

# PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

## **Scaling Relations between Seismic Moment and Rupture Area of Earthquakes in Stable Continental Regions**

**Paul Somerville**

URS Corporation

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## ABSTRACT

This report describes the development of scaling relations between seismic moment and rupture area of earthquakes in stable continental regions (SCR). The report reviews existing relations, develops new relations, and compares the new relations with the existing relations. It also compares the scaling relations of SCR earthquakes with those in tectonically active continental regions (TCR). Three different methods of estimating rupture area—based on aftershocks, slip models, and duration—were used to analyze the relation between seismic moment and rupture area, using earthquake source parameters compiled from published literature. For each category of data, the relations obtained were not significantly different from those obtained by constraining them to be self-similar. Accordingly, these self-similar relations were adopted in this study. The stress drops corresponding to these scaling relations range from 51 to 86 bars, with an average of 65 bars. This value is comparable to the value of 58 bars obtained by Leonard [2010]. Because Leonard [2010] did not document his data and used an undifferentiated mixture of different ways of measuring fault area, the relation that he developed is less soundly based than that developed in this study. However, the two relations are not significantly different, and the Leonard [2010] relations have the advantage of having been derived in a self-consistent manner for a wide range of earthquake categories, including crustal earthquakes in tectonically active regions. Consequently, it is recommended that the Leonard [2010] scaling relations for SCR earthquakes be used for the NGA-East Project. To a first approximation, the results of this study and that of Somerville et al. [1997] indicate that the rupture areas of SCR earthquakes are about half those of TCR earthquakes, and their stress drops are about 2.8 times higher. Allmann and Shearer [2009] find less of a difference, presumably because their intraplate category includes some earthquakes that the NGA-East Project would assign to TCR instead of SCR. Their study indicates that the rupture areas of intraplate earthquakes are about two-thirds those of TCR earthquakes, and their stress drops are about two times higher.



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# 1 Introduction

This report, which is a follow-up to a previous in-depth investigation [Somerville 2011], describes the development of scaling relations between seismic moment and rupture area of earthquakes in stable continental regions (SCR). The report reviews existing relations, develops new relations, and compares the new relations with the existing relations. It also compares the scaling relations of SCR earthquakes with those in tectonically active continental regions (TCR).

## 1.1 SELF-SIMILAR SCALING RELATIONS

Self-similar scaling relations have the property of scale invariance. For example, self-similar scaling relations arise when the average displacement on a fault rupture surface changes at the same rate as its change in area, yielding constant stress drop. The scaling relations that we obtained for SCR earthquakes in this study are not significantly different from those obtained by constraining them to be self-similar. Self-similar scaling relations have the advantage of simplicity, and so we adopted self-similar scaling relations in this study.

## 1.2 METHODS FOR ESTIMATING FAULT RUPTURE AREA OF EARTHQUAKES

In the following sections of the report, we describe four alternative approaches to estimating the rupture areas of earthquakes.

### 1.2.1 Aftershocks and Surface Faulting

The aftershock dimensions and surface rupture length (if present) provide indirect information about the rupture areas of earthquakes. The approach has been used by investigators such as Wells and Coppersmith [1994] and Hanks and Bakun [2002] to estimate the rupture areas of earthquakes. These indirect methods have limitations. For example, surface rupture length can only be used with earthquakes that produce surface rupture. Aftershocks typically occur in a volume of crust surrounding the earthquake rupture surface and may extend beyond the ends of the rupture zone of the earthquake, and so the aftershock zone may not provide a reliable indication of the dimensions of the mainshock rupture.

## 1.2.2 Earthquake Slip Models

Procedures for characterizing earthquake sources for the simulation of strong ground motion were developed by Somerville et al. [1999], based on the finite-fault rupture models of 15 crustal earthquakes in tectonically active regions. These rupture models were derived from the inversion of a combination of strong motion, teleseismic and geodetic data. This method accounts for seismic wave propagation effects through the computation of synthetic seismograms. The slip distributions of these events are highly variable, characterized by asperities (regions of large slip) surrounded by regions of low slip. These data were used to develop scaling relationships between seismic moment and a set of fault parameters that are needed for predicting strong ground motions, including fault length, fault width, rise time (duration of slip at a point on the fault), and the size, slip contrast and location of asperities.

In the course of developing ground motion models in eastern North America, Somerville et al. [2001] used published rupture models of three earthquakes that occurred in eastern Canada [Hartzell et al. 1994] to develop earthquake source scaling relations for eastern North America. Somerville et al. [2009] derived rupture models of four earthquakes that occurred in Australia: the 1968 Meckering earthquake and the three large earthquakes of the 1988 Tennant Creek sequence in the course of developing ground motion models for Australia. All four earthquakes occurred within the cratonic region of Australia.

## 1.2.3 Source Duration

The rupture duration of an earthquake contains information about the dimensions of the fault rupture surface based on an assumed value of rupture velocity. Estimates of the source duration can be obtained by computing synthetic seismograms, adjusting the source duration used in the synthetic seismograms to optimize the fit between the synthetic and recorded waveforms, usually from teleseismic *P*-waves. This method accounts for seismic wave propagation effects through the computation of synthetic seismograms.

Somerville et al. [1987] analyzed the source durations from earthquakes in eastern North America and other stable continental regions. Stress drop is calculated from seismic moment and source duration estimates using the model of Cohn et al. [1982], in which rupture duration is assumed to reflect the effects of rupture propagation and dislocation rise time over a circular fault surface embedded in a homogeneous medium. Assuming a rupture speed that is 0.8 times the shear wave velocity of 3.5 km/sec, the duration  $\tau$  (in seconds) of the shear wave pulse, averaged over the angle between the fault plane and the ray path, is related to the fault radius  $r$  (in kilometers) by

$$\tau = 0.75r$$

The stress drop  $\Delta\sigma$  is related to seismic moment  $M_o$  and duration by:

$$\Delta\sigma = 1.87 \times 10^{-22} \times M_o / \tau^3$$



and to seismic moment and fault rupture area  $A$  by:

$$\Delta\sigma = 2.468 \times 10^{-21} \times M_o / A^{1.5}$$
$$\text{Log}_{10}\Delta\sigma = \text{Log}_{10}M_o - 1.5\text{Log}_{10}A - 20.6076$$

#### **1.2.4 Corner Frequency**

The frequency domain equivalent of source duration is the corner frequency of the source radiation. In practice, measurements are made using seismograms, which contain seismic wave propagation effects that are difficult to separate from source effects. Allmann and Shearer [2009] did a global analysis of earthquake stress drops using corner frequency methods. One set of events that they studied consists of 61 “intraplate” earthquakes, which have varying distances from plate boundaries depending on the region. These distances are typically about 150 km, so this category includes more events than just those on stable continental regions. They also studied 48 “continental transform fault” events and 81 “continental collision boundary” events.

### **1.3 COMPILATION OF EARTHQUAKE SOURCE PARAMETERS**

In this study, we used the Aftershock, Slip Model, and Duration methods to analyze the relation between seismic moment and rupture area. The earthquake source parameters that were compiled from published literature are listed in Table 1; these parameters are not available for more recent events such as the 1997 Cap-Rouge, 2002 Au-Sable-Forks, 2005 Riviere-du-Loup, and 2010 Val-des-Bois earthquakes. This table includes 29 events that have source duration, mostly from older events already studied; source duration is not routinely reported in earthquake catalogs. It includes eight events that have slip models, mostly from smaller eastern Canadian and larger Australian events. It also includes 12 events with aftershock/surface faulting data from a wide variety of regions. Multiple methods are available for many events; there are only 30 different events in Table 1. For a given event, we used the same seismic moment estimate with the fault rupture areas estimated from each of the different methods. Table 1 provides references for each method used. The distribution of events by region and magnitude range is given in Table 2.

