Supplementary Materials for

Global variations of large megathrust earthquake rupture characteristics

Lingling Ye, Hiroo Kanamori, Thorne Lay

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section S1. Uncertainty in estimating seismic moment, source duration, radiated energy, and REEF

Seismic moment is the most robust measurement of earthquakes determined from long-period observations, so we neglect its contribution to the uncertainty of REEF estimates.

The total source duration $T$ used in this study is defined by the time when the moment time function (time integral of MRF from finite-fault models\cite{21}) reaches $\sim$95\% of the final value. Total duration measures can be influenced by water reverberations and late scattered waves. We ignore very weak tails in MRFs as these are likely to be artifacts of inaccurate modeling of the coda in combination with the positivity constraint used in the slip inversion. The uncertainty in source duration estimated this way is $\sim$10\% for large earthquakes; some M7 events might have larger uncertainty of $\sim$20\%. A 10\% variation of $T$ results in a 30\% variation in estimated $E_{R,\text{min}}$ thus the duration uncertainty can affect the REEF estimates significantly. Because the definition of $T$ described above is somewhat subjective, we consider another definition of $T$ using $T_c$, the MRF centroid delay time measured from the origin time. $T_c$ estimated from our MRFs of finite-fault slip models are consistent with those determined by the inversion of long-period waves as provided by the global Centroid Moment Tensor catalog and Wphase inversions\cite{21}. The advantage of using this definition is that $T_c$ can be determined objectively without any subjective judgement and $2T_c$ gives a reasonable estimate of $T$. However, if the MRF has a long tail or slow rise time, $2T_c$ underestimates or overestimates $T$, respectively. As shown in fig. S3, the REEF values estimated with $T=2T_c$ show similar regional patterns, with only minor differences, to those found using our measures of total durations (Fig. 4). Although we present the REEF values using the measured total duration in this study, use of a different definition of $T$ would not significantly affect our conclusions.

We estimate the radiated energy by combining the moment-rate spectrum (MRS) estimated from finite-fault inversion at low frequency (0-0.05 Hz) and the average P-wave displacement spectrum at high frequency (0.05 – 1 Hz) (ref. 21). The displacement
spectrum is corrected for attenuation, radiation pattern and surface reflection. We use the model of Perez-Campos et al.\textsuperscript{32} for the attenuation correction\textsuperscript{33}. For correction of the radiation pattern and surface reflection, we follow the method of Boatwright and Choy\textsuperscript{34}, in which the effect of surface reflection is only approximately accounted for. To make sure that this correction is sufficiently accurate for our purpose we compare the P-wave displacement spectrum with that from MRS derived from slip inversion at the cross-over frequency, 0.05Hz. The finite-fault inversion accounts for the effect of surface reflections.

The radiated energy obtained from the broadband spectrum over the 0-1 Hz band accounts for most radiated energy (> ~95% for the assumption that the high-frequency spectrum has the fall-off slope of -2) for $M_w \geq 7$ earthquakes. However, our radiated energy estimates, as well as those from other studies, do not fully account for finite source effects, free surface effects, and scattering of wave propagation. Thus, we cannot rigorously estimate absolute errors in energy estimation. Despite those limitations, with the recent availability of extensive global broadband seismic recordings, the measurement accuracy of radiated energy has been significantly improved over the last century (fig. S4).

As we focus on relative REEF values, only the relative uncertainty in radiated energy is needed. Out of the 119 total events in this study, we consider 90 earthquakes which have three independent estimates of radiated energy from USGS-NEIC, IRIS, and our previous study (ref., 21), noted as $E_R^{(\text{USGS-NEIC})}$, $E_R^{(\text{IRIS})}$ and $E_R^{(\text{YKLR})}$, respectively. Figure S5a shows the ratio $E_R^{(\text{USGS-NEIC})}/E_R^{(\text{YKLR})}$ and $E_R^{(\text{IRIS})}/E_R^{(\text{YKLR})}$ as a function of magnitude. No obvious trend with magnitude is seen but $E_R^{(\text{IRIS})}$ and $E_R^{(\text{USGS-NEIC})}$ are about 83% and 42% of $E_R^{(\text{YKLR})}$. Thus, the difference between the estimates from these data sets is probably due to small differences in time windows, frequency bands, weighting of P and S radiation, and velocity structures used in the calculations. Then, as a measure of relative uncertainty of energy estimate for each event, we calculate the geometric mean and standard deviation of $E_R^{(\text{IRIS})}/0.83$, $E_R^{(\text{USGS-NEIC})}/0.42$ and $E_R^{(\text{YKLR})}$ for each event (fig. S5b and S5c). Except for a few large outliers, standard deviations range from ~1.2 to ~1.8
with an average of ~1.45. We thus infer that the uncertainty of relative radiated energy estimates for large megathrust earthquakes is about 45%.

