Appendix J: Spatial Seismicity Rates and Maximum Magnitudes for Background Earthquakes

By Mark D. Petersen[1], Charles S. Mueller[1], Arthur D. Frankel[1], and Yuehua Zeng[1]

USGS Open File Report 2007-1437J
CGS Special Report 203J
SCEC Contribution #1138J
Version 1.0

2008

U.S. Department of the Interior
U.S. Geological Survey

California Department of Conservation
California Geological Survey

[1]**U.S. Geological Survey, Golden, Colorado**

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

State of California
ARNOLD SCHWARZENEGGER, Governor

The Resources Agency
MIKE CHRISMAN, Secretary for Resources

Department of Conservation
Bridgett Luther, Director

California Geological Survey
John G. Parrish, Ph.D., State Geologist

U.S. Geological Survey, Reston, Virginia 2008

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth,
its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Petersen, M.D., Mueller, C.S., Frankel, A.D., and Zeng, Yuehua. 2008, Spatial seismicity rates and maximum magnitudes for background earthquakes, *Appendix J in* The Uniform California Earthquake Rupture Forecast, version 2 (UCERF 2): U.S. Geological Survey Open-File Report 2007-1437J and California Geological Survey Special Report 203J, 8 p. [http://pubs.usgs.gov/of/2007/1437/j/].

Contents

Basic Methodology

The background seismicity model is included to account for M 5.0 - 6.5 earthquakes on faults and for random M 5.0 – 7.0 earthquakes that do not occur on faults included in the model (as in earlier models of Frankel et al., 1996, 2002 and Petersen et al., 1996). We include four different classes of earthquake sources in the California background seismicity model: (1) gridded (smoothed) seismicity, (2) regional background zones, (3) special fault zone models, and (4) shear zones (also referred to as C zones). The gridded (smoothed) seismicity model, the regional background zone model, and the special fault zones use a declustered earthquake catalog for calculation of earthquake rates. Earthquake rates in shear zones are estimated from the geodetically determined rate of deformation across an area of high strain rate. We use a truncated exponential (Gutenberg-Richter, 1944) magnitude-frequency distribution to account for earthquakes in the background models.

Catalog

As in 1996 and 2002, we combine several earthquake lists into a final catalog for the western U.S. (WUS) hazard analysis (Mueller and others, 1997). In the WGCEP zone, however, we allow contributions from two of the best-researched source catalogs only. (1) The catalog developed by the California Geological Survey (called CGS hereinafter) has been updated and extended through 2006 (Felzer and Cao, Appendix H). Their analysis of this catalog also provides estimates for magnitude uncertainties and rounding errors for the CGS earthquakes (Appendix H, I). (2) A new catalog developed by Pancha and others (2006) at the University of Nevada (UNR) is primarily focusing on significant earthquakes in the Basin & Range province, and it includes new moment-magnitude estimates for many older earthquakes. In the WGCEP zone before duplicate-checking and declustering (below), CGS contributes ~4440 earthquakes with M greater than or equal to 4.0 and UNR contributes ~410 earthquakes with M greater than or equal to ~4.8. The corresponding contributions to the catalog used for the hazard analysis (after declustering, M ≥ 4) are ~1780 from CGS and ~20 from UNR.

Magnitudes are either moment magnitudes reported from the original sources or are other magnitudes that are assumed to be equal to moment magnitude. Foreshocks and aftershocks are identified and deleted from the catalog using the methodology of Gardner and Knopoff (1974), yielding a declustered catalog of independent earthquakes for the hazard analysis. Non-tectonic (man-made) seismic events are deleted from the catalog if they are clearly associated with a transient process that is no longer active (e.g., large nuclear explosions at the Nevada Test Site), or if the source is ongoing but we have no reason to expect that future large, hazardous events will be associated with the activity (e.g. some mining-related events). The final catalog for the WGCEP zone includes ~1800 independent earthquakes from 1850 through 2006 with moment magnitude equal to or greater than 4.0. (The catalog is clearly incomplete in much of the WUS below the magnitude-4 level; in our judgment the catalog of earthquakes with M ≥ 4 is sufficient to define the future background hazard.) The guidelines provided for the CGS catalog in Appendix H are extended to estimate magnitude uncertainty and rounding errors for the UNR earthquakes.

