Earthquake Rate Model 2 of the 2007 Working Group for California Earthquake Probabilities, Appendix D: Magnitude-Area Relationships

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Summary

The Working Group for California Earthquake Probabilities must transform fault lengths and their slip rates into earthquake moment-magnitudes. First, the down-dip coseismic fault dimension, *W*, must be inferred. We have chosen the *Nazareth and Hauksson* (2004) method, which uses the depth above which 99% of the background seismicity occurs to assign *W*. The product of the observed or inferred fault length, *L*, with the down-dip dimension, *W*, gives the fault area, *A*. We must then use a scaling relation to relate *A* to moment-magnitude, *Mw*. We assigned equal weight to the Ellsworth B (*Working Group on California Earthquake Probabilities*, 2003) and *Hanks and Bakun* (2007) equations. The former uses a single logarithmic relation fitted to the M≥6.5 portion of data of Wells and Coppersmith (1994); the latter uses a bilinear relation with a slope change at M=6.65 (A=537 km^2) and also was tested against a greatly expanded dataset for large continental transform earthquakes. We also present an alternative power law relation, which fits the newly expanded *Hanks and Bakun* (2007) data best, and captures the change in slope that Hanks and Bakun attribute to a transition from area- to length-scaling of earthquake slip. We have not opted to use the alternative relation for the current model. The selections and weights were developed by unanimous consensus of the Executive Committee of the Working Group, following an open meeting of scientists, a solicitation of outside opinions from additional scientists, and presentation of our approach to the Scientific Review Panel. The magnitude-area relations and their assigned weights are unchanged from that used in Working Group (2003).

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 uncertainties 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