With uncertainties from rupture duration cubed (~30%) and radiated energy (~45%), the uncertainty of relative REEF values is about a factor of 2. There is greater uncertainty in absolute values of radiated energy, so it is important to compare REEF values that use consistently estimated values of $E_R$. Regionally consistent behavior that emerges from the measurements is subject to even less uncertainty. In the categorization based on regional average REEF values in Fig. 5, the low-REEF failures have average values of ~5-10 with relatively small variation, less than a factor of ~2, whereas the high-REEF failures have average values of ~20-50 with large variation (Figs. 4, S6). Japan, S. Kurils and South Sumatra have medium average REEF values. Low and high REEF regions with enough samples have well-separated ranges of REEF values (Figs. 4, S6), justifying the basic categorization.

section S2. Roughness of the MRF

One can also represent rupture complexity by the roughness of estimated moment-rate functions (MRFs) derived from finite-fault inversion for large events\textsuperscript{21}. We compute $\gamma$ by

$$
\gamma = \frac{\int_0^T \dot{\mathcal{M}}(t)^2 \, dt}{\int_0^T \dot{\mathcal{u}}(t)^2 \, dt} = \frac{E_R^M}{E_{R,\text{min}}},
$$

and call it the MRF roughness. Here, $\dot{\mathcal{M}}(t)$ and $\dot{\mathcal{u}}(t)$ are time derivatives of the observed and the parabolic moment-rate functions respectively. $E_R^M$ is the radiated energy estimated from an observed moment-rate function determined from finite-fault inversion. Note that $E_R^M$ is different from the broad-band radiated energy, $E_R$. Since high-frequency signals are filtered out as a result of limited knowledge of small-scale Earth structure and simplicity of model parameterizations used for inverting teleseismic data, the estimated
MRF is smoothed and depleted in high-frequency components. This is true for both point-source MRFs estimated by deconvolution methods and MRFs from finite-fault modeling. In contrast, the $E_R$ measurement captures the total radiated energy more completely by the virtue of how the propagation effects are handled. As shown in fig. S7, most $REEF$ values are larger than $\gamma$ for a given event, because of the missing high-frequency energy in $E_R^M$. The difference between $REEF$ and $\gamma$ tends to increase as the magnitude decreases, because the high-frequency components are more important for smaller events (fig. S8). Figure S9 shows all MRFs with values of $REEF$ ($E_R/E_{R_{min}}$) and $\gamma$.

section S3. Possible geological factors

Many studies have explored the influence of subduction zone parameters on great earthquakes globally. Early studies (e.g., ref. 38) in the 1980s found that great earthquakes tend to occur in regions with relatively young subducting lithosphere and high plate convergence rate. This hypothesis has been challenged by the occurrence of the 2011 Tohoku earthquake associated with subduction of an old plate. With greater spatial sampling of subduction zone properties, correlations between maximum earthquake size and a variety of geological and tectonic parameters, such as subducted sediment thickness$^{6,7}$, seamount or seafloor roughness$^{39}$, seismic coupling$^{40}$, gravity anomaly$^{27}$, and slab dip angle$^{41}$ have been examined.

To explore what controls rupture complexity (rather than just earthquake size), we examine correlations of these factors with $REEF$ in fig. S10. There is no clear correlation between $REEF$ and subduction-zone parameters. Investigations with more global samples accompanied by dynamic modeling under varying regional conditions may elucidate the fundamental controls on rupture complexity.
table S1. Asperity size, spacing, and earthquake sizes for the modified asperity representation (Fig. 5).

<table>
<thead>
<tr>
<th># of asperities</th>
<th>$R$ (total asperity area/Total area)</th>
<th>$\bar{R}$ (single asperity area/total area)</th>
<th>$L$ (2D inter-asperity spacing (1D))</th>
<th>$M_w$ for single asperity rupture</th>
<th>$M_w$ for rupture of all asperities</th>
<th>$M_w$ for all asperity rupture with excess slip*</th>
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</thead>
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<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 (0)</td>
<td>9.50</td>
<td>9.50</td>
<td>9.50</td>
</tr>
<tr>
<td>2</td>
<td>1/2</td>
<td>1/4</td>
<td>1/2 (1/4)</td>
<td>8.60</td>
<td>8.80</td>
<td>9.10</td>
</tr>
<tr>
<td>3</td>
<td>1/3</td>
<td>1/9</td>
<td>$\sqrt{2}/3$ (2/9)</td>
<td>8.07</td>
<td>8.39</td>
<td>8.69</td>
</tr>
<tr>
<td>4</td>
<td>1/4</td>
<td>1/16</td>
<td>$\sqrt{3}/4$ (3/16)</td>
<td>7.69</td>
<td>8.10</td>
<td>8.40</td>
</tr>
</tbody>
</table>

