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Dependence of earthquake size distributions on convergence rates at subduction zones

Robert McCaffrey

Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, New York

Abstract. The correlation of numbers of thrust earthquakes of moment magnitude 7 or greater in this century at subduction zones with convergence rate results from a combination of lower recurrence intervals for earthquakes of a given size where slip rates are high and a peak in the global distribution of subduction zone convergence rates at high values (55 to 90 mm/yr). Hence, physical mechanisms related to convergence rate, such as plate interface force, slab pull, or thermal effects, are not required to explain the distribution of large earthquakes with convergence rate. The seismic coupling coefficient ranges from 10% to 100% at subduction zone segments where convergence is faster than 45 mm/yr but does not correlate with rate. The coefficient is generally orders of magnitude lower at rates below 40 mm/yr which may be due to long recurrence intervals and a short sampling period (94 years).

Introduction

Subduction zone thrust earthquakes of magnitude 7 and greater during this century tend to occur predominantly where convergence rates are high, which has led to the idea that faster subduction creates some physical condition that enhances the generation of larger earthquakes. *Kanamori* [1977a] noted variation among the world's subduction zones in what he called 'coupling', or the tendency of subduction to occur by seismic slip. This definition of coupling is expressed as the ratio of seismic slip to total slip, known as seismic coupling coefficient [*Peterson and Seno*, 1984; *Pacheco et al.*, 1993]. A correlation between the convergence rate and sizes of the largest earthquakes to occur at trenches was used to imply that some mechanism, other than a decreased earthquake recurrence time, accompanies faster subduction [*Uyeda and Kanamori*, 1979; *Ruff and Kanamori*, 1980; 1983; *Kanamori*, 1983] leading *Uyeda and Kanamori* [1979] and *Ruff and Kanamori* [1980, 1983] to redefine coupling in terms of forces acting across the plate interface. Here I examine the global distribution of subduction zone thrust earthquake sizes relative to convergence rate to test whether a physical explanation is required or, instead, that the distribution is simply a consequence of the dependence of earthquake recurrence intervals on convergence rate. At a 95% confidence level, the observed distribution of large ($M_w \geq 7$) and great ($M_w \geq 8$) subduction zone earthquakes relative to convergence rates can be explained by the distribution of convergence rates at trenches and recurrence intervals based on convergence rates. I conclude that the observed dependence of earthquake size on convergence rate at subduction zones does not require other convergence rate related mechanisms beyond its influence on recurrence times.

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Recurrence Intervals and Convergence Rates

The seismic moment rate and the frequency at which earthquakes of a given size occur should both increase with convergence rate. To quantify this, let us say that the number of events per unit time of seismic moment greater than or equal to M_o is distributed as $N(M_o) = \alpha\ M_o^{-\beta}$ for values of M_o less than some maximum moment M_m, where α and β are constants that depend on frequency - magnitude and moment - magnitude relationships [*Wyss*, 1973; *Molnar*, 1979]. This expresses how the total seismic moment in some time period is distributed among events of different sizes. Because the seismic moment release rate on a thrust fault of length L, down-dip width W, rigidity μ (7 x 10^{10} N/m^2) and slip rate v is μLWv, the recurrence interval T for earthquakes of seismic moment M_o or greater can be written as

$$T(M_o) = \frac{M_m^{1-\beta}\ M_o^{\beta}}{(1-\beta)\ \mu\ L\ W\ v} \tag{1}$$

[see *Molnar*, 1979]. Hence, the recurrence interval for an earthquake of a given seismic moment varies as the inverse of the convergence rate. If such earthquakes are uniformly distributed in time, the number of expected events of moment equal to or greater than M_o in a given time period τ is then $\tau\ /\ T$ or,

$$N(M_o) = \left[\frac{\mu\,\tau(1-\beta)}{M_m^{1-\beta}\ M_o^{\beta}}\right]\left[v\,L(v)\,W(v)\right] \tag{2}$$

I examine the global distribution of earthquake sizes with respect to convergence rate both to see whether or not it follows (2) and to understand which of the terms v, $L(v)$, and $W(v)$ have greatest impact on the distribution. I use the distribution of moment magnitudes M_w, rather than seismic moments M_o, by the conversion M_w = 2/3 log M_o - 10.7 (the scalar seismic moment M_o is in dyne-cm; *Hanks and Kanamori* [1979]).

