Earthquake Rate Model 2.2 of the 2007 Working Group for California Earthquake Probabilities, Appendix D: Magnitude-Area Relationships

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Summary

To estimate the down-dip coseismic fault dimension, *W*, the Executive Committee has chosen the *Nazareth and Hauksson* (2004) method, which uses the 99% depth of background seismicity to assign *W*. For the predicted earthquake magnitude-fault area scaling used to estimate the maximum magnitude of an earthquake rupture from a fault's length, *L*, and *W*, the Committee has assigned equal weight to the Ellsworth B (*Working Group on California Earthquake Probabilities*, 2003) and *Hanks and Bakun* (2002) (as updated in 2007) equations. The former uses a single relation; the latter uses a bilinear relation which changes slope at M=6.65 (A=537 km^2).

Needs of the Working Group

The Working Group for California Earthquake Probabilities (WGCEP) must be able to assign earthquake magnitudes from inferred fault geometry. The length of past fault ruptures and the length of continuous fault traces are the best observed parameters. In contrast, the down-dip fault dimension W is poorly resolved, resulting in considerable uncertainty in fault area, A. The Working Group thus seeks a proxy for fault width that can be applied to all California faults, with appropriate uncertainties. For vertical strike-slip faults, W is closely related to the depth of the brittle-ductile transition; for thrust and normal faults, W is less well constrained by the transition, and uncertsainties are greater.

Empirical relations between fault area and moment-magnitude suggest that the static earthquake shear stress drop is roughly constant over a large range of magnitudes; the magnitude of the stress drop may transition to fault-length scaling for continental strike-slip earthquakes over M_w=7 (*Scholz*, 1990). We will thus consider several magnitude-area scaling relationships. The frequency-magnitude distribution for California is partly dependent on the magnitude-area relation, and so these two efforts must be consistent in approach and in parameter definitions.

Magnitude-Area Summit Meeting

The Working Group hosted a meeting to solicit advice from the scientific community on magnitude-area relations. Participants reviewed the Working Group 02 approaches and considered subsequent advances pertinent to this problem. Paul Somerville was also contracted by the Working Group to prepare a review paper on the subject. Present at the November 1, 2006, Menlo Park videoconference were Bill Ellsworth, Jessica Murray, Donald Wells, Tom Hanks, Bill Bakun, Ruth Harris, Paul Somerville, Ned Field, Ken Hudnut, Colin Williams, Egill Haukkson and Ross Stein. In addition, Paul Segall, Roland Bürgmann, and Jim Savage contributed references or written comments. Paul Somerville provided a written review of magnitude-area relations for the Working Group, and Tom Hanks wrote a comment on the Somerville report, which is referenced at the end of this one. The agenda and presentations given at the meeting by Ellsworth, Field, Somerville, Hanks, Murray, and Williams, as well as the Hanks letter are available at: http://www.WGCEP.org/activities/meetings/110106

