Upper plate rigidity determines depth-varying megathrust earthquake rupture behavior

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Main text

Seismological data provide evidence of a depth-dependent rupture behavior of subduction megathrust earthquakes¹. As compared to deeper events of similar magnitude, shallow ruptures have larger slip, longer duration, radiate energy that is depleted in high frequencies, and have a larger discrepancy between their surface wave and moment magnitudes¹⁻³. These source properties make them prone to generate devastating tsunamis without clear warning signs. Conventional wisdom attributes the depth-dependent rupture behavior to variations in fault mechanics⁴⁻⁷. Conceptual models, however, have yet failed at identifying the fundamental physical causes of the contrasting observations, and do not provide a quantitative framework to predict and link them. Here we demonstrate that the observed differences do not require changes in fault mechanics. We use compressional-wave velocity models from worldwide subduction zones to show that their common underlying cause is a systematic depth variation of elastic properties of the rock body overriding the megathrust, which deforms by dynamic stress transfer during co-seismic slip. Using realistic elastic properties with accurate earthquake focal depth estimates allows predicting amount of slip and provides unambiguous magnitude estimations with unparalleled early tsunami warning potential.

Subduction megathrust earthquakes result from episodic, unstable sliding within the seismogenic zone⁸, a fault segment that is thought to extend from ~40-50 km to ~5-10 km depth. Great earthquakes initiating within the seismogenic zone can propagate updip from this limit, as evidenced for the 2011 Mw9.0 Tohoku-Oki and 2010 Mw8.8 Maule events^{9,10}, while a particular class of events known as “tsunami earthquakes”, appear to rupture only the shallowest, allegedly non-seismogenic part of the megathrust¹¹ (Extended Data fig. 1). The seemingly anomalous characteristics of shallow ruptures suggest a depth-dependency of the rupture process¹⁻³, commonly attributed to changes in fault properties⁴⁻⁷. However, current conceptual models trying to explain the differences are qualitative and case-dependent, they treat the different rupture characteristics individually, as if they were caused by unrelated factors, and do not pinpoint the primary physical causes. Slow rupture propagation^{12,13} and large slip^{14,15}, for instance, are commonly attributed to the presence of weak subducting sediment¹⁶, whereas pore pressure-related weakening^{4,5}, or a depth-dependent distribution of initial stresses⁶, have also been proposed to explain large slip and high-frequency depletion. None of these models explains the remarkable Mw-Ms discrepancy of shallow earthquakes.

We propose a conceptual change to this unsolved question. Our hypothesis is that changes in fault mechanics are not necessarily required to explain the observed depth-dependent trends of the rupture characteristics. Instead, we postulate that it mainly reflects depth variations of the overriding plate elastic properties at a larger scale. This hypothesis stands on the fact that downgoing oceanic slabs and overriding plates exhibit contrasting permanent deformation patterns^{17,18} (fig. 1). Overriding plates display widespread contractional structures indicating a dominant sub-horizontal principal compressional stress, whereas oceanic plates are dominated by extensional faulting, implying a $\sim 90^\circ$ rotation of the orientation of the principal stresses across the megathrust. Sedimentary strata of under-thrusting plates have sub-horizontal attitude, typically lack contractional deformation, and are cut by normal faults, supporting that the principal compressional stresses are sub-vertical immediately below the megathrust fault. Thus, the distribution of tectonic structures and the inferred orientation of principal stresses support that the elastic energy released during megathrust earthquakes has fundamentally accumulated in overriding plates (fig. 1). Correspondingly, co-seismic deformation should affect overriding plates, with negligible effect on under-thrusting plates. Hence, the recorded tectonic history supports that the elastic properties of the overriding plate need to be considered to understand the earthquake phenomena, given the constraints they impose to dynamic stress transfer during co-seismic slip.

Our hypothesis implies that differences in rupture behavior should be predictable and quantifiable if the depth distribution of elastic properties is known, and this information could be used to improve tsunami hazard assessment. To test it, we used 48 compressional-wave velocity (V_P) models obtained with travel-time modelling of wide-angle reflection and refraction seismic profiles across Circum-Pacific and Indian Ocean subduction zones (Extended Data fig. 1 and table 1). We averaged V_P at the lower part of the overriding plate as a function of inter-plate boundary depth below seafloor, from the surface to ~ 25 km depth (fig. 2 and Methods). The travel-time-based V_P models allow resolving the rock volume encompassing the propagating rupture front (Extended Data fig. 3 and Methods). The global $V_P(z)$ trends of accretionary and erosional margins, where z is inter-plate boundary depth below seafloor, display slight differences at depths shallower than 5 km, and gradually converge below this depth (fig. 2b and Extended Data fig. 4a). $V_P(z)$ variations probably reflect differences in rock nature between the two margin types in the shallow part, and a progressive rock compaction and fracture decreasing at deeper levels, as suggested by seismic images (fig. 1). On average, V_P increases by a factor of 2.0-2.5, from ~ 3.0 km/s at ~ 1 km depth to ~ 6.5 km/s at ~ 25 km depth (fig. 2c), with gradient decreasing downwards (Extended Data fig. 5a).