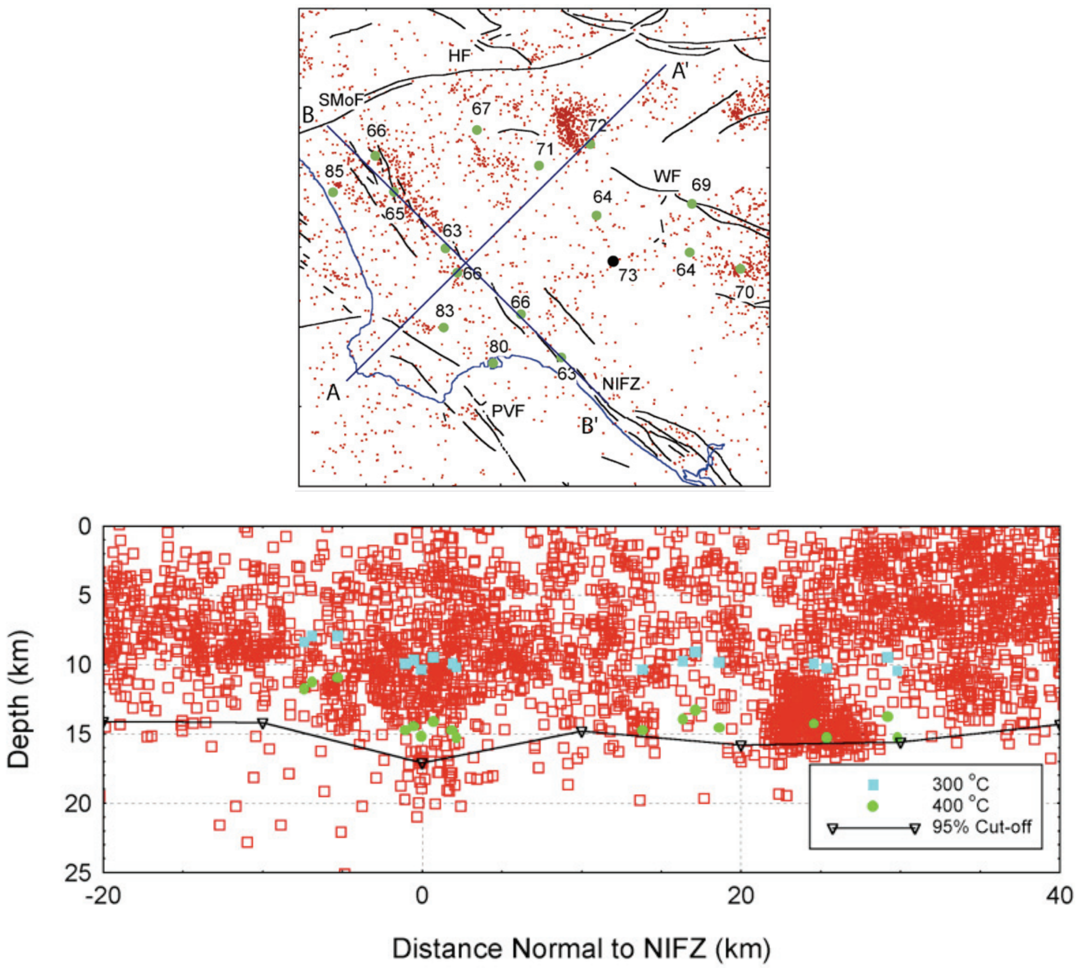


Figure 1. Relocated seismicity from *Hauksson and Shearer* (2005) compared with the inferred 300 and 400°C isotherms, suggesting that seismicity extends to about 400°-425°C across the Los Angeles Basin. The line above which 95% of the (red) earthquakes locate is shown in black (Collin Williams, written comm., http://pubs.usgs.gov/of/2003/of03-214/WG02_OFR-03-214_AppendixA.pdf)

Estimation of downdip fault dimension, *W*

The WGCEP has 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.

In contrast, the limited geodetic sampling and large ambiguities in the inferred maximum depth of coseismic slip and interseismic locking depth render geodetically-derived 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 from 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.

Some areas of California have extensive seismic refraction studies and seismic reflection profiling for oil prospecting or research (*Fuis and others*, 2003). Oil well data has also been used to infer the deeper fault geometry (*Shaw and others*, 2002; *Guzofski and Shaw*, 2005). For thrust faults, in particular, such data provide estimates of the fault width, *W*. These observations and interpretations provide ancillary evidence for comparison to seismicity, but are too limited to furnish a uniform approach to estimation of the depth of earthquake ruptures.

Limitations associated with estimating *W* from microseismicity

The approach of *Nazareth and Hauksson* (2004) suffers where background seismicity is sparse, such as along the Cholame-Simmler segment and parts of the Mojave segment of the San Andreas fault, along many of the Eastern California shear zone faults, and along the San Gregorio fault. For many thrust faults, seismicity is distributed and so the lower depth of seismicity may lie beneath the major thrust fault. This may be the case for the Coalinga and Kettleman Hills thrusts east of the central San Andreas faults. But even with these acknowledged weaknesses, the coverage of hypocenters 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•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 2002 M=7.9 Denali, Alaska, right-lateral earthquake may have ruptured to as much as 20 km depth, whereas background seismicity only extended to about 10 km depth (*Eberhart-Phillips and others*, 2003). 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 contrast, 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).