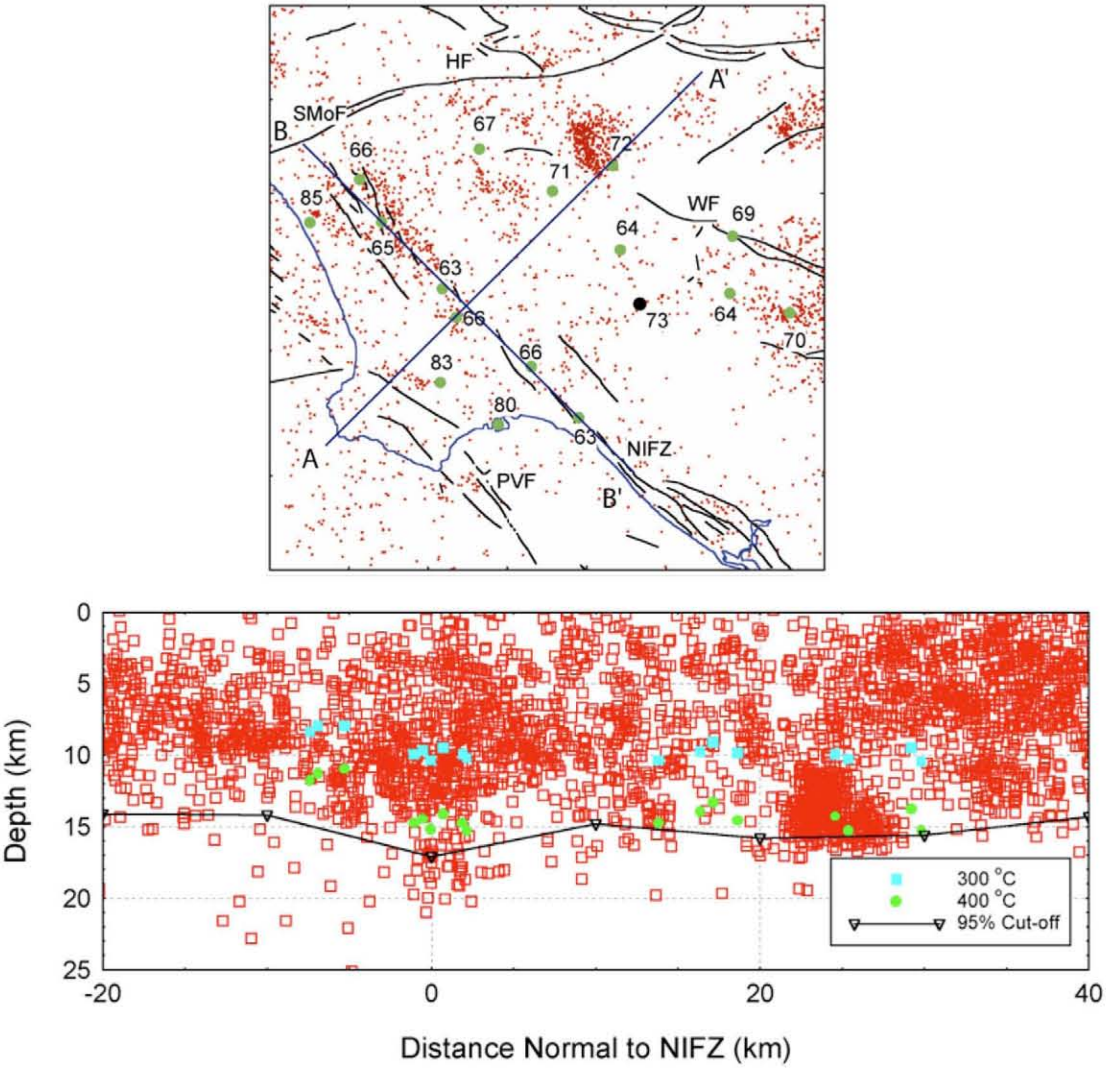


Figure 1. Relocated seismicity from *Hauksson and Shearer* (2005) compared with the inferred 300 and 400°C isotherms, suggesting that seismicity extends to about 400°-425°C across the Los Angeles Basin (Collin Williams, written comm., http://pubs.usgs.gov/of/2003/of03-214/WG02_OFR-03-214_AppendixA.pdf)

Estimation of Downdip Fault Dimension, *W*

Limited geodetic sampling and large ambiguities in the inferred maximum depth of coseismic slip and the interseismic locking depth render geodetic estimates of the down-dip fault dimension, *W*, inadequate for the purposes of WGCEP. The problem is compounded when faults are closely spaced, which is frequently the case, and this arises regardless of the quality and density of the surface deformation data because the locking depth (and slip rates) inferred on such faults are not independent. There is wide consensus on these conclusions by tectonic geodesists, including Hudnut, Murray, Savage, Bürgmann, and Segall. In contrast, the microseismicity coverage is more complete and uniform than is the geodetic coverage.

The higher the observed heat flow, the shallower the maximum depth of seismicity is found to extend. Heat flow observations are generally consistent with the assumption that the maximum depth of seismicity along California faults corresponds to the 350°-400°C isotherm (figure 1). This means that the lower depth of seismicity may trace the brittle-ductile transition on most faults (see Collin Williams' Appendix in Working Group on California Earthquake Probabilities, 2003). But heat flow coverage is even more spatially limited than the geodetic data and the observations are variable in quality. Thus, we regard the thermal measurements and models more as a test of other approaches, rather than an indpendent data set that can be used to estimate a lower depth of faulting for all California faults.

