the inversion of strong-motion and broadband teleseismic data, Bulletin of the Seismological Society of America, v. 81, no. 5, p. 1540-1572.

Wald, D.J., Worden, B.C., Quitoriano, V., and Pankow, K.L., 2005, ShakeMap Manual: Technical Manual, User's Guide, and Software Guide, Version 1.0, U.S. Geological Survey, http://pubs.usgs.gov/tm/2005/12A01, (last accessed February 12, 2009).

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Figures 3 through 12

```
sf1906
   geodetic
   pgvpgagrid
   waveforms
      aagaard
         RandomHypo06
         RandomHypoC
         RandomHypoS
         Song
         SongMod
         SongModHypoC
         SongModHypoS
      gravesbb
         RandomHypo06
         RandomHypoC
         RandomHypoN
         RandomHypoS
         Song
         SongMod
         SongModHypoC
         SongModHypoN
         SongModHypoS
      harmsen
         RandomHypo06
         Song
         SongMod
         SongModHypoS
      larsen
         RandomHypo06
         RandomHypoC
         RandomHypoN
         RandomHypoS
         Song
         SongMod
         SongModHypoC
         SongModHypoN
         SongModHypoS
      petersson
         Song
         SongMod
lomaprieta
   pgvpgagrid
   waveforms
      aagaard
         Beroza
         Wald
      dolenc
         Beroza
         Wald
      gravesbb
         Beroza
         Wald
      harmsen
         Beroza
         Wald
      larsen
         Beroza
         Wald
```

Figure 3. Directory tree for 1906 San Francisco earthquake simulation results and 1989 Loma Prieta earthquake simulation results.

```
aagaardt2_RandomHypo06.geodeticdisp.txt
aagaardt2_RandomHypoC.geodeticdisp.txt
aagaardt2_RandomHypoS.geodeticdisp.txt
aagaardt2_Song.geodeticdisp.txt
aagaardt2_SongMod.geodeticdisp.txt
aagaardt2_SongModHypoC.geodeticdisp.txt
aagaardt2_SongModHypoS.geodeticdisp.txt
gravesbb_RandomHypo06.geodeticdisp.txt
gravesbb_RandomHypoN.geodeticdisp.txt
gravesbb_RandomHypoS.geodeticdisp.txt
gravesbb_Song.geodeticdisp.txt
gravesbb_SongMod.geodeticdisp.txt
gravesbb_SongModHypoC.geodeticdisp.txt
gravesbb_SongModHypoN.geodeticdisp.txt
gravesbb_SongModHypoS.geodeticdisp.txt
gravest1_RandomHypo06.geodeticdisp.txt
gravest1_RandomHypoC.geodeticdisp.txt
gravest1_RandomHypoN.geodeticdisp.txt
gravest1_RandomHypoS.geodeticdisp.txt
harmsent1_Song.geodeticdisp.txt
harmsent1_SongMod.geodeticdisp.txt
harmsent1_SongModHypoS.geodeticdisp.txt
larsent1_RandomHypo06.geodeticdisp.txt
larsent1_RandomHypoC.geodeticdisp.txt
larsent1_RandomHypoS.geodeticdisp.txt
larsent1_Song.geodeticdisp.txt
larsent1_SongMod.geodeticdisp.txt
larsent1_SongModHypoC.geodeticdisp.txt
larsent1_SongModHypoN.geodeticdisp.txt
larsent1_SongModHypoS.geodeticdisp.txt
peterssont2_Song.geodeticdisp.txt
peterssont2_SongMod.geodeticdisp.txt
song_Song.geodeticdisp.txt
```

Figure 4. Geodetic displacement files for 1906 San Francisco earthquake simulation. The first part of the filename identifies the modeling group and bandwidth: `aagaardt2` (Aagaard, 0.5 Hz), `gravesbb` (Graves, 10 Hz), `gravest1` (Graves, 1 Hz), `harmsent1` (Harmsen and others, 1 Hz), `larsent1` (Larsen and others, 1 Hz), and `peterssont2` (Petersson and others, 0.5 Hz). The file beginning with song contains displacements calculated by Song and others based on geodetic models and triangulation data. The second part of the filename identifies the earthquake scenario (RandomHypo06, RandomHypoC, etc.). See figure 7 for a description of the file format.

```
aagaardt2_RandomHypo06_bayarea.pgvgrid.txt
aagaardt2_RandomHypoC_bayarea.pgvgrid.txt
aagaardt2_RandomHypoS_bayarea.pgvgrid.txt
aagaardt2_Song_bayarea.pgvgrid.txt
aagaardt2_SongMod_bayarea.pgvgrid.txt
aagaardt2_SongModHypoC_bayarea.pgvgrid.txt
aagaardt2_SongModHypoS_bayarea.pgvgrid.txt
gravesbb_RandomHypo06_cenca.pgvgrid.txt
gravesbb_SongMod_cenca.pgvgrid.txt
gravesbb_SongModHypoN_cenca.pgvgrid.txt
gravest1_RandomHypo06_cenca.pgvgrid.txt
gravest1_RandomHypoC_cenca.pgvgrid.txt
gravest1_RandomHypoN_cenca.pgvgrid.txt
gravest1_RandomHypoS_cenca.pgvgrid.txt
gravest1_Song_cenca.pgvgrid.txt
gravest1_SongMod_cenca.pgvgrid.txt
gravest1_SongModHypoC_cenca.pgvgrid.txt
gravest1_SongModHypoN_cenca.pgvgrid.txt
gravest1_SongModHypoS_cenca.pgvgrid.txt
harmsent1_RandomHypo06_bayarea.pgvgrid.txt
harmsent1_SongMod_bayarea.pgvgrid.txt
larsent1_RandomHypo06_cenca.pgvgrid.txt
larsent1_RandomHypoC_cenca.pgvgrid.txt
larsent1_RandomHypoS_cenca.pgvgrid.txt
larsent1_Song_cenca.pgvgrid.txt
larsent1_SongMod_cenca.pgvgrid.txt
larsent1_SongModHypoC_cenca.pgvgrid.txt
larsent1_SongModHypoN_cenca.pgvgrid.txt
larsent1_SongModHypoS_cenca.pgvgrid.txt
peterssont2_Song_cenca.pgvgrid.txt
peterssont2_SongMod_cenca.pgvgrid.txt
```

