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Selection of Earthquake Scaling Relationships for Seismic-Hazard Analysis

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Abstract A fundamentally important but typically abbreviated component of seismic-hazard analysis is the selection of earthquake scaling relationships. These are typically regressions of historical earthquake datasets, in which magnitude is estimated from parameters such as fault rupture length and area. The mix of historical data from different tectonic environments and the different forms of the regression equations can result in large differences in magnitude estimates for a given fault rupture length or area. We compile a worldwide set of regressions and make a first-order shortlisting of regressions according to their relevance to a range of tectonic regimes (plate tectonic setting and fault slip type) in existence around the world. Regression relevance is based largely on the geographical distribution, age, and quantity/quality of earthquake data used to develop them. Our compilation is limited to regressions of magnitude (or seismic moment) on fault rupture area or length, and our shortlisted regressions show a large magnitude range (up to a full magnitude unit) for a given rupture length or area across the various tectonic regimes. These large differences in magnitude estimates underline the importance of choosing regressions carefully for seismic-hazard application in different tectonic environments.

Introduction

Prior to this study, limited attention has been paid to the appropriate use of magnitude-area or magnitude-length scaling relationships (hereafter referred to simply as regressions) in seismic-hazard analysis, despite the considerable body of literature on the topic (e.g., Kanamori and Allen, 1986; Scholz *et al.*, 1986). Well-known regressions, such as those of Wells and Coppersmith (1994) and Hanks and Bakun (2008) are applied the world over, often with limited consideration as to their applicability to a particular tectonic environment. A poignant example is that the above regressions underestimate the 4 September 2010 M_w 7.1 Darfield, New Zealand, earthquake by about 0.3 magnitude units when applied to the length or area of the earthquake source (e.g., Quigley *et al.*, 2012; Fig. 1). The development of a Global Earthquake Model (GEM) active fault source database (see Data and Resources) has highlighted the need for compilation and assessment of global regressions and for recommendations for their use in different tectonic regimes. GEM is developing global models and tools for seismic-hazard and risk analysis. Our study is also timely for providing guidance to seismic-hazard analysis in general.

The purpose of this paper is to provide a compilation of regressions from around the world. Part of this effort is the development of a simplistic framework for grouping regressions according to tectonic regime and a brief evaluation of the regressions according to quality and quantity of regression data. We also provide a tabulation and description of what we consider to be the highest quality (shortlisted) regressions, along with recommendations on their application in the various tectonic regimes. While there remains considerable debate in the seismological community regarding the controls on/most appropriate way to model magnitude scaling, our compilation does not attempt to address these fundamental issues. We instead simply report regressions that already exist in the literature and provide first-order guidance for application to seismic-hazard assessment based on obvious differences between the regressions and underlying datasets. Finally, we do not include regressions specific for oceanic earthquakes in this compilation, aside from those relevant to subduction interface and intraslab environments.

Methodology

Regression Compilation and Assessment

The compilation and documentation of regressions from around the world is provided in Appendices A and B. Our compilation was achieved by searching the literature and is limited to regressions of magnitude (or seismic moment) on fault rupture area or length. These are the most readily-measurable/estimated parameters that are commonly applied to seismic-hazard modeling and can be derived from either geologic (surface rupture) or geophysical (aftershocks or

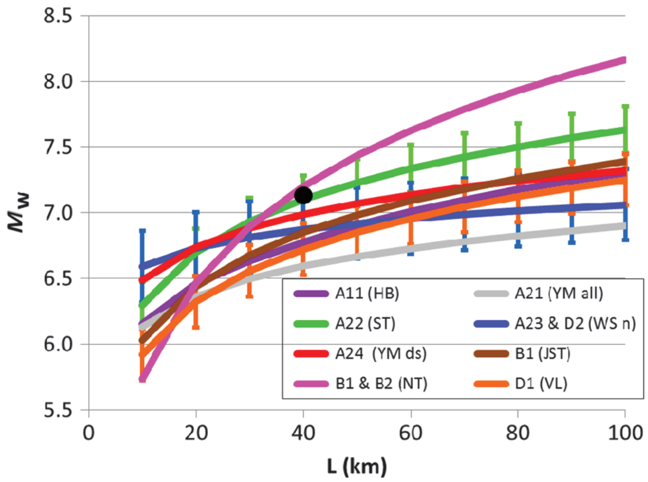

Figure 1 Moment magnitude on rupture length for the shortlisted regressions for crustal earthquakes (underlined in Table 2). For regressions involving seismic moment and rupture area, moment magnitude is derived from the equation $M_0 = 16.05 + 1.5M_w$ (Hanks and Kanamori, 1979), in which M_0 is seismic moment and M_w is moment magnitude. Rupture length is derived from area, assuming a constant fault width of 15 km. The exception is the width of 8 km used for the Villamor *et al.* (2001) regression (VL), which is developed from earthquakes within the thin crust of the Taupo volcanic zone backarc rift zone. The use of length for all regressions allows them to be plotted on one graph. We limit our length to 100 km for simplicity and because most faults are less than 100 km (i.e., a meaningful comparison). Where possible, one-standard-deviation error bounds are shown on the regression curves (i.e., if standard deviations are provided in the relevant documentation). Subduction zone regressions (class C in Tables 1 and 2) are not shown on this figure, as the assumption of a constant width for a range of lengths is inappropriate for subduction sources. Identifiers in the legend correspond to the tectonic regime classifications in Table 1; for example, A11(HB) signifies plate boundary crustal ("A"), fast slip rate ("1"), and strike-slip dominated ("1"). Abbreviations in parentheses refer to authors of the regressions: HB, Hanks and Bakun (2008); YM, Yen and Ma (2011); ST, Stirling *et al.* (2008); WS, Wesnousky (2008); NT, Nuttli (1983); JST, Johnston (1994); and VL, Villamor *et al.* (2001). Slip types: all, all slip types; n, normal; ds, dip-slip. The solid black circle on the graph shows the position of the magnitude and source length of the 2 September 2010 M_w 7.1 Darfield, New Zealand, earthquake.

geodetic data) constraints. We also mainly focus our study on regressions most useful for constraining the magnitudes of ground-rupturing earthquakes (around $M_w > 6.5$–7) or blind earthquakes with similar source dimensions. At these magnitudes, the differences between surface and subsurface length estimations are minimal in terms of magnitude estimation.

The regression equations are accompanied by a description of the regression and the underlying earthquake dataset and recommendations from the authors (if available) and us on the use of the regression for specific tectonic regimes (see Tectonic Regime Framework). The regressions are also assigned a quality score (1, best available; 2, good; 3, fair) according to the quality and quantity of the regression dataset. This is a very arbitrary (and therefore readily debatable) score and is based largely on the size of the regression dataset and age of publication. Logically a regression that does not include the last 10–20 years of data and/or has a small dataset (unless focused on a specific environment) will not score as highly as one that is more data-rich and recent. To some extent, the prior frequency of regression usage is a criterion taken into consideration, although we are aware of widespread misuse of some regressions (e.g., Wells and Coppersmith [1994] applied to intraplate areas of Europe). We attempted to consider the scientific aspects of regression formulation (e.g., inclusion of bilinear scaling) in our assignment of a quality score but decided this was too subjective and contentious to serve as a basis for evaluation. Appendix A comprises regressions that are generally of a higher quality score (with some exceptions; see Classification of Regressions According to Tectonic Regime section), and Appendix B comprises the remainder of the regressions.

Finally, it is important to note that this regression compilation is not comprehensive, in that it may not have captured all regressions available, particularly if these regressions are older and not published in journal papers or books (e.g., Mason and Smith, 1993). However, we are confident that our large compilation captures the range of regressions from around the world, particularly those developed in the last decade.

Tectonic Regime Framework

The definition of tectonic regimes and grouping of regressions into these regimes are the results of our own assessment, using any guidelines or recommendations we can glean from the regression publications. However, the common absence of recommendations in the regression publications requires us to make our own assignment of regressions to specific tectonic regimes based upon where the regression data were collected. Some regression datasets are restricted to specific tectonic regimes, whereas others span multiple regimes or have a global coverage. In the latter cases, we assign these regressions to the tectonic regime responsible for most of the regression dataset. Our tectonic regime categories (plate tectonic setting and fault slip type) are shown in Table 1. These categories are based on our understanding of the broad differences in fault parameters such as slip rate, slip type, stress drop, recurrence interval, seismogenic thickness, heat flow, and lithology between the different tectonic regimes.

Classification of Regressions According to Tectonic Regime

In Table 2 we provide the regressions most applicable to the categories of tectonic regime listed in Table 1. The regressions are shown in the published form, and this is typically in terms of M_w on area or length, consistent with the most frequent application in seismic-hazard analysis (i.e., M_w estimated from source length or area). A subset of regressions (bold in Table 2) is shortlisted as our recommended regressions for use in each tectonic regime. Examples of these shortlisted regressions are also plotted in Figure 1.

