

THE REVISED 2002 CALIFORNIA PROBABILISTIC SEISMIC HAZARD MAPS JUNE 2003

by

**Tianqing Cao, William A. Bryant, Badie Rowshandel, David Branum, and
Christopher J. Wills**

INTRODUCTION

These maps show an estimate of the likelihood of earthquake ground motions, based on a probabilistic seismic hazard analysis. Such analysis incorporates seismic and geologic information to consider the probability of all possible damaging earthquakes, calculates the potential range of ground motions for each potential earthquake, and arrives at a level of ground shaking that has a given probability, using the formulation first developed by Cornell (1968).

In 1996, the Department of Conservation, Division of Mines and Geology (now the California Geological Survey or CGS) and U.S. Geological Survey (USGS) completed an intensive effort and released the 1996 California probabilistic seismic hazard maps ([Petersen et al., 1996](#)). In 2000 the USGS began the process of revising the 1996 maps. To solicit suggestions, four regional workshops for Pacific Northwest, Central and Eastern U.S., California, and Intermountain West were convened by USGS in 2000 and a user workshop was convened by Applied Technology Council and USGS in 2001 (Frankel et al., 2002). CGS joined the effort led by USGS to revise the 1996 USGS/CDMG hazard maps. In addition, the Working Group on California Earthquake Probabilities (WG02) developed consensus models of recurrence times and magnitudes of large earthquakes on the major faults of the San Francisco Bay region (WGCEP, 1999, 2003). The details of the revision and the process to achieve the revision for the 2002 maps have been documented in the USGS Open-File Report 02-420 ([Frankel et al., 2002](#)). Here, we try to briefly summarize the new model and to highlight some of the important changes.

Frankel et al. (2002) emphasized that most of the changes are incremental and were suggested by the participants consisting of geoscientists and engineers in four regional workshops.

EARTHQUAKE SOURCES

In the revision of the 1996 models, USGS and CGS changed aspects of the models for the two basic types of earthquake sources, fault sources and area sources. These changes are summarized here.

Fault Sources:

Displacement of the earth's crust along faults releases energy in the form of earthquakes and in some cases in aseismic creep. The amount of energy available to a fault is determined by considering the slip-rate of the fault, its area (fault length multiplied by down-dip width), maximum magnitude, and the rigidity of the displaced rocks. These factors are combined to calculate the moment (energy) release on a fault. The total seismic energy release for a fault source is sometimes partitioned between two different recurrence models, the characteristic and truncated Gutenberg-Richter (G-R) magnitude-frequency distributions. These models incorporate our knowledge of the range of magnitudes and relative frequency of different magnitudes for a particular fault.

The partition of moment and the weights for multiple models are given in the following summary.

Class A faults (slip rate > 5mm/yr, 100% moment for characteristic)
San Francisco Bay area (adopted the WG02 results for magnitudes and recurrence rates)
Southern San Andreas fault (two new cascade models, each weighted 50%)
San Andreas fault, creeping section (M=6.2, floating, occurrence rate=0.0165 events/yr)
Others

Class B faults (all other faults, 2/3 moment for characteristic, 1/3 moment for G-R, b-value=0.8; 1996 used 0.9 and 50%/50% for the 1996 model)

Cascadia subduction zone (4 models: revised 1996 model, 50% weight; west model, 10%; mid model, 20%; east model, 20%; each model has two magnitude branches: M=8.3 and M=9.0; details, see Frankel et al., 2002)

Area Sources (Gridded Seismicity):

Earthquakes also occur in areas where they cannot be clearly assigned to a particular fault. Earthquake recurrence in these zones is based on models that consider the historic occurrence of earthquakes in the area and calculate magnitude-frequency distributions for each zone. A Gaussian smoothing process is applied to the historical background seismicity (Cao, et al., 1996) to distribute the earthquake potential through a grid of points that covers the zone.