Distribution of Earthquakes with Convergence Rate

Pacheco and Sykes [1992] compiled magnitudes and seismic moments for earthquakes from 1900 through 1989, called the PS catalog that includes most events with magnitudes equal to and above 7.0. From the PS catalog, I selected all thrust type (PS catalog types t, r, rs, and ts) earthquakes that occurred near trenches from 1900 to 1977 and added subduction thrust events from the Harvard centroid - moment tensor (HCMT) [*Dziewonski et al.*, 1981] catalog for 1977 through 1993 with moment magnitudes of 7 or greater. Trenches included are South America, Middle America, Antilles, Aleutian, Kuriles, Japan, Solomon, New Hebrides, Tonga, Izu - Bonin - Mariana, Ryukyu, Philippine, Sandwich, and Java. Lengths of individual trenches should not influence the earthquake distributions since all of them are more than 1000 km long, except Japan which is 600 km long. The largest earthquake in the catalog, the 1960 Chile event of $M_w = 9.5$, also had the longest rupture length (1000 km; *Thatcher* [1990]). Hence, the earthquake size distribution below $M_w = 9.5$ will not be controlled by the physical length of the trenches; on the basis of length alone, all trenches are capable of producing earthquakes as large as the largest, except Japan which would be limited to M_w = 9 or smaller.

Of 96 events selected from the PS catalog, 25 do not have estimates of seismic moment independent of M_s. All of these are below $M_s = 8$ and all but 4 are below $M_s = 7.8$ so should not be affected by saturation of the M_s scale that occurs near $M_s = 8.1$ [*Geller*, 1976]. Because $M_s \approx M_w$ in the range 7 to 8 [*Kanamori*, 1977b; *Ekström and Dziewonski*, 1988], for events below $M_s = 8$ that do not have moment estimates, I estimate moment from the surface wave magnitude by letting M_w equal the unadjusted M_s from the PS catalog.

For each of the 149 events of $M_w \geq 7$, I estimate the convergence rate at the epicenter using rotation poles from *DeMets et al.* [1990] and *Seno et al.* [1993]. The numbers of earthquakes and the seismic moments were binned according to convergence rate using 5 mm/yr increments of convergence rate. Variations in convergence rate along strike of individual trenches are smooth and small; at most 2 mm/yr per 100 km (at Middle America) but typically less than 1 mm/yr per 100 km [*McCaffrey*, 1994]. By using 5 mm/yr bins, large sections of trenches will fall in the same or adjacent bins. In binning the earthquakes, the number of events N associated with a magnitude is the number equal to or larger than the given magnitude (as used in 2).

Figure 1 shows the numbers of subduction zone thrust earthquakes of $M_w \geq 7$ (149 events), ≥ 7.5 (77 events), and ≥ 8 (24 events) from 1900-1993 (PS and HCMT catalogs) and those in the HCMT catalog (1977-1993) as distributed with convergence rate. Equation 2 predicts that for any magnitude the number should increase linearly with convergence rate; such a general trend is apparent for rates of 30 to 90 mm/yr but these trends intersect the convergence rate axis near 30 mm/yr rather than near zero.

