Regional difference in scaling laws for large earthquakes and its tectonic implication

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Abstract

For large earthquakes occurred at and around plate boundaries, we examined relations between seismic moment M_0, fault length L, fault width W and average fault slip D, and found the following scaling laws. For interplate strike-slip events, the well-known L-cubed dependence of seismic moment M_0 breaks when L exceeds 30 km, and D and M_0 increase with L as $D = \Delta\tau L/\mu(\alpha L + \beta)$ and $M_0 = \Delta\tau W L^2/(\alpha L + \beta)$, respectively, with W is 15 km and the average stress drop $\Delta\tau$ is 1.4 MPa. For intraplate strike-slip events we obtained the same relations, except for much higher stress drop (4.6 MPa). For underthrust events at island-arc subduction zones we found also the saturation of fault width ($W \leq 100$ km) and the breakaway from the L-cubed dependence of M_0 for the events larger than $L = 200$ km.

Introduction

To characterize a seismic source, we generally use seismic moment M_0, fault area S (or fault length L and fault width W), average fault slip D, and average stress drop $\Delta\tau$, all of which are directly observable quantities except for $\Delta\tau$. So far various empirical relations between these parameters have been proposed by many investigators. Among them the most widely accepted relation is the $S^{3/2}$ dependence of seismic moment M_0. On the basis of a classical theory of circular cracks in a uniformly stressed elastic medium, Aki (1972)[2] has demonstrated that the $S^{3/2}$ dependence of M_0 can be reasonably explained by assuming the average stress drop to be nearly constant over a broad range of source dimension. In the case of non-circular faults, as demonstrated by Kanamori and Anderson (1975)[3], the $S^{3/2}$ dependence of M_0 still holds, if the aspect ratio ($W/L < 1$) of actual faults is nearly constant as indicated by Abe (1975)[1]. Assuming a constant aspect ratio of faults, we can read the $S^{3/2}$ dependence of M_0 as the L-cubed dependence of M_0. However, as pointed out first by Scholz (1982)[8] and later by Shimazaki (1986)[12] and Romanowicz (1992)[6], the general L-cubed dependence of M_0 breaks for large strike-slip earthquakes on quasi-vertical faults. This break in the moment-length relation results from that at least the two basic assumptions, fault aspect ratio to be constant and initial stress field to be uniform, do not hold for large strike-slip earthquakes.

W-model and L-model

For small- and medium-sized earthquakes, the stress accumulation around the source region may be regarded as uniform, and so we can apply the classical theory of a shear crack in a uniformly stressed elastic medium. In this case, on the assumption of constant stress drop, the average fault slip D scales with the fault width W (W-model), and we obtain the L-cubed dependence of M_0. As an observational fact, however, we know that the fault width W is saturated for large earthquakes. If the downward rupture growth is forcibly stopped at a certain depth by the existence of a strong barrier, we can still apply the conventional W-model and obtain the linear L-dependence of M_0 as claimed by Romanowicz (1992[6], 1994[7]). In reality the downward rupture growth is limited to a certain depth because of the existence of ductile unstressed region extending under the brittle seismogenic zone (Sibson, 1984[11]; Marone and Scholz, 1988[4]). In this case we can no longer apply the crack theory in a uniformly stressed elastic medium, and so the conventional W-model. What we should apply is the theory of an in-plane crack in a uniformly stressed elastic layer, as pointed out by Scholz (1982)[8]. According to the crack theory in a uniformly stressed elastic layer, the average fault slip D scales with the fault length L (L-model), and so we obtain the L-squared dependence of M_0 as claimed by Scholz (1982[8], 1994a[9]).