Area sources include:

C zones (4 shear zones - Foothills fault system, Mohawk-Honey Lake zone, Rate for NE California; and Western Nevada zone; same as in the 1996 model, b=0.8)

Brawley Seismic Zone (hazard for gridded seismicity with anisotropic smoothing, b=0.9)

Alternative model for creeping section San Andrea fault (hazard for gridded seismicity with anisotropic smoothing, $b=0.9$)

Deep earthquakes (depth > 35 km, at northern California; $M_{\max}=7.2$, $M_{\min}=4.0$, $b=0.8$)

Extensional tectonics region (hazard for gridded seismicity with isotropic smoothing, $b=0.8$)

Non-extensional tectonic region (hazard for gridded seismicity with isotropic smoothing, $b=0.8$)

Significant Source Modeling Changes

Let us highlight some of the major changes from the 1996 model. For the San Francisco Bay region, WG02 applied the Monte Carlo sampling method for the magnitude and recurrence rate of each fault. The mean occurrence rate of a fault for each magnitude bin is determined from the realizations. The details of the two cascade models for the southern San Andreas fault are described in Appendix A of Frankel et al. (2002). The creeping section of the San Andreas fault is modeled using a floating earthquake of magnitude 6.2 and occurrence rate 0.0165 events/yr. The background hazard from M5.0-6.0 earthquakes for the creeping section of the San Andreas fault is modeled as an area source using smoothed historical seismicity. The Brawley Seismic Zone is also modeled as an area source using anisotropically smoothed historical seismicity within 10 km of the source. The 1996 model of the Cascadia subduction zone, which is weighted 50% in the 2002 hazard calculations, was revised with respect to location of the eastern edge of the rupture zone in the vicinity of northwestern Washington (Frankel et al., 2002). In addition, three new Cascadia subduction zone models are added (called west, mid, and east models), based on the work of Flück et al. (1997).

The hazard from the background seismicity is calculated using different combinations of attenuation relations for the extensional and non-extensional tectonic regions. This difference will be described in the following section when attenuation relations are discussed.

One important achievement of the 2002 model is that the predicted rate of M6.5-7 earthquakes now matches the observed historical rate (see Fig. 6, Frankel et al., 2002). This contrasts with the 1996 model which over-predicted the rate by a factor of 2. Frankel et al. (2002) attributed this achievement to four reasons: 1) more moment going to characteristic model (2/3 instead of 50%), 2) the inclusion of aleatory and epistemic uncertainties for fault magnitude (see more details in the following section), 3) the use of two new fault area-magnitude formulas by Ellsworth (WGCEP, 2003) and Hanks and Bakun (2002), which predict higher magnitudes for the fault rupture area larger than certain values (see below), and 4) the elimination of magnitude overlap (M6.5 to 7.0) between background seismicity (gridded seismicity) and fault sources.

FAULT RUPTURE AREA-MAGNITUDE RELATION

In the 1996 model, there was only one branch for magnitudes for Class B faults that were calculated from the fault area-magnitude relation of Wells and Coppersmith (1994):

$$M = 0.98 \log A + 4.07,$$

Where A is the fault rupture area in square km. In the 2002 model, two branches of area-magnitude relations are introduced in the logic tree. One branch is the combination of the Wells and Coppersmith (1994) relation for $A < 500 \text{ km}^2$ and the Ellsworth (WGCEP, 2003) relation for $A \geq 500 \text{ km}^2$:

$$M = \log A + 4.2.$$

The other branch is the combination of the Wells and Coppersmith (1994) relation for $A < 468 \text{ km}^2$ and the Hanks and Bakun (2002) relation for $A \geq 468 \text{ km}^2$:

$$M = 4/3 \log A + 3.07.$$

The above two branches are each weighted 50%. It should be emphasized that the hazard calculations are carried out for each branch to the end and then the hazards are summed together with equal weight (50%). The different magnitudes and occurrence rates of the two branches are not averaged at any times in the process. The two newly introduced area-magnitude relations output higher magnitudes compared with the Wells and Coppersmith (1994) relation but lower occurrence rates.

ATTENUATION RELATIONS

In the 2002 model, fault sources and area sources are divided into two types of regions: extensional and non-extensional tectonic regions. The extensional region is mostly located in eastern California and the non-extensional region is in western and southern California (see Fig. 5, Frankel et al., 2002). For the fault and gridded sources in the extensional tectonic region, five equally weighted attenuation relations are used. They are Boore et al. (1997), Sadigh et al. (1997), Abrahamson and Silva (1997), Campbell and Bozorgnia (2003), and Spudich et al. (1999). For the non-extensional tectonic region, only the first four equally weighted relations are used.