Hazard from earthquakes shallower and deeper than 35 km is modeled separately (see Hazard From Gridded Seismicity below). We carry over the catalog completeness levels and *b*-values

(b=0.8 for both shallow and deep seismicity) from the 2002 hazard analysis (Frankel and others, 2002); these values were checked using the new catalog, and found to be consistent with the 2002 model. The earthquakes included in the background source models are shown in Figure 1.

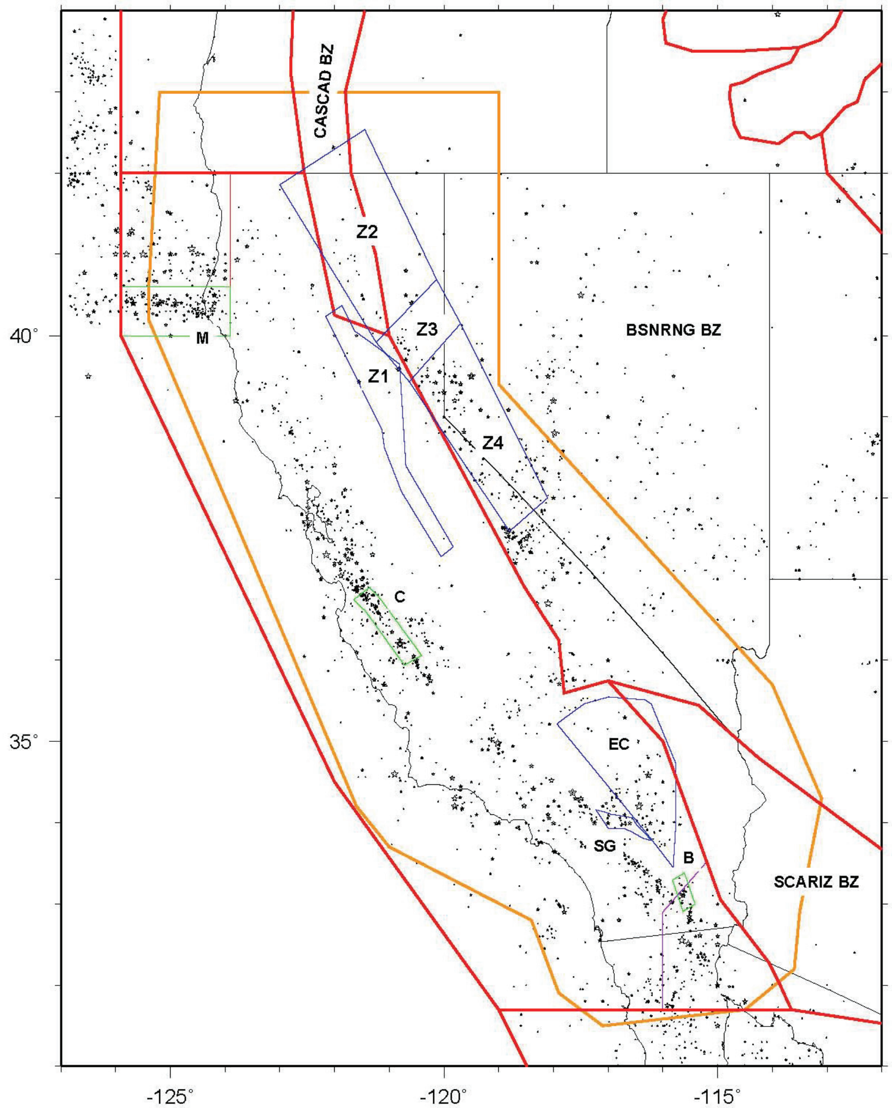

Figure 1. The map shows the earthquake catalog and the boundaries of special zones used in the seismicity source model. The orange line marks the boundary of the WGCEP zone. Red lines mark the boundaries of completeness-level and background-seismicity source zones. Three of the background zones contribute to modeled seismicity rates in the WGCEP zone: Cascade province ("CASCAD BZ"), the Basin & Range province ("BSNRNG BZ"), and a zone in southeastern California - southwestern Arizona ("SCARIZ BZ"). Green lines mark the boundaries of three zones with anisotropic smoothing of gridded seismicity: Brawley seismic zone ("B"), San Andreas fault creeping section ("C"), and Mendocino fault ("M"). Blue lines mark the boundaries of special shear zones: 1-4 ("Z1-Z4"), Eastern California ("EC"), and San Gorgonio ("SG").