Figure 5. Peak ground velocity files for 1906 San Francisco earthquake simulation. The first part of the filename identifies the modeling group and bandwidth: `aagaardt2` (Aagaard, 0.5 Hz), `gravesbb` (Graves, 10 Hz), `gravest1` (Graves, 1 Hz), `harmsent1` (Harmsen and others, 1 Hz), `larsent1` (Larsen and others, 1 Hz), and `peterssont2` (Petersson and others, 0.5 Hz). The second part of the filename identifies the earthquake scenario (for example, RandomHypo06, RandomHypoC). The third part of the filename identifies the region covered: bayarea (San Francisco Bay Area) or cenca (Central California). The fourth part of the filename identifies the file contents: pgvgrid (peak ground velocity) or `pgvpgagrid` (peak ground velocity and peak ground acceleration). See figure 8 for a description of the file format.

```
aagaardt2_Beroza.pgvgrid.txt
aagaardt2_Wald.pgvgrid.txt
dolenct1_Beroza.pgvgrid.txt
dolenct1_Wald.pgvgrid.txt
gravesbb_Beroza.pgvgrid.txt
gravesbb_Wald.pgvgrid.txt
gravest1_Beroza.pgvgrid.txt
greavest1_Wald.pgvgrid.txt
harmsent1_Beroza.pgvgrid.txt
harmsent1_Wald.pgvgrid.txt
```

Figure 6. Peak ground velocity files for 1989 Loma Prieta earthquake simulations. The first part of the filename identifies the modeling group and bandwidth: aagaardt2 (Aagaard, T>2.0s), dolenct1 (Dolenc and others, T>1.0s), gravesbb (Graves, T > 0.1s), gravest1 (Graves, T>1.0s), and harmsent1 (Harmsen and others, T>1.0s). The second part of the filename identifies the earthquake source model (Beroza or Wald). The last part of the filename identifies the file contents: pgvgrid (peak ground velocity) or pgvpgammigrid (peak ground velocity, peak ground acceleration, and modified Mercalli intensity). See figure 8 for a description of the file format.

```
# Author: Robert Graves
# Scenario: RandomHypoN
# Date: 12-Jan-2007
# Bandwidth (Hz): 1
# Column 1: WGS84 longitude (deg)
# Column 2: WGS84 latitude (deg)
# Column 3: East-west displacement (m) (+ is eastward)
# Column 4: North-south displacement (m) (+ is northward)
-123.57948   39.68653  -0.1472   0.0260
-123.09623   39.51588  -0.1472   0.0260
-123.44608   39.36167  -0.1472   0.0260
-123.55445   40.33394  -0.1472   0.0260
-124.12427   40.15683  -0.1472   0.0260
-123.31282   39.13548  -0.1472   0.0260
-123.58740   39.06616  -0.1472   0.0260
-122.75873   39.37693  -0.1472   0.0260
```

Figure 7. Geodetic displacement file format. A geodetic displacement file contains the final horizontal geodetic displacement at each point in a set of points. The file header contains the following information: name of author; earthquake scenario or source model; date simulation was performed; bandwidth (highest seismic wave frequency included in the simulation); and description of data fields. Following the header is a series of lines, each corresponding to one point in the set of points. On each line are four numbers: the longitude, in degrees (WGS84 coordinates); the latitude, in degrees (WGS84 coordinates); the east component of displacement, in meters; and the north component of displacement, in meters.

```
# Author: Stephen Harmsen, Stephen Hartzell
# Scenario: SongMod
# Date: 10-Nov-2006
# Bandwidth (Hz): 1.0000
# Column 1: WGS84 longitude (deg)
# Column 2: WGS84 latitude (deg)
# Column 3: Peak ground velocity (m/s)
-123.85000  39.00000  0.000
-123.83330  39.00000  0.000
-123.81670  39.00000  0.000
-123.80000  39.00000  0.000
-123.78330  39.00000  0.000
-123.76670  39.00000  0.000
-123.75000  39.00000  0.000
-123.73330  39.00000  0.000
```

Figure 8. Peak ground velocity file format. A peak ground velocity file contains the peak ground velocity at each point on a dense grid of points. This file format is useful for constructing maps of ground motion intensity. The file header contains the following information: name of author; earthquake scenario or source model; date simulation was performed; bandwidth (highest seismic wave frequency included in the simulation); and description of data fields. Following the header is a series of lines, each corresponding to one point in the grid of points. On each line are three numbers: the longitude, in degrees (WGS84 coordinates); the latitude, in degrees (WGS84 coordinates); and the peak ground velocity at the given point, in meters per second. Some files also include the peak ground acceleration. If so, the peak ground acceleration appears as a fourth number on each line. Some files also include both peak ground acceleration and modified Mercalli intensity. If so, the peak ground acceleration appears as a fourth number on each line, and the modified Mercalli intensity appears as a fifth number on each line.

```
# Rupture trace for the 1906 ground motion modeling.
#
# Columns are:
# (1) Longitude (WGS84)
# (2) Latitude (WGS84)
-124.39208  40.26896
-124.38281  40.26298
```

