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Earthquake supercycle in subduction zones controlled by the width of the seismogenic zone

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A supercycle describes a long-term cluster of differently-sized megathrust earthquakes, leading up to the final complete failure of a subduction zone segment[1,2]. The precise controls on supercycles are unclear, although structural and frictional heterogeneities are proposed[1]. We recognize that supercycles are suggested to occur in those regions[1–4] where the estimated downdip width of the seismogenic zone[5–7] is larger than average. Here we investigate the link between supercycles and the seismogenic zone downdip width using a two-dimensional numerical model[8]. In our simulations, the first megathrust earthquakes in a supercycle generally rupture only the outermost parts of the seismogenic zone. These partial ruptures are stopped owing to a large excess of strength over stress, and transfer stresses towards the centre of the seismogenic zone. In addition to the continued tectonic loading, they thereby gradually reduce the strength excess so that the largest megathrust events finally rupture the entire seismogenic zone and release most of the accumulated stress. A greater width increases the average strength excess and thus favours supercycles over ordinary cycles of only similarly sized complete ruptures. Our results imply that larger than thus far observed earthquakes could conclude a supercycle where seismogenic zone widths are larger than average.

In subduction zones, an oceanic plate moves into the mantle beneath an overriding plate along the plate boundary megathrust fault. In a first-order description of a seismic cycle, the two plates are locked together along patches of the megathrust around which stresses slowly accumulate during a long interseismic period until they locally overcome the plate boundary strength. A megathrust earthquake nucleates and releases the stored stresses in rapid slip during the coseismic period.

Observations show that such earthquakes exhibit a high variability in rupture area and slip in several subduction zones, involving large ($M_w > 7$) and great ($M_w \geq 8.5$) megathrust earthquakes[9–12]. Where and when great megathrust earthquakes occur is not well understood[13,14]. Up to the 2011 $M_w = 9.0$ Tohoku earthquake, only large earthquakes were known from the historical and instrumental record in the north-eastern Japan subduction zone. Together with other arguments this led to the general impression that great megathrust earthquakes would not occur there[15,16]. In hindsight, we know that they can and that such superevents with nearly complete stress drop[17] might be part of a supercycle that transcends ordinary seismic cycles[2].

On the basis of long palaeoseismic and palaeogeodetic records, supercycles in subduction zones were originally proposed for the Mentawai section of the Sunda megathrust[1]. The interpretation of a long record of turbidites led to the suggestion of supercycles in Cascadia[2]. Furthermore, supercycles or supercycle events were suggested for subduction zones in southern Chile[2], and based on shorter records in Hokkaido[2], north-central Chile[3], and Ecuador–Colombia[4]. These locations where supercycles are suggested to occur are highlighted on a global map (Fig. 1).

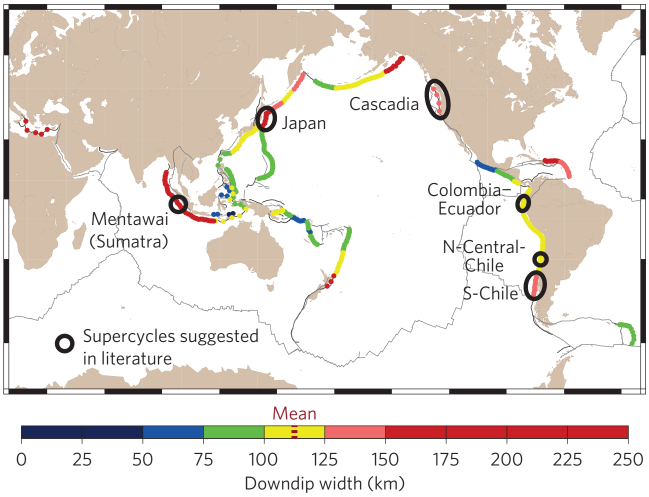

Figure 1 | Downdip width of seismogenic zones and proposed supercycles. Downdip seismogenic zone width values averaged over estimates from refs 5–7 (Supplementary Table 1). The mean value of all estimates (111 km) is indicated. Dotted lines indicate those subduction zones where only one estimate is used. Subduction zones for which supercycles have been proposed are shown with black circles (for references see main text).

In Fig. 1 we also show an estimate of the seismogenic zone downdip width W for each subduction zone segment by averaging the two available global studies[5–7] (Supplementary Table 1). These two estimates are mainly derived using hypocentre locations of moderate interface thrust earthquakes, each yielding an average width value over variations along the strike of a subduction segment. They provide consistent estimates on the width for most subduction zones, although they are debatable for subduction zone segments with at present sparse seismicity or considerable along-strike variations in width (see Supplementary Discussion 1).