The WGCEP has therefore used the method of *Nazareth and Hauksson* (2004) to estimate the lower seismogenic fault depth from background seismicity. Nazareth and Hauksson demonstrate, albeit with a limited southern California dataset, that the depth above which 99.9% of the moment release of background seismicity occurs reasonably estimates the maximum depth of rupture in moderate to large earthquakes.

Limitations Associated with Estimating *W* from Microseismicity

The approach of *Nazareth and Hauksson* (2004) suffers where background seismicity is sparse, such as along the San Andreas Cholame-Simmler segment, and parts of the Mojave segment, along many of the Eastern California shear zone faults, and along the San Gregorio fault. In other areas, such as the many thrust faults, seismicity is distributed and the lower depth of seismicity may lie beneath the major thrust fault. This may be the case for the Coalinga and Kettleman Hills thrusts. But even with these acknowledged weaknesses, coverage is still far superior to geodetic, heat flow, and seismic profiling. For the thrust faults, seismic inferences can be modified by published interpretations of reflection and refraction profiles (for example, *Shaw and Suppe*, 1996).

It is also possible that the lower depth extent of $M \geq 7.4$ shocks will prove to exceed the lower depth of background seismicity, in which case the moment release per unit fault length increases for large earthquakes. The Denali earthquake may have ruptured to as much as 20 km depth, whereas background seismicity only extended to about 10 km depth. However, both the depth of seismicity and the teleseismic inversion of the lower depth of faulting along the Denali fault are very poorly constrained, rendering this comparison dubious. In onctrast, geodetic estimates of the rupture depth of 10-12 km (*Wright and others*, 2004) are consistent with the aftershock and background seismicity, and thus require no coseismic deepening (figure 2).

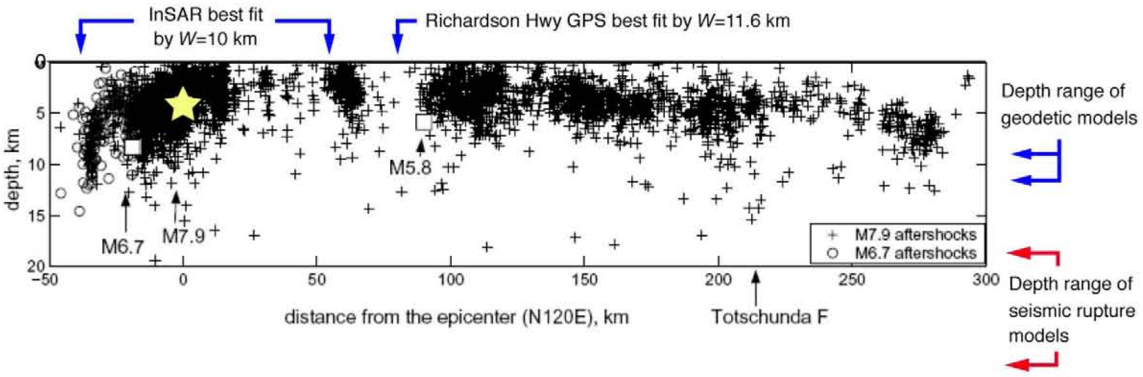


Figure 2. The aftershocks of the 2002 M=7.9 Denali shock (*Eberhart-Phillips and others*, 2003) compared to geodetic (*Wright and others*, 2004) and telesesmic (Asano and others, 2005; Oglesby and others; 2004, Ozacar and others, 2003) inferences for the lower depth of coseismic rupture.

Rolandone and others (2004) argued that the immediate Landers aftershocks extended 3 km deeper than the background seismicity, and returned to the background depth over the succeeding 3-4 years (figure 3). However, this result could be an artifact of the depth scatter, which increases with the number of earthquakes measured. Because the rate of aftershocks decays with time, there is a much greater sample during the first posteismic year than afterward. In the Landers area, the background seismicity rate was so low that the depth extent is also poorly determined.