The attenuation relations used for the Cascadia subduction zone are Youngs et al. (1997) and Sadigh et al. (1997) with equal weight. For the deep earthquakes (depth $> 35 \text{ km}$) in northern California, the attenuation relations used are Youngs et al. (1997) and Atkinson and Boore (2002) with equal weight.

SOIL CORRECTION

The new psha maps are for peak ground acceleration (PGA), and 0.3 and 1.0 second spectral acceleration of 5% damping at 10% probability of exceedance in 50 years

with soil correction. The maps are calculated for a firm-rock site condition. The shear wave velocity V_{s30} for this site condition is 760 m/s or the BC boundary in NEHRP (FEMA, 1994, 1997) site classification. Then the NEHRP (FEMA, 1994, 1997) soil correction coefficient tables and the Wills et al. (2000) California soil map are used to get the final maps.

In 1999 we released maps based on the 1996 hazard model with soil correction (Petersen et al., 1999). The soil correction was performed using the shear wave velocity correction term in the attenuation relation by Boore et al. (1997). This correction is not ground motion level dependent but the NEHRP correction is. In the NEHRP correction, the ground amplification due to soft soils gradually diminishes when ground motion increases to 0.5 g or above for PGA and to 1.25 g or above for SA at 0.3 second. This is called the nonlinear effect of soil response. A simple comparison of these two different soil corrections is shown in Table 1. In the table, the shear wave velocity V_{s30} is in m/sec. Therefore, the corrected ground motions in the new maps should be lower than the 1999 maps at those places where the ground motion levels are high and soils are soft and if the ground motion levels are similar before soil correction. At high ground motion levels ($PGA > 0.3$ g; $SA(0.3 \text{ sec}) > 0.75$ g), the Boore et al. (1997) amplifications are much higher than the NEHRP (1994, 1997) corrections.

Table 1a – PGA

Soil Profile Type	Boore-Joyner-Fumal		NEHRP (1994) Correction Factors for Different PGA Values (g)				
	Factor	V_{s30}	≤ 0.1	0.2	0.3	0.4	≥ 0.5
B	1.10	1,070	1.0	1.0	1.0	1.0	1.0
C	1.44	520	1.2	1.2	1.0	1.0	1.0
D	1.89	250	1.6	1.4	1.2	1.1	1.0
E	2.29	150	2.5	1.7	1.2	0.9	-

Table 1b – SA (0.3 sec)

Soil Profile Type	Boore-Joyner-Fumal		NEHRP (1997) Correction Factors for Different SA (0.3 sec) Values (g)				
	Factor	V_{s30}	≤ 0.25	0.50	0.75	1.00	≥ 1.25
B	1.32	1,070	1.0	1.0	1.0	1.0	1.0
C	1.76	520	1.2	1.2	1.0	1.0	1.0
D	2.36	250	1.6	1.4	1.2	1.1	1.0
E	2.90	150	2.5	1.7	1.2	0.9	-

Table 1c – SA (1.0 sec)

Soil Profile Type	Boore-Joyner-Fumal		NEHRP (1997) Correction Factors for Different SA (1.0 sec) Values (g)				
	Factor	V_{s30}	≤0.1	0.2	0.3	0.4	≥0.5
B	1.21	1,070	1.0	1.0	1.0	1.0	1.0
C	2.00	520	1.7	1.6	1.5	1.4	1.3
D	3.34	250	2.4	2.0	1.8	1.6	1.5
E	4.77	150	3.5	3.2	2.8	2.4	-