Table 1
Tectonic Regime Classification Scheme, Comprising Plate Tectonic Settings, Subclasses, and Slip Types

Plate Tectonic Setting	Subclass	Slip Type*
A. Plate boundary crustal	A1: Fast plate boundary faults (> 10 mm/yr)	Strike-slip dominated (A11)
	A2: Slow plate boundary faults (< 10 mm/yr)	All faults (A21)
		Strike-slip (A22)
		Normal (A23)
		Reverse (A24)
B. Stable continental		Reverse (B1)
		Strike-slip (B2)
C. Subduction	Continental megathrust	Thrust (C1)
	Marine	Thrust (C2)
	Intraslab	Normal (C3)
D. Volcanic	Thin crust (< 10 km)	Normal (D1)
	Thick crust (> 10 km)	Normal (D2)

*The identifiers in parentheses allow cross referencing to Table 2 and have the following derivation: first character (A–D), primary tectonic regime; second character (1–2), tectonic subregime; and third character (1–4), mechanism or slip-type. For example, A11 indicates a plate boundary crustal setting (A), fast subclass (1), and strike-slip mechanism (1).

Shortlisted regressions are generally those with a quality score of 1 and are described in more detail in Appendix A. Some regressions of lower quality scores (2 and 3) are also shown in Table 2, Figure 1, and Appendix A, if the relevant tectonic regimes are poorly represented in the regression literature (e.g., stable continental B1 and B2). Regressions from Appendix B are not included in Table 2 as they do not satisfy our selection criteria to the same degree as our shortlisted regressions.

Notable omissions from the above shortlisting process are the regressions of Wells and Coppersmith (1994). Despite being long-time industry standard regressions, they are not included due to being relatively old and, in our view, have been superseded by the more modern regressions listed in Table 2.

Results and Discussion

The shortlisted regressions in Figure 1 and Table 2 are almost entirely assigned a quality score of 1. This is to be expected, as our intention is to identify recent and relevant regressions for each of the tectonic regimes in Table 1. The exceptions are the stable continental (B) regimes (quality score = 3), for which the most suitable regressions are based on a combination of old and small datasets (Nuttli, 1983; Johnston, 1994; Anderson *et al.*, 1996). In contrast, several regressions with small datasets score highly due to recency of development (e.g., Wesnousky, 2008). The lack of more recently developed regressions for stable continental regimes means that these older regressions default to being the most suitable for these environments. The Nuttli (1983) and Johnston (1994) regressions are specifically developed from stable continental earthquake data, whereas the Anderson *et al.* (1996) regression combines a mixed interplate/intraplate earthquake dataset but includes a negative dependence on slip rate in the regression equation (i.e., larger magnitudes for faults with slower slip rates).

The most obvious aspect of our compilation is that the differences between many of the regressions are large (Fig. 1). Differences as large as one magnitude unit are evident for rupture lengths of about 60–80 km. These are lengths commonly associated with fault sources in seismic-hazard models, so highlights the importance of choosing regressions carefully with respect to tectonic regime. Observations from Figure 1 specific to tectonic regimes are as follows:

- Shortlisted regressions for A11 (plate boundary fast strike-slip faults) and A21 (plate boundary all faults) tend to show some of the smallest magnitudes for a given fault length or area. This is consistent with plate boundary faults generally being thought to produce smaller magnitude scaling than faults away from the plate boundary (e.g., Scholz *et al.*, 1986).
- The shortlisted regression for A22 (plate boundary strike-slip faults) is developed from New Zealand oblique-slip earthquake data away from the main plate boundary zone and produces larger magnitudes than A11 and A21. We are uncertain as to why New Zealand oblique-slip earthquakes scale in this distinctive way. It may be due to them being dominantly oblique-slip earthquakes away from the main plate boundary zone.
- The shortlisted regression for A23 (plate boundary slow normal faults) is developed from normal-slip earthquakes in the Basin and Range province and elsewhere. The resulting magnitudes are lower for a given rupture length or area than A22, which is consistent with expectation that normal-slip produce smaller magnitudes than other slip types (e.g., Schorlemmer *et al.*, 2005).
- The shortlisted regression for A24 (plate boundary slow reverse faults) produces magnitudes intermediate between A11/A21 and A22. This may be due to the mix of slip types contained in the earthquake dataset for the Yen and Ma (2011) regression for dip-slip events.
- The shortlisted regression for B1 and B2 (stable continental reverse and strike-slip faults) produce a large spread of magnitudes for a given rupture length, reflecting the large uncertainties in earthquake scaling for stable continental environments. The Nuttli (1983) regression produces the largest magnitudes in this context, which is again consistent with earthquakes in stable continental regions being thought to produce larger magnitudes for a given rupture length or area than earthquakes in plate boundary areas (e.g., Kanamori and Allen, 1986; Scholz *et al.*, 1986). This is not, however, reflected in the Johnston (1994) regression, which shows similar scaling to some of the regressions representative of plate boundary settings. It is therefore important to consider both scaling behaviors in the relevant seismic-hazard applications.

Table 2
Shortlisted Regressions for Each Combination of Tectonic Setting, Subclasses and Slip Type Given in Table 1

Tectonic Regime*	Reference for Regression†	Regression Equations‡	Units	Quality Score§	Comments‖
A11	**Hanks and Bakun (2008)**; $A \leq 537$ km^2	$M_w = \log A + (3.98 \pm 0.03)$	A: area (km^2)	1	Best represented by Hanks and Bakun regressions. Regression datasets are dominated by fast-slipping plate boundary faults. Regressions should be chosen according to the relevant fault area range.
	Hanks and Bakun (2008); $A > 537$ km^2	$M_w = 4/3 \log A + (3.07 \pm 0.04)$	‖	1	
	Wesnousky (2008); strike-slip	$M_w = 5.56 + 0.87 \log L$ $\sigma = 0.24$ (in M_w)	L: surface rupture length (km)	1	
	Leonard (2010)	$M_w = 3.99 + \log A$	A: area (km^2)	1	
A21	**Yen and Ma (2011); all**	$\log A_e = -13.79 + 0.87 \log M_0$ $\sigma = 0.41$ (in A_e) $\log M_0 = 16.05 + 1.5M$	A_e: effective area (m^2)	1	Best represented by Yen and Ma regression as datasets contain a mix of plate boundary earthquakes of strike-slip and dip-slip mechanisms.
A22	Hanks and Bakun (2008); $A \leq 537$ km^2	$M_w = \log A + (3.98 \pm 0.03)$	A: area (km^2)	1	Larger magnitudes produced by Stirling *et al.* (2008) than by others (larger D–L scaling)
	Stirling *et al.* (2008); New Zealand; oblique-slip	$M_w = 4.18 + 2/3 \log W + 4/3 \log L$ $\sigma = 0.18$ (in M_w)	L: subsurface rupture length (km) W: width (km)	1	
	Wesnousky (2008); strike-slip	$M_w = 5.56 + 0.87 \log L$ $\sigma = 0.24$ (in M_w)	L: surface rupture length (km)	1	
	Yen and Ma (2011); strike-slip	$\log A_e = -14.77 + 0.92 \log M_0$ $\sigma = 0.40$ (in A_e) $\log M_0 = 16.05 + 1.5M_w$	A_e: effective area (m^2)	1	
A23	**Wesnousky (2008); normal**	$M_w = 6.12 + 0.47 \log L$ $\sigma = 0.27$ (in M_w)	L: surface rupture length (km)	1	Basin and range-rich normal-slip earthquake dataset.
A24	Stirling *et al.* (2008); New Zealand; oblique slip	$M_w = 4.18 + 2/3 \log W + 4/3 \log L$ $\sigma = 0.18$ (in M_w)	W: width (km) L: subsurface rupture length (km)	1	Yen and Ma (2011) dip-slip dataset dominated by reverse and thrust-slip earthquakes from wide area (Taiwan and east Asia).
	Wesnousky (2008); reverse	$M_w = 4.11 + 1.88 \log L$ $\sigma = 0.24$ (in M_w)	L: surface rupture length (km)	1	
	Yen and Ma (2011); dip-slip	$\log A_e = -12.45 + 0.80 \log M_0$ $\sigma = 0.43$ (in A_e) $\log M_0 = 16.05 + 1.5M_w$	A_e: effective area (m^2)	1	
B1	Anderson *et al.* (1996)	$M_w = 5.12 + 1.16 \log L - 0.20 \log S$ $\sigma = 0.26$ (in M_w)	L: surface fault length (km) S: slip rate (mm/yr)	2	Equal priority to the three regressions. Nuttli (1983) and Johnston (1994) regressions are developed exclusively for stable continental regions (> 500 km from plate boundaries), but dataset is old. Anderson *et al.* (1996) dataset includes stable continental earthquakes, and negative coefficient on slip rate has a major influence on M_w. Johnston (1994) database dominantly reverse events.