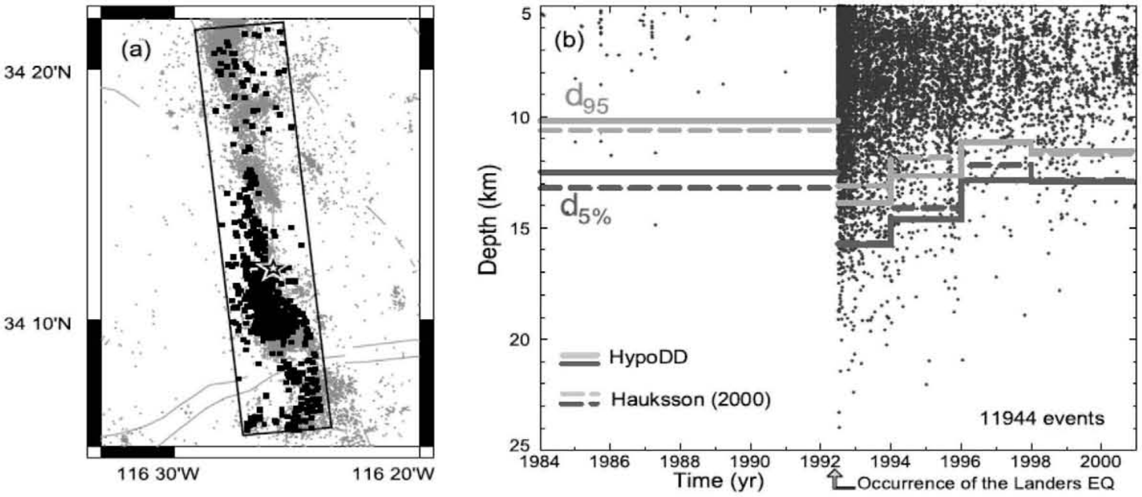


Figure 3. Depth of seismicity along the 1992 Landers rupture, showing a coseismic deepening of the lower depth of seismicity followed by a gradual return to pre-1992 depths, from *Rolandone and others* (2004).

In contrast, the 1999 Izmit aftershocks have a very similar depth distribution to the background seismicity measured with the same IZINET seismic network beginning in 1992 by *Ito and others* (2002) (figure 4). Here the background rate is much higher than at Landers and so is more reliable. Thus we find that the evidence does not suggest that earthquake ruptures commonly exceed the background seismicity depth by a significant amount.