We recognize that the thus far suggested supercycles tend to occur in those subduction zones with a estimated downdip width that is larger than the average of all ($W \sim 111$ km, Fig. 1). This suggestive link between the seismogenic downdip width and supercycle occurrence is potentially biased by our short observational record with respect to the long recurrence interval of megathrust earthquakes[14].

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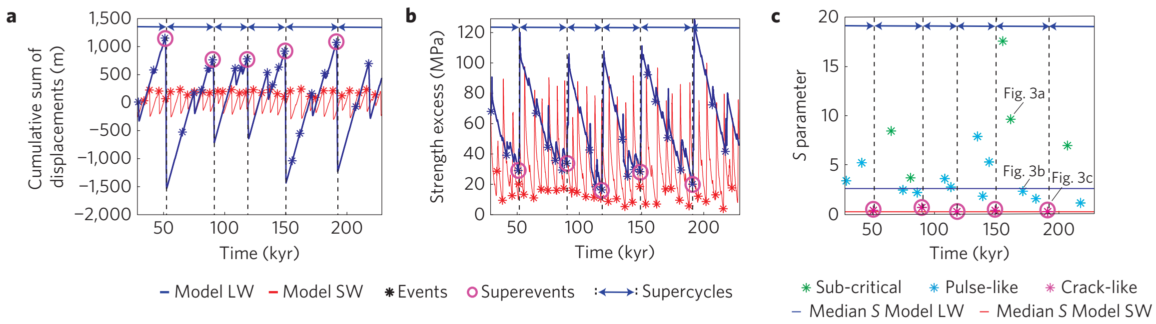

Figure 2 | Long-term and short-term characteristics of wide (LW) and narrow (SW) downdip width reference models. a–c, Functions and parameters, averaged over the downdip width of the respective seismogenic zone (Methods). Detrended, cumulative sum of displacements over time (**a**), evolution of strength excess (**b**) and *S* parameter (**c**). Colours of each event in **c** indicate the rupture style in model LW. Examples of each rupture style during one supercycle are shown in Fig. 3a–c, as indicated. Shown results are upscaled and events are selected according to a picking algorithm (Supplementary Methods).