We then use V_P to derive rigidity ($\mu = \rho V_S^2$, where ρ is density and V_S is shear-wave velocity), which affects important aspects of earthquake rupture. In the absence of direct $V_S(z)$ measurements, we apply well-established $\rho(V_P)$ and $V_S(V_P)$ empirical relationships from experimental data of multiple rock types¹⁹ (Methods). The resulting $\rho(z)$ and $V_S(z)$ distributions are shown in Extended Data fig. 3, and $\mu(z)$ in fig. 2d. The trend shows a 4-5-fold μ increase between the surface and ~ 25 km depth, from <10 GPa at 1-2 km depth to 40-45 GPa at ~ 20 -25 km depth, with gradient decreasing downwards (Extended Data fig. 5b). Based on the observed rates of variation we define three domains along the megathrust: shallow (0-5 km), transitional (5-10 km) and regular (10-25 km) (fig. 2d).

The depth trend of elastic properties within the three domains strongly conditions the predicted differences in rupture characteristics. To show this, we compare predicted ratios of amount of slip, rupture duration, and corner frequency, as well as M_W - M_S , for earthquakes of equal magnitude and equal stress drop²⁰, computed based on classical self-similar source theory taking as a reference the values at 25 km depth (fig. 3 and Methods). Our results show that, for all the source properties considered, relative changes concentrate in the shallow domain. For a given earthquake magnitude and stress drop, the predicted amount of slip is ~5-10 times larger in the shallow domain than in the regular domain (fig. 3a), whereas rupture duration is 2-3 times larger (fig. 3b), and corner frequency (f_c) 1-2 octaves lower (fig. 3c). The f_c lowering implies that shallow earthquakes should be depleted in high frequencies. The high-frequency depletion originates a depth-dependent discrepancy between M_W and M_S because these two earthquake magnitudes are based on data at different frequencies (Extended Data fig. 6b). The predicted M_W - M_S difference for a M_W 7.5 event is 0.2-0.3 in the regular domain, but increases to 0.6-0.8 in the shallow domain due to the f_c decrease (fig. 3d). Fig. 4 presents a conceptual model summarizing all these predictions.

The obtained values agree with average trends of rupture properties of natural examples. One example is tsunami earthquakes, infrequent, but well-documented events that rupture only the shallowest megathrust and generate anomalously large tsunamis for their magnitude^{11,21} (Extended Data fig. 1 and table 2). These events display all the characteristics of shallow ruptures, including long duration, high-frequency depletion inducing subdued seismic shaking, and large M_W - M_S discrepancy^{13,21,22}. These characteristics, however, are not unique of tsunami earthquakes. Great earthquakes rupturing from deep into the seismogenic zone to close to the trench axis exhibit similar rupture properties in their shallow-depth portion¹.

Studies of tsunami earthquakes based on seismological, geodetic and tsunami modelling support that slip did not only concentrate in the shallow domain, but it actually increased upwards to peak near the trench axis^{13,23}. Likewise, slip of some great tsunamigenic earthquakes appear to have peaked close to the trench, more clearly for the M_W 9.1, 2011 Tohoku-Oki event, with maximum slip exceeding 50 m near the trench axis^{9,24}, and for the M_W 8.8, 2010 Maule event¹⁰. Current understanding attribute large shallow slip to the frictional properties of fault-rock materials²⁵, or to local features like near-trench slumps²⁶, and subducting relief²⁷. However, the 4-5-fold μ decrease in the shallowest part of the megathrust (fig. 2d) implies a 5-10-fold increase in slip relative to regular earthquakes of the same size (fig. 3a). This trenchward slip increase is consistent with the large shallow slip required to generate large tsunamis by either tsunami earthquakes^{12,14} or great earthquakes rupturing to the trench²⁸. Specifically, a 5-fold reduction of μ between regular and shallow domain depths was inferred to fit tsunami wave amplitudes of the M_S 7.0-7.2, 1992 Nicaragua tsunami earthquake¹⁵ (Extended Data fig. 1 and table S2).