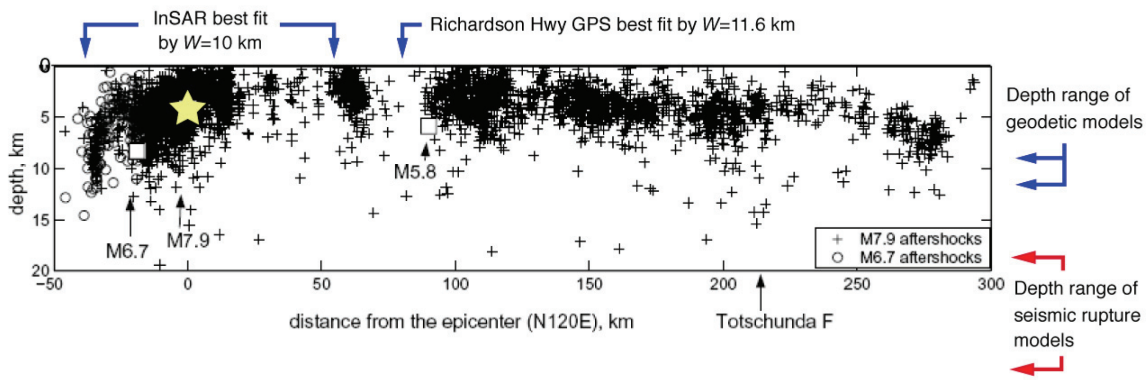


Figure 2. The aftershocks of the 2002 M=7.9 Denali shock (*Eberhart-Phillips and others*, 2003) compared to geodetic (*Wright and others*, 2004) and telesesmic (Asano and others, 2005; Oglesby and others; 2004, Ozacar and others, 2003) inferences for the lower depth of coseismic rupture. The depth of the background seismicity is too poorly known to be meaningfully compared to the aftershocks. Along-strike distances are shown along the average strike of the rupture.

Rolandone and others (2004) argued that the Landers aftershocks occurring in the first weeks to year after the mainshock 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.

In contrast, the first month of aftershocks to the M=7.6 Izmit, Turkey, earthquake exhibit 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 seismicity rate is much higher than at Landers, and so is more reliable. Thus we find that the evidence at hand does not suggest that earthquake ruptures commonly exceed the background seismicity depth by a significant amount.

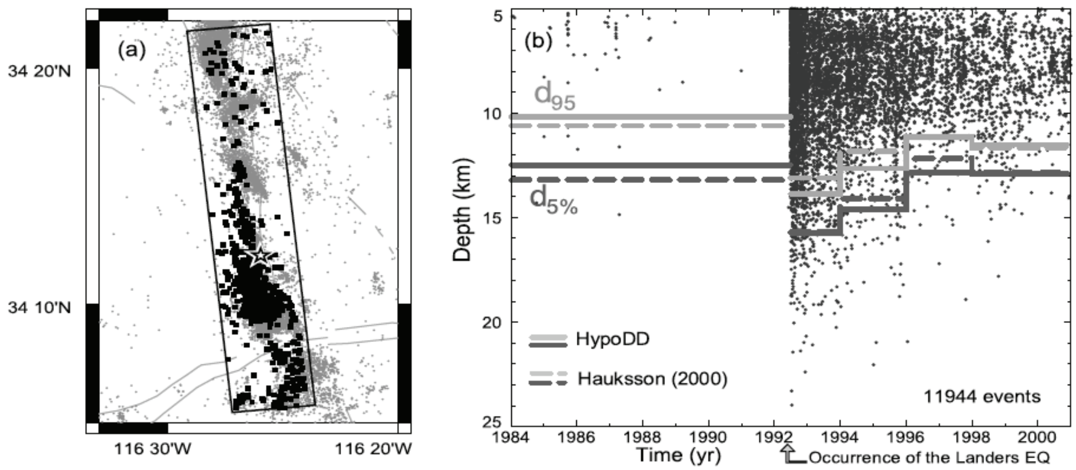


Figure 3. Depth of seismicity along the 1992 M=7.3 Landers, California, rupture, showing the background seismicity rate during 1984-1992, an apparent coseismic deepening of the lower depth of seismicity, followed by a gradual return to roughly pre-1992 depths (*Rolandone and others* 2004).