Maximum Magnitude

The background seismicity model covers earthquakes from M 5.0 to 7.0, except over modeled faults where the maximum magnitude is reduced to avoid double-counting due to the overlap of magnitudes between M6.5 and 7.0 on fault sources and magnitudes between 5.0 and 7.0 in the gridded seismicity model (Petersen and others, 2000). Although this overlap has only a minor effect on the hazard estimates, we resolve this issue by lowering the M_{max} over the faults for the gridded seismicity models; M_{max} is lowered over dipping faults and within 10 km of vertical faults. For the Gutenberg-Richter case the M_{max} of the gridded seismicity calculation is set to M6.5, which is the M_{min} of the Gutenberg-Richter relation for the fault. For the characteristic case, the M_{max} is set to M_{char} or M7.0, whichever is smaller. M_{max} is set to 7.0 for the gridded seismicity calculation for areas off of faults. When the hazard is calculated from the gridded seismicity, two calculations are performed using the M_{max} grids for the characteristic and Gutenberg-Richter fault cases. The exceedance frequencies from the hazard curves are then added with the appropriate weights for the characteristic (weight = 2/3) and Gutenberg-Richter (weight = 1/3) models used for faults in that area. We have updated the M_{max} model using the new magnitudes calculated for faults in the California and the rest of the WUS. Two alternative fault models were included in the logic tree so we have developed separate M_{max} grids for these two models. Thus, we have developed 4 new M_{max} grids that account for the two alternative fault models and the two magnitude-frequency relations.

An M_{max} value of 7.2 is applied for the seismicity deeper than 35 km. This magnitude is similar to the reported moment magnitude for the 1949 Puget Sound earthquake, which is M 7.1.

Hazard from Gridded Seismicity

Gridded (smoothed) seismicity models are used to estimate the rate of future moderate events on faults and random earthquakes off faults. These models account for the expectation that future large, damaging earthquakes will occur near past small-and moderate-size events. In the WUS virtually all the magnitude 5 and greater earthquakes have occurred near previous M ≥ 4 earthquakes.

Seismicity rates for the gridded seismicity models are determined by counting earthquakes in grid cells with dimensions of 0.1° longitude by 0.1° latitude, accounting for variable completeness using Weichert's (1980) maximum-likelihood method. In Weichert's method one M 4 earthquake counts toward the rate as much as one M 6 earthquake. For a zone covering most of California (including the most seismically active regions near the coast) we use completeness levels of 4 ≤ M < 5 since 1933, 5 ≤ M < 6 since 1900, and M ≥ 6.0 since 1850. Outside of this coastal zone we use 1963, 1930, and 1850, respectively. These completeness parameters apply to both shallow and deep seismicity, and are the same levels used in the 1996 and 2002 hazard models.

A two-dimensional spatial Gaussian function with a correlation distance of 50 km is used to smooth the gridded rates in California (Frankel, 1995; for both shallow and deep seismicity, isotropic unless otherwise noted). Smoothing parameters are based on judgments about earthquake location uncertainties and spatial patterns in the maps after applying different smoothing parameters (Frankel et al., 1996). The *a*-value and a *b*-value determine the rate of earthquakes in the Gutenberg-Richter distribution. The Gutenberg and Richter *a*-value used in the model describes the annual incremental rate of earthquakes between M-0.05 and M+0.05 (0.1 bin width centered on M=0), and the *b*-value describes the relative rate of different magnitudes or the slope of the magnitude-frequency distribution. We assign a *b*-value of 0.8 based on analysis of the WUS and California declustered catalogs.

The gridded seismicity model is based on the magnitude-frequency distribution from the earthquake catalog, and predicts the total number of earthquakes in California from M 5.0 to 7.0. In addition to this gridded model we also allow earthquakes between M 6.5 and 7.0 to occur on faults included in the model. We cannot expect the background source model to match the total historical rate of M 6.5 – 7.0 if we are using the historical rate of earthquakes to define the gridded seismicity and then adding additional earthquakes on faults. Thus, we need to either reduce the rate of earthquakes on faults or reduce the rate of gridded seismicity if we want to match the historical rate of seismicity. Our preliminary studies indicate that about 50 percent to 67 percent of the M≥ 6.5 earthquakes statewide since 1800 are associated with modeled faults. Further analysis in the Discussion section of this report also indicates that 2/3 of the M≥ 6.5 events in the catalog occur on or near A and B faults in the model, while the remaining 1/3 of the events occur elsewhere. For the 2007 background gridded seismicity model we have simply reduced the rate of earthquakes with M ≥ 6.5 by 2/3 to match the historical rate of off-fault seismicity. This reduction of seismicity rate allows us to smooth only those earthquakes that occur off the faults included in the model, and significantly reduces the discrepancy between the modeled and historical rates. We recognize that additional research is needed to provide a more satisfactory long-term solution to this issue.