The slow rupture propagation and long duration compared to deeper events of the same magnitude is a key characteristic of tsunami earthquakes, to the point that they are often referred to as “slow tsunami earthquakes”^{12,13}. Their average propagation velocity is ~1-2 km/s²², whereas for deeper events it is ~3 km/s, in agreement with predicted propagation velocity differences between the shallow and regular domains (Extended Data fig. 4c). The predicted increase of source duration also agrees with observations of

normalized duration for M_w 5.0-7.5 earthquakes of Circum-Pacific subduction zones²⁴ (Extended Data fig. 7a). These data show that duration of earthquakes shallower than ~10 km depth, which include 6 tsunami earthquakes, is 2-3 times longer than for deeper events, as predicted by our model (fig. 3b and Extended Data fig. 7b). Smaller magnitude events occurring within the rupture areas of the M_w 9.2, 2004 Sumatra-Andaman²⁹ and the M_w 9.1, 2011 Tohoku-Oki³⁰ earthquakes, also show longer normalized duration in the near-trench zone.

Another characteristic of tsunami earthquakes is a high-frequency deficit compared to regular events of equal magnitude¹³. The resulting ground shaking is weaker and tsunami hazard based on human perception is therefore underestimated. This was the case of the 1992 Nicaragua earthquake, where mild shaking caused little damage and the tsunami hit the coast unexpectedly. But this feature is not unique to tsunami earthquakes. Seismological data of recent great tsunamigenic earthquakes support a pattern of two distinct rupture modes for the M_w 9.1, 2004 Sumatra-Andaman¹, the M_w 9.1, 2011 Tohoku-Oki³¹, the M_w 8.8, 2010 Maule³², and the M_w 8.3, 2015 Illapel³³ events (Extended Data fig. 1 and table 2). Those earthquakes initiated deep into the seismogenic zone with rupture radiating high-frequency energy and producing strong shaking, followed by shallow rupture with lower frequency content that generated large seafloor deformation and originated the tsunamis. The trend of higher frequency content in the regular domain (fig. 3c and Extended Data fig. 6a) due to the spectral amplitude decay (Extended Data fig. 6b) can also be explained by the depth-dependent overriding rock properties, without calling for a hypothetical depth-dependent stress drop trend that is barely supported by seismological data²⁰.

Owing to high-frequency depletion, the initial magnitude estimation of the 1992 Nicaragua earthquake was M_s 6.8 (later corrected to 7.0-7.2), too low to issue a tsunami alert. However, the M_w 7.6-7.8 calculated after more detailed data analysis, if available earlier, would have prompted the alert. On average, tsunami earthquakes have $|M_w| \approx 7.6$ and $|M_w - M_s| \approx 0.65$ (Extended data table 2), so that they have larger $M_w - M_s$ than regular earthquakes of the same magnitude. These $M_w - M_s$ discrepancies are difficult to explain for M_w 7.6 magnitude earthquakes rupturing the regular domain, where $M_w - M_s$ should be $\leq \sim 0.3$ (fig. 3d). However, the depth-dependent elastic properties imply that the $M_w - M_s$ discrepancy for earthquakes of this magnitude can increase to 0.6-0.8 when rupture concentrates in the shallow domain (fig. 3d), in agreement with observations.

Although shallow megathrust earthquake ruptures are infrequent, their slip distribution peaking near the trench makes them particularly hazardous. Extended Data fig.8 shows that a M_w 7 earthquake rupturing the regular domain has the same spectral amplitude at 20 s as a M_w 8 event rupturing the shallow domain, and thus the same M_s , if depth-dependent changes of elastic properties are taken into account. The associated tsunami hazard of these two events is radically different, but it cannot be forecast based on M_s . Proper magnitude and tsunami hazard evaluation require incorporating focal depth information and the local $V_P(z)$. In the interim lack of local velocity models, tsunami forecast can be improved using the global trends obtained here (fig. 2).

In summary, inter-plate fault mechanics may play a role controlling different aspects of the seismic cycle, but do not seem to be required to explain the overall depth-dependent

trend of the source properties considered here. We show quantitatively that the observed characteristics of both shallow and regular earthquakes reflect the elastic properties of the rock volume undergoing dynamic stress transfer. However, note that our model uses average physical properties to explain global trends of source characteristics rather than individual examples. The observed variability of physical properties across different systems (fig. 2b) implies that proper analysis of particular seismic events would require determination of the elastic properties throughout their specific rupture zone. These properties should be incorporated into numerical models to be able to evaluate the potential effect of complex fault mechanics on rupture characteristics.