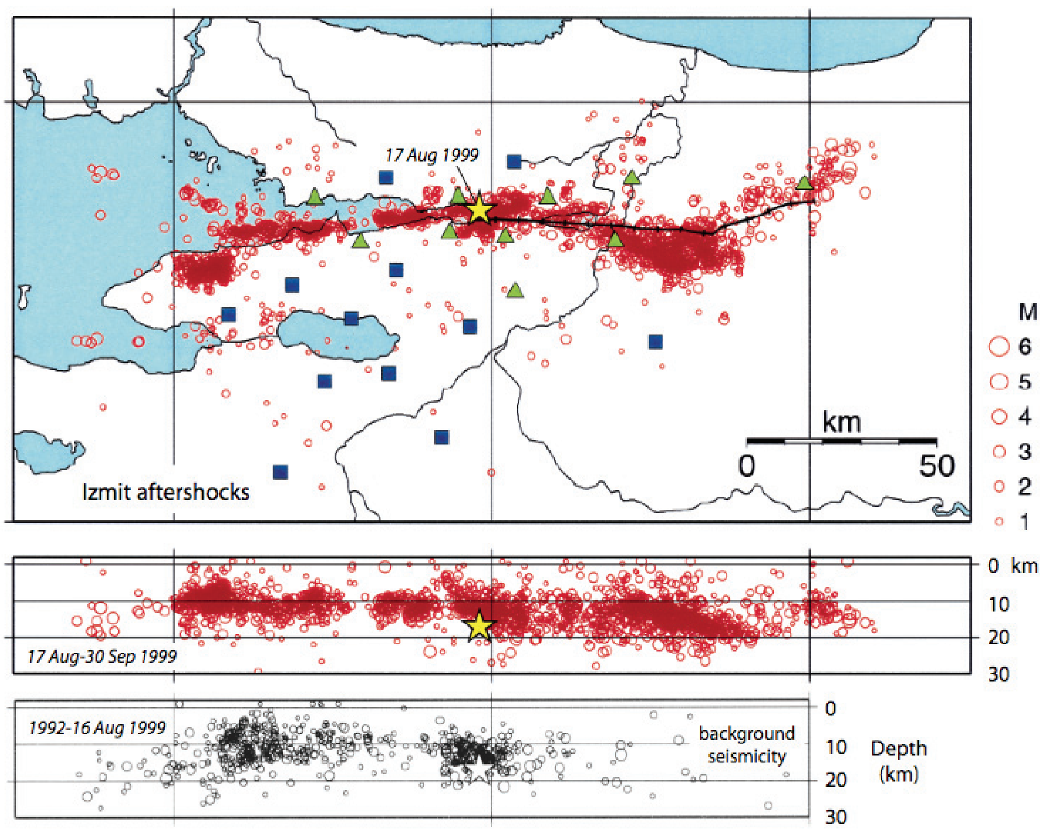


Figure 4. Depth cross-sections along the 1999 Izmit, Turkey, rupture from *Ito and others* (2002) exhibit little, if any, coseismic deepening. The depth above which 95% of the shocks occur is about 20 km for both background seismicity (black) and the first 45 days of aftershocks. Seismic stations are the blue squares and green triangles.