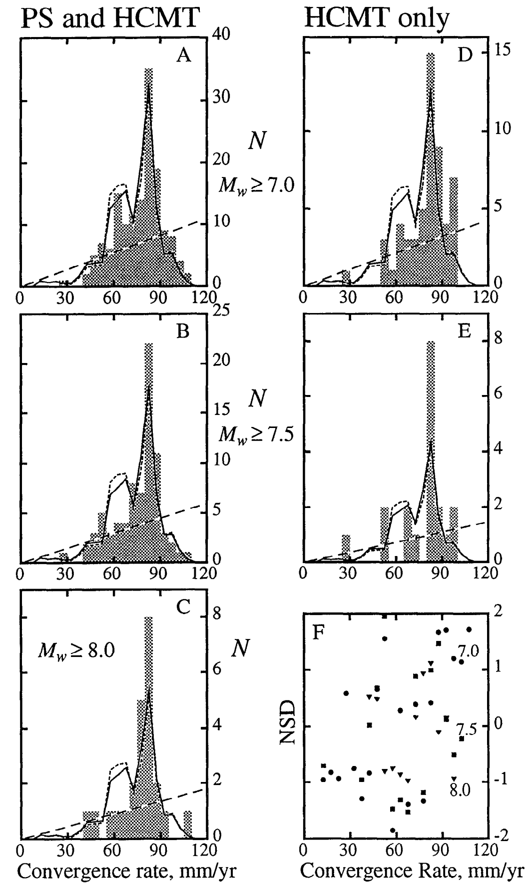

Fig. 1. Numbers of thrust earthquakes at subduction zones as a function of convergence rate at trenches for (a and d) $M_w \geq 7.0$, (b and e) $M_w \geq 7.5$, and (c) $M_w \geq 8$. (a) to (c) show the combined *Pacheco and Sykes* [1992] and HCMT catalogs (1900-1993) while (d) and (e) are for the HCMT catalog only (1977-1993). Lines show the predicted numbers of events from (2) for the following cases: long-dashed lines, assuming that convergence rates are uniformly distributed at the world's trenches; solid lines, using trench lengths as distributed with convergence rate (shown in Figure 2a); short-dashed lines, using fault area as distributed with convergence rate (shown in Figure 2b). Note the changes in vertical scales. (f) Number of standard deviations (NSD) that the observed number of earthquakes (*Nobs*) in any bin is away from the expected number (*Ncalc*) in that bin. NSD = (*Nobs* - *Ncalc*) / $\sqrt{Ncalc}$. *Ncalc*, from (2), is shown as the solid lines in (a)-(c). If *Ncalc* is less than 0.5, NSD is not plotted (no bin in which fewer than 1 event is predicted has more than 1 observed event). Points labeled 7.0 (dots), 7.5 (squares), and 8.0 (triangles) refer to the distributions for the magnitude ranges in Figures 1a, 1b, and 1c, respectively. All observed numbers of earthquakes in (a)-(c) are within 2 standard deviations of their expected values.

Comparison of Observed to Expected Distributions

To understand the distribution of large earthquakes with convergence rate, I use (2) to estimate the expected distributions of events over 94 years (1900-1993) and over the 17 years (1977-1993) for which HCMT solutions are available. The influence of the terms v, Lv, and LWv on the distributions are examined separately. The first term on the right-hand side of (2), containing M_m and β, controls the distribution of events with seismic moment while the second term controls how these events are distributed with convergence rate. Hence, M_m and β are important to this study only in that they give the correct numbers of events above the magnitude of interest. The theoretical value of $\beta = 2/3$ [*Molnar*, 1979] and $M_m = 3.5 \times 10^{25}$ Nm (for $M_w \geq 7.0$) and $M_m = 9 \times 10^{24}$ Nm (for $M_w \geq 7.5$) give the correct number of observed events. The HCMT thrust events at subduction zones give $\beta = .63$ for $7.0 \leq M_w \leq 7.5$ and $\beta = .89$ for $M_w \geq 7.5$ which are close to the theoretical values of 2/3 and 1, respectively, expected for these magnitude ranges [*Okal and Romanowicz,* 1994].

Influence of Convergence Rate Alone

To examine the influence of the convergence rate alone on the distribution of earthquake sizes, I first assume that convergence rates are uniformly distributed at the world's trenches, so that $L(v)$ and $W(v)$ are constants. Because the total length of the trenches considered is 36,000 km and there are 24 convergence rate bins (0 to 120 mm/yr in 5 mm/yr increments), I assume that each 5 mm/yr range of v occurs at 1500 km of trench length. Initially, I also use W = 100 km, an average of values estimated by *Pacheco et al.* [1993] for the world's subduction zones based on earthquake depth distributions. Using L=1500 km and τ = 94 years for the combined data and τ = 17 years for HCMT data, the expected distributions of earthquakes are shown with the dashed, sloping lines in Figure 1. Relative to these expected distributions, strong peaks are apparent at high slip rates and events at low rates are lacking. Convergence rate alone does not predict the distribution of earthquakes very well.