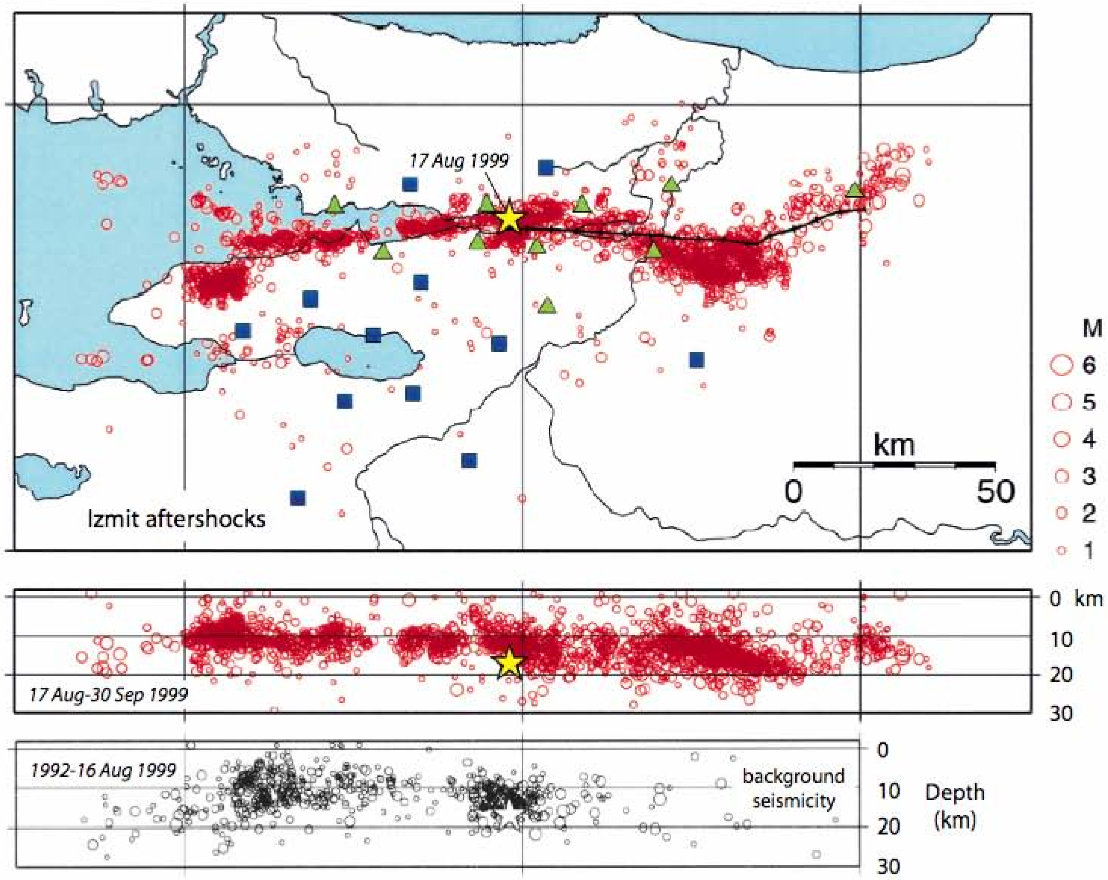


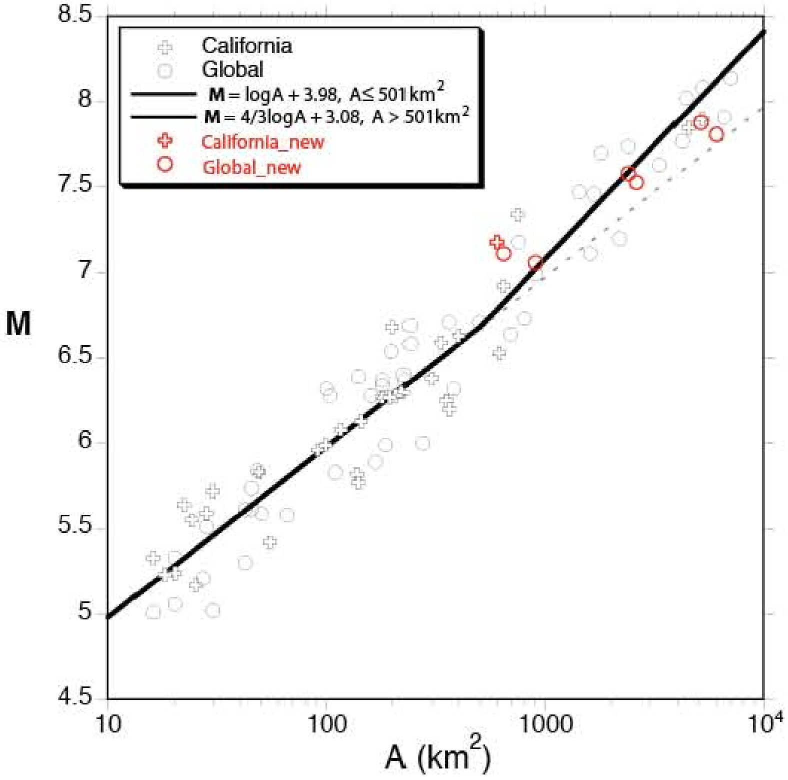
Figure 4. Depth cross-sections along the 1999 Izmit, Turkey, rupture from *Ito and others* (2002) exhibit little, if any, coseismic deepening.