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Author contribution

VS had the original idea, conceived the physical model, selected and digitized the P-wave velocity profiles, performed the calculations, made all figures except figure 1, and wrote the first draft of the manuscript. CRR made the geological interpretation of the physical model, contributed to identify its implications, processed and pre-stack depth migrated Java 07 and interpreted both seismic images on figure 1, and contributed to write the manuscript.

Data and code availability

The digitized values of P-wave seismic velocity above inter-plate boundary versus depth and seafloor depth along the 48 wide-angle seismic profiles used here, as well as the scripts necessary to process the data and reproduce the main results and figures presented in this work, are available at the public research data repository *figshare* (<https://doi.org/10.6084/m9.figshare.9729302.v1>).

Main figure legends

Figure 1 | Tectonic structure of the shallow region of two types of subduction zones where tsunamis are generated. **a)** Depth-migrated multi-channel seismic image of the Java Trench. The overriding plate is made of accreted sediment thrust sheets, with different structure where the prism is $>\sim 5$ km thick (inset **b**), and in the front, where it is $<\sim 5$ km thick (inset **c**). Thrust at the front gradually rotated as material accumulated, thickening the prism landward (**c**), but when thrusts are too steep to continue slipping, out-of-sequence thrusts and folding further thicken and compact the prism (**b**). **d)** Pre-stack depth migration of the Japan Trench dominated by tectonic erosion¹⁷. The igneous basement flexes accumulating elastic energy and is cut by normal faults in its upper section (inset **e**). The frontal ~ 25 km is a sediment prism $<\sim 5$ km thick, with thrust faulting (inset **f**). Both margins (**a**, **d**) show contraction structures in the overriding plate indicating sub-horizontal main compressional stress. However, under the mega-thrust fault, the downgoing plate displays a fundamentally different structure: The top of the oceanic igneous crust is traced from the incoming plate into the under-thrusting slab, overlaid by a layer of little deformed sediment strata. The oceanic plate is characterized by horst and graben associated to bend-faulting, indicating a sub-vertical main stress. We interpret that the properties of the rock body deforming during rupture propagation (in red in the images) should change significantly within the frontal ~ 50 km of the margin. Stresses will be transferred through relatively consolidated material at ~ 10 km depth to progressively more fractured material at ~ 5 km depth, and a highly disaggregated upper plate, in the thinnest frontal ~ 15 km of the overriding plate.

Figure 2 | Convergent margin structure and P-wave velocity at the lower part of overriding plates. **(a)** Conceptual model with main geological features of convergent margins, based on geophysical data of Central and South America. V_P decrease and intensified faulting towards the trench is interpreted to reflect increasing porosity and fracturing degree (see also fig. 1). **(b)** Colored circles show digitized V_P values of the lower part of the upper plate just above the inter-plate boundary, as a function of inter-plate boundary depth below seafloor (depth b.s.) (z). Red circles correspond to accretionary margins and yellow circles to accretionary margins. Location of profiles in the compilation is shown in Extended Data fig. 1. Additional information and references

are provided in Extended data table 1. Orange lines with arrowheads indicate correspondence between different depth domains in (a) and V_P distribution (b). (c) Orange circles show average V_P as a function of z , obtained by averaging $V_P(z)$ values in (b) within a 1 km-thick sliding window. (d) Blue circles show μ as a function of z , obtained from $\rho(z)$ and $V_S(z)$ in Extended Data fig. 4. Data point values in c and d are fitted with a fourth-order polynomial regression (black lines). The size of error bars is one standard deviation.

Figure 3 | Predicted earthquake rupture and energy release characteristics. (a)

Blue circles show slip ratio (D_R) for an earthquake of a given magnitude as a function of inter-plate boundary depth b. s. (z). D_R is calculated taking as reference unit the slip at $z=25$ km. (b) Red circles show relative Mode III rupture duration (T_R) for an earthquake of a given magnitude, as a function of z . T_R is calculated taking as reference the rupture duration per unit length at $z=25$ km. (c) White circles show corner frequency ratio (f_R) for an earthquake of a given magnitude as a function of z . f_R is calculated taking as reference unit the corner frequency at $z=25$ km. The dashed and dotted black lines show frequencies one and two octaves lower than the reference one, respectively. (d) Black lines show the difference between M_W and M_S as a function of z , for earthquakes of $M_W=6.5, 7, 7.5$, and 8. Orange, yellow and white rectangles in all panels indicate the depth extension of the shallow, transitional and regular domains referred to in the text. See details on the calculations in the main text. Data point values in a-c are fitted with a fourth-order polynomial regression (black lines). The size of the error bars is one standard deviation.