EPISTEMIC AND ALEATORY UNCERTAINTIES

The epistemic and aleatory uncertainties in the 2002 model are introduced to characteristic magnitude M_{char} and to maximum magnitude M_{max} for the truncated G-R recurrence model. The epistemic uncertainty accounts for the model uncertainty and the aleatory uncertainty accounts for the intrinsic randomness of data or observations (Cao et al., 1996). The assumed standard deviation for magnitude is 0.24 and is equally split into epistemic and aleatory. The uncertainties are implemented in the logic tree by discrete branches. For most of the faults, the epistemic uncertainties are represented by three branches with magnitudes $M_{char} + 0.2$, M_{char} , and $M_{char} - 0.2$ (the same for M_{max}). The only exception is for the two southern San Andreas fault cascade models, in which 0.1 instead of 0.2 is used. So for most of the faults, the uncertainties are truncated at 0.2 or slightly less than two standard deviation ($0.12 \times 2 = 0.24$). The weights for these three branches are 0.2, 0.6, and 0.2, respectively. The recurrence rate for each branch is determined using the condition that each branch has the same moment rate. For the aleatory uncertainties, there are seven branches with magnitudes M_{char} , $M_{char} \pm 0.05$, $M_{char} \pm 0.10$, and $M_{char} \pm 0.15$. The weights for all seven branches follow a truncated normal distribution at ± 0.15 with a standard deviation of 0.12. Figure 1 is a partial logic tree showing the epistemic and aleatory magnitude uncertainties. We have described above how the uncertainty ranges are assigned when uncertainties are included. When uncertainty should be included is dependent on the magnitude. Table 2 lists when the uncertainty is included.

Table 2

Recurrence Model	Magnitude	Epistemic	Aleatory
Characteristic	$M \geq 5.8$	yes	yes
	$M < 5.8$	no	no
G-R	$M \geq 6.5$, not floating	yes	no
	$M < 6.5$, not floating	no	no
	$M \geq 5.8$, floating	yes	yes
	$M < 5.8$, floating	no	no

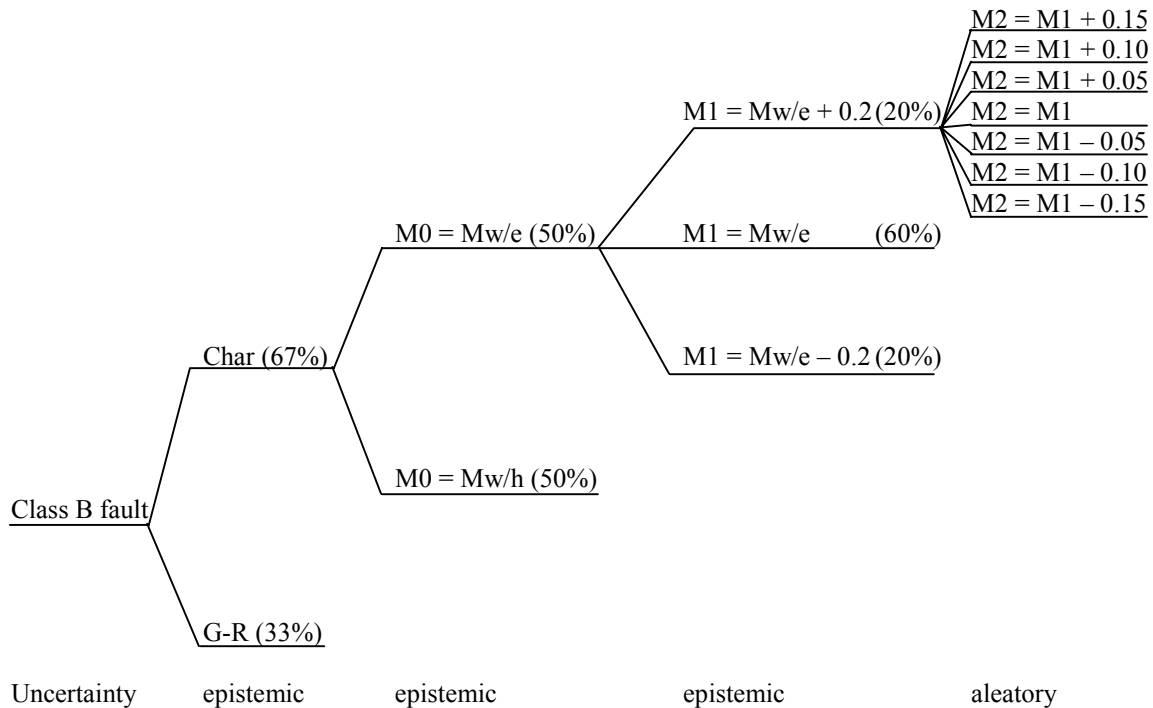


Figure 1. A partial logic tree to show the epistemic and aleatory magnitude uncertainties. The symbol M_w/e represents the magnitude from a combination of Wells and Coppersmith (1994) and Ellsworth (WGCEP, 2003) formulas; the symbol M_w/h represents the magnitude from a combination of Wells and Coppersmith (1994) and Hanks and Bakun (2002) formulas. Only the top branch in this partial logic tree is drawn completely and the other similar branches are omitted here. This part of the logic tree would have 84 ($=7 \times 3 \times 2 \times 2$) final branches. The percentages after the magnitude are the weights. The branches for different attenuation relations are not shown here.