Figure 9. Rupture trace file format. This file lists the coordinates of the rupture trace used in the 1906 San Francisco earthquake simulations. Following the header is a series of lines with the longitude and latitude (both in degrees and WGS84 coordinates). This file is named `sf1906/rupturetrace.txt.`

```
# Location of time history sites for the 1906 ground motion modeling.
#
# Stations beginning with the prefix "SF" are Boatwright and Bundock
# (2005) intensity sites. Stations beginning with the prefix "CT" are
# centroids of census tracks
#
# Columns are:
# (1) Longitude (WGS84)
# (2) Latitude (WGS84)
# (3) Station name
-120.872500  35.645556  SF001
-121.596360  36.608150  SF002
-121.958050  37.394720  SF003
-122.487660  38.324130  SF004
-122.238480  37.764370  SF005
-122.124760  37.712120  SF006
-123.767500  39.223611  SF007
-123.050710  38.834460  SF008
```

Figure 10. Waveform site list file format. This file lists the stations used in the 1906 San Francisco earthquake simulations. Following the header is a series of lines, each corresponding to one station. On each line are three numbers: the longitude, in degrees (WGS84 coordinates); the latitude, in degrees (WGS84 coordinates); and the name of the station. This file is named `sf1906/stations.txt`. The 11 digit number following CT is the census track number.

```
# Author: Brad Aagaard
# Scenario: RandomHypo06
# Date: 26-Oct-2006
# Bandwidth (Hz): 0.500000
# Station: SF003
# Target location (WGS84 longitude, latitude) (deg): -121.95805  37.39472
# Actual location (WGS84 longitude, latitude) (deg): -121.96131  37.39611
# Distance from target to actual location (m): 327.7
# Column 1: Time (s)
# Column 2: East-west velocity (m/s) (+ is eastward)
# Column 3: North-south velocity (m/s) (+ is northward)
# Column 4: Up-down velocity (m/s) (+ is upward)
  0.0000e+00  0.0000e+00  0.0000e+00  0.0000e+00
  1.0000e-01  0.0000e+00  0.0000e+00  0.0000e+00
  2.0000e-01  0.0000e+00  0.0000e+00  0.0000e+00
  3.0000e-01  0.0000e+00  0.0000e+00  0.0000e+00
  4.0000e-01  0.0000e+00  0.0000e+00  0.0000e+00
  5.0000e-01  0.0000e+00  0.0000e+00  0.0000e+00
  6.0000e-01  0.0000e+00  0.0000e+00  0.0000e+00
  7.0000e-01  0.0000e+00  0.0000e+00  0.0000e+00
```

Figure 11. Waveform file format. A waveform file contains a synthetic seismogram. It records the ground velocity at a given station for each time step in the simulation. The waveform file header contains the following information: name of author; earthquake scenario or source model; date simulation was performed; bandwidth (highest seismic wave frequency included in the simulation); station name; longitude and latitude of the station (WGS84 coordinates); longitude and latitude of the point where the waveform data was actually computed; distance from the station to the point where the waveform data was actually computed; and description of data fields. Following the header is a series of lines, each corresponding to one time step in the simulation. On each line are four numbers: the time, in seconds relative to the origin time; the east component of ground velocity, in m/s; the north component of ground velocity, in meters per second; the up component of ground velocity, in meters per second. A waveform file is always given a name that matches the station name.

```
# Nominal coordinates of stations used in this study,
# compiled from a variety of sources.
#
# Columns are:
# (1) Longitude (WGS84)
# (2) Latitude (WGS84)
# (3) Elevation wrt MSL (m)
# (4) Station name
 -121.9522    36.9740     6.6    CAP
 -121.5690    37.0090    60.9    GILB
 -121.7140    37.3380   464.7    HALL
 -121.3970    36.8480    90.2    HOL
 -121.9903    37.2008   197.5    LEX
 -121.8970    37.4300     7.1    MILP
 -121.8510    37.3400    30.8    SJIN
 -121.8030    37.2100   225.3    SNJ
```

Figure 12. Loma Prieta station file format. This file lists the stations used in the 1989 Loma Prieta earthquake simulations. Following the header is a series of lines, each corresponding to one station. On each line are four numbers: the longitude, in degrees (WGS84 coordinates); the latitude, in degrees (WGS84 coordinates); the elevation of the station, in meters; and the name of the station. This file is named `lomaprieta/stations.txt`.

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Appendix

Appendix—Methodology Details

In this appendix we explain the information in tables 1 and 4. See Aagaard and others (2008a,b) for a thorough discussion of the simulations.

Problem Statement

All the ground-motion modeling codes solve the elastic wave equation in heterogeneous media, given kinematic boundary conditions on the fault surface. The kinematic boundary condition on the fault prescribes fault slip as a function of time for each point on the fault surface. The modeler is also given the 3D fault geometry; the surface topography; a 3D velocity model, which describes the 3D variation in rock properties; and a set of stations on the earth's surface. The modeler's job is to solve the elastic wave equation throughout the modeling domain and to report the calculated motion of each station as a function of time. These outputs are synthetic velocity time-histories.

Validation

Every ground-motion simulation has its limitations and approximations. The size of the modeling domain, spatial resolution, bandwidth, and features that can be included in a model are all limited by the available computing resources and numerical techniques. There are also considerable uncertainties in the slip-time function, fault geometry, and rock properties.

Two techniques have been used to validate the modeling results. First, the results produced by the different codes were compared to each other. Since each code employs a unique set of tradeoffs and techniques, agreement between the codes provides some assurance of the robustness of the results.

Second, the results were compared to observed data. In the case of the 1989 Loma Prieta earthquake, modern instrumental records are available to serve as a basis of comparison. For the 1906 San Francisco earthquake, no such instrumental records exist, but it is still possible to perform some comparisons based on accounts of ground-shaking intensity and damage.