Figure 4 | Conceptual model of megathrust seismogenic zone domains. Cartoon

displays: (1) The main geological and tectonic features of the upper and subducting plate based on geophysical data of Central and South America. Dotted black lines in the upper plate indicate isovelocity contours. Overriding plate faulting and fracturing increases toward the trench; hereby reducing V_P , ρ , V_S and rigidity (μ). Deformation and fracturing concentrate above subducting sediment and inter-plate boundary. (2) Differences of earthquake rupture and energy release characteristics for megathrust earthquakes occurring within the shallow (red) and regular (blue) domains discussed in main text. Red (blue) ellipses labelled EQ₁ (EQ₂) are rupture zones of the same size occurring within the shallow (regular) domains. Depth-dependent changes in elastic properties quantitatively explain that, compared to EQ₂, EQ₁ should have up to 2-3 times slower propagation velocity, so that 2-3 times longer duration; 5-10 times larger slip, so high tsunamigenic potential; 1-2 octaves lower corner frequency, so high-frequency depletion and subdued seismic shaking; a 3-4 times larger M_W-M_S discrepancy, of up to 0.6-0.8 for a $M_W 7.5$ earthquake (fig. 3). The model predicts that the shallowest ruptures, and especially those reaching the trench axis, should show the largest differences with respect to regular events in all the analyzed attributes, as it is observed in natural examples.

d

a

Figure 1

Figure 2

Figure 3

Figure 4

Methods

Joint reflection and refraction travel-time modelling of wide-angle seismic data

The methods used to obtain the 2D V_P models included in our compilation (Extended Data table 1) include both forward³⁴ and inverse³⁵⁻³⁷ techniques. All the selected profiles (Extended Data fig. 1) share two common key aspects. First, they are travel-time-fitting techniques based on ray tracing approaches, and second, they include seismic phases reflected at the inter-plate boundary. The joint modelling of first arrival (i.e. refracted waves within the overriding and subducting plates) and inter-plate reflection travel-times allow mapping not only the V_P structure but also the location and geometry of the inter-plate boundary, from the trench to depths ranging between ~15 km and ~30 km depending on data quality and experiment setup. When 2D V_P models and multi-channel seismic data (fig. 1) are spatially coincident, they can be combined to improve the geological interpretation of seismic velocities (Extended Data fig. 2). Monte Carlo-type statistical analysis of several profiles, with multiple inversions using different initial models and assuming realistic travel-time picking errors, provides V_P uncertainty. Above the inter-plate boundary, it typically is of 0.05-0.1 km/s at the shallowest megathrust sector and of 0.2-0.3 km/s at ~25 km depth³⁸⁻⁴¹

Resolution of travel-time-based seismic modelling vs. wavelength of the stress wavefield associated to earthquake rupture propagation

Using seismic velocity models to infer earthquake rupture-related properties implicitly assumes that rupture propagation is affected by the properties of a rock volume that can be resolved by V_P models resolution. Rupture initiation depends on the stress distribution surrounding the crack tip, and the subsequent rupture propagation and material deformation reflect the dynamic stress transfer around the crack tip⁴². Rupture propagation velocity is limited by the speed at which stresses can propagate through the material (i.e. V_S for mode III rupture)⁴³. Additionally, near-field ground motion recordings of large subduction earthquakes consistently display a peak frequency f_{sw} of ~1-4 Hz^{44,45}. This implies that the stress transfer, whose limiting propagation velocity along the megathrust varies with depth as indicated in Extended Data fig.3c, has an associated wavelength $\lambda_{sw}(z) = V_S(z)/f_{sw}$, ranging from ~0.5-1.5 km near the surface to ~1.5-4.0 km at 25 km depth (blueish polygon in Extended Data fig. 3).

Modern wide-angle seismic data can resolve V_P of the rock body equivalent to the wavelength of the stress wavefield. For ray-based, travel-time-fitting methods such as the ones used in this study (Extended data table 1), model resolution is inferred to be limited to the width of the first Fresnel zone, $R_F = \sqrt{\frac{zV_P}{2f_s}}$, where z is the imaged target depth, V_P is P-wave velocity, and f_s is the peak frequency of the seismic source. Taking the $V_P(z)$ values in Extended Data fig.2c and $f_s=8-12$ Hz, which is the typical frequency content of records, we obtain $R_F(z)$ ranging from ~0.3-0.4 km near the trench to ~2.5-3.5 km at 25 km depth (reddish area in Extended Data fig. 3). The comparable size of the region resolved by travel-time-based velocity models at all depths and the wavelength of the seismic wavefield associated to rupture propagation (Extended Data fig. 3), supports that the modeled $V_P(z)$ in fig. 2, as well as the rest of V_P -derived

properties (fig. 2d and Extended Data fig. 4), represent the physical properties influencing the dynamic stress transfer associated to the propagating seismic rupture.