(*continued*)

Table 2 (*Continued*)

Tectonic Regime*	Reference for Regression[†]	Regression Equations[‡]	Units	Quality Score[§]	Comments[‖]
	Nuttli (1983)	$\log M_0 = 3.65 \log L + 21.0$ $\log M_0 = 16.05 + 1.5M_w$	M_0: seismic moment (dyn·cm) L: subsurface fault length (km)	3	
	Johnston (1994)	$M_w = 1.36^* \log L + 4.67$	L: surface rupture length (km)	3	
B2	**Anderson *et al.* (1996)**	$M_w = 5.12 + 1.16 \log L - 0.20 \log S$ $\sigma = 0.26$ (in M_w)	L: surface fault length (km) S: slip rate (mm/yr)	2	As for B1
	Nuttli (1983)	$\log M_0 = 3.65$ $\log L + 21.0$ $\log M_0 = 16.05 + 1.5M_w$	M_0: seismic moment (dyn·cm) L: subsurface fault length (km)	3	
C1	**Strasser *et al.* (2010); interface events**	$M_w = 4.441 + 0.846 \log_{10}(A)$ $\sigma = 0.286$ (in M_w)	A: rupture area (km^2)	1	Diverse dataset and M_w dependence on interface area makes the Strasser *et al.* (2010) regression the most suitable for using on a wide variety of subduction megathrusts.
C2	**Strasser *et al.* (2010); interface events**	$M_w = 4.441 + 0.846 \log_{10}(A)$ $\sigma = 0.286$ (in M_w)	A: rupture area (km^2)	1	As for C1
	Blaser *et al.* (2010); oceanic/subduction reverse	$\log_{10} L = -2.81 + 0.62M_w$ Sxy = 0.16 (orthogonal standard deviation)	L: subsurface fault length (km)	1	
C3	**Ichinose *et al.* (2006)**	$\log_{10}(A_a) = 0.57(\pm 0.06)M_0 - 13.5(\pm 1.5)$ $\sigma = 16.1$ (in A_a)	A_a: combined area of asperities (km^2) M_0 = seismic moment (dyn·cm)	1	Only regression of relevance to intraslab earthquakes.
D1	**Villamor *et al.* (2001); New Zealand; normal**	$M_w = 3.39 + 1.33 \log A$ $\sigma = 0.195$ (in M_w)	A: area (km^2)	1	Only regression of relevance to volcanic-normal earthquakes in thin crust (rift environments).
D2	**Wesnousky (2008); normal**	$M_w = 6.12 + 0.47 \log L$ $\sigma = 0.27$ (in M_w)	L: surface fault length (km)	1	Basin and range-rich normal-slip dataset.
	Mason (1996)	$M_w = 4.86 + 1.32 \log L$ $\sigma = 0.34$ (in M_w)	L: surface rupture length	2	Intermountain west-dominated normal-slip dataset.

*The "Tectonic Regime" identifiers relate to the IDs given in parentheses in Table 1. For example, A11 signifies "Plate Boundary Crustal/Plate Boundary Fast Slipping/Strike-Slip Dominated."

[†] Primary reference for regression. Bold regression information corresponds to the shortlisted regressions (those having the highest quality score and/or most suitable regressions for the given tectonic regimes). Regression information not in bold provides close alternatives to the shortlisted regressions for the given tectonic regimes.

[‡] Regression equations and standard deviations or standard errors (if available). Applicable parameters are in parentheses; for example, "in M_w" means the standard deviation is for M_w. The standard Hanks and Kanamori (1979) equation is also provided in cases for which seismic moment needs to be converted to moment magnitude. Use of A_a (combined asperity area on fault plane) is possible for well-modeled sources and correlates with M_0.

[§] Quality scores: 1, best available; 2, good; 3, fair.

[‖] Justification for shortlisting of regression into this table.

- The shortlisted regression for D1 (rift within thin crust) and D2 (rift within thicker crust) tend to show smaller magnitudes for a given rupture length than the majority of the shortlisted regressions, so is again consistent with the expectation that normal slip types produce smaller magnitudes than other slip types (e.g., Wells and Coppersmith, 1994).

A synthesis of the above observations is that regressions dominated by plate boundary earthquakes show tendency to produce smaller magnitudes for a given rupture length or area than do stable continental areas and produce similar-or-larger magnitudes than earthquakes in rift environments. The differences in scaling for these regressions make sense from physical grounds. Previous studies (e.g., Scholz *et al.*, 1986; Schorlemmer *et al.*, 2005) suggest that earthquake scaling should vary according to slip type and plate tectonic setting, so our study is at least partially consistent with the previous work.

Conclusions and Recommendations

We provided a large compilation of magnitude-area and magnitude-length scaling relationships and shortlisted some for application in seismic-hazard applications such as GEM. The equations are provided, as well as relevant dialog and guidelines to assist with the use of regressions in seismic-hazard modeling. The shortlisted regressions generally have been chosen as the best representatives of specific tectonic regimes (defined according to plate tectonic setting and slip type). Graphical comparison of the regressions generally reveals obvious differences in regressions for the different tectonic regimes, and the majority of these differences make sense according to a tectonic regionalization of magnitude scaling. Specifically, the categories of tectonic regime (Table 1) are based on our understanding of the broad differences in fault parameters such as slip rate, slip type, stress drop, recurrence interval, seismogenic thickness, heat flow, and lithology between the different tectonic regimes. However, in some cases large differences exist between regressions for particular tectonic regimes (e.g., one of the regressions for stable continental regimes). It is important for seismic-hazard models to adequately represent this important source of epistemic uncertainty.

Our study has been motivated by a need to assist scientists and practitioners in making the appropriate choice of regressions for seismic-source modeling. We have tackled a topic area that is the focus of considerable debate in the literature, with fundamental issues surrounding whether or not earthquake scaling is regionalized and what physical factors control earthquake scaling. We therefore offer the following recommendations for future development and selection of regressions for seismic-hazard application, in which the first recommendation seeks to push the boundaries of the understanding of earthquake scaling, and the rest address the most appropriate use of our compilation:

- We recommend that a large funded project akin to the Next Generation Attenuation (NGA) project be initiated to develop an up-to-date quality-assured master regression database (like the NGA quality-assured strong-motion database, or flatfile). The NGA project involved key ground-motion prediction modelers using the flatfile to develop updated regressions and then comparing the resulting ground-motion predictions as a cross-validation exercise. In the NGA context, regression developers would produce a set of regressions for international application from the same master database and then undertake a cross-validation exercise. This effort would focus attention on the scientific basis for regression development and eliminate uncertainties due to data quality and quantity. Clearly the epistemic uncertainty in regression formulation is very large, and preferred methods have not yet been defined in the international seismological community.
- Regression users should ensure that their choice of regression is as compatible as possible with the tectonic regime of interest.
- Regressions should not be used beyond the magnitude range of data used to develop the regression. Exceptions to this recommendation should be justified, as regressions are often used incorrectly in this respect.
- Where possible, regression users should use a selection of regressions (e.g., by way of a logic tree framework) according to the tectonic regime framework given in Table 2 and carefully evaluate the consequences of the particular selection of regressions.
- Regression users should aim to use regressions of quality score $= 1$ whenever possible, although we acknowledge this may not be possible for some tectonic regimes (e.g., stable continental).
- Regression developers should strive to develop regressions for specific tectonic regimes, rather than combining all available earthquake data from an ensemble of tectonic regimes.
- Regression developers should provide clear recommendations regarding the tectonic regimes relevant to their regressions.
- Regression developers should always provide standard deviations and/or standard errors for their regression equations. Many of the regressions are not accompanied by any indication of statistical uncertainty in the relevant documentation.

Data and Resources

Regression equations are available from published literature and from unpublished documents that are available from the authors on request. The SRCMOD database of finite-source rupture models is available online at http://www.seismo.ethz.ch/srcmod (last accessed July 2012), and the GEM Faulted Earth website can be viewed online at http://www.nexus.globalquakemodel.org/gem-faulted-earth/posts (last accessed September 2013).

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Appendix A

Documentation of Regressions Shown in Table 2

The regressions are ordered as in Table 2. Some regression datasets include a mix of different types of magnitude. The regression developers have either converted these magnitudes to M_w or assumed that they approximate M_w, unless the regression magnitude type is shown as being different to M_w.

Hanks and Bakun (2008) Relationships

$$M_w = \log A + (3.98 \pm 0.03) \quad \text{for } A < 537\ \text{km}^2,$$

$$M_w = (4/3)\log A + (3.07 \pm 0.04) \quad \text{for } A > 537\ \text{km}^2,$$

in which A is the fault area in square kilometers.