Wave-Propagation Codes

Different wave-propagation codes were used by each of the ground-motion modeling groups that participated in modeling the 1906 San Francisco earthquake. Four of these codes were also used in the modeling the 1989 Loma Prieta earthquake. The characteristics of the codes are summarized in tables 1 and 4, respectively. The members of the modeling groups (listed with the primary researcher first) are:

- Aagaard — Brad Aagaard
- Dolenc — David Dolenc, Douglas Dreger, and Shawn Larsen
- Graves — Robert Graves
- Harmsen — Stephen Harmsen and Stephen Hartzell
- Larsen — Shawn Larsen, Douglas Dreger, and David Dolenc
- Petersson — Anders Petersson, Arthur Rodgers, Kathleen McCandless, Stefan Nilsson, and Bjorn Sjogreen.

Aagaard used an unstructured, finite-element code that is second-order accurate in space and time. The finite-element mesh consists of 4-node tetrahedra. The element size is variable and equal to approximately 1/10th of the local wavelength of a shear wave with period 2.0 seconds. The fault surface is an internal boundary of the finite-element mesh, and fault slip is represented as a displacement discontinuity on this surface. The fault surface is smoothed by applying a Laplacian smoothing to the vertex coordinates.

The Dolenc, Graves, Harmsen, and Larsen groups used staggered-grid, finite-difference codes, which are fourth-order accurate in space and second-order accurate in time. (Dolenc and Larsen are the same code.) Petersson used a node-centered, finite-difference method that is second-order accurate in space and time. All the finite-difference codes represent fault slip as a set of evenly distributed point sources. Dolenc, Graves, Larsen, and Petersson used a uniform discretization size. Harmsen used a discretization size of 50 m in the top 700 m with a horizontal grid size of 150 m at depths greater than 700 m. The vertical grid size is 50 m down to a depth of 950 m; it then increases linearly to 150 m at a depth of 1,500 m, and to 250 m at a depth of 30 km.

Graves employed a hybrid method, that combines a deterministic finite-difference calculation for frequencies $f < 1.0$ Hz with a stochastic calculation for frequencies 1.0 Hz $< f < 10.0$ Hz. The short-period waves are generated by dividing the fault surface into subfaults and assuming each subfault emits randomly phased seismic waves with an omega-squared spectrum. These short-period waves are propagated through the model with a simple 1D Green's function. This modeling technique also applies site corrections across all periods to account for near-surface, period-dependent, nonlinear site effects. We refer to Graves's deterministic finite-difference calculations as long-period simulations ($T > 1.0$ s) and to Grave's hybrid simulations as broadband simulations ($T > 0.1$ s).

Material Properties and Attenuation

All the models used the U.S. Geological Survey Bay Area Velocity Model version 05.1.0 for material properties (Brocher and others, 2006). The Aagaard, Dolenc, and Petersson simulations do not include attenuation. Larsen (and Harmsen for the Beroza source model of the 1989 Loma Prieta earthquake) used the attenuation contained in the U.S. Geological Survey Bay Area Velocity Model. Graves and Harmsen (except for Harmsen's run with the Beroza source model of the 1989 Loma Prieta earthquake) used a simplified attenuation model developed by Graves. In this simplified model, Qs scales as a power of Vs. The power-law exponent is 1.0 for Vs < 0.9 km/s, 1.5 for 0.9 km/s < Vs < 3.4 km/s, and 0.0 for Vs > 3.4 km/s.

Topography and Water

For the Aagaard simulations topography and bathymetry are included by making the top surface of the finite element mesh conform to the surface topography, including the 3D curvature of the earth. The topography is smoothed using the same Laplacian filtering applied to the fault surface.

The Dolenc, Graves, Harmsen, and Petersson finite-difference codes require a planar top surface. There are two techniques for obtaining a planar top surface. Dolenc, Graves, and Petersson "bulldoze" the surface by removing all material above a certain elevation and filling in all voids below the elevation with a generic material. Bulldozing tends to remove low-velocity layers near the earth's surface. Harmsen "squashes" the surface by vertically distorting the upper part of the velocity model so as to flatten the topography. Squashing preserves near-surface low-velocity layers at the expense of distorting the geologic units in the upper part of the velocity model (for example, in the top 1 km). The Larsen finite-difference code includes topography.

The Aagaard code does not include water (bodies of water are filled with air). The Dolenc, Larsen, and Petersson codes include water (Vs = 0) in the simulations. The Graves code fills bodies of water with generic sediment (V_p = 2200 m/s, V_s = 760 m/sec, density = 2100 kg/m^3). In the Harmsen code, bodies of water are eliminated by squashing.

Slip-Time Function

The slip-time function gives fault slip as a function of time, for each point on the fault surface. All the models use the integral of Brune's far-field time function (Brune, 1970),

$$D(t) = D_{final}(1 - e^{-t/t_0}(1 + \frac{t}{t_0})) \tag{1}$$

$$t_0 = \frac{D_{final}}{eV_{max}} \tag{2}$$

$$V_{max}[\mathrm{m/s}] = C_{tr}\sqrt{D_{final}[\mathrm{m}]} \tag{3}$$

for the slip time history where $D(t)$ is slip as a function of time, t is time since the initiation of slip at a given point on the fault, t_0 is a time constant, D_{final} is the final slip at a point, V_{max} is the peak slip rate, and C_{tr} is a constant that controls the rise time. For the 1989 Loma Prieta earthquake, $C_{tr} = 1.5$. For the 1906 San Francisco earthquake,

$$C_{tr} = \begin{cases} 0.6 & z \geq 0 \text{ km} \\ -0.12z + 0.6 & -5.0 \text{ km} < z < 0 \text{ km} \\ 1.2 & z \leq -5.0 \text{ km} \end{cases} \tag{4}$$

where z is elevation with respect to mean sea level.

