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Global correlations between maximum magnitudes of subduction zone interface thrust earthquakes and physical parameters of subduction zones ☆

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ABSTRACT

The maximum earthquake magnitude recorded for subduction zone plate boundaries varies considerably on Earth, with some subduction zone segments producing giant subduction zone thrust earthquakes (e.g. Chile, Alaska, Sumatra–Andaman, Japan) and others producing relatively small earthquakes (e.g. Mariana, Scotia). Here we show how such variability might depend on various subduction zone parameters. We present 24 physical parameters that characterize these subduction zones in terms of their geometry, kinematics, geology and dynamics. We have investigated correlations between these parameters and the maximum recorded moment magnitude (M_W) for subduction zone segments in the period 1900–June 2012. The investigations were done for one dataset using a geological subduction zone segmentation (44 segments) and for two datasets (rupture zone dataset and epicenter dataset) using a 200 km segmentation (241 segments). All linear correlations for the rupture zone dataset and the epicenter dataset ($|R|$ = 0.00–0.30) and for the geological dataset ($|R|$ = 0.02–0.51) are negligible-low, indicating that even for the highest correlation the best-fit regression line can only explain 26% of the variance. A comparative investigation of the observed ranges of the physical parameters for subduction segments with $M_W > 8.5$ and the observed ranges for all subduction segments gives more useful insight into the spatial distribution of giant subduction thrust earthquakes. For segments with $M_W > 8.5$ distinct (narrow) ranges are observed for several parameters, most notably the trench-normal overriding plate deformation rate ($v_{OPD\perp}$, i.e. the relative velocity between forearc and stable far-field backarc), trench-normal absolute trench rollback velocity ($v_{T\perp}$), subduction partitioning ratio ($v_{SP\perp}/v_{S\perp}$, the fraction of the subduction velocity that is accommodated by subducting plate motion), subduction thrust dip angle (δ_{ST}), subduction thrust curvature (C_{ST}), and trench curvature angle (α_T). The results indicate that $M_W > 8.5$ subduction earthquakes occur for rapidly shortening to slowly extending overriding plates ($-3.0 \leqslant v_{OPD\perp} \leqslant 2.3$ cm/yr), slow trench velocities ($-2.9 \leqslant v_{T\perp} \leqslant 2.8$ cm/yr), moderate to high subduction partitioning ratios ($v_{SP\perp}/v_{S\perp} \leqslant 0.3$–$1.4$), low subduction thrust dip angles ($\delta_{ST} \leqslant 30°$), low subduction thrust curvature ($C_{ST} \leqslant 2.0 \times 10^{-13}$ m^{-2}) and low trench curvature angles ($-6.3° \leqslant \alpha_T \leqslant 9.8°$). Epicenters of giant earthquakes with $M_W > 8.5$ only occur at trench segments bordering overriding plates that experience shortening or are neutral ($v_{OPD\perp} \leqslant 0$), suggesting that such earthquakes initiate at mechanically highly coupled segments of the subduction zone interface that have a relatively high normal stress (deviatoric compression) on the interface (i.e. a normal stress asperity). Notably, for the three largest recorded earthquakes (Chile 1960, Alaska 1964, Sumatra–Andaman 2004) the earthquake rupture propagated from a zone of compressive deviatoric normal stress on the subduction zone interface to a region of lower normal stress (neutral or deviatoric tension). Stress asperities should be seen separately from frictional asperities that result from a variation in friction coefficient along the subduction zone interface. We have developed a global map in which individual subduction zone segments have been ranked in terms of their predicted capability of generating a giant subduction zone earthquake ($M_W > 8.5$) using the six most indicative subduction zone parameters ($v_{OPD\perp}$, $v_{T\perp}$, $v_{SP\perp}/v_{S\perp}$, δ_{ST}, C_{ST} and α_T). We identify a number of subduction zones and segments that rank highly, which implies a capability to generate $M_W > 8.5$ earthquakes. These

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include Sunda, North Sulawesi, Hikurangi, Nankai-northern Ryukyu, Kamchatka-Kuril-Japan, Aleutians-Alaska, Cascadia, Mexico-Central America, South America, Lesser Antilles, western Hellenic and Makran. Several subduction segments have a low score, most notably Scotia, New Hebrides and Mariana.

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1. Introduction

At subduction zones oceanic lithosphere is recycled back into the Earth's mantle. The process of subduction is largely driven by subducted slabs of oceanic lithosphere, which are denser than the ambient mantle and are thus pulled downward by gravity (Elsasser, 1971; Forsyth and Uyeda, 1975; Hager, 1984; Davies and Richards, 1992). The potential energy that is released during sinking is used primarily to drive flow in the mantle, to move and deform the tectonic plates, and to deform the slab. Part of this potential energy is also used to overcome resistance at the subduction zone fault plate boundary, where part of the energy is released during interplate subduction zone thrust earthquakes.

