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Earthquake scaling, fault segmentation, and structural maturity

地震のスケーリング則、断層のセグメンテーションと構造的な成熟度

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Abstract

Slip and length measurements on earthquakes suggest large stress drop variability. We analyse an extended set of slip-length measurements for large earthquakes ($M \geq 6$) to seek for the possible origin(s) of this apparent variability. We propose that such variability arises from earthquakes breaking a variable number of major fault segments. That number depends on the strength of the inter-segment zones, which itself depends on the structural maturity of the faults. We propose new D_{max}–L parameterizations based on that idea of multiple segment-ruptures. In such parameterizations, each broken segment roughly scales as a crack, while the total multi-segment rupture does not. Stress drop on individual segments is roughly constant, only varying between 3.5 to 9 MPa. The slight variation that is still observed depends on fault structural maturity; more mature faults have lower stress drops than immature

要約

地震時におけるすべり量と断層長さの測定結果は、大きな応力降下のばらつきを示唆している。我々は、この明らかなばらつきの考えられる原因を追究して、大地震（M≥6）のすべり量と断層長さを測った拡張的セットを分析する。このようなばらつきは、様々な数の主要な断層セグメントを破壊する地震によって生じることを提案する。その数はセグメント間のゾーンの強さに依存し、それ自体が断層の構造的成熟度に依存する。我々は、この複数のセグメント破壊の考え方に基づいて新しい Dmax－L パラメータ化を提案する。このようなパラメータ化では、各破壊セグメントは大雑把にクラックとして測定されるが、複数セグメント破壊の全体としてはそうではない。各セグメントの応力降下量はほぼ一定であり、3.5～9MPa の間でしか変化しない。

(D_{mean}) on earthquakes to scale with rupture length (L) when $L \leq 2W_{seism}$ (W_{seism} being the thickness of the seismogenic layer), and tapers off for long ruptures ($L > 2W_{seism}$). While available D–L earthquake data have long been too few to show whether or not that

– for ruptures with $L \leq 2W$, $D_{mean} = \alpha * (L/2)$

– for ruptures with $L > 2W$, $D_{mean} = \alpha * (1/[1/L + 1/2W])$ (1)

It is important to note that, in the formulation of that equation, S&S01 postulate that α is proportional to a constant static stress drop, while W represents the width

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model; large earthquakes of similar size (i.e., similar length and width) obviously can produce different slips and stress drops, as it has been pointed out by many authors e.g., [2,17–21]. We focus here on such slip variability and seek for its possible origin(s). We compile all available slip-length measurements for

アジア（広義）、トルコ、西米、日本の４つの地震活動地域で発生している、大規模（M>～ 6）、浅い（破壊領域幅<40km、平均値に相当する W_{mean} は 18km）、混合焦点機構の内陸地震（横ずれ、逆断層、正断層）の、変位量と断層長さについての２５０個程度のデータを検討する。これらの地域では、長期的な活断層は一般によく知られており、その表面形状（全長、セグメンテーション、断層タイプ、関連二次断層帯）、年代、最大すべり率、合計累積変位量が一般的に決定されている。

2. Data sets

We examine displacement-length data for a set of ~250 large ($M \geq \sim 6$), shallow (rupture width ≤40 km, with an average value W_{mean} 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 (broad sense), Turkey, West US, Japan. In these regions, long-term active faults are generally well known, with their surface geometry (total length, segmentation, strike variations, associated secondary fault networks), age, maximum slip rate and total cumulative displacement being generally determined. We use these long-term parameters (where available) to qualify the structural maturity of the faults that broke during the analyzed earthquakes, as explained in Table 1 (supporting online material). Doing so, we classify the broken faults in three classes, basically 'immature', 'intermediate', and 'mature' (Table 1). Earthquake slip-length data are compiled from literature (references in Tables 2 and 3; supporting online material). We consider here the maximum displacement (D_{max}), not the mean (D_{mean}), for it is best constrained. Besides, Manighetti et al. [21] have shown that $D_{max} = 2 * D_{mean}$ for most large earthquakes worldwide, a property that is found to be scale-independent. Being aware that rupture slip and length measured at surface may be lower than actual maximum slip and length produced at depth, we compile both surface measurements (209 earthquakes; Table 2) and slip-length values inferred at depth from earthquake source models (56 earthquakes; Table 3), and analyze them separately. Surface data are screened for quality, and a 'quality weight' assigned to each data from criteria defined in Table 2. Note that, since error bars cannot be properly defined for most data, weighting them with a quality factor is the best we can do to discriminate poor and robust data. While such quality screening is a fundamental step to discuss any scaling law, it has never been done before (in terms of quality weighting of each data). Concerning slip-length data at depth, we did not attempt to 'qualify' the quality of the various earthquake source models. Rather we chose to average the different D_{max}–L values proposed for the same earthquakes (Table 3).