The rise time t_{95} is defined to be the time it takes for 95 percent of the final slip to occur, that is, $D(t_{95}) = 0.95D_{final}$. For this slip-time function, the rise time is given by

$$t_{95} = 1.745\frac{D_{final}}{V_{max}}. \tag{5}$$

1906 San Francisco Source Models

The source models used for the 1906 San Francisco earthquake simulations are summarized in figures 13 through 15. The source model specifies the final slip and time of slip initiation for each point on the fault surface. There are nine source models. Two of the source models, named Song and SongMod, are models of the 1906 earthquake. The other seven source models are hypothetical scenarios, chosen to characterize the potential variability in ground motions for future events of this size on the northern San Andreas Fault.

Our Song source model (fig. 14) is based on Song and others (2008). The original Song and others source model only contains slip variations at long length-scales and a gross estimate of the rupture speed. It specifies slip on 10 km along-strike and 12 km down-dip patches, with the average rupture speed determined over portions of the fault ranging in length from 40 km to 120 km. The first 120 km of rupture north of the hypocenter propagates faster than the shear-wave speed before dropping below the shear wave speed for the remaining northward propagation. Our Song source model is the same as the original Song and others source model except that the rupture speed in the upper 5 km of the fault tapers down to 60 percent of the original Song and others value.

The SongMod source model (fig. 14) is a modified version of the Song model, which is better suited for modeling ground motions in the period range of interest (periods of 1 to 2 seconds and longer). Three modifications are applied to the Song model. First, shorter length scale variations in final slip are added to the model. The additional variations in final slip are randomly phased, and passed through a low-pass spatial filter whose amplitude falls off as the inverse square of the wavenumber for large wavenumbers. The filter's correlation length (equal to the reciprocal of the filter's corner wavenumber) is $10^{0.5M_W-2}$ kilometers, which evaluates to 79 km or 89 km for magnitude 7.8 or 7.9 events, respectively.

Second, local variations in rupture speed are added to the model, so the rupture propagates more quickly through regions with larger final slip. This is done by adjusting the slip initiation times according to

$$t_r = t_{orig} - t_{shift}(slip) \tag{6}$$

where t_r is the slip-initiation time, t_{orig} is the original slip-initiation time from the Song model, and $t_{shift}(slip)$ is a timing perturbation that scales linearly with final slip such that t_{shift}=1.0 s at the location of maximum final slip and t_{shift}= 0 at locations where the final slip is equal to its average value.

Third, the average slip was reduced from 4.3 m to 3.0 m, and a few small perturbations to the large length scale distributions of slip and rupture speed were made. The smaller average slip results in a moment magnitude 7.8 event compared to a moment magnitude 7.9 event. This yields a better fit to the Boatwright and Bundock intensities.

The three hypothetical scenarios SongModHypoN, SongModHypoC, and SongModHypoS (fig. 14) use the same distributions of slip and rupture speed as the SongMod source model, but they have alternative hypocenter locations: one near the northern end of the rupture (Rockport), one near the center of the rupture (Bodega Bay), and one near the southern end of the rupture (San Juan Bautista), respectively.

The four hypothetical scenarios RandomHypo06, RandomHypoN, RandomHypoC, and RandomHypoS (fig. 14) use the same hypocenters as the corresponding SongMod scenarios, but with a different distribution of final slip. The slip distribution was produced by generating a slip distribution with random phase at all wavelengths and passing it though the wavenumber squared low-pass spatial filter mentioned above, while constraining the average slip to be the same as in the SongMod model. Several such slip distributions were generated. The one selected for use has a spatial distribution of final slip that differs substantially from the SongMod source model.

For our slip time function, the rise time t_{95} is in the range of 3 to 4 seconds for slip in the range of 4 to 8 m when $C_{tr} = 1.2$. This is consistent with the rise times in kinematic source inversions extrapolated to events of this size.