Regional Background Models

In contrast to the gridded (smoothed) seismicity model, regional background zones account for earthquake potential spread uniformly across tectonic environments or local areas with similar geologic or strain characteristics. The regional zones are shown in Figure 1. Earthquake rates within zones are determined by counting recorded earthquakes within the zone over some time period, computing an annualized rate, and spreading this rate uniformly across the entire area.

For the WUS we carry over from 1996 and 2002 a model that consists of several regional background zones that implement a hazard floor to provide at least some protection against potential future earthquakes in areas with little or no historical seismicity. The average seismicity rate for each region is determined from the catalog (M ≥ 4 since 1963). We feel that background zones are not needed in the most seismically active regions of California, but regional background zones in the Basin and Range province, the Cascade volcanic province, and a region of southeastern California contribute to modeled rates in the WGCEP zone (Figure 1). These regions are geologically and seismologically distinct; the reasoning behind the zonation is discussed in detail in the 1996 documentation.

As in 1996 and 2002, the regional background zones are implemented in a way that does not penalize areas of high seismicity in order to provide a hazard floor in areas of low seismicity. In each grid cell the historical seismicity rate from the gridded seismicity model is compared with the floor value from the applicable regional background zone. If the historical rate exceeds the floor value, the final cell rate simply equals the historical rate. If, however, the floor value exceeds the historical rate, then the gridded seismicity and regional background models are combined with respective weights 0.67 and 0.33 to give the final cell rate. This scheme is slightly conservative; the modeled seismicity rate exceeds the historical rate in the WUS by about 16 precent

Special Fault Zones

One problem with the gridded smoothing method is apparent in some parts of California where seismicity that occurs in narrow linear zones is over-smoothed into nearby aseismic regions. For 2007 we implement an anisotropic spatial smoothing scheme that principally smooths the seismicity rate along the fault strike direction and does not spread much of the seismicity rate perpendicular to the strike direction. Using respective correlation distances of 75 and 10 km for directions parallel and normal to seismicity trends, we apply this method to earthquakes within 10 km of the Brawley seismic zone in southern California, within 20 km of the creeping section of the San Andreas fault in central California, and within 25 km of the Mendocino fracture zone in offshore northern California (Figure 1 and Table 1; also removing the Mendocino fault source that was used in previous models).

Table 1. Source parameters for special fault zones.

Zone	Mmin	Mmax	Virtual Fault Strike (º)	b-value
Brawley	5.0	6.5	157	0.8
CreepingSection of SAF	5.0	6.0	-42.5	0.9
Mendocino	5.0	7.0	90	0.8

Shear (C) Zones

For several areas of the Basin and Range Province the moment estimated from geology is about half the moment estimated from Global Positioning System (GPS) data (Pancha and others, 2006). Shear zones account for earthquakes in these areas where faults are poorly defined and geodetic or seismic data indicate a higher level of shear strain rate. These zones are implemented using geodetic data and Kostrov's formula (Kostrov, 1974) that converts strain rate to moment rate.