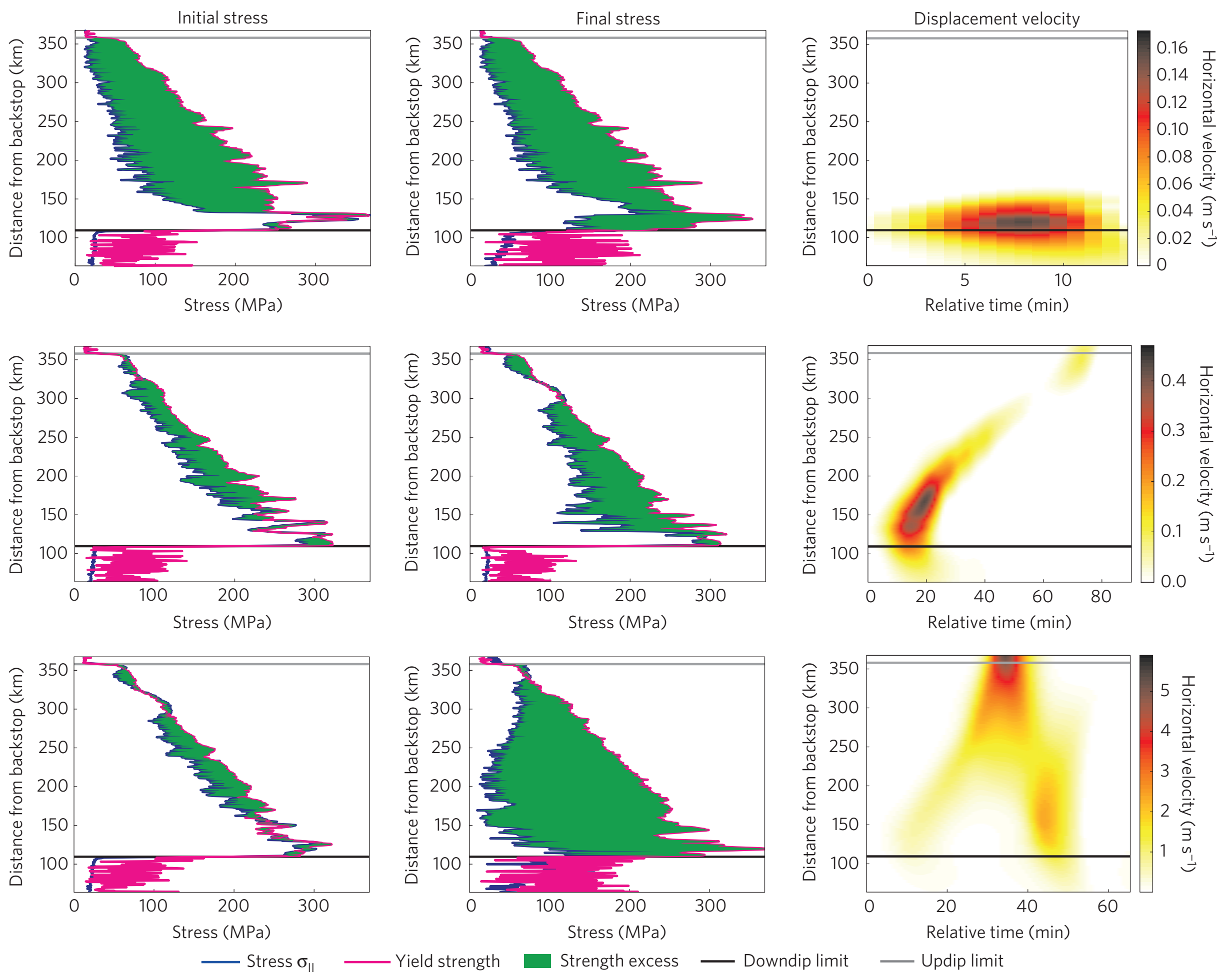

Figure 3 | Rupture styles in wide downdip width reference model (LW). a–c, Subcritical rupture (**a**), pulse-like rupture (**b**) and crack-like rupture (**c**) during one supercycle in model LW (Fig. 2c). Along interface profiles of initial second invariant of the deviatoric stress tensor and strength (left column), final second invariant of the deviatoric stress tensor and strength (central column) and spatiotemporal evolution of horizontal displacement velocity (right column). Shown results are upscaled (Supplementary Methods).

To overcome this limitation and to investigate synthetic data of longer timescales, we investigate the role of the seismogenic zone downdip width by applying the seismo-mechanical modelling approach[8] (Methods). This approach uses a two-dimensional, continuum-based numerical model of a simplified and scaled subduction zone (Supplementary Fig. 1), which incorporates a strongly rate-dependent friction formulation.

The two endmembers of long-term seismicity regimes are illustrated for one model with a large (LW) and one model with a small downdip width (SW) in Fig. 2. For these models, we determine the rupture styles of the events, which include subcritical, pulse-like and crack-like ruptures (Methods). We define subcritical ruptures as events that fail to propagate a long distance out of their nucleation region. Pulse-like ruptures are characterized by the existence of

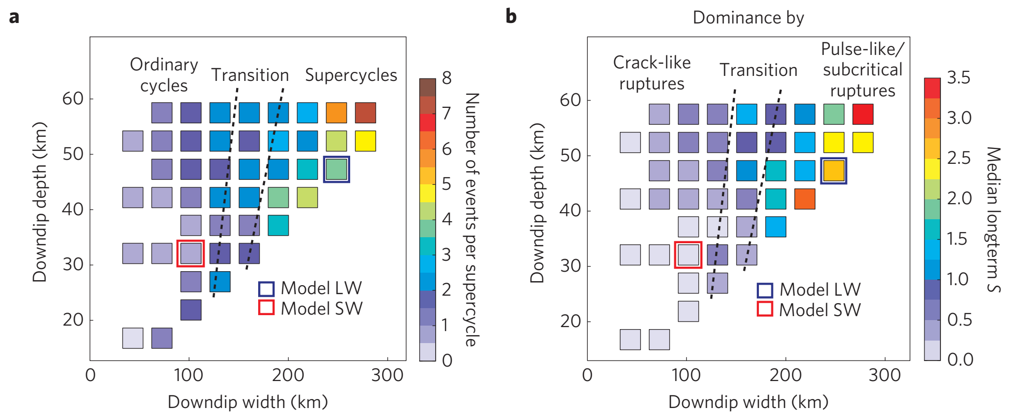

Figure 4 | Impact of the downdip seismogenic zone width and depth. a,**b**, Average number of events per supercycle (**a**) and median of the *S* parameter (**b**; see Supplementary Methods), indicating the dominance of different rupture styles. Dashed lines indicate the transition from ordinary cycles to supercycles (**a**) as well as from the dominance of crack-like to pulse-like and subcritical ruptures (**b**).

significant healing during the rupture propagation[18]. Consequently, they have a local duration of coseismic displacements that is short compared to the total rupture duration. In contrast, in a crack-like rupture most of the rupture area continues to slip until the end of the rupture[19].