### **1.4 DERIVATION OF RELATIONS BETWEEN SEISMIC MOMENT AND FAULT RUPTURE AREA**

We obtained separate relations between seismic moment and fault rupture area using each of the three methods: Aftershock, Slip Model, and Duration. In each case, the relations obtained were not significantly different from those obtained by constraining them to be self-similar. Accordingly, we adopted the self-similar relations in this study. The stress drops corresponding to these scaling relations were obtained using the method described in Somerville et al. [1987] described above and are listed in Table 3.

**Table 1 Earthquake source parameters.**

Date	Location	$M_w$	$H$	$M_o$ dyne.cm	Ref*	Slip Model				Aftershock/Surface Rupture				Duration		
						$L$ km	$W$ km	$A$ km <sup>2</sup>	Ref*	$L$ km	$W$ km	$A$ km <sup>2</sup>	Ref*	Dur (sec)	$A$ km <sup>2</sup>	Ref*
1925.3.1	Charlevoix	6.29	10	3.1E25	B92									5.0	140	B92
1929.11.18	Gr. Banks#1	7.13	20	5.5E26	B95									11.0	676	B95
1935.11.1	Timiskaming	6.44	10	5.1E25	ES85									5.0	140	ES85
1939.10.19	Charlevoix	5.30	8	1.0E24	SM87									1.5	12.6	SM87
1940.12.20	Ossipee	5.35	10	1.2E24	ES85									0.8	3.6	ES85
1963.3.3	Missouri	4.66	15	1.1E23	SM87									0.5	1.40	SM87
1963.9.4	Baffin Bay	6.10	7	1.6E25	LK80									3.0	50	LK80
1965.10.21	Missouri	4.60	4	9.0E22	SM87									0.5	1.40	SM87
1967.12.10	Koyna	6.30	4.4	3.2E25	L76									6.4	229	SM87
1968.10.14	Meckering	6.61	1	9.3E25	SM87	28	10	280	SG09					5.4	163	FM88
1986.3.30	Marryat Ck	5.81	1	5.8E24	M89					13	3	39	WC94	4	89	M89
1968.11.9	Illinois	5.38	25	1.3E24	SM87									0.7	2.73	SM87
1969.9.29	Ceres	6.37	11	4.0E25	NB86									5	140	NB86
1970.3.24	Lake McKay	5.99	12	1.1E25	LK80									2.5	35	LK80
1973.6.15	Maine	4.49	6	6.2E22	SM87									0.8	3.57	SM87
1979.6.2	Cadoux	6.08	6	1.5E25	SM87					16	6	96	WC94	2.0	22	SM87
1979.8.19	Quebec	4.75	6.5	1.5E23	SM87									0.9	4.52	SM87
1980.7.27	Kentucky	5.09	13.5	4.8E23	SM87									1.1	6.76	SM87
1982.1.9	Miramichi	5.50	7	2.0E24	HL94			17	HL94	5.4	4.0	22	WC94	1.5	12.6	HL94
1983.10.7	New York	4.90	7	2.5E23	SM87									0.6	2.01	SM87
1983.12.22	Guinea	6.32	13	3.4E25	DD84					27	14	378	WC94	5.0	140	DD84
1984.10.7	North Wales	5.30	20.7	1.0E24	WC94					3.0	3.2	9.6	WC94			
1988.1.22	Tennant Ck	6.26	2.7	2.8E25	FM88	12	16	192	SG09	13	9	117	WC94	4.2	99	M89
"	"	6.38	3.0	4.1E25	"	16	10	160	"	13	9	117	"	5.9	195	"
"	"	6.58	4.2	8.2E25	"	18	12	216	"	19	12	228	"	5.4	163	"
1988.11.25	Saguenay	5.82	26	6.1E24	SM90			33	HL94					1.8	18	S90
1989.12.25	Ungava	6.04	3	1.3E25	B94			33	HL94	10	5	50	WC94	3.0	50	B94
1993.9.30	Latur	5.99	6	1.1E25	RE98									2.1	24.6	R98
1997.5.21	Jabalpur	5.81	35	5.9E4	S06									1.9	20.2	S06
2001.1.23	Bhuj	7.67	22	3.6E27	AD03	60	35	2100	AD03	60	40	2400	MH06	25	3495	AD03

\*Initials of first two authors and last two digits of year in References

**Table 2 Distribution of events by region and magnitude.**

Region	Number of Events	Magnitude Range
Eastern Canada	9	$M_w$ 5.3 – 7.1
Eastern U.S	7	$M_w$ 4.5 – 5.4
Australia	7	$M_w$ 5.8 – 6.6
India	4	$M_w$ 5.8 – 7.7
Africa	2	$M_w$ 6.3 – 6.4
Europe	1	$M_w$ 5.3
Total	30	$M_w$ 5.3 – 7.7

**Table 3 Scaling relations between seismic moment and rupture area.**

( $\text{Log}_{10} \Delta A = \text{slope} \times \text{Log}_{10} M_o + \text{intercept}$  and  $\text{Log}_{10} \text{stress drop} = -20.6076 - \text{intercept} / \text{slope}$ ).

Model Region	Method	Reference	Slope	Intercept	Stress Drop
TCR	Slip Model	Somerville et al. [1999]	2/3	-14.65	23.4
TCR, $M_w < 7.0$	Aftershock	Hanks & Bakun [2002]	2/3	-14.74	31.9
TCR, dip slip	Various, mostly aftershock area	Leonard [2010]	2/3	-14.72	30.0
Continental collision boundary	Corner Frequency	Allmann and Shearer [2009]	2/3	-14.68	26.3
Continental transform fault	Corner Frequency	Allmann and Shearer [2009]	2/3	-14.77	35.4
ENAM	Source Duration	Somerville et al. [1987]	2/3	-15.12	118.4
SCR	Source Duration	Somerville et al. [1987]	2/3	-15.03	86.8
ENAM	Slip Model	Somerville et al. [2001]	2/3	-15.05	93.0
Intraplate (~150 km beyond plate boundary)	Corner Frequency	Allmann and Shearer [2009]	2/3	-14.911	59.5
SCR	Various, mostly aftershock area	Leonard [2010]	2/3	-14.89	58.0
SCR–Combination of three methods	Various	Somerville [2011] (this study)	2/3	-14.946	64.9
SCR–Aftershock	Aftershock	Somerville [2011] (this study)	2/3	-14.876	51.0
SCR–Duration	Source Duration	Somerville [2011] (this study)	2/3	-15.028	86.2
SCR–Slip Model	Slip Model	Somerville [2011] (this study)	2/3	-14.934	62.3

## 1.5 SUMMARY OF RELATIONS BETWEEN SEISMIC MOMENT AND FAULT RUPTURE AREA

A summary of the published analyses of the relation between seismic moment and fault rupture area reviewed above, together with those derived in this study, is given in Table 3. All of these relations are self-similar relations, in which the relation between average displacement and rupture area, which is a measure of static stress drop, is independent of seismic moment and therefore provides a convenient way of characterizing the scaling relation. Our measurements of static stress drop relate to the static stress drop of a circular crack embedded in an elastic medium; this gives values like Brune stress drops. Stress drop values for other fault geometries and for surface faulting earthquakes may differ from those computed in this study. Hence we use the term static stress drop as index of the relation between average displacement and rupture area in a set of earthquakes, and not as an accurate estimate of the actual stress drops of individual earthquakes.

Table 3 also includes results from a recent global analysis of earthquake source scaling relations by Leonard [2010]. He derived self-consistent relations between  $L$ ,  $W$ ,  $D$ , and  $M_o$  for all categories of earthquakes. The data that he used are undocumented, based mainly on existing compilations of source parameters, with areas mostly based on the Aftershock method. All of his scaling relations have self-similar scaling of seismic moment with rupture area, although the rupture widths have non-self-similar scaling.