The 1996 and 2002 national seismic hazard maps included four shear zones in northern California and Nevada (Figure 1). These zones were retained in the 2007 maps but the geometry was slightly modified to be consistent with recent geodetic strain data. For northeast California and northwest Nevada, we use broadly deformed geodetic shear zones to estimate the shear rate in the area. The shape of the updated C-zones was based on the shape of the maximum geodetic shear strain rate distribution in the area (Figure 2). We did not include the high shear strain rate in the central Nevada seismic belt because of significant post-seismic influences from the Pleasant Valley, Fairview Peak, and Dixie Valley earthquake sequences (Hammond, 2005). The GPS velocities in and around those C-zones are modeled using a broadly distributed shear deformation belt (left panel) to obtain the shear rates in those zones. The shear rate of the eastern California Foothills Fault System (zone 1) is based on fault slip rate studies (e.g., Clark et al., 1984). The rates of shear in zone 2 (Northeastern California), zone 3 (Mohawk-Honey Lake), and zone 4 (western NV) are based on a composite of geodetic, geologic, and seismicity strain rates. We found average geodetic shear rates of 7, 7, and 10 mm/yr for zones 2, 3, and 4, respectively. The corresponding geologic shear rates in the same zones are 2.3, 2, and 0 mm/yr. The corresponding seismicity shear rates are 0.6, 1.0, and 1.5 mm/yr. We used 50 percent of the residual shear rate between the geodetic and the combined geologic and seismic shear rates as our final shear rates for those zones. The rates for each zone are shown in Table 2.

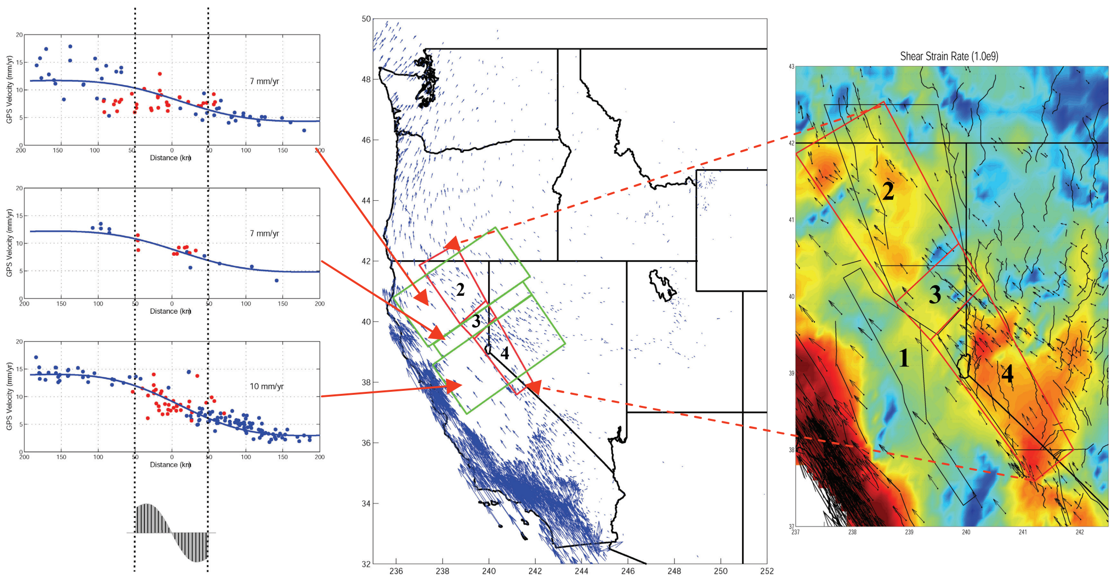

Figure 2. Map view of the GPS velocity vectors in the western US region (middle panel) with updated C-zones used in the 2007 national seismic hazard map based on the maximum shear strain rate map (right panel). The GPS velocities in and around those C-zones are modeled by a broadly distributed shear deformation belt (left panel). In the map on the far right the long zone in eastern CA is zone 1, the large zone in northeastern CA is zone 2, the small zone adjacent to zone 2 is zone 3 and encompasses the Mohawk Valley fault, and the southern zone that encompasses Reno, NV is zone 4.

In addition, two new shear zones were added to the 2007 model based on the Working Group on California Earthquake Probabilities report: a Mojave zone and a San Gorgonio zone (Figure 1; Appendix A, B). Parameters used to define these zones are outlined in table 2. These zones have a preferred strike and a Gutenberg-Richter magnitude-frequency distribution between M6.5 and 7.6. For the 2007 maps we have selected M7.6 as the maximum magnitude for these zones based on the magnitude of the 1872 Owens Valley earthquake.

Table 2. Source parameters for shear zones.