Description. The regression is developed for continental strike-slip earthquakes. Based on a relatively small dataset of large earthquakes and mainly suitable for large to great strike-slip earthquakes in plate boundary settings (e.g., San Andreas, Alpine, North Anatolian).

Data. Eighty-eight continental strike-slip earthquakes. Includes historical earthquakes since 1857 and 12 new $M_w > 7$ events added to the Wells and Coppersmith (1994) dataset. Regions for the seven new $M_w > 7$ events are Japan (1), Turkey (2), California (1), China (2), and Alaska (1). Magnitude range: 5–8 (M_w).

Application. Major plate boundary strike-slip faults. Not suitable for use on faults with slip rates less than ~1 mm/yr. Widely used in major seismic-hazard models around the world. Should be given significant weighting in logic tree framework for application to plate boundary strike-slip faults with high slip rates.

Tectonic Regime and Mechanism. A11, A22.

Quality Score. 1.

References. Wells and Coppersmith (1994) and Hanks and Bakun (2008).

Wesnousky (2008) Relationships

$M_w = 5.30 + 1.02 \log L$, all events (37 events used);

$M_w = 5.56 + 0.87 \log L$, strike-slip events (22 events used);

$M_w = 6.12 + 0.47 \log L$, normal events (7 events used);

and

$M_w = 4.11 + 1.88 \log L$, reverse events (8 events used),

in which L is the surface rupture length in kilometers.

Description. The regressions have been developed from earthquakes associated with rupture lengths greater than about 15 km, encompassing three slip types from both interplate and intraplate tectonic environments. The regression is applicable to earthquake sources of lengths greater than 15 km.

Data. Dataset limited to the larger surface rupture earthquakes of length dimension greater than 15 km and for which both maps and measurements of coseismic offset are available. A total of 37 events have been used, all continental earthquakes. These include 22 strike-slip, 7 normal, and 8 reverse-slip events. Regions: California (8), Turkey (7), Japan (5), Nevada (3), Australia (3), Iran (2), China (2), Mexico (1), Algeria (1), Philippines (1), Taiwan (1), Idaho (1), Montana (1), and Alaska (1). Magnitude range: 5.9–7.9 (M_w).

Application. All regions for the relevant slip types but acknowledging that the regression dataset will be dominated by plate boundary earthquakes. Should be given significant weighting in logic trees. The author indicates the relationship is most relevant to strike-slip sources.

Tectonic Regime and Mechanism. A11 (strike-slip), A22 (strike-slip), A23 (normal), A24 (reverse), and D2 (normal).

Quality Score. 1.

Reference. Wesnousky (2008).

Leonard (2010) Relationships

$M_w = 3.99 + \log A$, strike-slip;

$M_w = 4.00 + \log A$, dip-slip;

$M_w = 4.19 + \log A$, stable continental regions,

in which A is the fault area in square kilometers.

Description. Three regressions for seismic moment M_0. Regressions are developed by solving for width W, displacement D as a function of area A, and seismic moment M_0 (M_0 can then be used to solve for M_w). The regressions are developed using worldwide data and are provided in terms of fault area, fault rupture length, surface rupture length, and average surface displacement, for strike-slip, dip-slip, and stable continental regions (SCRs).

Data. Predominantly plate boundary earthquakes. Divided into two categories: (a) interplate and plate boundary (classes I and II; Scholz *et al.*, 1986) and (b) SCR (i.e., intraplate continental crust that has not been extended by continental rifting), which includes midcontinental (class III; Scholz *et al.*, 1986). Several datasets were used: Wells and Coppersmith (1994), Henry and Das (2001), Hanks and Bakun (2002), Romanowicz and Ruff (2002), and Manighetti *et al.* (2007). The database of Johnston (1994) was also used. The 2004 Sumatra–Andaman earthquake is included, as well as 12 surface rupturing earthquakes. Data are separated into strike-slip and dip-slip mechanisms.

Origin of Each Dataset

- *Wells and Coppersmith (1994)*: Two hundred and forty-four continental crustal ($h < 40$ km) earthquakes of all mechanism types, both interplate and intraplate.
- *Henry and Das (2001)*: Sixty-four shallow dip-slip and eight strike-slip events in the period 1977–1996, plus three recent earthquakes: 1998 Antarctic plate, 1999 Izmit (Turkey), 2000 Wharton Basin. Twenty-seven strike-slip earthquakes from Pegler and Das (1996) also included (large earthquakes in the period 1977–1992 based on relocated 30-day aftershock zones). Wells and Coppersmith (1994) dataset were also used but augmented with larger dip-slip events and subduction zone events.
- *Hanks and Bakun (2002)*: Strike-slip subset of the Wells and Coppersmith (1994) database, containing 83 continental earthquakes of which 82 have magnitudes $M_w \geq 7.5$.
- *Romanowicz and Ruff (2002)*: The following datasets are used: reliable $M_0 - L$ database of large strike-slip earthquakes since 1900 (Pegler and Das, 1996); data for great central Asian events since the 1920s (Molnar and Denq, 1984; Romanowicz, 1992); and data for recent large strike-slip events (e.g., Balleny Islands 1998; Izmit, Turkey 1999; and Hector Mines, California, 1999) that have been studied using a combination of modern techniques (i.e., field observations, waveform modeling, aftershock relocation).
- *Manighetti* et al. *(2007)*: Two hundred and fifty large ($M_w \geq \sim 6$), shallow (rupture width ≤ 40 km, with an average value of width of 18 km), continental earthquakes of mixed focal mechanisms (strike-slip, reverse, and normal), that have occurred in four of the most seismically active regions worldwide: Asia, Turkey, Western United States, and Japan.
- *Johnston (1994)*: SCR database of 870 earthquakes where moment could be estimated from waveform or isoseismal data. Surface rupturing earthquakes are included (e.g., three 1988 Tennant Creek events. Magnitude range: 4.2–8.5).

Application. Wide application, including low seismicity/intraplate regions but excluding normal faults regions (e.g., Great Sumatra fault). The author suggests using this relationship for all types of faults. Nevertheless, the author makes the comment that the relations were primarily developed from dip-slip data and assumes it also applies to strike-slip earthquakes out to fault lengths of 45 km and possibly 100 km, as it fits non-width-limited strike-slip earthquakes as well as other previous models.

Tectonic Regime and Mechanism. A11.

Quality Score. 1.

References. Molnar and Denq (1984), Scholz *et al.* (1986), Romanowicz (1992), Johnston (1994), Wells and Coppersmith (1994), Pegler and Das (1996), Henry and Das (2001), Hanks and Bakun (2002), Romanowicz and Ruff (2002), Manighetti *et al.* (2007), and Leonard (2010).

Yen and Ma (2011) Relationships

In terms of area:

$$\log A_e = -13.79 + 0.87 \log M_0, \text{ all slip types } (\sigma = 0.41);$$

$$\log A_e = -12.45 + 0.80 \log M_0, \text{ dip-slip types } (\sigma = 0.43);$$

$$\log A_e = -14.77 + 0.92 \log M_0, \text{ strike-slip types } (\sigma = 0.40).$$

In terms of length:

$$\log L_e = -7.46 + 0.47 \log M_0, \text{ all slip types } (\sigma = 0.19);$$

$$\log L_e = -6.66 + 0.42 \log M_0, \text{ dip-slip types } (\sigma = 0.19);$$

$$\log L_e = -8.11 + 0.50 \log M_0, \text{ strike-slip types } (\sigma = 0.20),$$

in which A_e is the effective area in square meters, L_e is the effective fault length in kilometers, and M_0 is the seismic moment in dyne centimeters. (Convert M_0 to M_w with the equation $\log M_0 = 16.05 + 1.5M_w$.)

Description. Developed exclusively from earthquakes in a collisional tectonic environment. Equation has a bilinear form.

Data. Twenty-nine events used: 12 dip-slip and 7 strike-slip events in Taiwan, plus 7 large events worldwide (Wenchuan, China, 2008; Kunlun, Tibet, 2001; Sumatra 2004; Bhuj, India, 2001); and 3 large thrust earthquakes from Mai and Beroza (2000) dataset. Magnitude range: 4.6–8.9 (M_w).

Application. Applicable to reverse-to-reverse-oblique faults in collisional environments. Use with significant weighting in a logic tree framework relevant to collisional environments.

Tectonic Regime and Mechanism. A21 (all types), A22 (strike-slip), A24 (dip-slip).

Quality Score. 1.

References. Mai and Beroza (2000) and Yen and Ma (2011).

Stirling *et al.* (2008) Relationship (New Zealand Oblique Slip)

$$M_w = 4.18 + (2/3) \log W + (4/3) \log L,$$

in which W is the width in kilometers and L is the subsurface rupture length in kilometers.