## 1.6 SEISMIC MOMENT–RUPTURE AREA SCALING RELATIONS FOR STABLE CONTINENTAL REGIONS

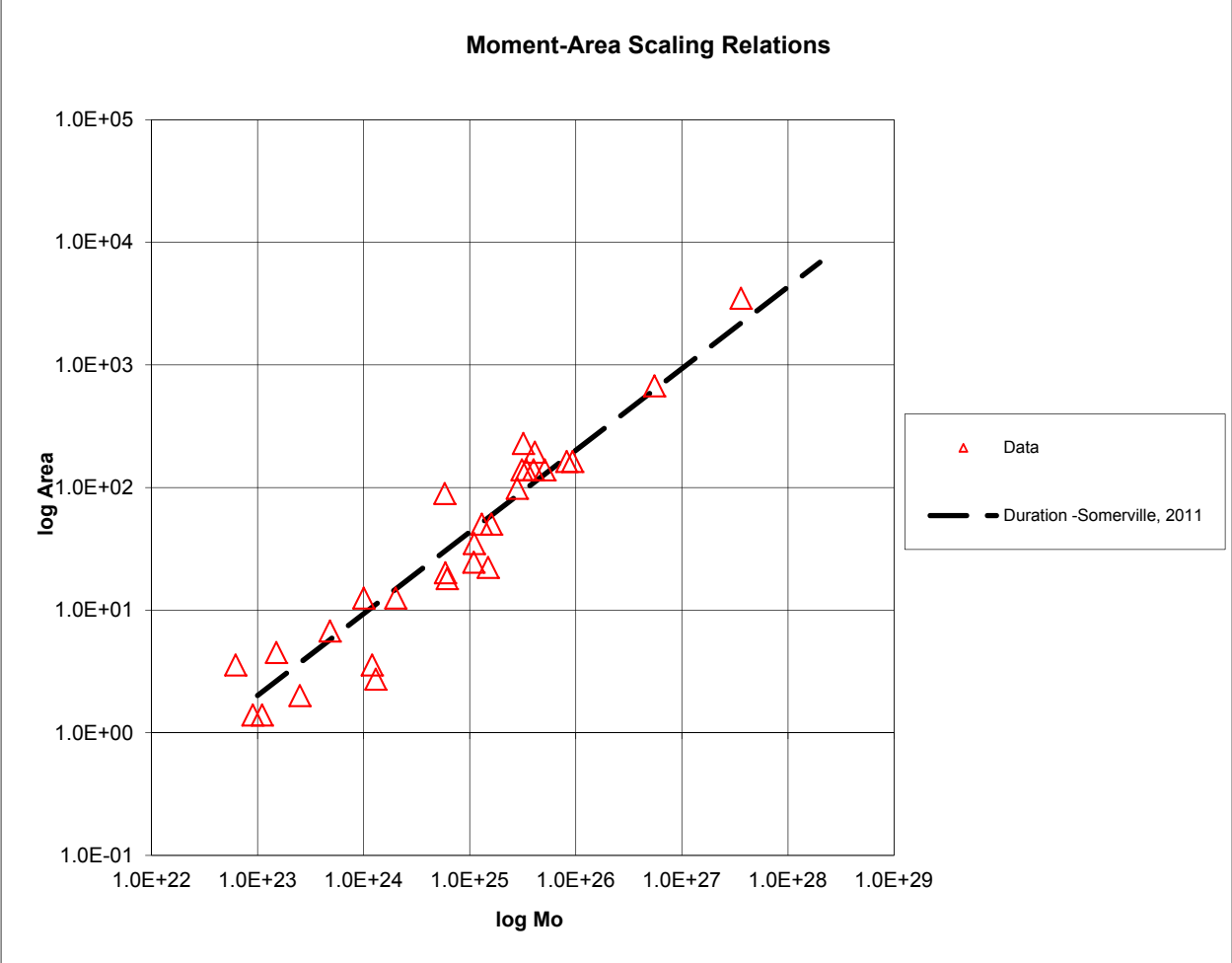
Table 3 lists the scaling relations obtained by the three different method categories used in this study, as well as the relation obtained by averaging these three relations. The seismic moment – rupture area scaling relations and the equivalent relation between magnitude and rupture area for the average of the models is as follows:

$$\text{Log}_{10}A = \frac{2}{3}\text{Log}_{10}M_o - 14.95$$

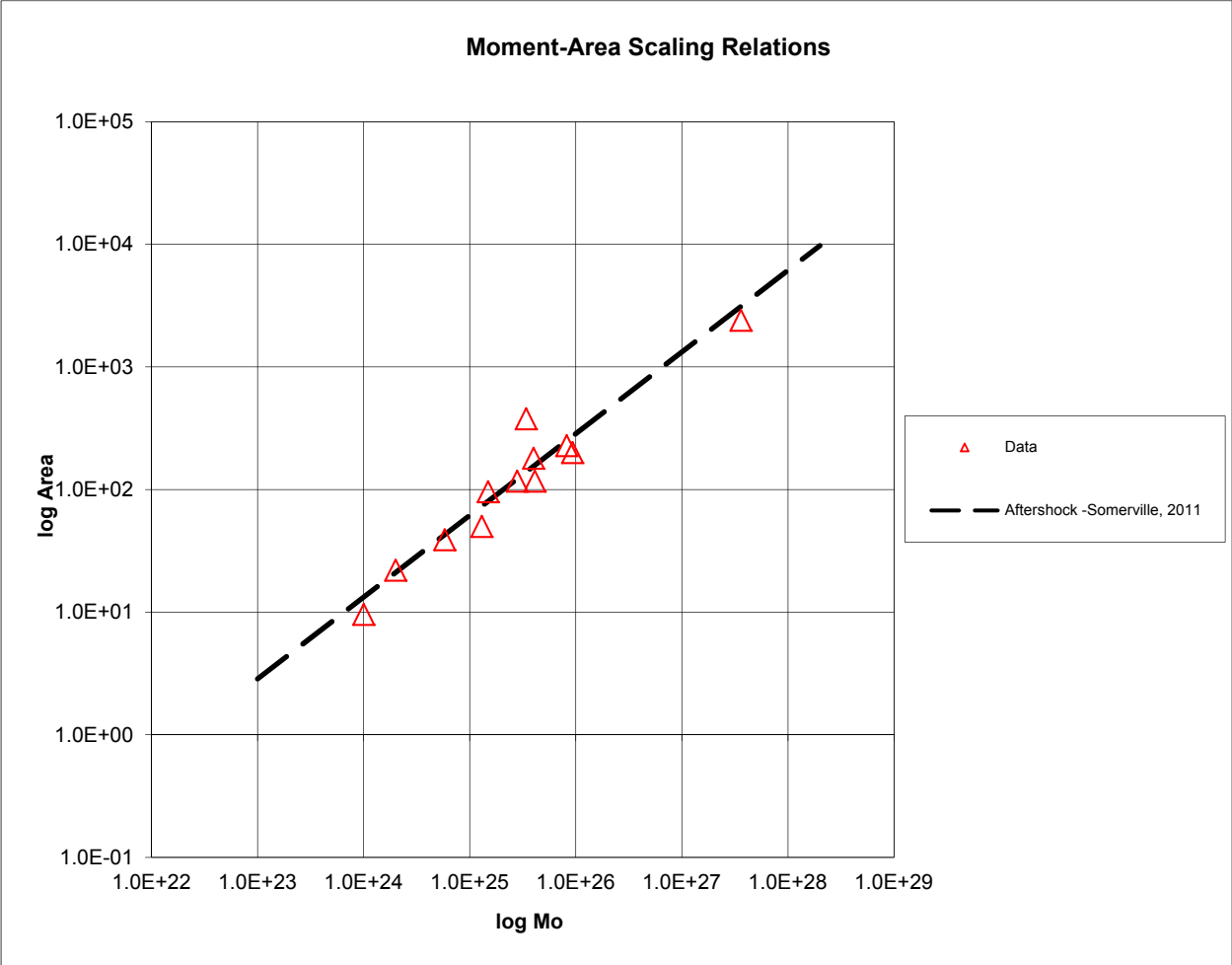
$$\text{Log}_{10}A = M_w - 4.25$$

The data and scaling relations for the three methods are shown in Figures 1, 2, and 3, and the three relations are shown together in Figure 4. Figure 5 shows these three relations together with the relations derived using duration by Somerville et al. [1987] and using slip model by Somerville et al. [2001]. These two earlier relations, based on much smaller data sets, both have larger stress drops than all of the three new models.

