# MAGNITUDE - RUPTURE AREA SCALING OF LARGE STRIKE-SLIP EARTHQUAKES

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## INTRODUCTION

There is unresolved debate, reviewed most recently by the Working Group on California Earthquake Probabilities (WGCEP, 2002), about the way in which the source parameters of large crustal earthquakes, especially strike-slip earthquakes, scale with earthquake magnitude (Mw). WGCEP (2002) considered both a self-similar model where average fault displacement D, fault length L and fault width W all increase uniformly together (Mw ~ log Area), and an L model developed by Hanks and Bakun (2001) where the displacement D grows in proportion to the fault length L with increasing magnitude once W reaches its maximum value at the base of the seismogenic zone (Mw ~ 4/3 log Area).

Here, we analyze recent crustal earthquakes whose rupture models have been derived from strong motion, teleseismic, and geodetic data, providing detailed images of the distribution of slip on the fault. We find a scaling relation (Mw = 1.05 log A + 3.87) that is quite similar to previously proposed self-similar models. For a given rupture area, this relationship predicts a significantly smaller magnitude (about 0.2 magnitude units less at large Mw) than the relations proposed by WGCEP (2002). The differences are mainly attributable to the more heterogeneous methods used to estimate rupture area by WCGEP (2002).

## APPROACH

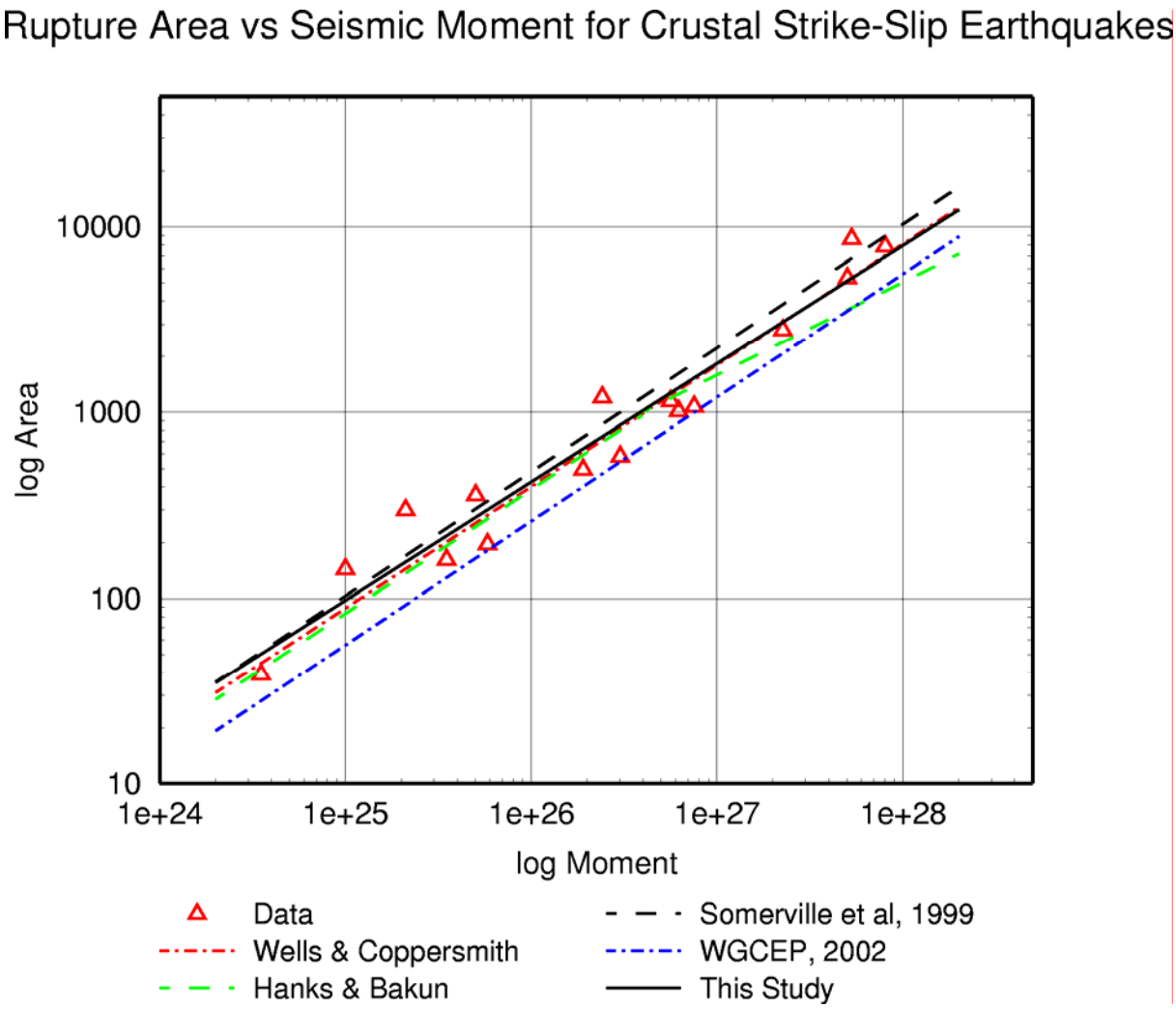
In this study, we used recent crustal earthquakes whose kinematic rupture models have been derived from strong motion, teleseismic, and geodetic data, providing detailed images of the distribution of slip on the fault. Since these rupture models are derived directly from the seismic radiation from the fault, they are ideally suited for scaling relations that are used to characterize rupture models for the prediction of strong ground motions from future earthquakes. Our analysis includes rupture models of several recent large strike-slip earthquakes, including the Mw 7.9 Denali, Alaska earthquake of 2002, the Mw 7.8 Kunlunshan, Tibet earthquake of 2001, and the Mw 7.4 Kocaeli, and Mw 7.2 Duzce, Turkey earthquakes of 1999. Development of a kinematic slip model involves selection of a starting model of the fault dimensions that is designed to err on the large side to avoid truncating the slip model. Accordingly, we trimmed the edges of each slip model following the procedure of Somerville et al. (1999); examples of reductions in rupture area are given in Table 2 (right). The earthquakes analyzed are listed in Table 1 below.