Estimation of $V_P(z)$ above the inter-plate boundary

To obtain the V_P values as a function of inter-plate boundary depth below the seafloor (fig. 2), we first digitized V_P just above the inter-plate boundary, inter-plate boundary depth, and seafloor depth/land topography, along the 48 wide-angle seismic profiles (Extended Data table 1). Second, we interpolated V_P , inter-plate boundary depth below sea surface (z_i), and seafloor depth/land topography (z_o) at constant x intervals (2 km) along each profile by applying Akima splines to obtain V_P as a function of upper plate thickness, $z=z_i-z_o$, using *Generic Mapping Tools (GMT)*⁴⁶. For simplicity, this value is referred to as “inter-plate boundary depth b. s.” throughout the manuscript and in the figures. Third, we interpolated V_P at constant z intervals (1 km) along each profile using also *GMT*. Fourth, for each z between 1 km and 25 km, we calculated the average V_P value of all profiles and its corresponding standard deviation. Finally, we used *GMT* to calculate a fourth-order polynomial regression fit of the $V_P(z)$ values.

Derivation of rock properties from $V_P(z)$

The $V_P(z)$ values shown in fig. 2c are used as a reference to calculate the rest of physical properties presented throughout the manuscript as a function of z . The shear-wave modulus, or rigidity, $\mu = \rho V_S^2$ (fig. 2d), is obtained by applying first empirically-based relations proposed by Brocher (2005)¹⁹ to estimate ρ (Extended Data fig. 4b) and V_S (Extended Data fig. 4c) from V_P , respectively. For density, it is $\rho = 1.6612V_P - 0.4721V_P^2 + 0.0671V_P^3 - 0.0043V_P^4 + 0.000106V_P^5$, whereas for shear velocity, it is $V_S = 0.7858 - 1.2344V_P + 0.7949V_P^2 - 0.1238V_P^3 + 0.0064V_P^4$. Both relationships are based on a compilation of V_P , V_S and ρ measures of a wide variety of Earth crustal rocks, obtained from wireline borehole logs, vertical seismic profiles, laboratory measurements, and seismic tomography models.

Derivation of depth-dependent earthquake rupture characteristics

1) Amount of slip

The seismic moment released during co-seismic rupture is, $M_0 = \int_S \mu D ds \approx \bar{\mu} \bar{D} S$, where D is co-seismic slip, μ is rigidity, and the integral runs over the whole rupture area, S . If we take average values over S ($\bar{D}$ and $\bar{\mu}$), M_0 can be estimated applying the right hand side. M_0 and S can be estimated from waveform data and aftershock location, but μ and D are generally unknown, so they have a tradeoff in the calculations. To show the effect of $\mu(z)$ for events of equal M_0 and S , we compare differences in the amount of slip as a function of depth as a slip ratio $D_R(z)$. Using as a unit reference the amount of slip at the Regular Domain depth of 25 km, $D_R(z)$ can be calculated as $D_R(z) = \frac{D(z)}{D^*} = \frac{\mu^*}{\mu(z)}$, where D^* , μ^* are amount of slip and rigidity at the reference depth of 25 km, and $D(z)$, $\mu(z)$ are at depth z . Fig. 3a displays $D_R(z)$ using $\mu(z)$ from the global compilation (fig. 2d).

2) Rupture duration

Given that stresses must accumulate at the crack tip for spontaneous propagation, rupture velocity (u) is limited by the velocity at which stresses are transmitted throughout the material. For mode III cracks, in which a shear stress acts parallel to the plane of the crack and parallel to the crack front, as in megathrust fault ruptures, the theoretical limiting velocity is V_s . Field data indicate that u is actually 70-90% of V_s at the depth of the largest slip. Thus, the observed $V_s(z)$ trend above the megathrust (Extended Data fig. 4c) implies that u should be significantly lower in the shallow domain than in the regular domain. To illustrate this effect we calculated the normalized source duration for a unit rupture length at different depths, $T_R(z)$, using $u(z)$ in Extended Data fig. 4c and taking as a reference the rupture duration at the Regular Domain depth of 25 km, as $T_R(z) = \frac{T(z)}{T^*} = \frac{u^*}{u(z)} = \frac{V_s^*}{V_s(z)}$, where T^* , u^* , and V_s^* are rupture duration per unit length, rupture velocity and shear velocity at the reference depth of 25 km, and $T(z)$, $u(z)$, $V_s(z)$ are at depth z .