* We assumed that seismic moment for compound rupture is three times larger than the sum of seismic moment of all single asperity ruptures, as observed for the Ecuador-Colombia large earthquake sequence$^{15}$. 
fig. S1. Map of static stress drop estimates for 119 global large megathrust earthquakes. Each static stress drop is determined from a finite-fault slip distribution with a unit of MPa. Stars indicate large tsunami earthquakes. Symbol sizes scale with earthquake magnitude.
**fig. S3.** Map view of REEF estimates with the total duration assumed to be equal to $2T_c$. Earthquakes are color-coded by the corresponding REEF values in log$_{10}$ scale. Symbol sizes scale with earthquake magnitude. It shows similar regional REEF variations to those in Figure 4, suggesting relative stable estimate of REEF using the measured total duration.
fig. S4. Comparison of radiated energy for magnitude ~7.5 earthquake measured by different methods. For the 1911 Pamir earthquake, radiated energy was measured by Galitzin in 1915 and Jeffrey in 1923\cite{36}. There are more than 2 orders of magnitude discrepancy between their results because of different methods. Gutenberg and Richter updated their empirical relations for earthquake magnitude and radiated energy estimates in 1942 and 1956\cite{37}, which ends up ~1.5 orders of magnitude difference in the radiated energy for M ~7.5 earthquakes. Since 1990 when the broadband seismic data has been openly available, various groups, such as Ye et al.\cite{21} (red dots), IRIS based on Convers and Newman\cite{35} (different from Ye et al.’s result by blue bars), and USGS based on Boatwright and Choy\cite{34} (different from Ye et al.’s result by green bars), have calculated radiated energy for large earthquake. The right-hand side of the figure compares those results for all Mw ~7.5 megathrust earthquakes from 1990 – 2016 with x-axis showing earthquake’s occurrence time. With the broadband seismic data and improved wave-field methods, the discrepancy between results from different groups using different methods is within a factor of ~2.
**fig. S5. Relative uncertainty estimation for radiated energy $E_R$.** (a) Ratios of radiated energy estimates for 90 earthquakes from IRIS$^{35}$ (red dots) and from USGS-NEIC$^{34}$ (blue dots) to our results$^{22}$ ($E_R^{(YLKR)}$), plotted against earthquake magnitude. On average, $E_R^{(IRIS)}$ and $E_R^{(USGS-NEIC)}$ are 83% and 42% of $E_R^{(YLKR)}$. (b) Geometric mean values of $E_R^{(IRIS)}/0.83$ and $E_R^{(USGS-NEIC)}/0.42$ and $E_R^{(YLKR)}$, normalized by $E_R^{(YLKR)}$, plotted against earthquake magnitude. The red bars show geometric standard deviations for the three estimates of each event. (c) Geometric standard deviations plotted against earthquake magnitude with an average of 1.45.
**fig. S6.** Map view of REEF values and regional average. Groups of events in different subduction zones are indicated by the initials and arrows. Stars are for large tsunami earthquakes. Symbols scale with earthquake magnitude. The insert figure shows regional logarithmic average REEF values arranged in ascending order, with standard deviation (bars) and number of events. Purple labeling indicates areas with better sampling for the regional average. Note systematic values for some regions as shown in Fig. 4, such as high-REEF at Colombia-Ecuador-Peru-N. Chile, N. Kurils, Solomon Islands and Sumatra, and low-REEF at Mexico-M. America, S. Chile, N. Japan-S. Kurils, and C. Aleutians.
fig. S7. REEF versus MRF complexity, $\gamma$. (a) $REEF$ and $\gamma$ for 119 large megathrust earthquakes. The dashed green line shows equal $REEF$ and $\gamma$, and three dashed gray lines show that $REEF$ are 2, 5, and 10 times larger than $\gamma$ respectively. MRF (black) and corresponding MRF for $E_{R_{\text{min}}}$ (red) for earthquakes with low $REEF$ and $\gamma$ associated with smooth rupture and with large $REEF$ and $\gamma$ associated with complex rupture are shown at (b) and (c) respectively. $REEF$ and $\gamma$ correlated with each other, but there is a substantial spread in $REEF$ for similar values of $\gamma$. 
**fig. S8.** Fraction of high-frequency ($f > 0.05$ Hz) radiated energy plotted with earthquake magnitude. Detailed seismic radiated energy measurement procedures are fully documented in Ye et al. (21). Stars and circles show events with and without constraints on rupture speed and source dimensions, respectively. Five large tsunami earthquakes are highlighted in blue. For most M7+ megathrust earthquakes, there is more radiated energy in the frequency range of 0.05-1 Hz than that at lower frequency, except for tsunami earthquakes and giant earthquakes.
fig. S9. MRF (black) and corresponding minimum $E_R$ MRF (red) for 119 global large megathrust earthquakes. The label of each event starts with regional code (fig. S8), occurrence date and magnitude ($M_W$). The $REEF (E/Er_{min})$ and MRF complexity, $\gamma$, are marked in red. Earthquakes are listed in ascending order of magnitude.
fig. S9. Continued.
fig. S10. Comparisons between REEF and subduction zone parameters. (a) Interseismic coupling coefficients from GEM report\textsuperscript{42}, (b) subducted sediment thickness from Syracuse et al.\textsuperscript{43}, (c) convergence rate\textsuperscript{43}, (d) slab age\textsuperscript{43}, (e) the product of convergence rate and slab age\textsuperscript{43}, and (f) thermal parameter\textsuperscript{43}. Red and blue dots are for events in Eastern Pacific subduction zones and other regions, respectively. R values in red and blue are their linear correlation coefficients and R\textsuperscript{2} would give coefficient of determination. Symbol sizes scale with earthquake magnitude.