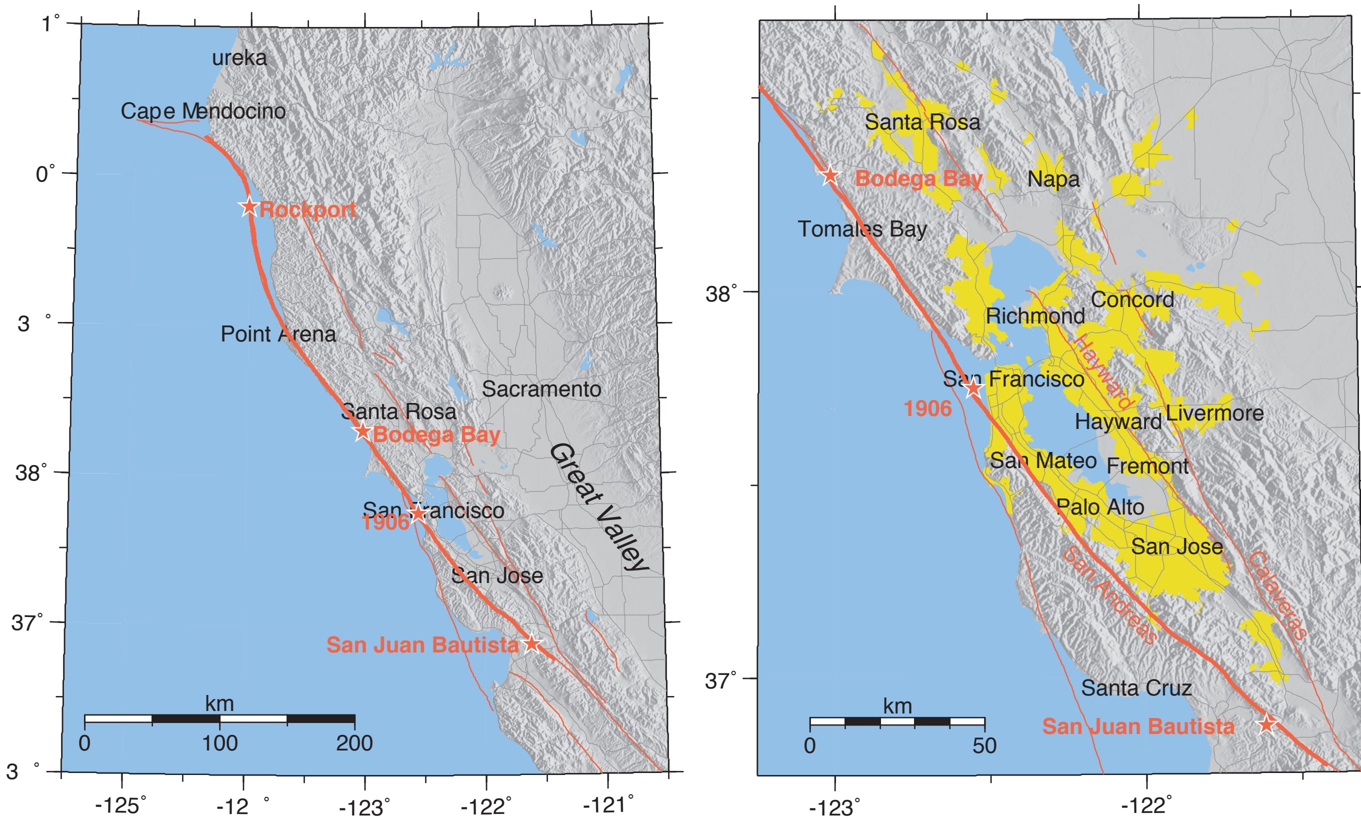

Figure 13. Hypocenter locations for the 1906 San Francisco earthquake simulations. Scenario epicenters are shown on maps of the entire rupture length (top left) and San Francisco Bay vicinity (top right). The thick red line shows the extent of the ruptures in the simulations, and the red stars denote the scenario epicenters. The yellow highlighted region shows the urbanized areas within the nine-county San Francisco Bay area.

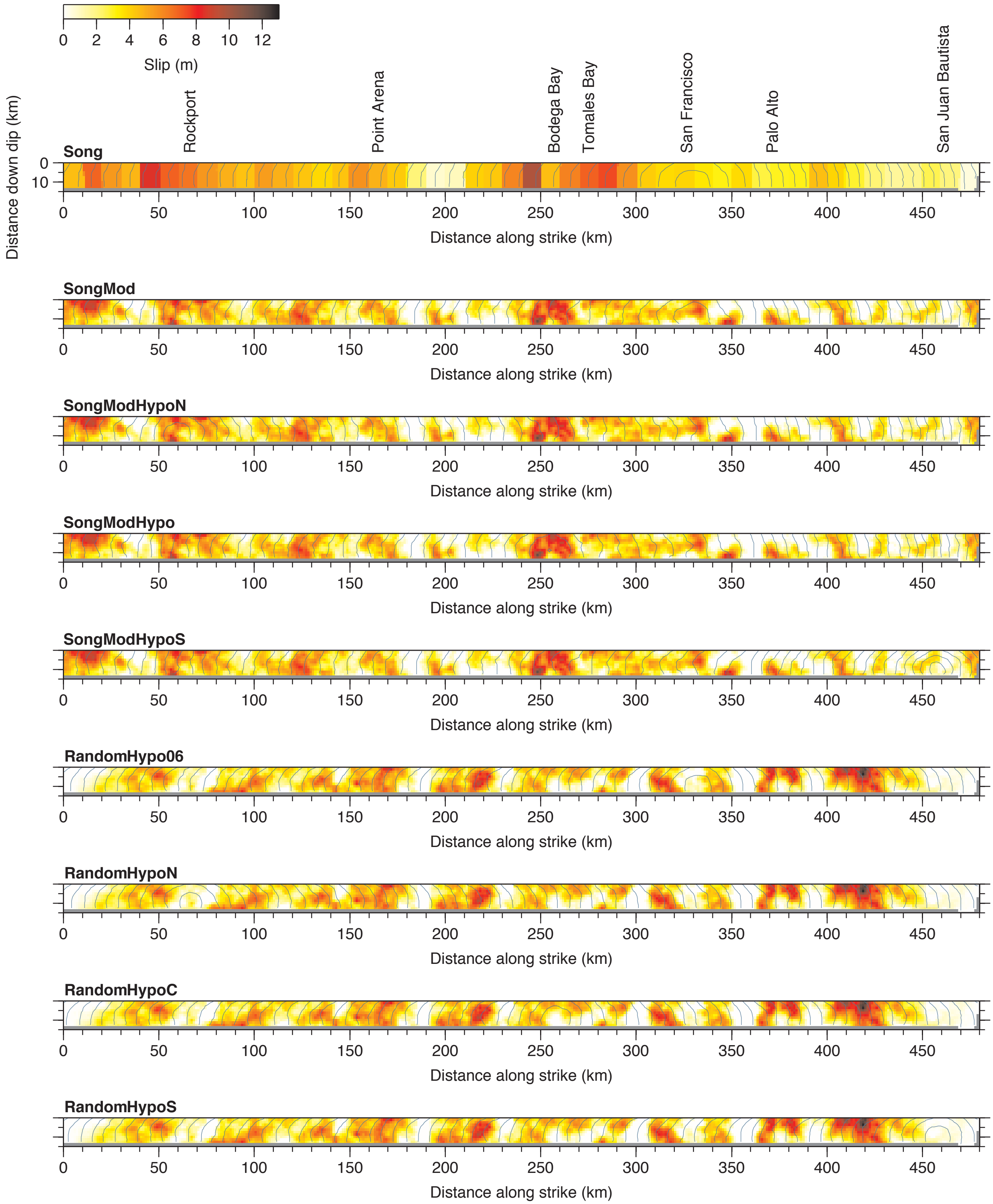

Figure 14. Source models for the 1906 San Francisco earthquake simulations. The top two panels are the slip models for the 1906 earthquake, and the bottom seven panels are the slip models for hypothetical scenarios. Colors depict the magnitude of right-lateral slip, and the contours show the slip-initiation time (contour interval is 2.0 s). The nonplanar fault geometry has been mapped onto a rectangular grid for display purposes.