Mechanism of tectonic loading

From the theoretical point of view, as discussed above, Romanowicz's W-model seems to be unreasonable, and Scholz's L-model to be reasonable. Observed data certainly show the L-squared dependence of M_0 for moderately large earthquakes, but not for very large earthquakes. The observed moment-length relation for very large earthquakes is linear. The key to this puzzle is in mechanism of tectonic loading at plate boundaries, as pointed out by Matsu'ura and Sato (1997)[5]. At plate boundaries, in general, stress accumulation on a fault plane is caused by viscous drag at the base of the lithosphere (base loading) and dislocation pile-ups at horizontal edges of the fault (edge loading). According to a theoretical model of tectonic loading by Matsu'ura and Sato (1997)[5], the stress accumulation rate after the occurrence of a large earthquake at transform plate boundaries is given by

$$\dot{\tau}(t) = V_{pl}\mu(\alpha + \beta/L) \quad , \tag{1}$$

where V_{pl} is a relative plate velocity, and μ, α and β are structural parameters. In the above equation, the first term on the right-hand side corresponds to the effect of base loading, and the second term to the effect of edge loading. Then, given an average coseismic stress drop $\Delta\tau$, we can calculate the recurrence time $T \equiv \Delta\tau/\dot{\tau}$ of earthquakes as

$$T = \Delta\tau L/V_{pl}(\alpha L + \beta) \quad . \tag{2}$$

For large interplate earthquakes the average coseismic fault slip D must be given by the product of the recurrence time T and the relative plate velocity V_{pl},

$$D = \Delta\tau L/\mu(\alpha L + \beta) \quad , \tag{3}$$

and so the seismic moment $M_0 \equiv \mu DWL$ can be written as

$$M_0 = \Delta\tau WL^2/(\alpha L + \beta) \quad . \tag{4}$$

Therefore, if we assume the average stress drop $\Delta\tau$ and the fault width W to be constant, the theoretical model of tectonic loading model expect the L-squared dependence of M_0 for moderately large earthquakes and the linear L-dependence of M_0 for very large earthquakes.

Regional difference in scaling laws and its tectonic implication

The purpose of the present study is to examine the validity of this expectation through the detailed analysis of observed data. For this purpose, first, we compiled the data of large earthquakes which occurred at and around plate boundaries, and classified them into four groups (interplate strike-slip events, intraplate strike-slip events, underthrust events at island-arc subduction zones, and underthrust events at continental-margin subduction zones) according to the type of faulting and tectonic setting, because the average stress drop and the maximum fault width will be strongly affected by them. For each group of earthquakes we examined relations between seismic moment M_0, fault length L, fault width W and average fault slip D, and found the following scaling laws.

In the case of interplate strike-slip events, the well-known L-cubed dependence of seismic moment M_0 breaks when L exceeds 30 km, because the extent of seismogenic zone is limited in depth. For large events ($L \geq 30$ km), D and M_0 increase with L as $D = \Delta\tau L/\mu(\alpha L + \beta)$ and $M_0 = \Delta WL^2/(\alpha L + \beta)$, respectively, with the fault width W is 15 km and the average stress drop $\Delta\tau$ is 1.4 km. Here, μ, α and β are structural parameters. For intraplate strike-slip events we obtained the same relations, except for much higher stress drop (4.6 MPa). The difference in stress drop between the interplate and intraplate events can be ascribed to difference in stress accumulation rates and so the length of inter-seismic periods, during which restoration of fault strength proceeds. In the case of underthrust events at island-arc subduction zones we found also the saturation of fault width $W \leq 100$ km and the breakaway from the L-cubed dependence of M_0 for the events larger than $L = 200$ km. Since the average dip-angle of plate boundaries at subduction zones is about 30°, this indicates that the extent of seismogenic zone in depth is limited to about 50 km at island-arc subduction zones. In the case of continental-margin subduction zones, on the other hand, we could not find the saturation of fault width nor the breakaway from the L-cubed dependence of M_0 from the analysis of the present data set ($W \leq 200$ km, $L \leq 1000$ km). This indicates that the lower limit of seismogenic zone is deeper than 100 km at continental-margin subduction zones. For sufficiently large earthquakes, in general, the downward rupture growth is limited to a certain depth because of the existence of ductile unstressed region extending under the brittle seismogenic zone. Since the brittle-ductile transition occurs at $300 - 400$°C, the difference in the lower limit of seismogenic zone between tectonically different regions may be attributed to difference in thermal state there.

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