**Table 1. Crustal Strike-slip Earthquakes used in This Study**

| Earthquake | Mw | Seismic Moment | Rupture Area | Sources |
|---|---|---|---|---|
| Denali | 7.9 | 8.00E+27 | 7846 | Asano et al. (2005), Ji (2005), Oglesby et al. (2004), Ozacar & Beck (2004), Thio (2005) |
| Kunlunshan | 7.8 | 5.30E+27 | 8633 | Antolik et al. (2004), Bouchon & Vallee (2004), Ozacar & Beck (2004), Velasco (2004) |
| San Francisco | 7.8 | 5.00E+27 | 5280 | Wald et al. (1996) |
| Kocaeli | 7.5 | 2.25E+27 | 2772 | Bouchon et al. (2002), Delouis et al. (2002), Sekiguchi et al. (2002), Thio and Graves (2004) |
| Landers | 7.2 | 7.50E+26 | 1072 | Cotton & Campillo (1995), Hernandez et al (1999), Wald & Heaton (1994), Zeng & Anderson (1999) |
| Hector Mine | | 6.20E+26 | 1014 | Ji et al. (2002), Kaverina et al. (2002) |
| Duzce | 7.1 | 5.60E+26 | 1152 | Thio et al. (2004) |
| Loma Prieta | 7.0 | 3.00E+26 | 581 | Beroza (1991), Steidl et al. (1991), Wald et al. (1991), Zeng & Anderson (1999) |
| Kobe | 6.9 | 2.40E+26 | 1080 | Ide & Takeo (1996), Sekiguchi et al. (1997), Wald (1996), Yoshida et al., Zeng & Anderson (2002). |
| Tottori | 6.8 | 1.90E+26 | 598 | Sekiguchi et al. (2003). |
| Yamaguchi | 6.5 | 5.80E+25 | 196 | Miyakoshi et al. (2000) |
| Imperial Valley | 6.5 | 5.00E+25 | 360 | Hartzell and Heaton (1983) |
| Superstition Hills | 6.3 | 3.50E+25 | 161 | Wald et al. (1990) |
| Morgan Hill | 6.2 | 2.10E+25 | 312 | Beroza & Spudich (1988), Hartzell & Heaton (1986) |
| Kagoshima | 6.0 | 1.00E+25 | 144 | Miyakoshi et al. (2000) |
| Coyote Lake | 5.7 | 3.50E+24 | 39 | Liu &Helmberger (1983) |

## RESULTS

The scaling relation derived from these data, Mw = 1.05 log A + 3.87, is close to the self-similar models of Somerville et al. (1999) and Wells and Coppersmith (1994). For a rupture area of 10,000 km2, this relationship estimates a magnitude of Mw 8.07, while the WGCEP self-similar relation estimates Mw 8.2 and the Hanks & Bakun (2001) relation estimates Mw 8.36.