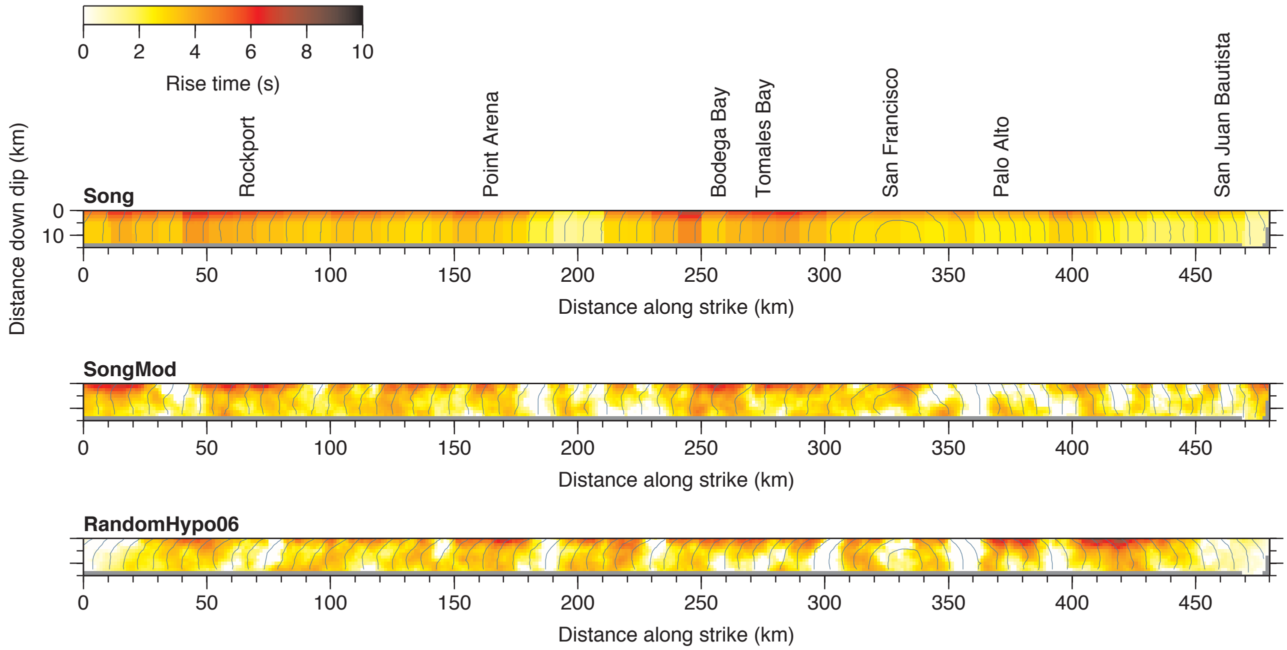

Figure 15. Rise times for the 1906 San Francisco earthquake simulations. Colors depict the magnitude of rise time, and the contours show the slip-initiation time (contour interval is 2.0 s). The nonplanar fault geometry has been mapped onto a rectangular grid for display purposes. For locations with zero slip, the rise time is shown as zero. Rise time is defined to be the amount of time required for 95 percent of the final slip to occur. The SongModHypoN, SongModHypoC, and SongModHypoS source models have the same rise time as the SongMod model. The RandomHypoN, RandomHypoC, and RandomHypoS source models have the same rise time as the RandomHypo06 model.