UPDATE OF FAULT PARAMETERS AND EARTHQUAKE CATALOG

Fault Parameters

The 2002 California fault parameters are listed in [Appendix A](#). Revisions to fault parameters used in the 1996 model are highlighted in yellow or gray. Many of the changes to 1996 fault parameters are relatively minor and generally reflect modifications to the digital fault traces resulting in minor length changes. Two significant changes occur in the San Francisco Bay region and the Southern California region.

We have incorporated the fault parameters of the major faults in the San Francisco Bay region delineated by the Working Group on California Earthquake Probabilities (WGCEP, 1999, 2003). Changes in the San Francisco Bay area include segmentation and slip rates of the San Andreas fault zone north of the creeping segment, modification of segmentation of the Hayward fault zone, changes in slip rate and segmentation of the Concord and Green Valley faults, and replacement of the Great Valley 6 blind thrust with the Mount Diablo blind thrust (see WGCEP (1999) and WGCEP (2003) for complete documentation of the San Francisco Bay Area faults).

Modifications for the 2002 Fault Parameters in Southern California are summarized in Table 3.

Table 3-Selected Revision in Southern California

Fault	Summary of Modifications
Compton thrust	Source deleted based on reported lack of late Qt. offset (Mueller, 1997).
Elysian Park (Lower)	Source replaced using Puente Hills blind thrust and Upper Elysian Park blind thrust.
Upper Elysian Park	Source replaces Elysian Park (Lower) blind thrust. Slip rate and fault geometry from Oskin, et al (2000).
Pleito	Dip modeled at 45° in order to accommodate spatial relationship with San Andreas fault.
Puente Hills blind thrust	Source parameters from Shaw and Shearer (1999), Shaw, et al (2000), and Christofferson, et al (2001).
Raymond	Slip rate increased from 0.5 mm/yr, based on slip rate study by Marin, et al (2000).
Rose Canyon	Fault extended to south to include Holocene active Silver Strand fault (activity based on Kennedy and Clarke, 1999a and b).
San Joaquin Hills	New source added, based on model by Grant, et al (1999) and Grant and Runnerstrom (written communication, 11-01).
Sierra Madre	Slip rate reduced from 3 mm/yr to 2 mm/yr, minor modifications to digital fault trace and minor length modification

Other modifications to the 1996 fault parameters include:

- Genoa fault - slip rate increased to 2 mm/yr – Nevada is modeling;
- Antelope Valley fault - Nevada is modeling;
- Segmentation changes to Maacama fault zone - southern, central, and northern segments of Maacama fault zone and Garberville-Briceland fault are combined into one rupture model; slip rate has not changed;
- Bartlett Springs fault system – Bartlett Springs, Lake Mountain, and Round Valley faults are combined into one rupture model; slip rate has not changed.

Earthquake Catalog

The CGS earthquake catalog was updated to the end of 2000 and then updated further to the end of 2001 by USGS. This catalog is an update from the CDMG 1996 catalog (Petersen et al., 1996). We merged the catalogs for northern and southern California to get an extended catalog, which goes to 2001. The second step was to merge the extended catalog with the recently published catalog for $M \geq 5.5$ by Topozada et al. (2000). This catalog has been updated by Topozada and Branum (IASPEI, 2002) and Topozada et al. (2002). The updated cataloged can be downloaded from the [CGS website](#).