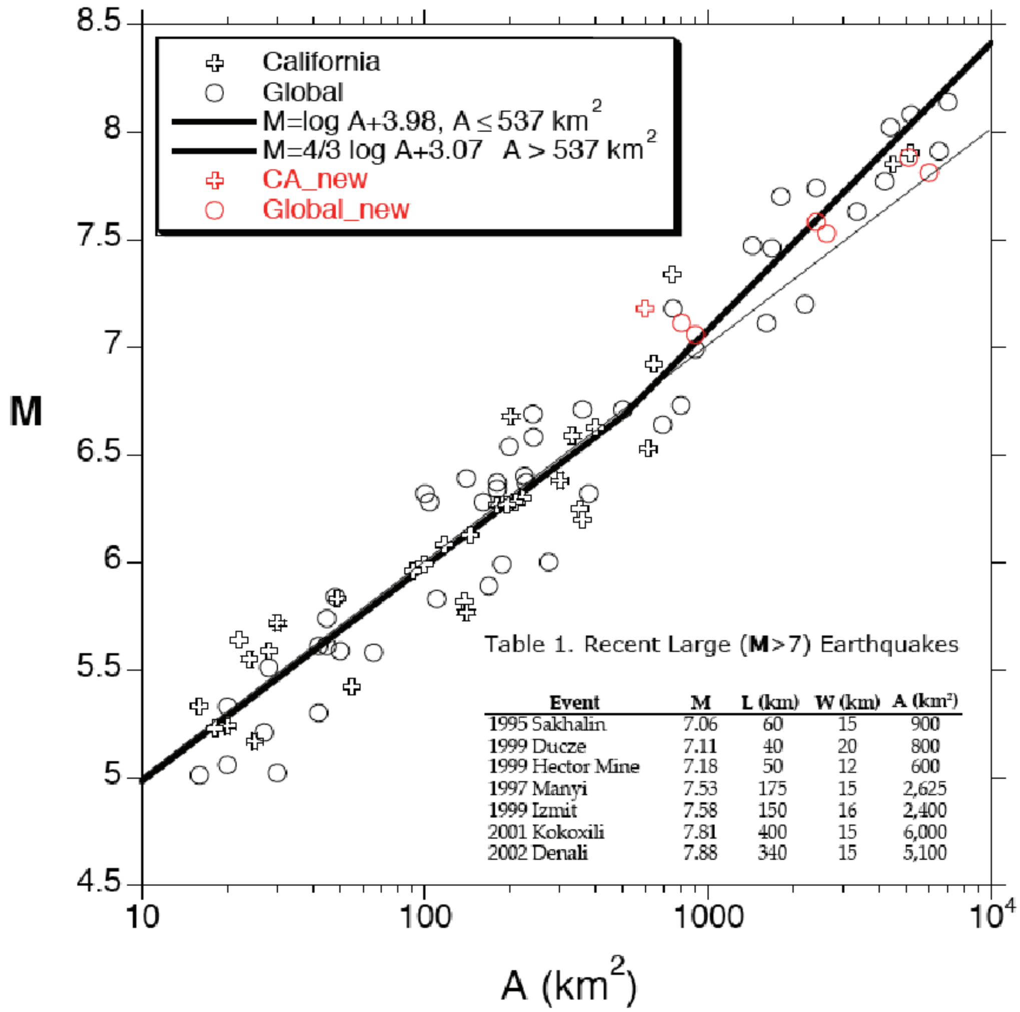
The Executive Committee of the Working Group thus concludes that contemporary seismicity provides the most sound and consistent method available to estimate the lower depth. The upper depth of faulting is left unresolved by this method, but we will arbitrarily set this to be 0 km except in special cases. 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 the database furnished by *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, 2007), *Ellsworth* (*Working Group on California Earthquake Probabilities*, 2003), as well as *Somerville* (2006), present these alternatives:

$M_w = 4.20 + 1.0 \log(A)$	('Ellsworth B' of *Working Group*, 2003)
$M_w = 3.98 \pm 0.3 + 1.0 \log(A)$	(for $A<537$ km^2; *Hanks and Bakun*, 2007)
$M_w = 3.08 \pm 0.4 + 4/3 \log(A)$	(for $A>537$ 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)

A single logarithmic relation was fit by the *Working Group* (2003) to observations from *Wells and Coppersmith* (1994) for continental strike-slip earthquakes with areas A>500 km^2, corresponding M>6.5; this has become known as 'Ellsworth B' (eqn 4.5b and Figure 4.2e in *Working Group*, 2003)(Figure 6). *Hanks and Bakun* (2007) furnish a dataset of 88 continental strike-slip earthquakes with moment-magnitudes and earthquake rupture areas. To the landmark database of *Wells and Coppersmith* (1994), they have added twelve M>7 shocks, most of these occurring since 1994, and they also revised some of the earlier moment and area estimates based on recent publications. *Hanks and Bakun* (2007) includes historical earthquakes from 1857. Somerville, by contrast uses a more uniform dataset of recent earthquakes for which seismic inversaions are available. Somerville makes extensive use of teleseismic and strong motion inversions of coseismic slip. These inversions have the attribute that some slip is typically distributed down to the lower depth of the surface over which slip is inverted. This artiface may bias the inversions to overestimate *W*. Somerville also 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 in assigning *A*.