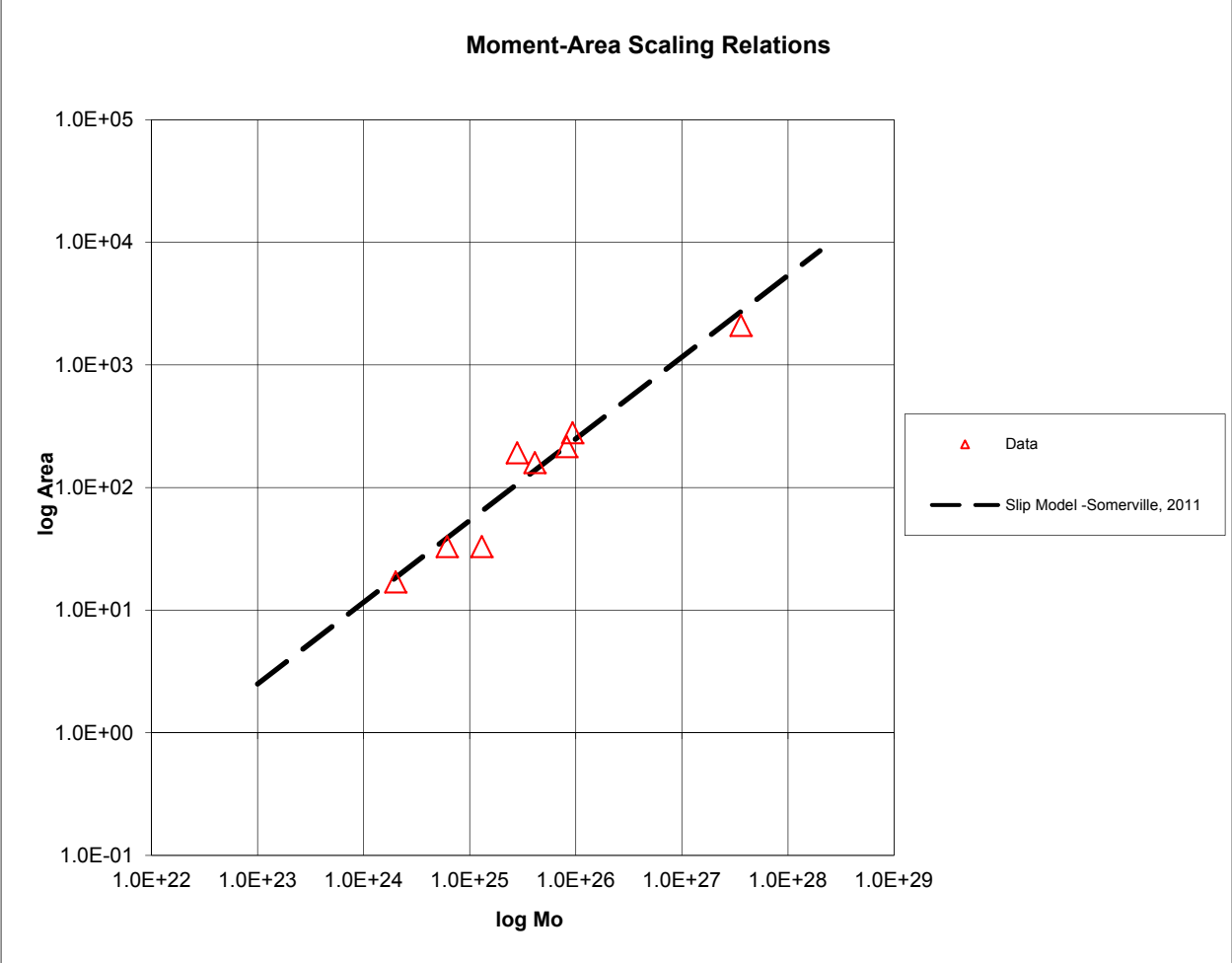
Figure 6 shows the similarity between the average model derived in this study and the model obtained by Leonard [2010] for SCR earthquakes. Figure 7 shows that both of these models have lower stress drops than the relations derived using duration by Somerville et al. [1987] and using slip model by Somerville et al. [2001].



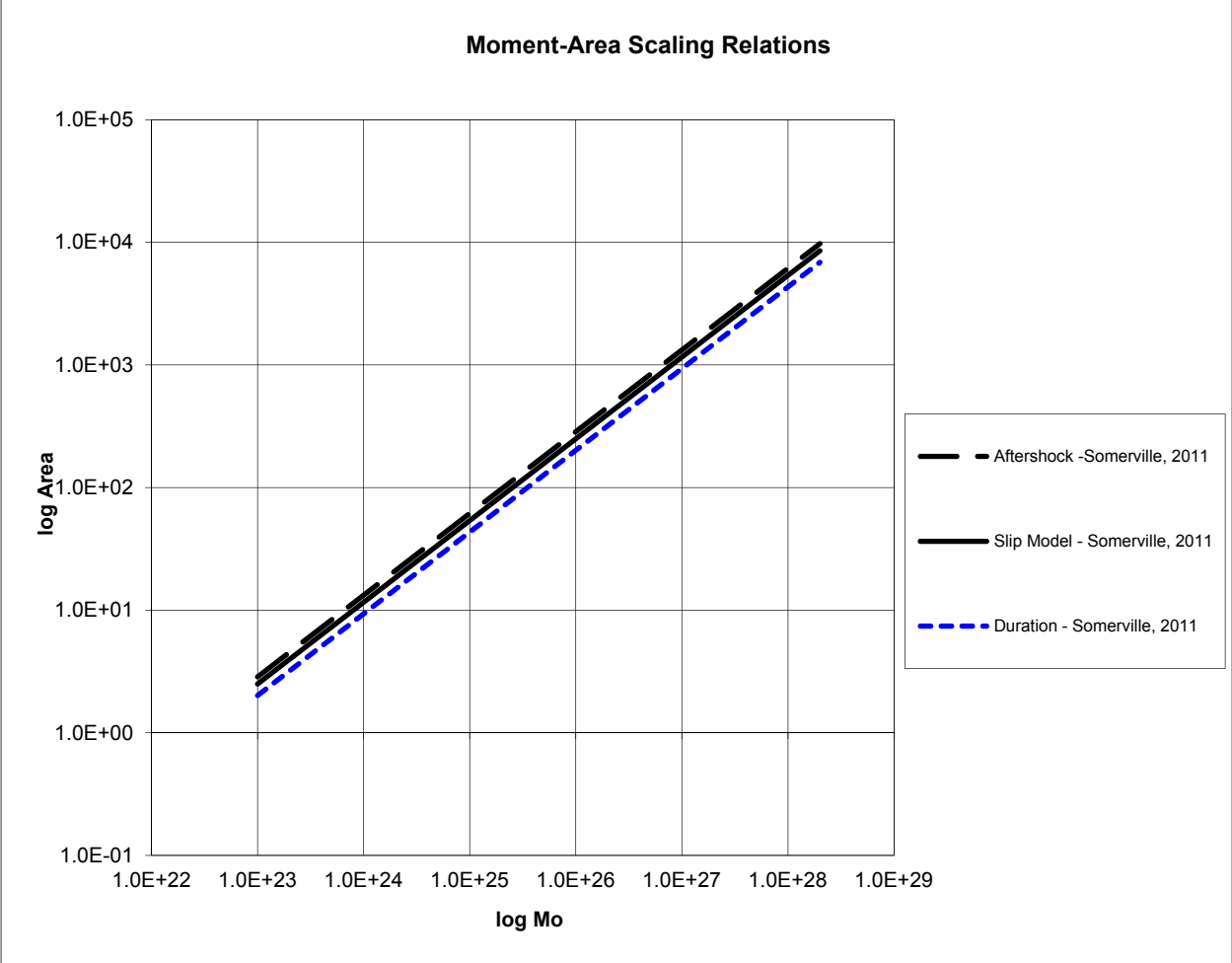
**Figure 1** Relation between seismic moment and rupture area derived from source duration.