Description. This regression has been developed for New Zealand strike-slip to reverse-slip earthquakes. It produces magnitudes that are larger than those of Wells and Coppersmith (1994) and Hanks and Bakun (2008), and magnitudes that are appropriate for New Zealand fault sources based on expert judgment. The regression has been applied to numerous studies in New Zealand and Australia in recent years. The regression is documented in a consulting report but was first published in the reference below.

Data. Twenty-eight New Zealand strike-slip to reverse earthquakes on low slip rate faults. The data were obtained from body-wave modeling studies of historical and contemporary earthquakes where fault mechanism, depth, source duration, and seismic moment were obtained (Berryman *et al.*, 2002). Magnitude range: 5.6–7.8 (M_w).

Application. The authors recommend that the regression should be used for strike-slip–to–convergent-dip-slip faults, not for major plate boundary faults. Performs well for strike-slip to oblique-slip faults other than the primary plate boundary faults (e.g., Alpine fault, San Andreas fault) and for strike-slip to oblique-slip faults in low seismicity regions, that is, larger magnitudes for given fault rupture lengths.

Tectonic Regime and Mechanism. A22, A24.

Quality Score. 1.

References. Berryman *et al.* (2002) and Stirling *et al.* (2008).

Anderson *et al.* (1996) Relationship

$$M_w = 5.12 + 1.16 \log L - 0.20 \log S,$$

in which L is the surface fault length in kilometers and S is the slip rate in millimeters per year.

Description. Least-squares regression for a dataset of 43 earthquakes on faults with known slip rates. The authors demonstrate a negative dependence of magnitude on slip rate.

Data. Worldwide dataset, although most from California. Other regions include Nevada (2), Missouri (1), Montana (1), Mexico (1), Philippines (1), Turkey (5), Japan (5), China (2), and New Zealand (3). Limited to regions with seismogenic depth from 15 to 20 km. Magnitude range: 5.8–8.2 (M_w).

Application. Interplate to intraplate environments where earthquake magnitude and fault slip rate data are available. Although based on a relatively small earthquake dataset, the negative dependence of magnitude on slip rate makes this a potentially suitable regression for use in a wide variety of environments. However, the small size and age of the earthquake dataset should limit the weight placed on this regression in a logic tree framework.

Tectonic Regime and Mechanism. B1, B2.

Quality Score. 2.

Reference. Anderson *et al.* (1996).

Nuttli (1983) Relationship

$$\log M_0 = 3.65 \log L + 21.0,$$

in which M_0 is the seismic moment in dyne centimeters and L is the subsurface fault length in kilometers. (Convert M_0 to M_w with the equation $\log M_0 = 16.05 + 1.5M_w$.)

Description. Developed for midplate earthquakes (>500 km from plate margins), both continental and oceanic. Magnitude-length relationships are obtained from derived fault lengths, not direct length measurements (empirical data are M_0 and magnitudes m_b and M_s).

Data. Published data for 143 midplate earthquakes. Magnitude range: 0.4–7.3 (M_s).

Application. Intraplate settings. The regression is 30 years old, so some key intraplate earthquakes are not included in regression database. However, being one of only two intraplate regressions in this compilation makes it a valuable inclusion.

Tectonic Regime and Mechanism. B1, B2.

Quality Score. 3.

Reference. Nuttli (1983).

Johnston (1994) Relationship

$$M_w = 1.36 \log L + 4.67,$$

in which L is the surface rupture length in kilometers.

Description. A regression developed for SCRs. The authors consider this regression to be statistically indistinguishable from regressions for interplate and active continental plate interior regions. They conclude that SCR earthquakes have comparable stress drops and source scaling to events in active tectonic regions. It uses 10 stable continental surface rupture earthquakes from Australia, Africa, India, and Canada. The dataset is dominated by thrust events, most of them from Australia. The authors indicate that the regressions are not very robust, and their conclusions cannot be considered definitive until more data are available, especially for the larger magnitudes.

Data. Ten earthquakes in SCRs and with surface rupture. Events include five earthquakes in west (3) and central (2) Australia, two in west Africa, one in northeast Africa, one in India, and one in Canada. The database is dominated by thrust events (seven events), with two strike-slip events and one oblique. Surface rupture lengths range from 3 to 140 km. Magnitude range: 5.46–7.79 (M_w).

Application. SCRs. As the relationship is based on only 10 earthquakes and has been referred to as "purely empirical" and "not well constrained" (Leonard, 2010), it should therefore be used in seismic-hazard analyses with other relevant regressions.

Quality Score. 3.

References. Johnston (1994) and Leonard (2010).

Strasser *et al.* (2010) Relationships

In terms of length:

$$M_w = 4.868 + 1.392 \log_{10}(L), \text{ interface events (95 events used);}$$

$$M_w = 4.725 + 1.445 \log_{10}(L), \text{ intraslab events (20 events used).}$$

In terms of area:

$$M_w = 4.441 + 0.846 \log_{10}(A), \text{ interface events (85 events used);}$$

$$M_w = 4.054 + 0.981 \log_{10}(A), \text{ intraslab events (18 events used),}$$

in which L is the surface rupture length in kilometers, and A is the rupture area in square kilometers.

Description. Regressions for worldwide subduction interface and intraslab events. Relationship parameters are also available for width and length parameters as well as for area in terms of magnitude (instead of magnitudes in terms of area). Interface relationships show stress drop to be a decreasing function of magnitude, which may be due to larger magnitudes involving a greater proportion of nonasperity areas than smaller magnitudes.

Data. Subduction interface and intraslab events taken primarily from the SRCMOD database (Mai, 2004; see also Data and Resources). Ninety-five interface events (magnitude range $M_w = 6.3$–9.4) and 20 intraslab events (magnitude range $M_w = 5.9$–7.8).

Application. Subduction interface and intraslab sources.

Tectonic Regime and Mechanism. C1, C2.

Quality Score. 1.

References. Mai (2004) and Strasser *et al.* (2010).

Blaser *et al.* (2010) Relationships

Relationships for Oceanic and Subduction Events. In terms of length:

$$\log_{10} L = -2.81 + 0.62 M_w, \text{ reverse-slip (26 events used).}$$
$$\text{Magnitude range}: 6.1\text{–}9.5 (M_w)(\text{Sxy} = 0.16).$$
$$L \text{ range}: 13\text{–}1400 \text{ km.}$$

$$\log_{10} L = -2.56 + 0.62 M_w, \text{ strike-slip (16 events used).}$$
$$\text{Magnitude range}: 5.3\text{–}8.1 (M_w)(\text{Sxy} = 0.19).$$
$$L \text{ range}: 7.0\text{–}350 \text{ km.}$$

$$\log_{10} L = -2.07 + 0.54 M_w, \text{ all slip types(47events used).}$$
$$\text{Magnitude range}: 5.3\text{–}9.5 (M_w)(\text{Sxy} = 0.18).$$
$$L\text{range}: 7.0\text{–}1400 \text{ km.}$$

In terms of width:

$$\log_{10} W = -1.79 + 0.45 M_w, \text{ reverse-slip (23 events used).}$$
$$\text{Magnitude range}: 6.1\text{–}9.5 (M_w)(\text{Sxy} = 0.14).$$
$$W \text{ range}: 12\text{–}240 \text{ km.}$$

$$\log_{10} W = -0.66 + 0.27 M_w, \text{ strike-slip (14 events used).}$$
$$\text{Magnitude range}: 5.3\text{–}7.8 (M_w)(\text{Sxy} = 0.21).$$
$$W \text{ range}: 4\text{–}30 \text{ km.}$$

$$\log_{10} W = -1.76 + 0.44 M_w, \text{ all slip types (40 events used).}$$
$$\text{Magnitude range}: 5.3\text{–}9.5 (M_w)(\text{Sxy} = 0.17).$$
$$W \text{ range}: 4\text{–}240 \text{ km,}$$

in which L is the subsurface fault length in kilometers, W is the rupture width in kilometers, and Sxy is the orthogonal standard deviation. (Note: only the relationships for oceanic/subduction events are shown.)

Description. Developed for subduction zones. Based on a large dataset of 283 earthquakes. Most of the focal mechanisms are represented, but the analysis is focused on large subduction zones. The authors recommend the relationships be used by applying orthogonal regression methods. Exclusion of events prior to 1964 (when the World Wide Standard Seismograph Network [WWSSN], was established) shows no saturation on rupture width for strike-slip earthquakes. Thrust relationships for pure continental and pure subduction zone rupture areas are almost identical. The authors recommend different scaling relationships be used according to focal mechanism.

Data. Published data for 283 earthquakes. Database composed of 196 source estimates by Wells and Coppersmith (1994), 40 by Geller (1976), 25 by Scholz (1982), 31 by Mai and Beroza (2000), 36 by Konstantinou *et al.* (2005), and 31 by several other authors analyzing single large events. Magnitude range (for oceanic/subduction zones): 5.3–9.5 (M_w).