Event	M	L (km)	W (km)	A (km²)
1995 Sakhalin	7.06	60	15	900
1999 Ducze	7.11	40	20	800
1999 Hector Mine	7.18	50	12	600
1997 Manyi	7.53	175	15	2,625
1999 Izmit	7.58	150	16	2,400
2001 Kokoxili	7.81	400	15	6,000
2002 Denali	7.88	340	15	5,100

Figure 5. Observations and model fit by *Hanks and Bakun* (2007). The light dashed line is the continuation of the A<537 km^2 curve for A>537 km^2. The observations added in 2007 are are in red, and appear in the inset table.

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•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).

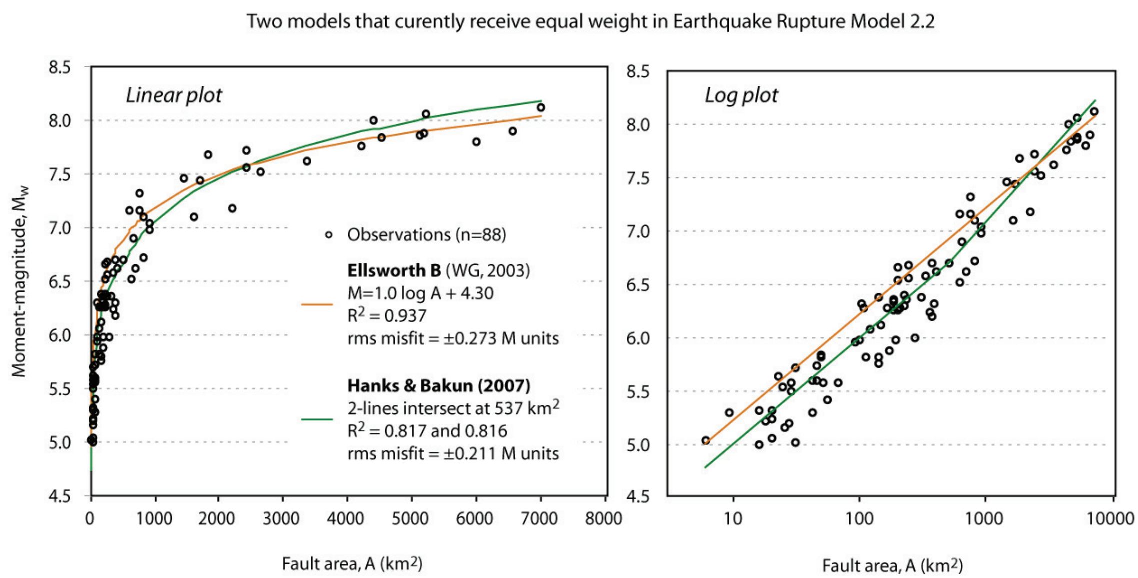


Figure 6. Magnitude-Area relations used in Earthquake Rate Model 2. Note that the correlation coefficient R^2 is weighted by the number of observations, *n*. Since there are two curves, the corresponding coefficient for each is lower than for the combined fit in 'Ellsworth B'.

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 twelve 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 and others*, 1983). Thus far, we have received no reply to this request.

Uncertainty on magnitude and area assignments

One caveat on the use of the database is that the earthquakes have no assigned errors in either magnitude or area, and so none of the regressions are weighted. This is most important for the largest shocks, which exert the greatest leverage on the slope of the fitted curve, and which are most important for the Earthquake Rate Model. The parameters are likely less well known for large historical quakes, such as the 1857, 1905, 1920, and 1939 events, than they are for more recent shocks. A second caveat is that the dispersion associated with our use of the two models disappears where the curves intersect, at M=7.5 (Figure 6), and so we have added additional epistemic (knowledge-based) uncertainty at this magnitude band

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 procedure of the National Seismic Hazard Mapping Project uses for its maps. The aleatory uncertainty (due to random variability) is set to 0.12 magnitude (M) units, consistent with the *Working Group* (2002) and the *National Seismic Hazard Mapping Project* (2002). It is possible that this value is too low, since one-sigma confidence interval on most magnitudes in the database is about 0.2 magnitude units.

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 true feature of seismicity, the Executive Committee has favored magnitude-area assumptions that tend to minimize the excess rate of M~6.7 earthquakes.