**Figure 2** Relation between seismic moment and rupture area derived from aftershock area and surface rupture data.

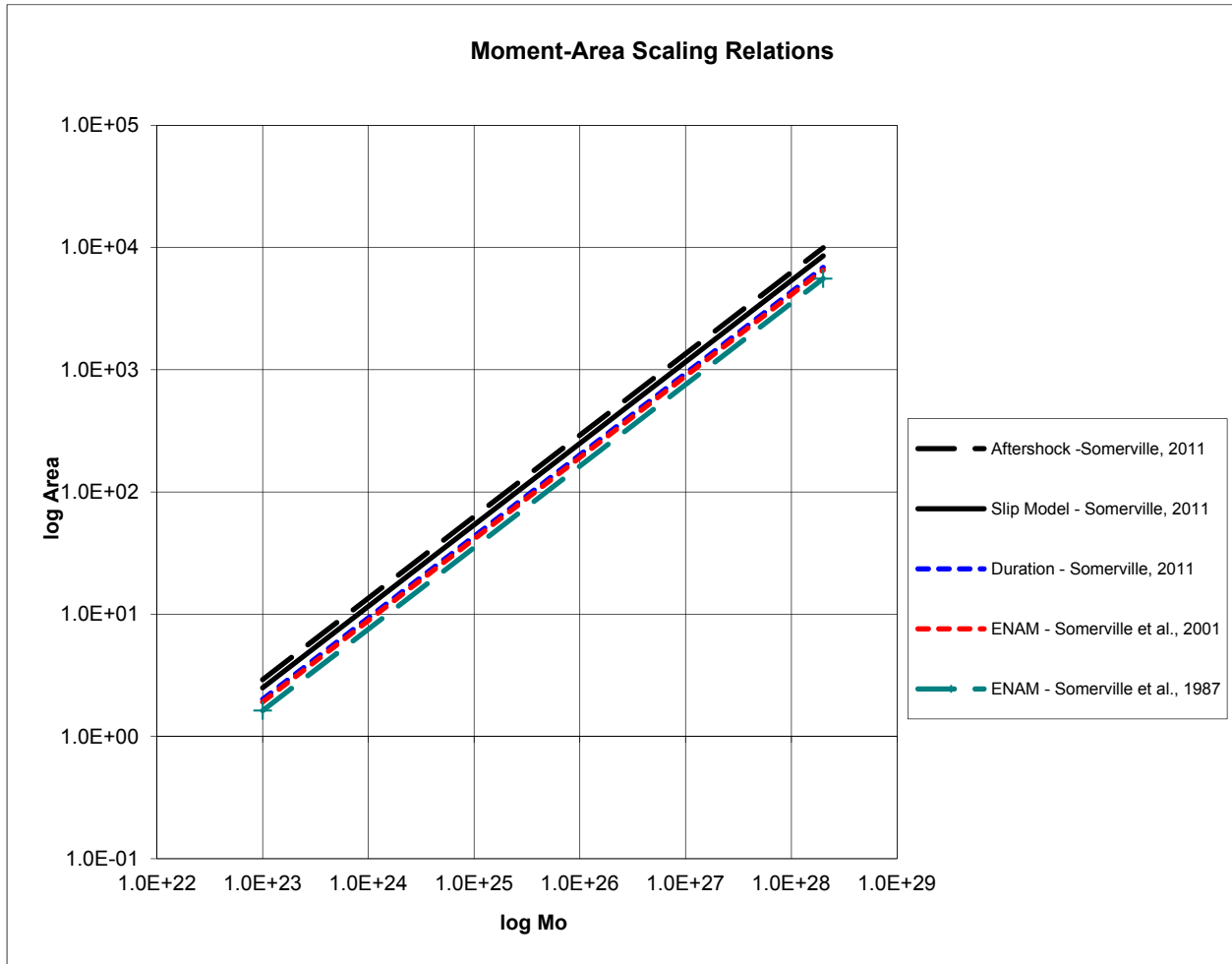


**Figure 3** Relation between seismic moment and rupture area derived from slip models.

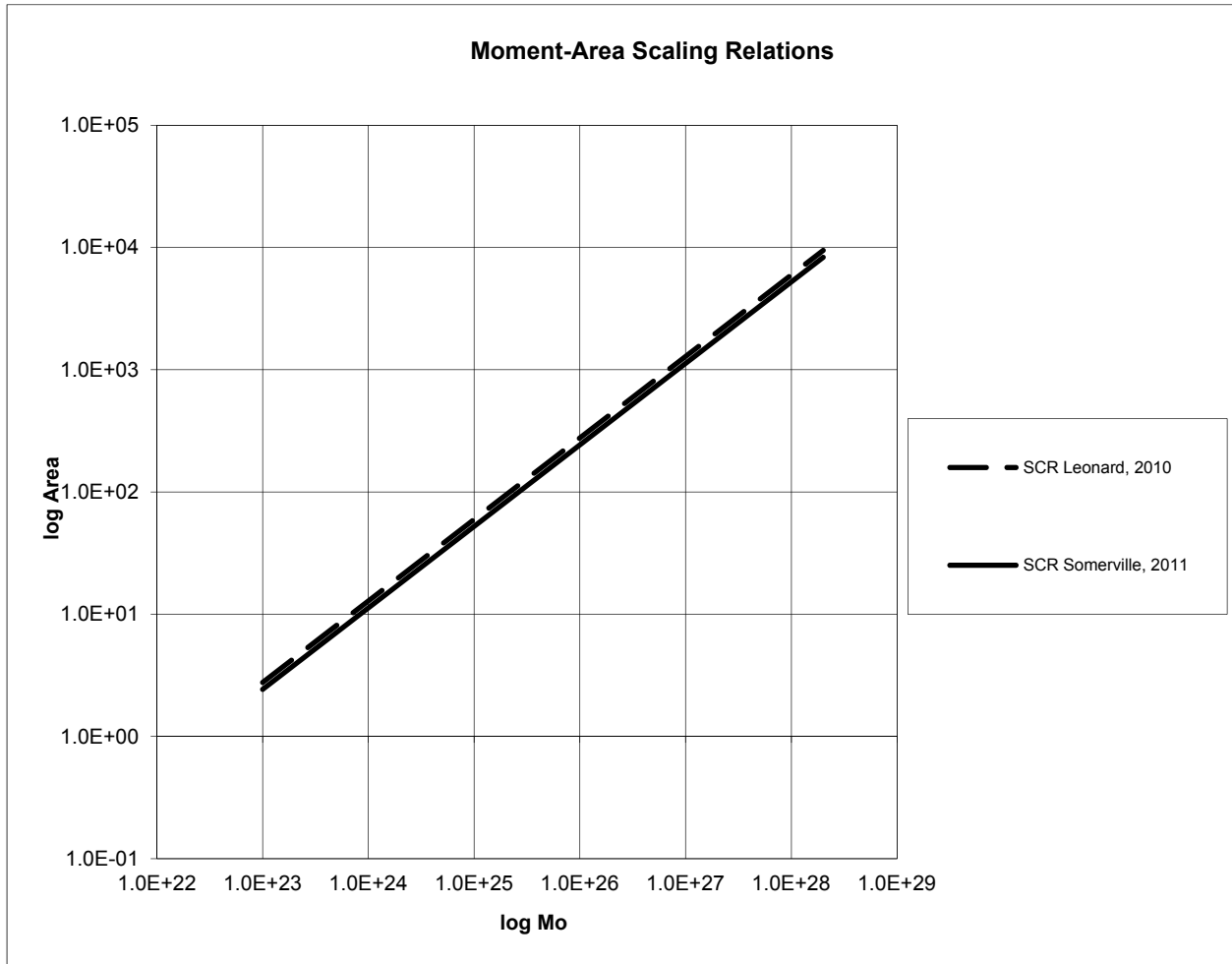


**Figure 4** Comparison of relations between seismic moment and rupture area derived from three different methods.

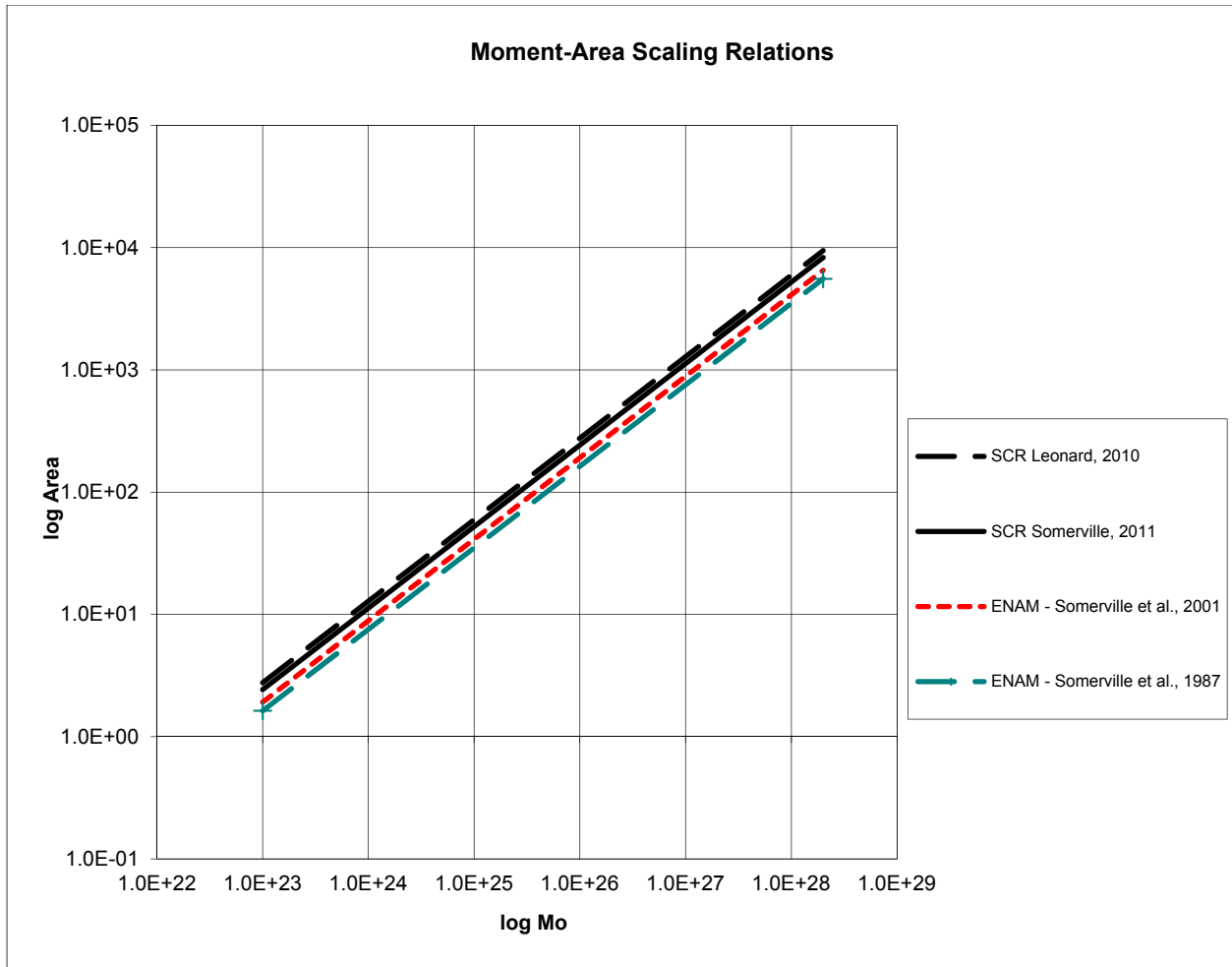




**Figure 5** Comparison of relations between seismic moment and rupture area derived from three different methods with previous relations using Duration [Somerville et al. 1987] and Slip Model [Somerville et al. 2001].



**Figure 6** Comparison of Leonard [2010] and Somerville [2011] relations between seismic moment and rupture area.



**Figure 7** Comparison of Somerville [2011] with Leonard [2010] relations between seismic moment and rupture area with previous relations using Duration [Somerville et al. 1987] and Slip Model [Somerville et al. 2001].

## 1.7 EPISTEMIC UNCERTAINTY AND ALEATORY VARIABILITY IN STRESS DROP

We have shown that in a self-similar source scaling relation, the static stress drop is independent of seismic moment and therefore provides a convenient way of characterizing the scaling relation. We calculated the values of  $\text{Log}_{10}$  of the stress drops of the earthquakes for each method category and then calculated the standard deviation (aleatory variability of the values about the mean) and standard error (epistemic uncertainty in the mean) for each method category. The results are listed in Table 4. The Aftershock and Duration categories have means that are statistically significantly different from each other (as measured by the standard errors of the means), but the mean for the Slip Model category is not statistically significantly different from the mean of either of the other models.