Application. Subduction zones (especially oceanic).

Tectonic Regime and Mechanism. C2.

Quality Score. 1.

References. Geller (1976), Scholz (1982), Wells and Coppersmith (1994), Mai and Beroza (2000), Konstantinou *et al.* (2005), and Blaser *et al.* (2010).

Ichinose *et al.* (2006) Relationship

$$\log_{10}(A_a) = 0.57(\pm 0.06) M_0 - 13.5(\pm 1.5),$$

in which A_a is the combined area of asperities in square kilometers and M_0 is the seismic moment in dyne centimeters. (Convert M_0 to M_w with the equation $\log M_0 = 16.05 + 1.5 M_w$.)

Description. Developed for intraslab earthquakes at global scale.

Data. Data from the 3 events in Cascadia (1949 Olympia, Washington; 1965 Seattle-Tacoma; and 2001 Nisqually) and several Japan (9 events taken from Asano *et al.* [2003] and Morikawa and Sasatani [2004]) and Mexico (14 events taken from Hernandez *et al.* [2001], Iglesias *et al.* [2002], Yamamoto *et al.* [2002], and Garcia *et al.*, [2004]) intraslab earthquakes (26 events in total). Magnitude range: 5.4–8.0 (M_w).

Application. Intraslab earthquake source modeling.

Tectonic Regime and Mechanism. C3.

Quality Score. 1.

References. Hernandez *et al.* (2001), Iglesias *et al.* (2002), Yamamoto *et al.* (2002), Asano *et al.* (2003), Garcia *et al.* (2004), Morikawa and Sasatani (2004), and Ichinose *et al.* (2006).

Villamor *et al.* (2001) Relationship (New Zealand; Normal Slip)

$$M_w = 3.39 + 1.33 \log A,$$

in which A is the area in square kilometers.

Description. This New Zealand-based regression has been developed from Taupo volcanic zone earthquakes for application to normal faults in volcanic and rift environments. It was developed for a consulting project but first published in the reference below.

Data. Seven large earthquakes in the Taupo volcanic zone (three strike-slip and four normal events), including the M_w 6.5 Edgecumbe 1987 earthquake. Magnitude range: 5.9–7.1 (M_w).

Application. Only for use with normal faults in thin weak crust (e.g., New Zealand's Taupo volcanic zone). Use in rift environments but with careful examination of the results.

Tectonic Regime and Mechanism. D1.

Quality Score. 1.

Reference. Villamor *et al.* (2001).

Mason (1996) Relationship

$$M_w = 4.86 + 1.32 \log L.$$

For which $\sigma = 0.34$ (in M_w), M_w is the moment magnitude, and L is the subsurface fault length in kilometers.

Description. Developed from the Wells and Coppersmith (1994) regression for normal fault earthquakes, but coefficients adjusted for normal fault earthquakes in the intermountain west.

Data. Normal-slip earthquakes drawn from a dataset of 65 intermountain historical and prehistoric earthquakes. Magnitude range: 6.5–7.2 (M_w).

Application. Normal faulting settings such as the Basin and Range.

Tectonic Regime and Mechanism. D2.

Quality Score. 2.

Reference. Mason (1996).

Appendix B

Other Regressions

The following is a documentation of the regressions that have not been shortlisted for reasons provided in the Introduction. The purpose of including these regressions in the paper is to demonstrate that our compilation and evaluation has been a thorough procedure, in that it has captured all of the readily available published regressions in the literature. Furthermore, it allows access to all available regressions if so desired. Some regression datasets include a mix of different types of magnitude. The regression developers have either converted these magnitudes to M_w or assumed that they approximate M_w, unless the regression magnitude type is shown as being different to M_w. The regressions are ordered alphabetically by source.

Ambraseys and Jackson (1998) Relationships

$$M_s = 5.13 + 1.14 \log L, \text{ for historical and instrumental data } (\sigma = 0.15, \text{ in } M_S),$$

and

$$M_s = 5.27 + 1.04 \log L, \text{ for instrumental data } (\sigma = 0.22, \text{ in } M_S),$$

in which L is the surface fault length in kilometers.

Description. The regression has been developed from strike-slip, normal, and thrust events in the Eastern Mediterranean region.

Data. Collected from a variety of published and unpublished sources and from field investigations, with 25% collected by the first author. Uses both historical and instrumental data in the Eastern Mediterranean region and the Middle East. One hundred and fifty events used to obtain the scaling relationship, all of them associated with coseismic surface faulting. Only 35 events are common to the Wells and Coppersmith (1994) database; 55% of the data are strike-slip events, 30% normal events, and 15% thrust faults. Magnitude range: $M_s \geq 5.1$.

Application. Eastern Mediterranean, Middle East, and similar environments (i.e., plate boundary transpressional to transtensional environments). Regression dataset is reasonably large and therefore makes the regressions suitable for application in Eastern Mediterranean/Middle East.

Quality Score. 1.

Reference. Ambraseys and Jackson (1998).

Bonilla *et al.* (1984) Relationships

$$M_s = 6.04 + 0.708 \log L,$$
all types of faults (45 events used);

$$M_s = 5.71 + 0.916 \log L,$$
reverse and reverse-oblique faults (12 events used);

$$M_s = 6.24 + 0.619 \log L, \text{ strike-slip (23 events used)};$$

$$M_s = 5.58 + 0.888 \log L, \text{ plate margins (9 events used)};$$

$$M_s = 6.02 + 0.729 \log L, \text{ plate interiors (36 events used)};$$

$$M_s = 4.94 + 1.296 \log L, \text{ United States and China } k = 1.75 \text{ attenuation region (9 events used)};$$

$$M_s = 4.88 + 1.286 \log L, \text{ United States } k = 1.75 \text{ attenuation region (5 events used)};$$

$$M_s = 6.18 + 0.606 \log L, \text{ Turkey (9 events used)};$$

$$M_s = 5.17 + 1.237 \log L,$$
Western North America (12 events used),

in which L is the surface rupture length in kilometers.

Description. Magnitude-length and/or displacement relationships obtained for five types of mechanisms: normal, reverse, normal oblique, reverse oblique, and strike-slip. One hundred published and unpublished events analyzed, 48 of them used to obtain the equation, which correspond to the ones with error estimations in reported length or displacement. Tests made for ordinary and weighted least-squares regression methods (ordinary least squares found to be the appropriate approach).

Data. Forty-eight worldwide earthquakes, taken from published and unpublished data. No subduction events included. Fault length 3–450 km. Magnitude range: 6.5–8.3 (M_s).

Application. Worldwide application, although some relationships are specific for certain regions (United States $k = 1.75$ attenuation region, United States and China $k = 1.75$ attenuation region, Turkey, Western North America). No magnitude-length equations are available for normal mechanisms, but magnitude-displacement or displacement-length relations are also available for these events (not shown here). Age and size of the earthquake dataset limit the applicability of these regressions, and they therefore should be given very low weighting if used in a logic tree framework. An additional recommendation from the author is that the equations should not be extrapolated beyond the range of the dataset or applied to subduction zone sources.

Quality Score. 3.

Reference. Bonilla *et al.* (1984).

Dowrick and Rhoades (2004) Relationships

$$M_w = 4.39 + 2.0 \log L, \qquad L < 6.0 \text{ km};$$

$$M_w = 4.76 + 1.53 \log L, \qquad L \geq 6.0 \text{ km},$$

in which L is the subsurface rupture length in kilometers.

Description. Developed for New Zealand events. When results were compared to multiregional relationships, significant differences were found to regressions for California, Japan, and China. Authors consider multiregional relationships to be a poor estimation for New Zealand data, as they underestimate New Zealand magnitudes (by 0.4 magnitude units when compared to Wells and Coppersmith, 1994, Somerville *et al.*, 1999 and the lower part of the bilinear regression by Hanks and Bakun, 2002 relationships). The relations are influenced by structural restrictions placed on rupture width.

Data. Eighteen events in New Zealand. Magnitude range: 5.9–8.2 (M_w).

Application. New Zealand interplate. Use only in a logic tree framework with low weighting relative to other more widely used New Zealand-based regressions (e.g., Villamor *et al.*, 2001; Stirling *et al.*, 2008).

Quality Score. 3.

Reference. Dowrick and Rhoades (2004).

Ellsworth-B Relationship

$$M_w = \log A + 4.2,$$

in which A is the fault area in square kilometers.

Description. Simple magnitude-area scaling relationship applicable to all slip types in plate boundary areas. No stand-alone reference exists for this relationship, but it is documented in Working Group on California Earthquake Probabilities (WGCEP; 2003, 2008) and has been developed from worldwide earthquakes.