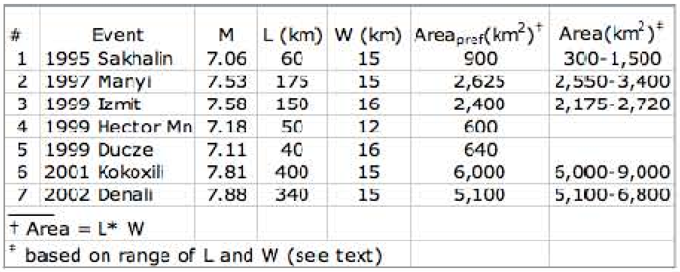
The Executive Committee of the Working Group thus believes that contemporary seismicity provides the most sound and consistent method available to estimate the lower depth. The upper depth of faulting is left unresolved by this method, but we will arbitrarily set this to be 0 km except in special cases. This might overestimate the potential fault area, but few alternative assumptions exist.

Magnitude-Area Relations Used to Infer Earthquake Size

Equations relating M_w to rupture area, *A*, are derived from empirical earthquake datasets, most notably *Wells and Coppersmith* (1994). Of greatest importance to WGCEP are large strike-slip earthquakes, for which the *Wells and Coppersmith* sample is small. Although essential, these datasets suffer from uncertainty in the down-dip dimension, *W*, and for many historical earthquakes there are also large uncertainties in M_w and in some cases, even the length of the rupture, *L*. Published equations by *Wells and Coppersmith* (1994), *Hanks and Bakun* (2002), *Ellsworth* (*Working Group on California Earthquake Probabilities*, 2003), as well as *Somerville* (2006), present alternatives.

$M_w = 4.20 + 1.0 \log(A)$ ('Ellsworth B' of Working Group, 2003)
$M_w = 3.98 + 1.0 \log(A)$ (for $A<500$ km^2; Hanks and Bakun, 2007)
$M_w = 3.08 + 4/3 \log(A)$ (for $A>500$ km^2; Hanks and Bakun, 2007)
$M_w = 3.87 + 1.05 \log(A)$ (Somerville, 2006)
$M_w = 3.98 + 1.02 \log(A)$ (Wells and Coppersmith, 1994)





#	Event	M	L (km)	W (km)	Area$_{pref}$(km^2)†	Area(km^2)‡
1	1995 Sakhalin	7.06	60	15	900	300-1,500
2	1997 Maryi	7.53	175	15	2,625	2,550-3,400
3	1999 Izmit	7.58	150	16	2,400	2,175-2,720
4	1999 Hector Mn	7.18	50	12	600	
5	1999 Ducze	7.11	40	16	640	
6	2001 Kokoxili	7.81	400	15	6,000	5,000-9,000
7	2002 Denali	7.88	340	15	5,100	5,100-6,800

† Area = L* W

‡ based on range of L and W (see text)

Figure 5. Revised observations and model fit by *Hanks and Bakun* (2007). The light dashed line is the continuation of the $A<501$ km^2 curve for all A. The added observations are are in red, and appear in the table.

Hanks and Bakun (2007) is an update of Hanks and Bakun (2002). Somerville, by contrast uses a more recent and so more uniform dataset. But Somerville makes extensive use of teleseismic and strong motion inversions of coseismic slip, which tend to distribute some slip to the lower depth of the surrface over whgich slip is inverted. It is also currently unclear that his method to infer W is compatible with how W is treated in the WGCEP fault section database and deformation model. For example, the USGS-CGS-SCEC California Reference Geologic Fault Parameter Database uses L and W. In contrast, Somerville trims the fault area on the basis of indpendent criteria (*Somerville* *and others*, 1999). How broad areas of low or no slip within a rupture zone is treated in calculating fault area needs consideration.

Hanks and Bakun (2002) provide a physical basis for a bilinear scaling in their equation (stress drop scaling by fault area for Mw<7 and scaling by fault length for M_w>7). However, there are too few observations at $M_w \geq 7.5$ to be confident in the departure from a single slope. In response to a request from the WGCEP, Hanks and Bakun (2007) updated their inventory of large strike-slip earthquakes by adding seven new events. The new data are compatible with the nearly identical bilinear relation proposed by Hanks and Bakun (2002).