The values for the three model categories were combined by taking a weighted average of the standard deviations of the three models, with weights based on the respective numbers of data points, and by calculating the standard error of the mean of the three mean values. These results are also listed in Table 4. In this combined model, the stress drop has an aleatory variability of a factor of 2.0, and the standard error of the mean has a coefficient of variation of 1.165. The coefficient of variation of the mean of the Allmann and Shearer [2009] estimate for intraplate earthquakes is 1.17, which is similar to the estimate for the combined three models.

An alternative assessment of the median, standard deviation, and standard error of stress drop was made by including the models of Leonard [2010] and Allmann and Shearer [2009]. The median value of the stress drop from those two studies and the three model estimates obtained in this study is 63.4 bars, which is quite similar to the value of 64.9 bars obtained using just the three model estimates from this study. The standard error of the estimate from the five models has a coefficient of variation of 1.08, which is less than the value of 1.165 for the combined three models. We consider the estimate of standard error from the five models to be more reliable, and accordingly we report this value (0.034 log<sub>10</sub> units) in Tables 4 and 5.

**Table 4 Epistemic uncertainty and aleatory variability of Log<sub>10</sub> (static stress drop).**

<b>Data Set</b>	<b>Mean</b>	<b>Epistemic uncertainty (standard error of mean)</b>	<b>Aleatory variability (standard deviation)</b>
Aftershock	51.0	0.0708	0.245
Slip Model	62.3	0.0836	0.236
Duration	86.2	0.0713	0.384
Combined–3 Models	64.8	0.0664	0.300
Combined–5 Models	62.4	0.0340	

## 1.8 EPISTEMIC UNCERTAINTY AND ALEATORY VARIABILITY OF MAGNITUDE-AREA SCALING RELATIONS

The measurements of epistemic uncertainty and aleatory variability in stress drop in Table 4 were used to estimate the epistemic uncertainty and aleatory variability of the magnitude-area scaling relations, based on the scaling relationships given above. The results for the combined 5 models are given in Table 5.