**COMPARISON WITH WGCEP MODELS**

The WGCEP models are largely based on data in which the earthquake rupture dimensions, and in some cases, the seismic moment, are either inferred from indirect data, such as the aftershock zone and surface rupture length, or are obtained from very preliminary analyses of the events. This may lead to a systematic bias that underestimates the fault rupture area. For example, Table 2 compares the models for the 1999 Kocaeli earthquake used by WGCEP (2002) and in this study. For this earthquake, this study found a rupture area of 2772 km2 from the average of 4 slip model inversion studies, 57% higher than the rupture area of 1767 km2 from the WGCEP (2002) average of three studies, only one of which was a published seismic slip model inversion.

**Table 2. Comparison of Data used by WCGEP (2002) and This Study**
**1999 Kocaeli Earthquake**

| AUTHOR | AREA | | METHOD |
|---|---|---|---|
| | | | |
| Delouis et al. (2002) | 2550 | | Slip model inversion |
| Wright et al. (2001) | 1700 | | INSAR |
| Yagi & Kikuchi (2000) | 1050 | | Preliminary automated slip model inversion |
| **AVERAGE - WGCEP** | **1767** | | |
| | | | |
| | Untrimmed | Trimmed | |
| Bouchon et al. (2002) | 2790 | 2790 | Slip model inversion |
| Delouis et al. (2002) | 3882 | 2700 | Slip model inversion |
| Sekiguchi & Iwata (2002) | 3285 | 2796 | Slip model inversion |
| Thio (2004) | 3040 | 2800 | Slip model inversion |
| **AVERAGE – THIS STUDY** | | **2772** | |

**COMPARISON WITH THE RESULTS OF OTHER STUDIES**

Our result is compatible with the conclusions of several recent studies. Bodin and Brune (1996) analyzed the Wells and Coppersmith (1994) data and concluded that the relation between surface slip and rupture length of strike-slip earthquakes cannot be explained by a simple quasi-static L or W model. They suggested instead that the data may reflect the effect of rupture dynamics, since in dynamic models the final slip need not be simply related to the fault dimensions. They conclude that if strength varies along strike, then long rupture is more likely to encounter conditions promoting large displacements.

Reviewing current data compilations, Jing et al. (2005) concluded that these data indicate that average slip continues to increase with L when L >> Wmax, but at a slower rate than implied by the L Model. Further, they found that the transition from linear to non-linear length scaling seems to occur at rupture lengths that are relatively large compared to the maximum rupture width. This suggests the limitation of static L and W models, in which fault slip is determined by the average stress drop and the final dimensions of fault rupture. Instead, they showed that the spatial heterogeneity of fault slip can play a key role in slip – length scaling. They found that their model did not generally result in linear scaling of rupture length, but that when a suite of faults with different smoothness is considered, the overall pattern of average slip with length is similar to that contained in data like those of Wells and Coppersmith (1984).

Mai and Beroza (2000) also concluded that the average displacement - rupture length scaling of rupture models is inconsistent with pure L or W scaling for simple constant stress-drop models, but suggests that the finite seismogenic width of the fault zone exerts a strong influence on the displacement for very large strike-slip earthquakes. The self-similar model, which would lie between the L and the W models, is compatible with this finding.

## IMPLICATIONS FOR STRONG MOTION SIMULATION

For empirical ground motion models, this 0.2 unit magnitude difference has minor significance, resulting in about 15% variability in ground motion level at long periods. This is because the empirical ground motion models implicitly account for the change in rupture area associated with the magnitude difference. However, for numerical waveform simulations where the fault area is fixed, the 0.2 units in magnitude (factor of two in moment) scales almost directly into ground motion level. The factor of two in ground motion variability is about six times greater than that predicted by the empirical relations. This large difference has important implications for seismic hazard analysis.

## CONCLUSIONS

We have used the rupture areas of crustal strike-slip earthquakes derived from seismic slip model inversions to derive a scaling relation between rupture area and seismic moment (or magnitude). We find that the rupture areas of large crustal strike-slip earthquakes have an approximately self-similar scaling relationship with magnitude and seismic moment, similar to the models of Wells and Coppersmith (1994) and Somerville et al. (1999). For a given rupture area, this relationship predicts a significantly smaller magnitude (about 0.2 magnitude units less at large M) than the self-similar relation of WGCEP (2002) and the L model of Hanks and Bakun (2001). The differences are mainly attributable to the more heterogeneous methods used to estimate rupture area in the WCGEP (2002) and Hanks and Bakun (2001) relations.

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