For uniformity and consistency with the 2002 National Seismic Hazard Mapping Project, the Executive Committee of the WGCEP has assigned equal weight to the Working Group on California Earthquake Probabilities (2003) 'Ellsworth B' relation, and to the Hanks and Bakun (2002) bilinear equations as updated by the inclusion of the additional data in Hanks and Bakun (2007). The Somerville (2006) and Wells and Coppersmith (1994) relations are nearly identical, and it could be argued that they should also assigned some weight. However, we judge that Wells and Coppersmith (1994) must be updated before it could be included, and that Somerville (2006) treats fault area in a manner incompatible with our assignment of earthquake magnitude from fault area. For this reason, they are not included.

Request for Additional Analysis by Donald Wells

The Executive Committee has asked Donald Wells to include the 12 years of earthquakes that have struck since his 1994 paper was published. In addition, there are new studies of many of the pre-1994 earthquakes that should cause these values to be reassessed. For example, the rutpure length of the 1973 M_w=7.5 Luhuo earthquake on the Xian Shiehe fault may need modification (Zhou, Allen, and Kanamori, *BSSA*, 73, 1585-1597, 1983). Thus far, we have received no reply to this request.

Uncertainty on the Mean Magnitude

Although two magnitude-area relations will be used with equal weight, there remains a value of M where the two curves intersect, and so near this interesection at M=7.6, the epistemic uncertainty (due to lack of knowledge) on M for a given A will be smaller than at other values. In part to ameliorate this localized problem, and in part to reflect epistemic uncertainty on all earthquake magnitudes, ±0.1 M unit correction is associated with all magnitudes. Some 60% of the weight will be given to the derived magnitude, 20% at -0.1 units, and 20% at +0.1 units. These values and their associated weights were chosen to follow the same procedure as the National Seismic Hazard Mapping Project uses for its maps. The aleatory uncertainty (due to random variability) is set to be 0.12 M units, consistent with the *Working Group* (2002) and the *National Seismic Hazard Mapping Project* (2002).

Impact on the Magnitude-Frequency Distribution for California

Although many parameter selections are needed to produce an all-California magnitude-frequency distribution, the WGCEP has found that most realizations of this distribution suffer from too high a rate of 6.25<M<6.75 earthquakes in comparison to the inferred historical rate, a cause of considerable concern. Global catalogs for the past 30-100 years (*Bird and Kagan*, 2004), as well as local network catalogs with a much greater range of magnitude completeness and a longer historical record, such as in the Kanto (greater Tokyo) region of Japan (*Grunewald and Stein*, 2006), exhibit no bulge, and so we regard the excess rate of moderate magnitude earthquakes in the California model as an artifact. Although the *Somerville* (2006) or *Wells and Coppersmith* (1994) magnitude-area relations exacerbate this excess earthquake frequency at about M~6.7, none of the magnitude-area relations we have considered removes it. So the magnitude-area relation is not the largest contributing factor in the disagreement between the model and data. Nevertheless, since the bulge is almost certainly a model artifact rather than a ture feature of seismicity, the Executive Committee has favored magnitude-area assumptions that tend to minimize the excess rate of M~6.7 earthquakes.

Conclusions

The WGCEP is charged with delivering a Poisson probability model to the National Seismic Hazard Mapping Project. For this, the Executive Committee has used the *Nazareth and Hauksson* (2004) method to estimate *W*. The few faults with known creep are also assigned aseismicity factors. The WGCEP assigns equal weight to the Ellsworth B (*Working Group on California Earthquake Probabilities*, 2003) and *Hanks and Bakun* (2007) magnitude-area relations.

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References

Asano, K., Iwata, T., and Irikura, K., 2005, Estimation of source rupture process and strong ground motion simulation of the 2002 Denali, Alaska, earthquake, *Bull. Seism. Soc. Am. 95*, 1701-1715.

Bird, P., and Y. Y. Kagan, 2004, Plate-tectonic analysis of shallow Seismicity: Apparent Boundary Width, Beta, Corner Magnitude, Coupled lithosphere thickness, and coupling in seven tectonic settings, *Bull. Seismol. Soc. Amer.*, *94*, 2380-2399; DOI: 2310.1785/0120030107.