C Zone	M_{min}	M_{max}	Virtual Fault Strike (°)	b-value	Ratio SS:Rev:Nor	Slip Rate (mm/yr)	Length (km)	Width (km)
Eastern CA Shear-Mojave	6.5	7.6	-47	0.8	1: 0: 0	2.0	219	15
San Gorgonio Knot	6.5	7.6	-67	0.8	1: 0: 0	2.0	102	18
Zone 1 (Foothills fault system)	6.5	7.6	-35	0.8	1: 0: 0	0.05	360	12
Zone 2 (North-eastern California)	6.5	7.6	-25	0.8	1: 0: 0	2.0	230	15
Zone 3 (Mohawk – Honey Lake)	6.5	7.6	-45	0.8	1: 0: 0	2.0	88	15
Zone 4 (Western Nevada	6.5	7.6	-45	0.8	1: 0: 0	4.0	245	15

Acknowledgements

We thank Ned Field, Karen Felzer, Tianqing Cao, Chris Cramer, Ken Campbell, and the other members of the Executive and Management Oversight Committees and the Scientific Review Panel for helpful comments. Figure 1 was generated with software from Wessel and Smith, 1991.

References Cited

Clark, M.M., Harms, K.K., Lienkaemper, J.J., Harwood, D.S., Lajoie, K.R., Matti, J.C., Perkins, J.A., Rymer, M.J., Sarna-Wojcicki, A.M., Sharp, R.V., Sims, J.D., Tinsley, J.C., III, and Ziony, J.I, 1984, Preliminary slip-rate table and map of late Quaternary faults of California: U.S. Geological Survey Open-File Report 84-106, 12 p., 5 plates, map scale 1:1,000,000.

Felzer, K., and T. Cao (2007). Appendix H: WGCEP historical California earthquake catalog, this report.

Felzer, K. (2007). Appendix I: Calculating California seismicity rates, this report.

Frankel, A., 1995, Mapping seismic hazard in the Central and Eastern United States: Seismological Research Letters, v. 66, p. 8–21.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E., Dickman, N., Hanson, S., and Hopper, M., 1996, National seismic-hazard maps—Documentation June 1996: U.S. Geological Survey, Open-File Report 96-532, 110 p.

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., Rukstales, K.S., 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 02-420.

Gardner, J.K., and Knopoff L., 1974, Is the sequence of earthquakes in southern California, with aftershocks removed, Poissonian?: Bulletin of the Seismological Society of America, v.64, p.1363–1367.

Gutenberg, B., and Richter, C. F., 1944, Frequency of earthquakes in California: Bulletin of the Seismological Society of America, v. 34, p. 185–188.

Hammond, W.C., 2005, The ghost of an earthquake, Science, Vol. 310. no. 5753, pp. 1440 – 1442.

Kostrov, V.V. (1974). Seismic moment and energy of earthquakes, Izv. Acad. Sci. USSR, *Phys. Solid Earth*, v.1, pp. 23-44

Lund, W.R., ed., 2006, Basin and Range Province Earthquake Working Group seismic-hazard recommendations to the U.S. Geological Survey National Seismic Hazard Mapping Program: Utah Geological Survey Open-File Report 477, 23 p.

Mueller, C., Hopper, M., and Frankel, A., 1997, Preparation of earthquake catalogs for the national seismic hazard maps—Contiguous 48 states: U.S. Geological Survey Open-File Report 97-464, 36 p.

Pancha, A., Anderson, J.G., and Kreemer, 2006, Comparison of seismic and geodetic scalar moment rates across the Basin and Range Province: Bulletin of the Seismological Society of America, v. 96, p. 11–32.

Petersen, M.D., Cramer, C.H., Reichle, M.S., Frankel, A.D., and Hanks, T.C., 2000, Discrepancy between earthquake rates implied by historic earthquakes and a consensus geologic source model for California: Bulletin of the Seismological Society of America, v. 90, p. 1117–1132.

Petersen, M.D., Bryant, W.A., Cramer, C.H., Cao, T., Reichle, M.S., Frankel, A.D., Lienkaemper, J.J., McCrory, P.A., and Schwartz, D.P., 1996, Probabilistic seismic hazard assessment for the state of California: California Division of Mines and Geology Open-File Report 96-08, U.S. Geological Survey Open-File Report 96-706.

Weichert, D.H., 1980, Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes: Bulletin of the Seismological Society of America, v. 70, p. 1337–1356.

Wessel, P., and Smith, W.H.F., 1991, Free software helps map and display data: EOS Trans. AGU, v. 72, no. 441, p. 445–446.