Model LW with an upscaled downdip width of 248 km is described as a supercycle-dominated regime. The largest events of similar size recur quasi periodically (Fig. 2a). Between them, a range of smaller events occurs and releases only part of the accumulated strain energy. The smaller events are either subcritical or pulse-like ruptures and nucleate mainly close to the downdip limit of the seismogenic zone (Fig. 3a,b), where the stress build-up due to tectonic loading is fastest. They cause a local stress drop and typically rupture only part of the seismogenic zone as they are stopped as a result of a large initial strength excess. At the stopping location, these partial ruptures leave a stress peak, and thereby transfer stresses from the limits towards the centre of the seismogenic zone such that they, in addition to the ongoing tectonic loading, decrease the strength excess in the entire seismogenic zone (Fig. 2b). Consequently, they contribute to bring the stress state to a critical level at which eventually a crack-like event ruptures the entire seismogenic zone and leads to a large stress drop (Figs 2b and 3c). These complete ruptures are the largest events and start a new supercycle with an initial long period of quiescence or small event activity. Therefore, they are referred to as superevents.

These mechanisms of towards-the-centre-directed stress transfer and intermittent criticality before system-wide events have already been suggested based on spring block[20] and strike-slip[21] numerical models, respectively. We combined these ideas with the evolution of rupture styles to describe the general evolution of stresses and events within a supercycle. We further relate the rupture styles to the *S* parameter, which represents the ratio of the initial strength excess and stress change during an event (Methods). The evolution of a majority of low-stress-drop, high-strength-excess subcritical or pulse-like events into a few high-stress-drop, low-strength-excess crack-like superevents leads to a high median *S* value (Fig. 2c). The temporal transition from pulse- to crack-like ruptures with the decrease of the *S* parameter (Fig. 2c) is consistent with results of two-dimensional dynamic rupture simulations[22]. This rupture style transition is also related to an increase of the stress level, which is consistent with dynamic rupture simulations[23] and laboratory experiments[24].

Model SW with a narrow seismogenic zone (upscaled $W = 102$ km) shows a more ordinary long-term recurrence pattern, as described in detail in ref. 8. It predominantly consists of the quasi-periodic recurrence of similar-sized complete ruptures (Fig. 2a). The interseismic stress build-up close to the seismogenic zone limits alone is sufficient to reduce the average strength excess within the seismogenic zone to a low value (Fig. 2b). At this critical stress state, evolving ruptures readily break the entire seismogenic zone in a crack-like style, which leads to significant stress drops. Consequently, model SW is related to a low median *S* parameter (Fig. 2c).

Exploring the parameter space shows that an increase of the downdip width leads to an increase of the number of events per supercycle, the median *S* values (Fig. 4), and the average recurrence interval between the largest events (Supplementary Fig. 2 and Supplementary Discussion 2). As illustrated by the reference models, this corresponds to a transition from ordinary cycles to supercycles. This is also related to a change in the dominance of the rupture style. Whereas crack-like ruptures dominate in narrow seismogenic zones, a sequence of subcritical and pulse-like ruptures prepare the occurrence of crack-like ruptures in wide seismogenic zones. This transition is due to an increase of the average strength excess in the seismogenic zone. It takes longer and a range of events to reach a critical stress state in the centre of wider seismogenic zones. Based on our models, the transition is at a downdip width of around 120–150 km.

Other factors that affect supercycles to a smaller degree are the downdip depth of the seismogenic zone, the effective static friction coefficient inside the seismogenic zone, which influences the average strength excess, and the maximum difference between static and dynamic friction coefficient (that is, friction drop). The deeper the seismogenic zone, the faster is the interseismic stress increase close to the limits at which events nucleate more frequently. This together more rapidly increases the stress in the centre of the seismogenic zone to a critical level, which leads to shorter recurrence intervals between the largest crack-like events (Supplementary Fig. 2). Thus, the transition in the long-term seismicity and rupture styles occurs at larger widths in deeper-located seismogenic zones (Fig. 4a,b). A lower static friction coefficient and smaller friction drops reduce the number of events per supercycle, the median *S* parameter in model LW (Supplementary Fig. 3), and the average recurrence interval between the largest events (Supplementary Fig. 2). This also indicates a transition from supercycles to ordinary cycles as well as a transition from the dominance of pulse-like to crack-like ruptures.