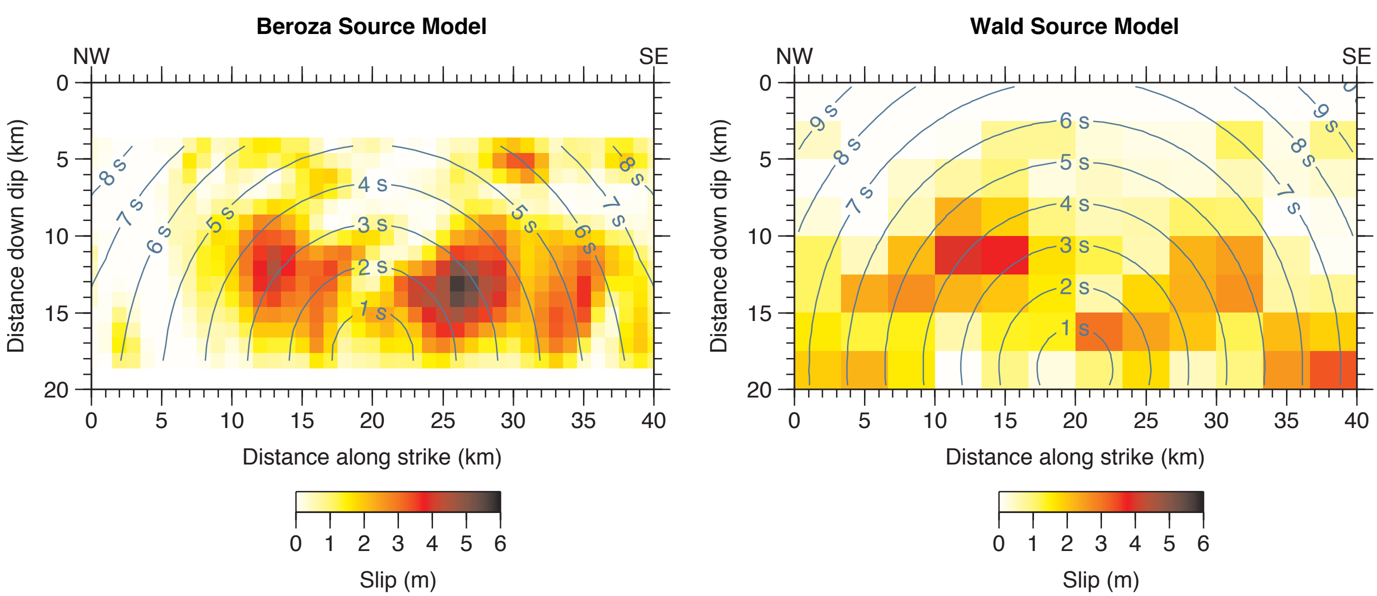

Figure 16. Source models for the 1989 Loma Prieta earthquake simulations. The Beroza model is shown on the left, and the modified Wald model is shown on the right. Colors depict the magnitude of slip, and the contours show the slip-initiation time (contour interval is 1.0 s). The down-dip coordinates of the Beroza source model have been aligned with those of the Wald source model.

1989 Loma Prieta Source Models

The source models used for the 1989 Loma Prieta earthquake simulations are summarized in figure 16. The 1989 Loma Prieta earthquake is a moment magnitude 6.9 event. There are two slip models named Beroza and Wald. The Beroza model is based on Beroza (1991), and the Wald model is based on Wald and others (1991). These two models employ significantly different representations of the source and are based on slightly different datasets.

The Beroza model represents the seismic source by using a spatially continuous slip field, and it is constrained by local stations with relatively few stations northwest of the epicenter. The rupture surface is approximated using a single plane, dipping at 70 degrees to the southwest, which strikes 130 degrees east of north. The rupture speed is 80 percent of the local shear-wave speed.

The Wald model represents the seismic source by using a piecewise uniform slip field; it is constrained by both teleseismic and local stations, with slightly more uniform azimuthal coverage than the Beroza model. The rupture surface is approximated using a single plane dipping at 70 degrees to the southwest, which strikes 128 degrees east of north. The rupture speed is 2.7 km/s, which is about 75 percent of the shear-wave speed in the primary source regions.

Two modifications were made to the Wald source model. First, the slip on the northwestern asperity was reduced by 1 m and the slip on the southeastern asperity was increased by 1 m, making the two regions of high slip more equal in moment release. Second, the slip-time function was replaced with the slip-time function described above, where peak slip rate is proportional to the square root of final slip. Figure 16 shows the modified Wald source model.

For our slip-time function, the rise time t_{95} is in the range of 1 to 2 seconds for final slip in the range 1 to 3 meters, which is consistent with the rise times in the original Beroza (1991) and Wald and others (1991) models.

Modified Mercalli Intensity

Maps of Modified Mercalli Intensity (MMI) show the severity of ground shaking. MMI is usually denoted by a Roman numeral ranging from I to XII. A value of II is barely strong enough to be felt, while a value of X denotes very violent shaking with extreme damage. The MMI is defined by how shaking affects people, structures, and landforms. For our simulations we translate the peak ground velocity (PGV) and peak ground acceleration (PGA) into MMI by using the following empirical relationship developed by Wald and others (2005)

$$MMI = \begin{cases} MMI_{PGA} & \text{if } MMI < \mathrm{V} \\ \frac{1}{2}((\mathrm{VII} - MMI_{PGA})MMI_{PGA} + (MMI_{PGA} - \mathrm{V})MMI_{PGV}) & \text{if } \mathrm{V} \le MMI < \mathrm{VII} \\ MMI_{PGV} & \text{if } MMI \ge \mathrm{VII} \end{cases}, \tag{7}$$

$$MMI_{PGA} = \begin{cases} 2.20\log(PGV) + 1.00 & \text{if } MMI < \mathrm{V} \\ 3.66\log(PGV) + 1.66 & \text{if } MMI \ge \mathrm{V} \end{cases}, \text{ and} \tag{8}$$

$$MMI_{PGV} = \begin{cases} 2.10\log(PGV) + 3.40 & \text{if } MMI < \mathrm{V} \\ 3.47\log(PGV) + 2.35 & \text{if } MMI \ge \mathrm{V} \end{cases}, \text{ where} \tag{9}$$

PGA is in the fraction of gravitational acceleration and PGV is in centimeters per second. To construct a map from instrumental data, ShakeMap adds false stations in areas with sparse station coverage and uses regional attenuation relationships to compute PGV and PGA values for the false stations. Then, the PGV and PGA values from both real and false stations are interpolated onto a regular grid, and the above formulas are used to compute MMI at each grid point.

For broadband simulations, which include periods $T > 0.1$s, the above formulas for MMI can be used. However, for long-period simulations, which include only periods $T > 1.0$ s, the above formulas for MMI produce values that are too low because the long-period simulations have unrealistically low PGA values. To avoid this difficulty, only the formulas that relate MMI to PGV (that is, MMI_{PGV}) are used for long-period simulations. For the 1906 San Francisco earthquake, the MMI value is above V in most locations, so the value of MMI is relatively insensitive to the level of PGA.

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Aagaard and others—**Data Files for Ground-Motion Simulations of the 1906 San Francisco Earthquake and Scenario**—Data Series 413