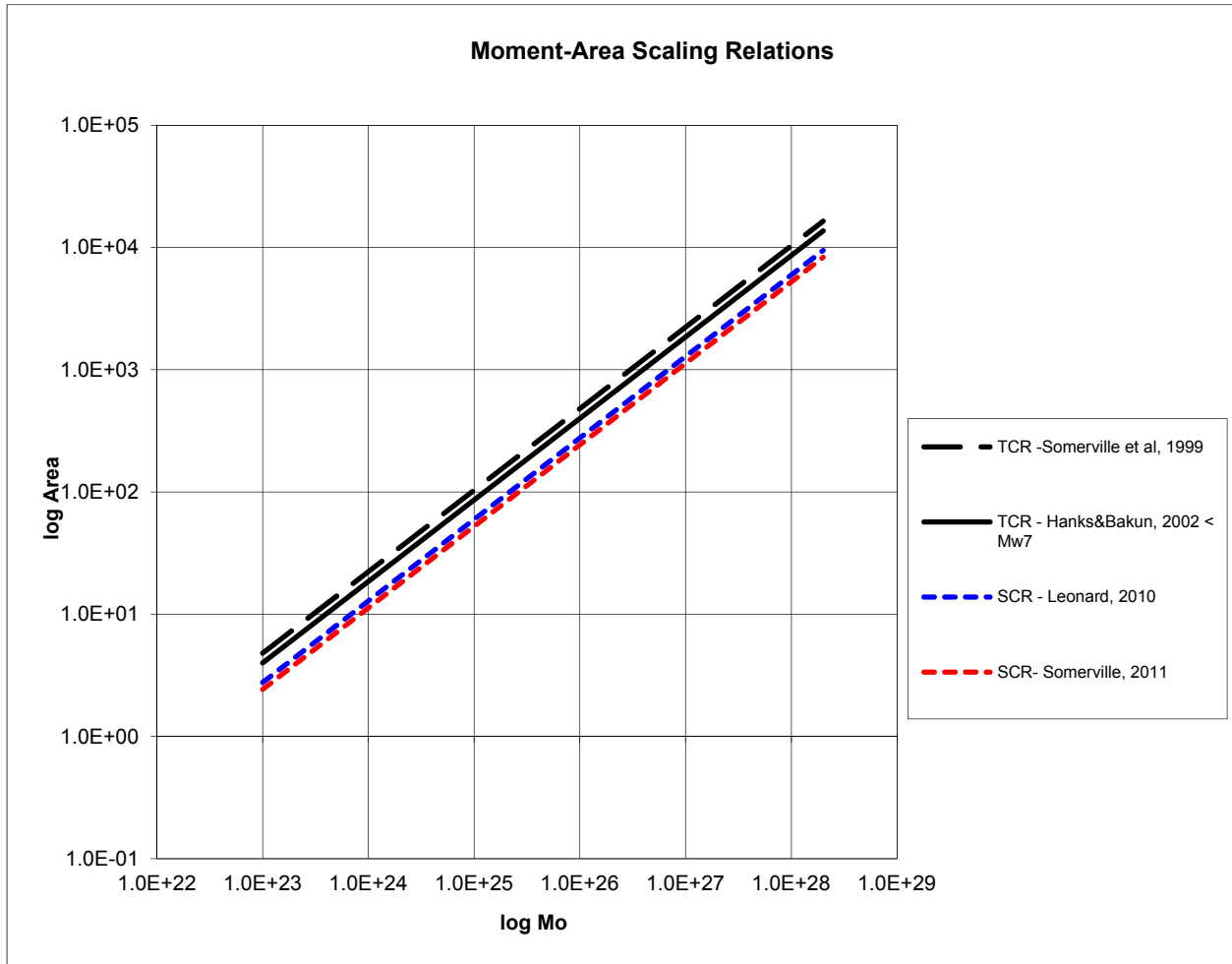
**Table 5** Epistemic uncertainty and aleatory variability of magnitude-area scaling relations.

Parameter	Epistemic Uncertainty (Standard Error of Mean)	Aleatory Variability (Standard Deviation)
Log <sub>10</sub> (area)	0.023	0.20
$M_w$	0.023	0.20
Log <sub>10</sub> (stress drop)	0.034	0.30
Log <sub>10</sub> (seismic moment)	0.034	0.30

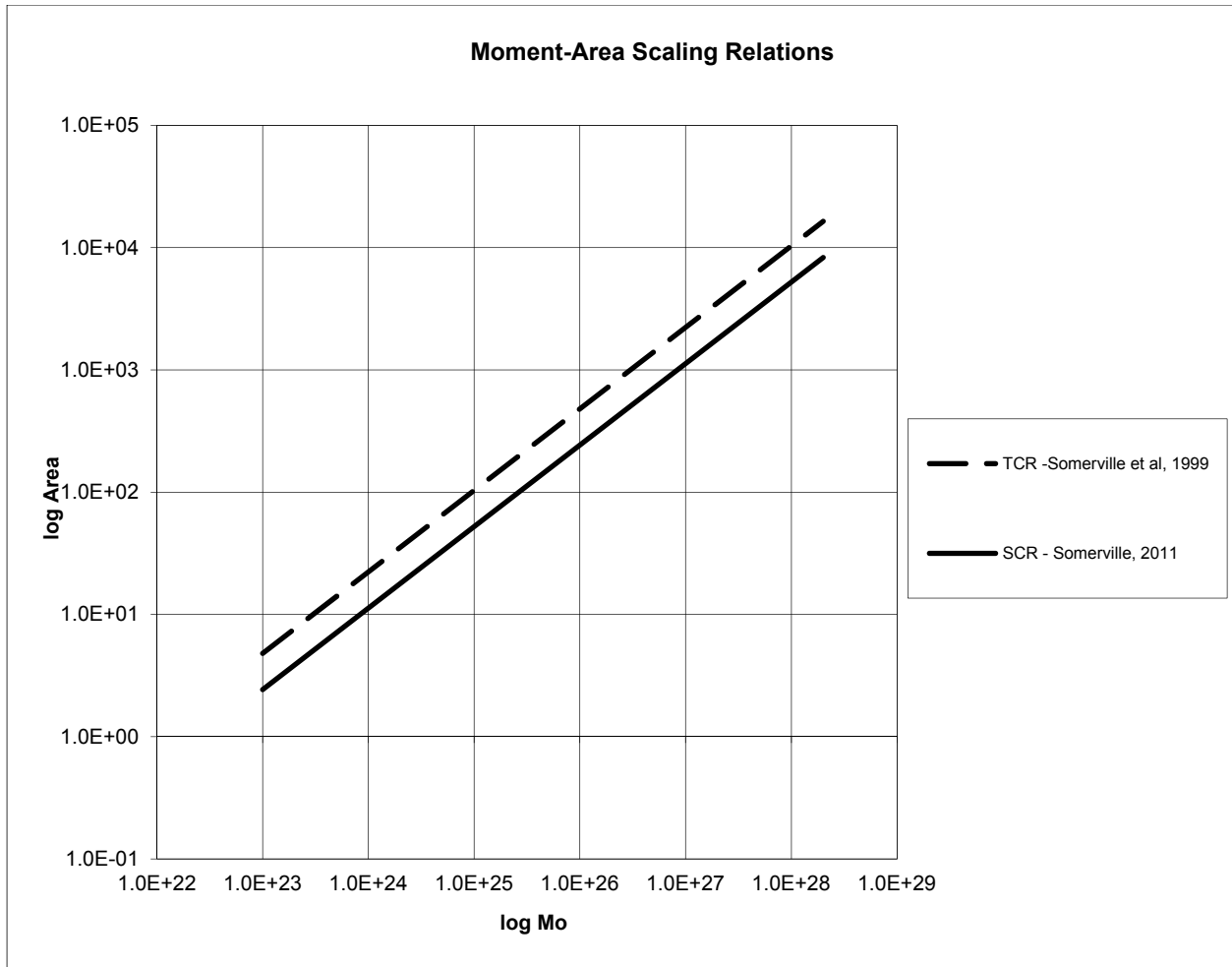
## 1.9 COMPARISON OF SCALING RELATIONS FOR EARTHQUAKES IN STABLE CONTINENTAL REGIONS AND TECTONICALLY ACTIVE CONTINENTAL REGIONS

Table 3 lists the scaling relations for earthquakes in tectonically active crustal regions (TCR) in addition to those for SCR earthquakes. These include estimates made using slip models [Somerville et al. 1999]; using aftershock areas for magnitudes less than 7 [Hanks and Bakun 2002]; using various data [Leonard 2010], and using corner frequencies for continental collision boundary and continental transform fault earthquakes [Allmann and Shearer 2009]. The stress drops of these relations all lie in the range of 23 to 35 bars. As shown in Figure 8, these values are significantly lower than those of SCR earthquakes, whose current estimates range from 58 bars based on various methods [Leonard 2010] to 59.5 bars from corner frequencies of Intraplate earthquakes (about 150 km beyond plate boundaries; see Allman and Shearer [2009]) to 64.9 bars (from the average of three methods in this study).