An alternative Magnitude-Area relationship for ERM 2

Here we fit *Hanks and Bakun* (2007) furnish a dataset anew and find that a single power law relation is compatible with the full range of the data and also contains the features that *Hanks and Bakun* (2002, 2007) ascribe to a transition from uniform stress drop scaling to slip that scales with fault length for large shocks. We thus argue that this single relation may be the best equation to use in Earthquake Rate Model 2.

Rather than fit the data expressly, *Hanks and Bakun* (2002, 2007) assumed constant stress-drop scaling for M<6.7 shocks, with slip proportional to rupture area, for which M=log A + 4.0. For larger shocks, they argue that the data indicates slip is instead linearly proportional to with fault length, in which case, M=4/3 log A + 3.0. They found that this scaling model is in accord with the data if the transition occurs at A~537 km^2.

Physically, they argue that once the down-dip width, W, reaches ~15 km (corresponding to L~34 km), ruptures grow by increased length, L.

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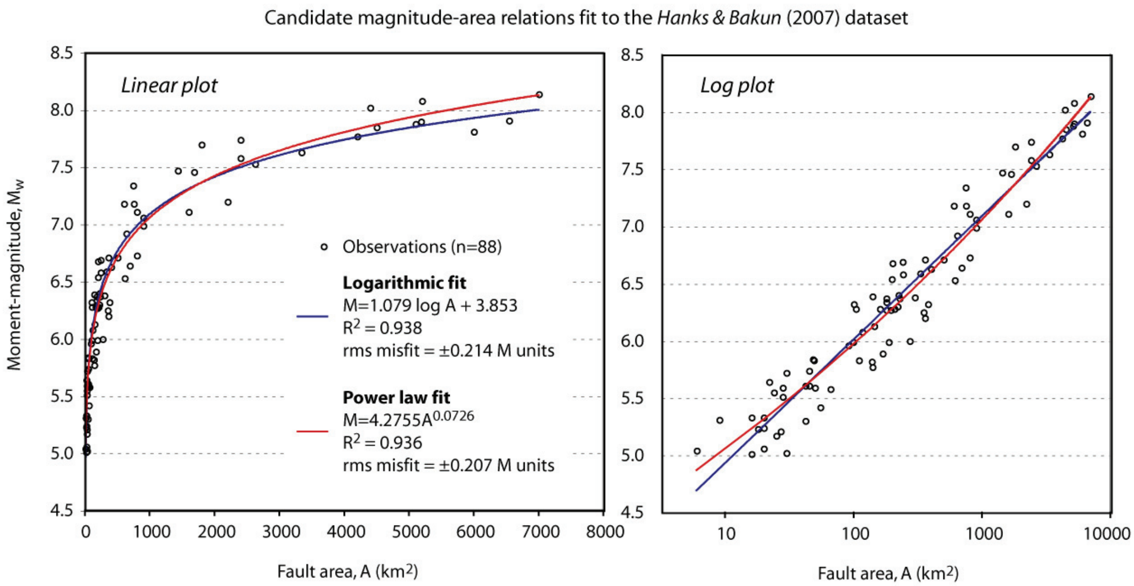

Figure 7. New fits of the full dataset to logarithmic and power law curves, and their corresponding statistics.

We have also fitted the full dataset (5.0 M_w 8.14) to a logarithmic and a power law curve (Figure 7). Not surprisingly, the correlation coefficient increases and the model residuals decrease in comparison to Ellsworth B of *Working Group* (2003), because it was developed from a far more limited dataset. The power law curve exhibits the lowest residuals of all four cases. Further, it displays the changing slope as a function of area that predicted by *Hanks and Bakun* (2002, 2007). The difference between the power law curve (Figure 8) and that of *Hanks and Bakun* (2007) (Figure 6) is that the 537 km^2 inflection point is replaced by a transitional slope change. This might be more realistic than the expectation that the lower seismogenic depth is everywhere 15 km, or any particular value. *Hauksson and Nazareth* (2004) find, for example, that the maximum depth of background seismicity varies from 8 km to 20 km along the San Andreas fault in southern California at sites where reliable estimates can be made; they further show that these background estimates are well correlated with the maximum depth of earthquake ruptures.