Influence of Convergence Rate and Fault Length

To examine the influence of the actual distribution of convergence rates at subduction zones on the distributions of large earthquakes, convergence rates were calculated every 10 km along all the trenches and lengths were summed in 5 mm/yr intervals (Figure 2a). Convergence rates are clearly not uniformly distributed at subduction zones; nearly 75% of the lengths of the world's trenches have convergence rates between 55 and 90 mm/yr. Using L as a function of v (from Figure 2a), W=100 km, and values for other parameters given above, the predicted distributions of earthquake sizes are shown by solid lines in Figure 1 (a through e) which match the observed distributions well. Apparently, the earthquake size distribution with convergence rate is mostly influenced by the strongly peaked distribution of convergence rates at trenches. A similar analysis using trench-normal convergence rates provides a much poorer fit to the observed earthquake distribution than the fit using the full convergence rate.

The $v\,L(v)$ match to the observed distribution is statistically acceptable at the 95% confidence level. The observed and calculated numbers of earthquakes at all convergence rates for the three magnitude ranges agree to within 2 standard deviations (95% confidence level) using this $vL(v)$ dependence (Figure 1f; the standard deviation is taken to be the square-root of the expected number of events). Using a χ^2 test also indicates that we cannot reject at the 5% level of significance the hypothesis that the observed distributions of earthquakes are the same as the expected $vL(v)$ distributions. (For $M_w \geq 7.0$, observed $\chi^2 = 27.6$ and $\chi^2(.05,19) = 30.1$, where the χ^2 arguments in parentheses are the significance level (0.05) and degrees of freedom (DOF), respectively. For $M_w \geq 7.5$, observed $\chi^2 = 17.5$ and $\chi^2(.05,14) = 23.7$, and for $M_w \geq 8.0$, observed $\chi^2 = 6.5$ and $\chi^2(.05,11) = 19.7$. DOF is the number of bins in which more that 1/2 event is expected, minus 1 due to constraint the total number of observed and calculated events is the same.)

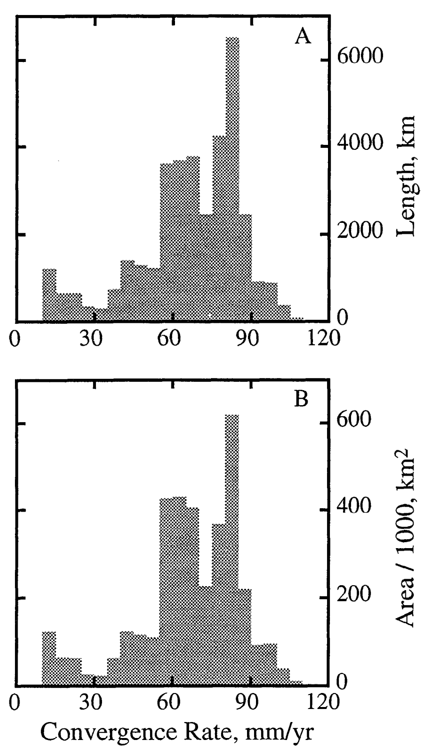

Fig. 2. (a) Global sum of trench lengths as a function of plate convergence rate. Lengths are binned in 5 mm/yr increments of rate. (b) Summed subduction thrust fault areas (LW) as a function of plate convergence rate; trench lengths L are taken from (a) and down-dip widths W are from *Pacheco et al.* [1993].

Influence of Convergence Rate and Fault Area

Using estimates of the down-dip width W of the fault plane at each trench [*Pacheco et al.*, 1993], I also summed fault areas (LW) as a function of convergence rate. Because the observed regional values for W deviate by only 50% or so from the value of 100 km used above, the distribution of fault areas (Figure 2b) resembles the distribution of fault lengths (Figure 2a). Using the areas derived for each convergence rate and other values given above, again the observed earthquake distribution can be matched well (short-dashed lines in Figure 1) but differs only slightly from the case in which a nominal value of W = 100 km was used. Therefore, I conclude that the tendency of $M_w \geq 7$ subduction zone earthquakes to occur where convergence is fast is largely a consequence of the tendency of most trenches to have high convergence rates.

Both the subduction zone fault length and fault area distributions show broad peaks at 55-70 mm/yr and sharper peaks at 80-85 mm/yr (Figure 2). The peaks at 80-85 mm/yr correspond to peaks in all of the observed earthquake distributions (Figure 1). Only the $M_w \geq 7$ distribution shows a peak in the 55-70 mm/yr range but still the observed number of events in this convergence rate range is too small. This suggests that the 94 year sampling period may be enough time to obtain a representative distribution of earthquakes up to M_w = 8.0 if the convergence rate is greater than 70 mm/yr. At slower rates, events as small as M_w = 7 appear to be under-represented.