Since the advent of plate tectonic theory it was recognized that subduction zones differ in many aspects that relate to their geometry, geology, physics and chemistry. At different subduction zones around the globe one might find differences in the age of the downgoing plate, nature of the overriding plate (continental/oceanic), overriding plate topography, overriding plate strain (extension/shortening), trench kinematics, subduction rate, subduction accretion/erosion rate, arc volcanism, slab dip angle, slab length, slab depth and trench curvature (e.g. Karig et al., 1976; Molnar and Atwater, 1978; Jarrard, 1986; Gudmundsson and Sambridge, 1998; Clift and Vannucchi, 2004; Heuret and Lallemand, 2005; Schellart, 2008). Similarly, it has been recognized that different subduction zones show differences in seismic behavior (e.g. Uyeda and Kanamori, 1979; Ruff and Kanamori, 1980; Peterson and Seno, 1984; Ruff, 1989; Pacheco et al., 1993; Stein and Okal, 2007). For example, several subduction zone segments have produced exceptionally large earthquakes in the last ~70 yr with moment magnitude $M_W \geqslant 9.0$, e.g. Alaska, Chile, Sumatra and Japan, while others have not, e.g. Scotia, New Hebrides and Mariana (Fig. 1). This could potentially be related to the relatively short period of global instrumental observations (McCaffrey, 1997, 2008; Stein and Okal, 2007), but it is also possible that there are essential physical ingredients that subduction zones require to be capable of producing giant earthquakes.

Numerous previous works have investigated the potential dependence between subduction zone thrust earthquake magnitude and various subduction zone parameters, including subducting plate age, subduction rate, sediment subduction, downdip extent of seismogenic zone, forearc structure, overriding plate velocity and overriding plate stress regime (e.g. Kelleher et al., 1974; Uyeda and Kanamori, 1979; Ruff and Kanamori, 1980; Peterson and Seno, 1984; Jarrard, 1986; Ruff, 1989; Pacheco et al., 1993; McCaffrey, 1993, 1997; Scholz and Campos, 1995; Llenos and McGuire, 2007; Stein and Okal, 2007; Heuret et al., 2011). In these previous works data are plotted for somewhat subjectively defined subduction zone segments, where the limits of such segments have some geological/structural/geometrical basis (e.g. aseismic ridge subduction, cusp, overriding plate nature) or can be somewhat arbitrary (such as for several South American segments). It is clear that the statistical correlation analyses performed in such studies are influenced by the choices of subduction zone segmentation.

In this paper we present a global investigation to test the dependence of the maximum subduction zone interplate thrust earthquake moment magnitude (M_W) on 24 subduction zone parameters. We test such dependence for all active subduction zones on Earth (23), which have been segmented into a total of 241 trench segments, each with a 200 km trench-parallel extent. Such segmentation into equal-length subduction segments gives equal weighing to each segment in the statistical analysis. For completeness, we also make such investigations using a geological subduction zone segmentation (total of 44 segments for 23 subduction zones), which is more in accordance with the previous works cited above. The 24 parameters are related to subduction zone geometry, kinematics, dynamics and geology. Our work shows that all the parameters have low or negligible correlations with M_W that are, with the exception of one, all statistically insignificant at 95% confidence level. Nevertheless, it will be demonstrated that very large subduction thrust earthquakes ($M_W > 8.5$) have only been observed under specific physical conditions with relatively narrow ranges for overriding plate deformation rate, trench migration velocity, subduction partitioning, subduction thrust dip angle, trench curvature angle and subduction thrust curvature. The relevance of these physical conditions can be explained in the framework of the physical parameters that quantify M_W. These findings provide new understanding as to why certain subduction zone segments have produced $M_W > 8.5$ earthquakes, which ones have the potential to produce them in the future, and which ones are not likely to produce them in the future. The findings also provide new understanding as to the occurrence and lateral rupture propagation of the three largest recorded earthquakes on Earth, namely the 1960 M_W 9.5 Chile earthquake, the 1964 M_W 9.2 Alaska earthquake and the 2004 M_W 9.1–9.3 Sumatra–Andaman earthquake.

2. Methods

2.1. Subduction zone parameters

In this paper we investigate the correlation between the maximum moment magnitude (M_W) for subduction zone interplate thrust earthquakes and 24 physical parameters of subduction zone characteristics. We have investigated 23 mature subduction zones in terms of subduction earthquakes and values for the 24 parameters. For several subduction zones, including Cyprus, Betic-Rif, Venezuela and South Shetland, the Wadati–Benioff zone is not accurately defined and/or subduction zone interface thrust earthquakes have not been recorded or could not be identified with confidence due to uncertainty in the subduction zone thrust geometry. This leaves us with 19 subduction zones for which the magnitudes, velocities, rates and values for the parameters were calculated (Fig. 1).

The correlations have been investigated using two different approaches that differ in the way that the 19 active subduction zones have been segmented. In one approach (referred to as the geological approach), the 19 subduction zones were divided into subduction zone segments based in particular on the geometrical characteristics of trench curvature (i.e. arcs), the nature of the overriding plate (continental or oceanic) or the presence of aseismic ridges/plateaus at the trench, resulting in a total of 40 segments. Narrow subduction zones (e.g. Scotia) are mostly represented by one data-point, while wide subduction zones (e.g. South America) are divided into 2–6 segments. In the other approach (in our view physically the most meaningful), each of the 19 subduction zones was divided into individual trench segments with a length of 200 km, resulting in a total of 228 subduction

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