3) Corner frequency

The $V_s(z)$ distribution also influences the frequency content of the energy released during an earthquake. This can be estimated from the spectral shape of the moment-rate spectrum, $\dot{M}(f)$, which is calculated based on waveform records. The reference spectra to compare with values obtained from observational data is, $\dot{M}(f) = \frac{M_0 f_c^n}{f^{n+f_c^n}}$, where f_c is the corner frequency, which marks the frequency where the spectrum starts to decay, and n is the slope of the spectral decay. A value of $n=2$ is typically used as a reference, as it fits the observed decay in most cases, whereas $f_c = cV_s \left(\frac{\Delta\sigma}{M_0}\right)^{\frac{1}{3}}$, where $c=0.49$ is a dimensionless constant, and $\Delta\sigma$ is stress drop. Thus, V_s of the region enclosing the propagating rupture front determines f_c , and therefore the spectral shape. In contrast to V_s , there is no clear evidence indicating a systematic, universal depth-dependence of $\Delta\sigma$ in subduction zones²⁰. Therefore, we assume that it is depth-independent, and we isolate the $V_s(z)$ effect on the corner frequency ratio, $f_R(z)$, for events of equal M_0 , using $f_c(V_s)$. Taking as a reference the f_c and V_s at the regular domain depth of 25 km, we have $f_R(z) = \frac{f_c(z)}{f_c^*} = \frac{V_s(z)}{V_s^*} = T_R(z)^{-1}$, where f_c^* and V_s^* are the corner frequency and shear-wave velocity at the reference depth of 25 km, and $f_c(z)$, $V_s(z)$ and $T_R(z)$ are at depth z .

4) Moment Magnitude vs. Surface Wave Magnitude

Another consequence of the V_s -dependent high frequency depletion is a depth-dependent discrepancy between the earthquake moment magnitude M_W , estimated from long-period waves (~ 250 s), and its surface wave magnitude M_S , estimated at shorter periods (~ 20 s) (Extended data fig. 6b). This effect is illustrated in fig. 3d, where each curve represents the difference between M_W and M_S calculated from the moment-rate spectrum as a function of depth using (4), for four different M_W . Given that f_c is anti-correlated with M_0 (5), M_S tends to saturate for large magnitudes, so that the M_W-M_S discrepancy increases with increasing M_W . However, fig. 3d shows that the discrepancy for any magnitude is also depth-dependent.

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Extended Data legends

Extended Data table 1 | Location of seismic profiles and margin type. Geographical locations of the 48 wide-angle seismic profiles along the circum-Pacific included in the data set. The type of margin is indicated in the fourth column with an A (accretionary) or an E (erosional), which correspond to the red and yellow circles in Extended Data fig.1, respectively. Reference number is indicated in the last column.

Extended Data table 2 | Location and magnitude of circum-Pacific megathrust earthquakes. Geographical location, date, and magnitudes of the circum-Pacific megathrust earthquakes shown in Extended Data fig.1. The list include the six largest magnitude earthquakes having occurred since 1960, as well as 12 events identified as tsunami earthquakes. Reference numbers for the source parameters and energy release characteristics of all the events are indicated in the last column

Extended data figure 1 | Location map of seismic profiles and recent great and tsunami earthquakes. Color-coded relief map of seafloor (blue-green) and emerged land (grey). Circles indicate location of the trench-crossing refraction and wide-angle reflection seismic (WAS) profiles used in this study. Yellow-filled circles are in accretionary prisms and red-filled circles in erosional margins. The location, type of margin and references for all profiles are listed in table S1. Numbered white stars show location of 12 events recognized as tsunami earthquakes according to the definition of Kanamori (1972): 1) Mw7.6, 1992 Nicaragua; 2) Mw7.6, 1960 Peru; 3) Mw7.5, 1995 Peru; 4) Ms7.2, 1947 Hikurangi; 5) Mw7.1, 2010 Solomon; 6) Mw7.6, 1994 Java; 7) Mw7.8, 2006 Java; 8) Mw7.8, 2010 Mentawai; 9) Mw8.0, 1896 Sanriku; 10) Mw7.5, 1975 Kurile; 11) Mw7.8, 1963 Kurile; 12) Mw8.2, 1946 Aleutian. Orange polygons display the rupture areas of the six largest megathrust earthquakes since 1960: Mw9.5, 1960 Valdivia; Mw9.2, 1964 Alaska; Mw9.1, 2004 Andaman Islands; Mw9.1, 2010 Tohoku-Oki; Mw8.8, 2010 Maule; Mw8.7, 1965 Rat Island. Hypocentral location, date, magnitude and references for all these earthquakes are listed in table S2.