Data. Continental strike-slip events from Wells and Coppersmith (1994) dataset with areas $A > 500\ \mathrm{km}^2$ corresponding to $M_w > 6.5$. Magnitude range: 6.5–8.5 (several types of magnitudes: mainly M_s but also some M_L and m_b).

Application. Best applied to continental strike-slip faults but can also be used in intraplate areas. Used by the WGCEP in the 2002 U.S. National Seismic Hazard Mapping Project with equal weight to the Hanks and Bakun (2008) relationship, indicating that it can be used with confidence in logic tree frameworks.

Quality Score. 1.

References. Wells and Coppersmith (1994), WGCEP (2003, 2008).

Mai and Beroza (2000) Relationships

In terms of area:

$$\log A = -11.18 - 0.72 \log M_0,$$
$$\text{all events (18 events used)} (\sigma = 0.26,\ \text{in area});$$

$$\log A = -8.49 - 0.57 \log M_0,\ \text{strike-slip events}$$
$$(8\ \text{events used}) (\sigma = 0.19,\ \text{in area});$$

$$\log A = -11.90 - 0.75 \log M_0, \text{dip} - \text{slip events}$$
$$(10\ \text{events used}) (\sigma = 0.31,\ \text{in area}).$$

In terms of length:

$$\log L = -6.13 - 0.39 \log M_0,\ \text{all events}$$
$$(18\ \text{events used}) (\sigma = 0.16,\ \text{in length});$$

$$\log L = -6.31 - 0.40 \log M_0,\ \text{strike-slip events}$$
$$(8\ \text{events used}) (\sigma = 0.12,\ \text{in length});$$

$$\log L = -6.39 - 0.40 \log M_0,\ \text{dip-slip events}$$
$$(10\ \text{events used}) (\sigma = 0.19,\ \text{in length}),$$

in which A is the area in square kilometers, L is the subsurface length in kilometers, and M_0 is the seismic moment in newton meters. (Convert M_0 to M_w with the equation $\log M_0 = 16.05 + 1.5 M_w$.)

Description. Developed from finite-fault rupture models. The dataset lacks very large strike-slip events. The scaling laws produce very similar results to those of Wells and Coppersmith (1994).

Data. Eighteen earthquakes, of which eight are large crustal strike-slip and 10 dip-slip earthquakes; regions: most of them in California (13), other regions: Idaho (1), Japan (2), Iran (1), Mexico (1). Magnitude range: 5.6–8.1 (M_w).

Application. To plate boundary environments. The small regression dataset potentially limits the stability of these regressions.

Quality Score. 2.

Reference. Mai and Beroza (2000).

Romanowicz and Ruff (2002) Relationships

$$\log M_0 = n \log L + \log(M_0)_{\min},$$

$$(M_0)_{\min} = 0.5 \times 10^{20}\ \mathrm{N{\cdot}m};$$
$$n = 1.20 \pm 1.4,\ \text{continental/interplate}$$
$$\text{strike-slip events (25 events used)},$$

$$(M_0)_{\min} = 1.0 \times 10^{20}\ \mathrm{N{\cdot}m};$$
$$n = 1.09 \pm 2.4,\ \text{continental/interplate}$$
$$\text{strike-slip events (16 events used)},$$

in which L is the rupture length in kilometers.

Description. Moment-length scaling laws developed for large continental strike-slip earthquakes. The regressions are developed according to a bimodal distribution of earthquake scaling.

Data. Several datasets have been combined to develop these regressions: Pegler and Das (1996); $M_0 - L$ data for large strike-slip earthquakes since 1900 (Romanowicz, 1992); great central Asian events since 1920 (Molnar and

Denq, 1984); and data from recent large strike-slip events. Continental strike-slip earthquakes from California (including San Francisco, 1906; Loma Prieta, 1989; and Hector Mines, 1999 events), Turkey (including Izmit, 1999), Japan, Tibet, Fiji, India, Papua, Honduras, Sudan, and Iran are included in the database.

Magnitude Range. $M_w \geq 5.5$ for the full dataset. Subsets of the data have been used to develop the various scaling laws.

Application. Interplate strike-slip (two regressions) and oceanic intraplate environments (two regressions).

Quality Score. 1.

References. Molnar and Denq (1984), Romanowicz (1992), Pegler and Das (1996), Romanowicz and Ruff (2002).

Shaw (2009) Relationship

$$M = \log A + \frac{2}{3}\log\frac{\max\left(1, \sqrt{\frac{A}{H^2}}\right)}{\left[1 + \max\left(1, \frac{A}{H^2\beta}\right)\right]/2} + \text{const.},$$

in which A is the rupture area in square kilometers, H is the seismogenic thickness in kilometers, $\beta = 2\chi$, in which $\chi = 3$, and const. is the constant.

Description. Developed for worldwide earthquakes, both small and large. The regression has been developed to address the hypothesis that earthquake stress drops are constant from the smallest to the largest events (most other regressions assume nonconstant stress-drop scaling), combined with a thorough treatment of the geometrical effects of the finite seismogenic layer depth. The relationship has been tested for strike-slip events, because they are the ones with the largest aspect ratio L/W. For these events (see Data below) the best fitting corresponds to $H = 15.6$ km and $\beta = 6.9$.

Data. Strike-slip events taken from Hanks and Bakun (2008) data as well as Wells and Coppersmith (1994), Hanks and Bakun (2002), and WGCEP (2003). These datasets do not have error bars. Magnitude range: 4.2–8.5 (several types of magnitudes: mainly M_s but also some M_L and m_b).

Origin of Each Dataset

- *Wells and Coppersmith (1994)*: Two hundred and forty-four continental crustal ($h < 40$ km) earthquakes of all mechanism types, both interplate and intraplate.
- *Hanks and Bakun (2002)*: Strike-slip subset of the Wells and Coppersmith (1994) database, which contains 83 continental earthquakes of which 82 have magnitudes $M_w \geq 7.5$.
- *Hanks and Bakun (2008)*: Eighty-eight continental strike-slip earthquakes. Includes historical earthquakes since 1857 and 12 new $M_w > 7$ events added to the Wells and Coppersmith (1994) dataset.

Application. Applicable to all types of faults in all regions around the world. Has not been used greatly in seismic hazard studies, so careful examination of regression results is recommended. The author states that the scaling law fits the whole range of magnitude-area data.

Quality Score. 2.

References. Hanks and Bakun (2002, 2008), WGCEP (2003), Shaw (2009)

P. G. Somerville, personal comm. (2006) Relationship

$$M_w = 3.87 + 1.05\log(A),$$

in which A is the area in square kilometers.

Description. Uses a uniform dataset of recent worldwide crustal earthquakes for which seismic inversions are available. Makes extensive use of teleseismic and strong-motion inversions of coseismic slip. The relationship provides near identical estimates of M_w to self-similar models.

Data. Sixteen large strike-slip events worldwide (United States, Japan, Tibet, and Turkey). Magnitude range: 5.7–7.9 (M_w).

Application. For use on all fault types in interplate tectonic settings, that is, western North America, Indonesia, Caribbean/central America, northern South America, New Zealand, Middle East, and southeast Asia. Paucity of documentation for this relationship makes it difficult to assess the quality of this regression, so recommended usage in a logic tree framework is with relatively low weighting. Use in intraplate settings after verifying results make sense (e.g., comparison of predicted to observed earthquake magnitudes and rupture areas). Use with low weighting in logic tree framework on account of small regression dataset.

Quality Score. 2.

References. WGCEP (2002), P. G. Somerville, personal comm. (2006), Somerville *et al.* (2006).

Somerville *et al.* (1999) Relationship

$$M_w = \log A + 3.95,$$

in which A is the rupture area in square kilometers.

Description. Developed from crustal earthquakes. The relationships are constrained to be self-similar and produce very similar results to those of Wells and Coppersmith (1994).

Data. Fifteen inland crustal earthquakes worldwide, most of them in California. Other regions are Canada (2), Iran (1), Idaho (1), and Japan (1). Mechanisms: one normal, six thrust events, six strike-slip events, two oblique earthquakes. Magnitude range: 5.7–7.2 (M_w).

Application. Crustal earthquakes worldwide. Can be used with greatest confidence at moderate-to-large magnitudes. Departure from self-similar scaling may occur for very large crustal strike-slip earthquakes at very large magnitudes. Use with significant logic tree weighting when focus is on moderate-to-large magnitude earthquake sources.

Quality Score. 2.

Reference. Somerville *et al.* (1999).

Stirling *et al.* (1996) Relationships

$$M_0 = 1.22(10^{18})L^{5.0}, \text{ strike-slip faults worldwide, } L < 50 \text{ km;}$$

$$M_0 = 2.37(10^{24})L^{1.3}, \text{ strike-slip faults worldwide, } L > 50 \text{ km;}$$

$$M_0 = 2(10^{23})L^{2.1}, \text{ large intraplate earthquakes in Japan,}$$

in which M_0 is the seismic moment in dyne centimeters and L is the surface or subsurface rupture length in kilometers. (Convert M_0 to M_w with the equation $\log M_0 = 16.05 + 1.5M_w$.)