THE NEW MAPS

Results of the 2002 probabilistic seismic hazard assessment show that the hazard has decreased along the Peninsula segment of the San Andreas fault and increased along the Calaveras fault due to the new assessment by WG02 on the San Francisco Bay region earthquake probabilities. The hazard is about the same as in the 1996 maps along the southern San Andreas fault where two new cascade models are introduced. In southern California the hazard along several faults has changed due to changes of modeling parameters. For example, the hazard along Sierra Madre fault has decreased due to new information on lower slip rates, the Brawley Seismic Zone is now modeled using historic seismicity, and the San Joaquin Hills and Puente Hills blind thrust faults have been added to the new fault source model.

REFERENCES

- Abrahamson, N.A., and Silva, W.J., 1997, Empirical response spectral attenuation relations for shallow crustal earthquakes: *Seismological Research Letters*, v. 68, no.1, p. 94-127.
- Atkinson, G.M. and Boore, D.M., 2002, Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions, *in review*.
- Boore, D.M., Joyner, W.B., and Fumal, T.E., 1997, Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: a summary of recent work: *Seismological Research Letters*, v. 68, p. 128-153.
- Campbell, K.W., and Bozorgnia, Y., 2003, Updated near-source ground motion attenuation relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra: *Bulletin of the Seismological Society of America*, *in press*.
- Cao, T., Petersen, M.D., and Reichle, M.S., 1996, Seismic hazard estimation from background seismicity in southern California: *Bulletin of the Seismological Society of America*, 86, p. 1372-1381.
- Christofferson, S.A., Dolan, J.F., Shaw, J.H., and Pratt, T.L., 2001, Determination of a Holocene slip rate on the Puente Hills blind-thrust fault, Los Angeles basin, California (abs): EOS, Transactions of the American Geophysical Union, Annual Fall Meeting, v. 82, no. 47, p. F933.
- Cornell, C.A., 1968, Engineering seismic risk analysis: *Bulletin of the Seismological Society of America*, v. 58, p. 1583-1606.
- Federal Emergency Management Agency, 1994, NEHRP Recommended Provisions for Seismic Regulations for New Buildings: Washington, D.C., FEMA 222A.
- Federal Emergency Management Agency, 1997, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures: Washington, D.C., FEMA 302.

- Flück, P., Hyndman, R.D., and Wang, K., 1997, Three-dimensional dislocation model for great earthquakes of the Cascadia subduction zone: *Journal of Geophysical Research*, 102, p. 20, 539-20, 550.
- Frankel, A.D., Petersen, M.D., Muller, C.S., Haller, K.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rukstales, K.S., 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps: U.S. Geological Survey, Open-File Report 02-420, 33 p.
- Grant, L.B., Mueller, K.J., Gath, E.M., Cheng, H., Edwards, R.L., Munro, R., and Kennedy, G.L., 1999, Late Quaternary uplift and earthquake potential of the San Joaquin Hills, southern Los Angeles Basin, California: *Geology*, v. 27, p. 1031-1034.
- Grant, Lisa, and Runnerstrom, Eric, 2001, Notes on proposed models for the San Joaquin Hills blind thrust: Unpublished written communication to W. A. Bryant, November 2, 2001.
- Hanks, T.C., and Bakun, W.H., 2002, A bilinear source-scaling model for $M - \log A$ observations of continental earthquakes: *Bulletin of the Seismological Society of America*, v. 92, p. 1841-1846.
- Kennedy, M.P., and Clarke, S.H., 1999a, Analysis of late Quaternary faulting in San Diego Bay and hazard to the Coronado Bridge: California Department of Conservation, Division of Mines and Geology Open-File Report 97-10A.
- Kennedy, M.P., and Clarke, S.H., 1999b, Age of faulting in San Diego Bay in the vicinity of the Coronado Bridge - an addendum to - Analysis of late Quaternary faulting in San Diego Bay and hazard to the Coronado Bridge: California Department of Conservation, Division of Mines and Geology Open-File Report 97-10B.
- Marin, M., Dolan, J.F., Hartleb, R.D., Christofferson, S.A., Tucker, A.Z., and Owen, L.A., 2000, A latest Pleistocene-Holocene slip rate on the Raymond fault based on 3-D trenching, East Pasadena, California: *EOS, Transactions of the American Geophysical Union*, v. 81, (48, supplement) F855.
- Mueller, K.J., 1997, Recency of folding along the Compton-Los Alamitos trend: Implications for seismic risk in the Los Angeles basin: *EOS Transactions of the American Geophysical Union*, v. 78, p. F702.
- Oskin, M., Sieh, K., Rockwell, T., Miller, G., Gupta, P., Curtis, M., McArdle, S., and Elliot, P., 2000, Active parasitic folds on the Elysian Park anticline: Implications for seismic hazard in central Los Angeles, California: *Geological Society of America Bulletin*, v. 112, p. 693-707.
- 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.
- Petersen, M., Beeby, D., Bryant, W., Cao, T., Cramer, C., Davis, J., Reichle, M., Saucedo, G., Tan, S., Taylor, G., Topozada, T., Treiman, J., and Wills, C., 1999, Seismic shaking hazard maps of California: California Division of Mines and Geology, Map Sheet 48.
- Sadigh, K., Chang, C.Y., Egan, J., Makdisi, F., and Youngs, R., 1997, Attenuation relationships for shallow crustal earthquakes based on California strong motion data: *Seismological Research Letters*, v. 68, p. 180-189.