Using the areas of the trench segments as a function of convergence rate (Figure 2b), I estimate the total expected seismic moment by $M_o(v) = \mu\, L(v)\, W(v)\, v\, t$. At rates greater than 40 mm/yr, the observed seismic moment is within 10% or better of the predicted moment (Figure 3). Below 40 mm/yr the observed moment is 3 to 4 orders of magnitude lower than expected, except for the peak near 30 mm/yr caused by the August, 1993, M_w = 7.8 Guam earthquake. Except for the lack of moment release below 40 mm/yr, there does not appear to be any correlation of the seismic coupling coefficient (the ratio of observed to expected moment) with convergence rate [see also *Pacheco et al.* 1993].

The paucity of large earthquakes at trenches where convergence rate is less than 35 mm/yr is attributed to the short time period for the data used relative to the long recurrence times at low slip rates, and, perhaps more importantly, to the fact that globally only a small fraction of trench lengths have such slow rates. For example, referring to Figure 1, fewer than 4 earthquakes of $M_w \geq 7$ are expected in 94 years at all trench segments where $v \leq 35$ mm/yr (these segments are the 1200 km long Antilles trench, the 1200 km long southern Chile trench, and 500 km of the Marianas trench south of 12.5°N). Only 2 earthquakes of $M_w \geq 7.5$ (one of which is the Guam earthquake) and less than one $M_w \geq 8$ are expected. Earthquakes of $M_w \geq 7$ will produce most of the seismic moment for the regions so the lack of seismic observed moment (Figure 3) may also be a consequence of the relatively short sampling period. This effect is exemplified by the 1993 Guam earthquake which increases the seismic coupling coefficient near the 30 mm/yr range from 10^{-4} to 10^{-1}.

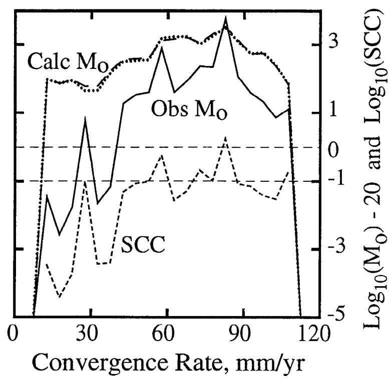

Fig. 3. Calculated and observed seismic moments at trenches in this century as function of convergence rate. Expected moments shown by dashed line are based on W=100 km and $L(v)$ from Figure 2a, and those shown by dotted line are based on the area LW from Figure 2b. Observed moments are typically within an order of magnitude of expected values for rates greater than 40 mm/yr. The short dashed line shows the seismic coupling coefficient (SCC; the ratio of observed to calculated moment). The peak near 30 mm/yr is due to the 1993 Guam earthquake. Moments and SCC are plotted on log scale (moments, in N-m, are reduced by a factor of 10^{20}).

Because few events are expected at these slow trenches in the 94 year sampling period, it is possible that the paucity of observed earthquakes is due to the short time rather than to any convergence rate related limitation on the size of the largest possible earthquake or to a tendency of slowly slipping subduction zones to slip aseismically. In summary, I suggest that we probably should not use global earthquake patterns in this century as evidence that slowly converging subduction zones, such as Cascadia, cannot produce magnitude 9 earthquakes.

Conclusions

The relations of subduction zone convergence rates to the numbers of earthquakes of $M_w \geq 7$, $M_w \geq 7.5$, and $M_w \geq 8$ and to the seismic moment release rate are examined. The observed relations are not statistically different from those expected on simple kinematic grounds (slip rate dependent recurrence times) and do not require that physical mechanisms that might cause an increase in seismic activity, such as an increase in interplate stress, be correlated with plate convergence rate. The lack of seismic moment release at trenches with convergence rates less than 40 mm/yr is attributed to the short sampling period and long recurrence rates for such events. Subduction zones with high convergence rates produce more large earthquakes simply because high slip rates result in shorter recurrence intervals and because fast subduction is globally dominant.

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R. McCaffrey, Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, NY 12180 (e-mail: robmcc@harold.geo.rpi.edu)

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