Description. Scaling laws for worldwide plate boundary earthquakes and intraplate events in Japan.

Data. Strike-slips events worldwide recorded in regional networks located in California, Mexico, New Zealand, Japan, China, and Turkey. Data taken from published papers (Wesnousky *et al.*, 1983; Romanowicz, 1992). Magnitude range: 5.7–7.8 (M_w).

Application. The authors recommend use of this regression for strike-slip faults worldwide and intraplate faults in Japan. Regression databases will now be significantly lacking with respect to the more modern earthquakes. Use only if logic tree framework requires a large number of regressions.

Quality Score. 3.

References. Wesnousky *et al.* (1983), Romanowicz (1992), and Stirling *et al.* (1996).

Stirling *et al.* (2002) Relationship

$$M_w = 5.88 + 0.80 \log L (50 \text{ events used}),$$

in which L is the surface rupture length in kilometers.

Description. Magnitude-length, magnitude-area, and displacement-length relationships developed to compare preinstrumental (pre-1900) and instrumental events in order to understand why Wells and Coppersmith (1994) regressions underestimate the magnitudes of many large worldwide earthquakes. Results show that these regressions produce significantly larger magnitudes than Wells and Coppersmith (1994) relationships.

Data. Three hundred and eighty-nine worldwide events, 305 instrumental (post-1900), and 84 preinstrumental (pre-1900). Expanded and updated dataset from Wells and Coppersmith (1994). Magnitude range: 4.6–8.7 (M_s, M_L, and M_w).

Application. The authors did not intend this regression to be used in seismic-hazard studies, so it should only be used if a large number of regressions are required for a logic tree framework. They further recommend that the regression only be used for the range of magnitudes, displacements, and rupture lengths contained in the regression dataset.

Quality Score. 2.

References. Wells and Coppersmith (1994) and Stirling *et al.* (2002).

Stock and Smith (2000) Relationships

$$\log M_0 = 3.1 \log L, \text{ small normal faults (32 events used);}$$

$$\log M_0 = 4.1 \log L, \text{ large normal faults (6 events used);}$$

$$\log M_0 = 2.9 \log L, \text{ small reverse faults (77 events used);}$$

$$\log M_0 = 2.9 \log L, \text{ large reverse faults (9 events used);}$$

$$\log M_0 = 3.2 \log L, \text{ dip-slip faults in Japan (21 events used);}$$

$$\log M_0 = 2.9 \log L, \text{ dip-slip events in eastern Russia (16 events used);}$$

$$\log M_0 = 2.8 \log L, \text{ small strike-slip faults in California (27 events used);}$$

$$\log M_0 = 2.1 \log L, \text{ large strike-slip faults in California (9 events used);}$$

$$\log M_0 = 2.9 \log L, \text{ small strike-slip faults outside California (33 events used);}$$

$$\log M_0 = 2.3 \log L, \text{ large strike-slip faults outside California (25 events used),}$$

in which M_0 is the seismic moment in dyne centimeters and L is the average dislocation (rupture) subsurface length in kilometers. (Convert M_0 to M_w with the equation $\log M_0 = 16.05 + 1.5 M_w$.) Large earthquakes ruptured the whole seismogenic layer; small earthquakes did not rupture the whole seismogenic layer.

Description. Scaling relationships obtained from a large dataset of more than 550 worldwide events. The influence of the mechanism and the size in the scaling relationships has been analyzed. No differences in the scaling behavior have been found between normal and reverse events or between events from different regions for this type of mechanisms.

Data. Database of more than 550 events obtained from several published papers (Kanamori and Anderson, 1975; Geller, 1976; Purcaru and Berckhemer, 1982; Scholz, 1982; Bonilla *et al.*, 1984; Kanamori and Allen, 1986; Scholz *et al.*, 1986; Shimazaki, 1986; Romanowicz, 1992; Wells and Coppersmith, 1994; Anderson *et al.*, 1996; Yeats *et al.*, 1997; Margaris and Boore, 1998). Magnitude range: 4.2–8.5 (several types of magnitudes: mainly M_s but also some M_L and m_b).

Application. Worldwide, although specific relationships have been developed from data in specific regions (California, Japan, and Eastern Russia). Regressions have not been widely used to date.

Quality Score. 2.

References. Kanamori and Anderson (1975), Geller (1976), Purcaru and Berckhemer (1982), Scholz (1982), Bonilla *et al.* (1984), Kanamori and Allen (1986), Scholz *et al.* (1986), Shimazaki (1986), Romanowicz (1992), Wells and Coppersmith (1994), Anderson *et al.* (1996), Yeats *et al.* (1997), Margaris and Boore (1998), and Stock and Smith (2000).

Vakov (1996) Relationships

$$M_s = 4.442 + 1.448 \log L, \text{ slip faults (31 events used);}$$

$$M_s = 3.862 + 1.988 \log L, \text{ normal + reverse-strike faults (13 events used);}$$

$$M_s = 4.171 + 1.949 \log L, \text{ strike-normal + strike-reverse faults (20 events used);}$$

$$M_s = 3.161 + 3.034 \log L, \text{ normal + reverse faults (18 events used);}$$

$$M_s = 4.524 + 1.454 \log L, \text{ strike-slip faults (44 events used);}$$

$$M_s = 4.323 + 1.784 \log L, \text{ oblique faults (33 events used);}$$

$$M_s = 4.270 + 1.947 \log L, \text{ dip-slip faults (38 events used);}$$

$$M_s = 4.805 + 1.348 \log L, \text{ strike-slip + oblique-slip faults (64 events used);}$$

$$M_s = 4.525 + 1.697 \log L, \text{ oblique + dip-slip faults (51 events used);}$$

$$M_s = 4.973 + 1.273 \log L, \text{ all faults (82 eventsused),}$$

in which L is the surface rupture length in kilometers.

Description. Magnitude versus area/length/width analyzed for worldwide events and different types of mechanisms. The authors have found dependence of the scaling relationships on the source mechanism but not on the regional setting. According to the authors, these relationships can also be used for the evaluation of earthquake mechanism types.

Data. Database of 400 events worldwide taken from existing sources. Subduction events from Japan, New Zealand, Taiwan, and Philippines have been excluded, as well as normal and thrust events with fault planes dipping less than 45°. A total of 137 events have been finally used in the scaling laws. Magnitude range: 4.5–8.5 (M_s).

Application. Worldwide. Not widely used to date.

Quality Score. 2.

Reference. Vakov (1996).

Wells and Coppersmith (1994) Relationships

$$M_w = 4.07 + 0.98 \log A, \text{ all slip types (148 events used);}$$

$$M_w = 3.98 + 1.02 \log A, \text{ strike-slip faults (83 events used);}$$

$$M_w = 4.33 + 0.90 \log A, \text{ reverse faults (43 events used);}$$

$$M_w = 3.93 + 1.02 \log A, \text{ normal faults (22 events used),}$$

in which A is the area in square kilometers.

Description. These regressions are developed for worldwide earthquakes. Are still considered by many to be industry standards but in reality are out of date in terms of data. Magnitudes tend to be less than those estimated from the more modern regressions.

Data. Two hundred and forty-four continental crustal ($h < 40$ km) earthquakes of all mechanism types, both interplate and intraplate, 127 are surface ruptures, and 117 calculated subsurface ruptures. Taken from published results. Magnitude range: 4.2–8.5 (several types of magnitudes: mainly M_s but also some M_L and m_b).

Application. The regressions should only be used in plate boundary regimes and in general should not be used if more modern regressions are available. Use with low weighting if it has to be used in a logic tree framework. The authors recommend that the all slip type regression be used for most situations; the use of subsurface rupture length and area regressions may be appropriate where it is difficult to estimate the near-surface behavior of faults, such as for buried or blind faults.

Quality Score. 2.

Reference. Wells and Coppersmith (1994).

Wyss (1979) Relationship

$$M_w = \log A + 4.15,$$

in which A is the fault area in square kilometers.

Description. Maximum magnitude values are found to be more reliably obtained from magnitude-area relationships than magnitude-length relationships.

Data. Worldwide events obtained from published databases. Some of the best data were collected by Kanamori and Anderson (1975). Magnitude range: 5.8–8.5 (M_s) (for the best data published in Kanamori and Anderson, 1975).

Application. $M_w > 5.6$ earthquakes worldwide. Age of regression is such that database will be significantly lacking with respect to more modern earthquakes. Only use if logic tree framework requires consideration of a large number of regressions.

Quality Score. 3.

References. Kanamori and Anderson (1975) and Wyss (1979).

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