Eberhart-Phillips and others, 2003, The 2002 Denali Fault Earthquake, Alaska: A Large Magnitude, Slip-Partitioned Event, *Science*, 300, 1113–1118, DOI: 10.1126/science.1082703.

Grunewald, E.D., and R.S. Stein, 2006, A new 1649–1884 catalog of destructive earthquakes near Tokyo and implications for the long-term seismic process, *J. Geophys. Res., 111*, doi:10.1029/2005JB004059.

Hanks, T. C., and W. H. Bakun, 2002, A bilinear source-scaling model for M-log A Observations of continental earthquakes, *Bull. Seismol. Soc. Amer.*, *92*, 1841-1846.

Hanks, T. C., and W. H. Bakun, 2007, M—log *A* observations for recent large earthquakes, submitted to *Bull. Seismol. Soc. Amer.*

Hauksson, E., and P. Shearer, 2005, Southern California Hypocenter Relocation with Waveform Cross-Correlation, Part 1: Results Using the Double-Difference Method, *Bull. Seismol. Soc. Amer.*, *95*, 896–903, doi:810.1785/0120040167.

Ito, A., *and others*, 2002, Aftershock activity of the 1999 Izmit, Turkey, earthquake revleaed from microearthquake observations, *Bull. Seismol. Soc. Amer.*, *92*, 418-427.

Nazareth, J. J., and E. Hauksson, 2004, The seismogenic thickness od the southern California crust, *Bull. Seismol. Soc. Amer.*, *94*, 940-960.

Oglesby, D.D., D.S. Dreger, R.A. Harris, N. Ratchkovski, and R. Hansen, 2004, Inverse kinematic and forward dynamic models of the 2002 Denali, Alaska earthquake. *Bull. Seism. Soc. Am. 94*, S214-S233.

Ozacar, A., S. L. Beck and D. H. Christensen, 2003, Source process of the 3 November 2002 Denali fault earthquake (central Alaska) from teleseismic observations, *Geophys. Res. Let. 30*, 1638.

Rolandone, F., R. Bürgmann, and R. M. Nadeau, 2004, The evolution of the seismic-aseismic transition during the earthquake cycle: Constraints from the time-dependent distribution of aftershocks, Geophys. Res. Lets., 31, L23610, doi:10.1029/2004GL021379.

Scholz, C.H., *The Mechanics of Earthquake Faulting*, Cambridge Univ. Press, Cambridge, 439 p.

Shaw, J.H., and J. Suppe, 1996, Earthquake hazards of active blind-thrust faults under the central Los Angeles basin, California, *J. Geophys. Res.*, *101,* 8623-8642.

Somerville, P., 2006, Review of magnitude-area scaling of crustal earthquakes, Rep. to WGCEP, 22 pp, URS Corp., Pasadena.

Somerville, P. G. and others, 1999, Characterizing earthquake slip models for the prediction of strong ground motion, *Seism. Res. Lett.*, *70*, 59-80.

Wells, D. L., and K. J. Coppersmith, 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. Seismol. Soc. Amer.*, *84*, 974-1002.

Working Group on California Earthquake Probabilities, 2003, Earthquake Probabilities in the San Francisco Bay Region: 2002–2031, *U.S. Geol. Surv. Open File Rep. 03-214*.

Wright, T.J., Z. Lu, and C. Wicks, 2004, Constraining the Slip Distribution and Fault Geometry of the Mw 7.9, 3 November 2002, Denali Fault Earthquake with Interferometric Synthetic Aperture Radar and Global Positioning System Data, *Bull. Seismol. Soc. Amer.*, 94, 175-189. doi:10.1785/0120040623.

Supplementary Material

Paul Somerville's report to the Working Group on California Earthquake Probabilities, revised after review by the Executive Committee, and a detailed *Comment* by Tom Hanks and a *Reply* by Paul Somerville, are available online through this link:

http://www.WGCEP.org/resources/documents/ERM2_1_Report/SomervilleReport_112706.pdf