To a first approximation, the results of this study and that of Somerville et al. [1997] indicate that the rupture areas of SCR earthquakes are about half those of TCR earthquakes, and their stress drops are about 2.8 times higher (Figure 9). Allmann and Shearer [2009] find less of a difference, presumably because their Intraplate category includes some earthquakes that we would assign to TCR instead of SCR. Their study indicates that the rupture areas of Intraplate earthquakes are about two-thirds those of TCR earthquakes, and their stress drops are about two times higher.



**Figure 8** Comparison of relations between seismic moment and rupture area for earthquakes in stable continental regions (this study and Leonard [2010]) with relations for earthquakes in tectonically active continental regions [Somerville et al. 1999; Hanks and Bakun 2002] ( $M_w < 7.0$ ).



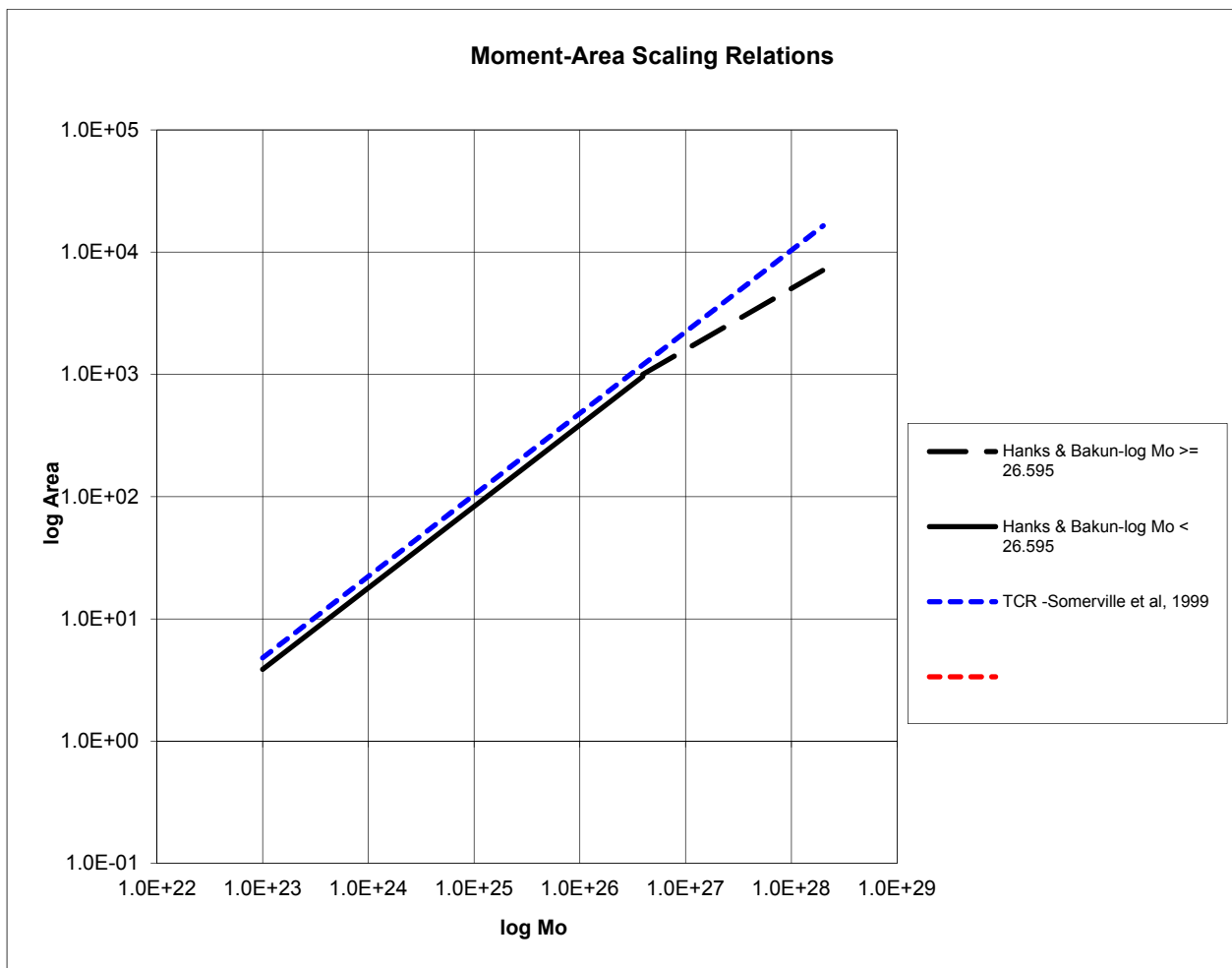
**Figure 9** Comparison of relations between seismic moment and rupture area for earthquakes in stable continental regions (this study) with the relation for earthquakes in tectonically active continental regions [Somerville et al. 1999].

**Table 6** Comparison of area and stress drop scaling of earthquakes in stable continental regions and tectonically active continental regions.

Author	Stress Drop			Area ratio SCR/TCR
	SCR/Intraplate	TCR	Ratio SCR/TCR	
Somerville	65	25	2.8 ( $2^{1.5}$ )	1/2
Allmann and Shearer	60	30	2.0	1/1.6 ( $1/2^{2/3}$ )

## 1.10 WIDTH SATURATION IN SCALING RELATIONS

Width scaling saturates in some manner as the seismogenic zone extends from the brittle zone into the ductile zones above and below it. This led Hanks and Bakun [2002] to propose a change in scaling of rupture area with seismic moment of TCR earthquakes from self-similar (constant stress drop) below magnitude 7 to increasing stress drop with increasing magnitude above magnitude 7. Below  $M_w$  7.0, there is general agreement that the scaling is self-similar (Figure 10).



**Figure 10** Comparison of the Somerville et al. [1999] relations between seismic moment and rupture area for earthquakes in tectonically active continental regions with the model of Hanks and Bakun [2002].



We have shown that SCR earthquakes have rupture dimensions that are about half those of TCR earthquakes. Furthermore, the TCR crust is also generally thicker than the SCR crust, and the shallow ductile zone is very thin or absent. This suggests that the saturation of width, if it occurs at all in SCR crust, is at magnitudes that are much larger than 7.0. In this report we have assumed that width saturation does not cause significant departure from self-similarity in the relation between seismic moment and rupture area in SCR earthquakes. This is consistent with the assumption of Leonard [2010] that all categories of earthquakes have self-similar magnitude – rupture area scaling.

### **1.11 GUIDANCE ON THE USE OF SCALING RELATIONS OF EARTHQUAKES IN STABLE CONTINENTAL REGIONS**

The analysis of scaling relations of earthquakes in SCR in this study used three different approaches to estimating fault area that all agreed fairly well. Leonard [2010] did not document his data and used an undifferentiated mixture of different ways of measuring fault area, and so the relation that he developed is less soundly based than that developed in this study. However, the two relations are not significantly different; the average stress drop value of 64.9 bars obtained from the three methods in this study is 1.12 times the value of 58 bars for Leonard [2010]. This is less than our estimate of 1.165 for the standard error of the mean of the three methods used in this report. The Leonard [2010] relations have the advantage of having been derived in a self-consistent manner for a wide range of earthquake categories, including crustal earthquakes in tectonically active regions. Consequently, it is recommended that the Leonard [2010] scaling relations for SCR earthquakes be used for the NGA-East Project.

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