For M=8.0, the logarithmic curve predicts an area of 5300 km^2, whereas the power law curve predicts 6900 km^2. For W=15 km, these areas correspond to rupture lengths, L, of 350 and 460 km, respectively. So, an important question is whether the power law curve fits the subset of earthquakes with the largest areas and magnitudes well. About half of these observations are associated with shocks in remote locations or those that occurred up to a century in the past, and so are uncertain. Others, however, struck in the past 35 years and were seismically and geologically well recorded, and so are more reliable. Taken as a whole, the power law curve satisfies the largest events quite well.

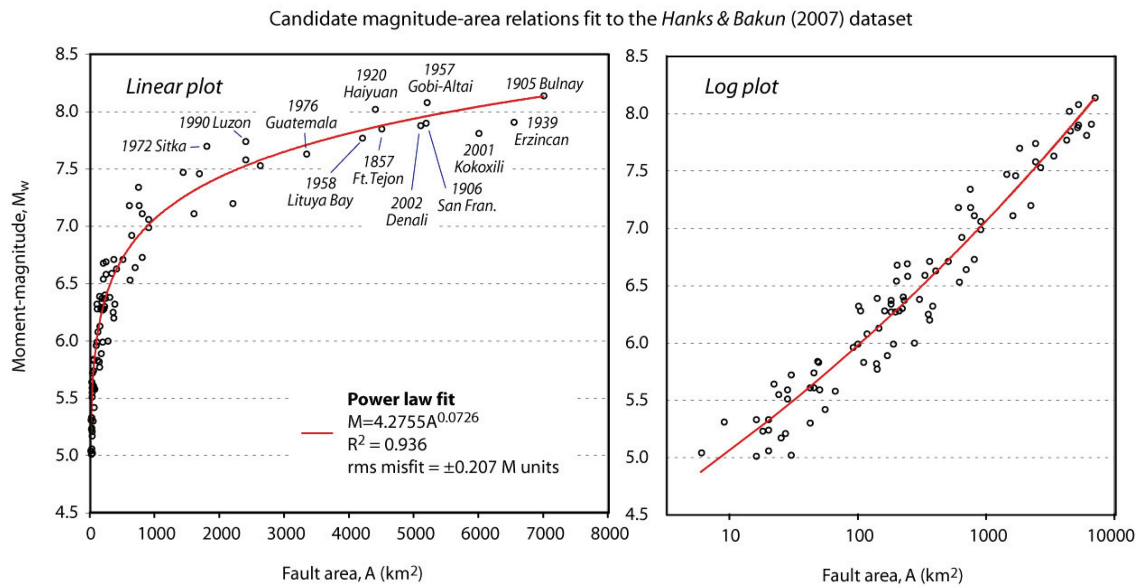

Figure 8. The power law curve, with the 12 largest earthquakes identified. Observations are from *Wells and Coppersmith* (1994) and *Hanks and Bakun* (2002, 2007).

We thus propose here that the most unbiased estimate of the relationship between magnitude and area for strike-slip earthquakes, irrespective of earthquake size, is represented by the power law relation,

$$M_w = 4.2775\ A^{0.0726} \qquad (1)$$

In addition to its low residuals, there are two other merits of using this relation in place of Ellsworth B and *Hanks and Bakun* (2007): We do not need to impose a fix where the two curves intersect, and we do not need to assume that the bottom of the seismogenic zone is uniform, which contradicts the *Hauksson and Nazareth* (2004) method by which we assign values of W in the Fault Section Database.

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* (2002, 2007) magnitude-area relations. However, an alternative approach that fits an expanded and updated dataset for continental strike-slip earthquakes better could instead use a single power-law relation. A further improvement would be the application of different magnitude-area relations for strike-slip and dip-slip faults, something that we have yet to undertake.

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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