Extended Data figure 2 | Superposition of multi-channel seismic image and P-wave velocity model. Example of superposition of a V_P model (color, see scale) on top of a spatially coincident multi-channel seismic image (shading) along profile NIC-20, acquired in the convergent margin of Nicaragua. This profile crosses the rupture area of the 1992 Nicaragua tsunami earthquake (Extended Data figure 1). Black lines show iso-velocity contours with their corresponding velocity values. White circles indicate the approximate location of the inter-plate boundary, where megathrust earthquakes take place.

Extended Data figure 3 | Resolution of V_P models and wavelength of rupture stress wavefield. The reddish polygon displays the width of the Fresnel zone as a function of depth assuming $V_P(z)$ in fig. 2a and energy sources with minimum (maximum) peak frequency $f_s=8$ Hz (12 Hz). The blueish polygon indicates the approximate wavelength of the stress wavefield associated to earthquake rupture propagation (λ_w), assuming $V_s(z)$ in Extended Data fig.5c as propagation velocity, and near-field ground motion spectra with minimum (maximum) peak frequency $f_{sw}=1$ Hz (4 Hz) (see Methods for details).

Extended Data figure 4 | Physical properties vs. inter-plate boundary depth. (a) Red (yellow) circles show V_P as a function of z . It is obtained by averaging digitized V_P values of accretionary and erosional margins (red and yellow circles, respectively, in fig. 2b). **(b)** White circles show density (ρ) just above the inter-plate boundary, as a function of z , obtained by applying Brocher's (2005) $\rho(V_P)$ relationship. **(c)** Red circles show shear-wave velocity (V_s) just above the inter-plate boundary, as a function of z , obtained by applying Brocher's (2005) $V_s(V_P)$ relationship. The pink polygon covers the range of possible mode III rupture velocities, as a function of z , according to field observations: $u(z)=0.7-0.9V_s(z)$. The black line is a fourth-order polynomial regression fit of the $V_P(z)$, $\rho(z)$ and $V_s(z)$ values, respectively. The size of the error bars in all cases is one standard deviation.

Extended Data figure 5 | P-wave velocity and rigidity gradients. (a) Red line shows the depth gradient of V_P as a function of inter-plate boundary depth, $\frac{\partial V_P(z)}{\partial z}$. It corresponds to the derivative of the $V_P(z)$ polynomial regression fit (black line in fig. 2c). (b) Blue line shows the depth gradient of μ as a function of inter-plate boundary depth, $\frac{\partial \mu(z)}{\partial z}$. It corresponds to the derivative of the $\mu(z)$ polynomial regression fit (black line in fig. 2d).

Extended Data figure 6 | Corner frequency and moment rate spectra. (a) Colored circles show corner frequency as a function of inter-plate boundary depth (z), for events of $M_w=5.8-8.6$. $\Delta\sigma=3$ MPa is used in the calculations, and $V_s(z)$ is taken from Extended Data fig.3c. The color scale indicates M_w . (b) Solid lines show calculated moment rate spectra for three events of $M_w=6.4$ (bottom), 7.4 (mid), and 8.4 (top). Black, blue and red lines correspond to V_s at $z=1$ km, 6 km, and 25 km, respectively, for each event. Colored circles indicate corner frequency according to color code in Extended Data fig.6a. Vertical dashed lines indicate periods of 250 s and 20 s, reference to calculate M_w and M_s , respectively. In all cases, note the high frequency depletion at shallow depths.

Extended Data figure 7 | Source duration of Circum-Pacific megathrust earthquakes. (a) White circles show scaled source duration of 525 moderate size ($M_w 5.0-7.5$) shallow megathrust subduction earthquakes from around the Circum-

Pacific, as a function of depth. Black circles show the same source parameters for six large tsunami earthquakes. Data are from Bilek and Lay (2002)²¹. This article contains all the information on the procedure followed to calculate the source parameters. **(b)** Red circles are the normalized source duration in (a) averaged within a 2 km-thick sliding window. Blue circles correspond to relative rupture duration in fig. 3b scaled to fit average normalized rupture duration within the regular domain in **(a)** (~3.5 s), and shifted 4.5 km down to compensate for the difference between depth below sea surface and depth below seafloor. Error bars are one standard deviation.

Extended Data figure 8 | Range of variation of M_w for a given M_s . White circles show M_w for events occurring at different inter-plate boundary depth b.s. (z) that have the same spectral amplitude at 20 s (hence equivalent M_s).