- Shaw, J.H., and Suppe, J., 1996, Earthquake hazards of active blind-thrust faults under the central Los Angeles Basin, California: *Journal of Geophysical Research*, v. 101, p. 8623-8642.
- Shaw, J.H., and Shearer, P.M., 1999, An elusive blind-thrust fault beneath metropolitan Los Angeles: *Science*, v. 283, p. 1516-1518.
- Shaw, J.H., Plesch, A., Fiore, P., Dolan, J., Christofferson, S., Pratt, T.L., Williams, R., and Odum, J., 2000, Structural geometry, segmentation, and slip on the Puente Hills blind-thrust system: Implications for earthquake hazards in metropolitan Los Angeles: EOS, Transactions of the American Geophysical Union, Annual Fall Meeting, p. F850.
- Spudich, P., Joyner, W.B., Lindh, A.G., Boore, D.M., Margaris, B.M., and Fletcher, J.B., 1999, SEA99: A revised ground motion prediction relation for use in extensional tectonic regimes, *Bulletin of the Seismological Society of America*, v. 89, p. 1156-1170.
- Topozada, T. Branum, D., Petersen, M., Hallstrom, C., Cramer, C. and Reichle, M., 2000, Epicenters of and areas damaged by $M \geq 5$ California earthquakes, 1800-1999: California Department of Conservation, Division of Mines and Geology Map Sheet 49.
- Topozada, T. R., and Branum, D., 2002, California $M \geq 5.5$ earthquakes, history and areas damaged, *in* Lee, W. H., Kanamori, H. and Jennings, P., *International Handbook of Earthquake and Engineering Seismology*, International Association of Seismology and Physics of the Earth's Interior.
- Topozada, T. R., Branum, D. M., Reichle, M. S., and Hallstrom, C. L., 2002, San Andreas fault zone, California: $M \geq 5.5$ earthquake history: *Bulletin of the Seismological Society of America*, v. 92, p. 2555-2601.
- Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, and surface displacements: *Bulletin of the Seismological Society of America*, v. 84, p. 974-1002.
- WGCEP (Working Group on California Earthquake Probabilities), 1999, Earthquake Probabilities in the San Francisco Bay Region: 2000 to 2030 - A Summary of Findings: U.S. Geological Survey Open-File Report 99-517, Online Version 1.0, 36 p.
- WGCEP (Working Group on California Earthquake Probabilities), 2003, Earthquake probabilities in the San Francisco Bay region: 2002-2031: U.S. Geological Survey Open-File Report 03-214.
- Wills, C.J., Petersen, M., Bryant, W.A., Reichle, M., Saucedo, G.J., Tan, S., Taylor, G., and Treiman, J., 2000, A site-condition map for California based on geology and shear-wave velocity: *Bulletin of the Seismological Society of America*, v. 90, s187-s208.
- Youngs, R.R., Chiou, S.J., Silva, W.J., and Humphrey, J.R., 1997, Strong ground motion attenuation relationships for subduction zone earthquakes: *Seismological Research Letters*, v. 68, no.1, p. 58-73.

APPENDIX A

2002 CALIFORNIA FAULT PARAMETERS

A Faults

B Faults

C Faults

References