3. Data analysis

We start analyzing in detail the Asian data set, for it is the densest. Fig. 1a shows the Asian surface D_{max}–L data, with symbol size proportional to quality weight. The data are rather dispersed, so that a single function cannot be found to adjust them all properly. However the overall shape of the data distribution resembles an

アジアのデータセットを詳細に分析し始める。それは一番密集しているからである。図 1a はアジアの地表の最大変位量—断層長（Dmax-L）データを示し、しるしの大きさはデータの質の高さを示している。 データはかなり分散しているため、それらをすべて正しく調整することはできない。

$M = \sum_i (\exp[(D_{obs} - D_{(\alpha,W)})^2 / D_s])$, where D_{obs} is the measured value of slip, $D_{(\alpha,W)}$ is the predicted value of slip, and D_s is an adjustable smoothing parameter (chosen here to be 7 times the standard deviation of D_{obs}). At this stage, we thus assume that α and W are free adjustment parameters. The existence of several, distinct zones of maximum in Fig. 1b indicates that the data cannot be fitted with a single model, but rather include several subsets associated with different models, i.e. different values of [α, W]. Three major zones are identified, whose shape is related to bias between α and W. Since we deal with a limited number of data, we must verify that this multimodal structure is not fictitious. We generated random models having the statistical properties of the data (average and variance of D depending on

L, distribution of L) and performed the same test as before. The multimodal structure with respect to the functional form of S&S01 that is exhibited by the data is not produced by sparse random series. We checked a dozen realizations to reach this conclusion. Examples are presented in Fig. A (supporting online material). We can thus conclude on firm ground that the Asian surface data set actually includes at least 3 distinct groups

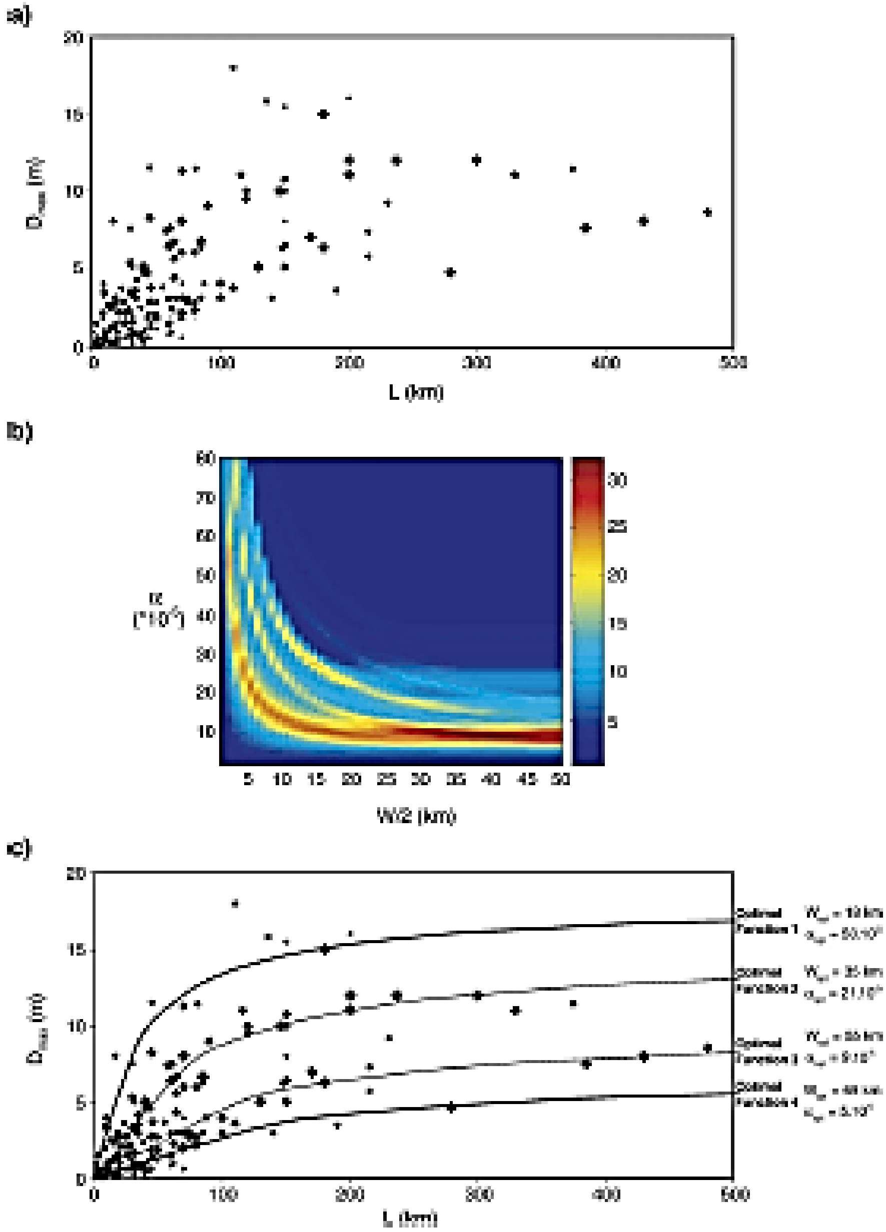

Fig. 2. Displacement-length surface data in the four Asia, West US, Turkey and Japan regions (from Table 2). (a) D_{max} versus L plot. Symbol size is pro… excluded for clarity… distinct data subset… indicated.

アジア、北西アメリカ、トルコ、日本の４地域における地表の最大変位量—断層長データ