Our numerical results support the tentative natural observations that the downdip width of the seismogenic zone plays a key role in determining the long-term seismicity behaviour and the occurrence of supercycles in subduction zones (see also Supplementary Results of simplified models of the subduction zones in Sumatra, southern Chile, Cascadia and north-east Japan, Supplementary

Fig. 4). They show that earthquake size variability during a supercycle can be purely explained by the along-dip evolution of stress heterogeneities within an updip- and downdip-bounded homogeneous seismogenic zone. Further a priori complexities, such as previously suggested structural or frictional heterogeneities[1], are not required to generate supercycles. On the basis of our model results, we do not expect supercycles in subduction zones with a relatively small seismogenic zone downdip width (smaller than about 120 km). Although, alternatively, the occurrence of supercycles in segments with a narrow downdip width might also be due to a large lateral width of the seismogenic zone. We conjecture that lateral limits of a seismogenic zone may act in a similar way to the up- and downdip limits. Moreover, interactions between separated seismogenic segments are thought to cause multi-segment ruptures[3,4] and complicate our simplest explanation of supercycles.

Despite these additional complexities that are expected to influence the natural seismicity pattern[25], our findings suggest that supercycles are more likely to occur in subduction zones with a large seismogenic downdip width. On the basis of width estimates from refs 5–7 (Fig. 1), we propose that supercycles could also occur in wide seismogenic zones, such as in Alaska, Java, Antilles and Kamchatka. Particularly, our results have implications for those subduction zones for which only $M_w < 8$ megathrust earthquakes are known to have ruptured the down- or the updip part of a wide seismogenic zone. These smaller earthquakes might have been contributing to bring the stress towards a critical state in the entire seismogenic zone. This would pave the way for larger than expected superevents that can propagate to the trench and potentially trigger larger than expected tsunamis. The 2011 $M = 9.0$ Tohoku earthquake was potentially such a crack-like superevent. This is supported by the observation of a nearly complete stress drop[17] and previous smaller, although still large megathrust earthquakes mainly along the downdip portion of the megathrust.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

All authors contributed in the design of the study. R.H. carried out, analysed and interpreted the numerical experiments, and conducted literature research. Y.v.D., T.G. and L.A.D. supervised this work. R.H. wrote the manuscript together with contributions from Y.v.D., T.G. and L.A.D. reviewed the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.H.

Competing financial interests

The authors declare no competing financial interests.

Methods

Numerical model and scaling procedure. Our continuum-based numerical model solves for the conservation equations of mass and momentum under the assumption of incompressibility, using an implicit finite-difference and marker-in-cell technique[8,26] (Supplementary Methods 1). We use a visco-elasto-plastic rheology. The numerical model set-up consists of a viscoelastic wedge, which is underthrusted by a rigid plate[8] (Supplementary Fig. 1). The megathrust is simulated as a frictional boundary layer, using a non-associative Drucker–Prager[27] plastic flow law with a pressure-dependent yield strength, and a strongly rate-dependent frictional formulation. The velocity-weakening seismogenic zone with a downdip width W is limited up- and downdip by velocity-strengthening areas with a significantly lower static friction (Supplementary Table 2). This numerical model was validated[8] against laboratory subduction experiments[28]. The numerical and laboratory model set-ups are similar with respect to the geometry, model sizes and physical parameters (for example, shear modulus, viscosity). Here, material properties (Supplementary Table 2), model dimensions and results of the numerical experiments are scaled up to natural values using scaling factors[28] that include a dual timescale for the interseismic and coseismic period. The scaling procedure is explained in detail in Supplementary Methods 2 and scaling factors are given in Supplementary Table 3.

Model limitations. General limitations of our simplified model are discussed in previous work[8,29]. Compared to nature our model produces longer recurrence intervals and larger displacements (see Supplementary Discussion 2). This is mainly due to a small scaled shear modulus of the visco-elastic wedge originating from the simulated laboratory model (refs 8,28). Below, we discuss possible effects of some of the model limitations on our results.

Our two-dimensional model ignores lateral variations in interseismic stress build-up and rupture propagation. It does not include lateral limits of the seismogenic zone. We conjecture that lateral interaction and propagation of earthquakes might be also promoted by larger downdip widths.

We acknowledge that our incompressible inertial formulation does not account for the full inertial dynamics[8]. Properly modelling pressure waves and the feedback from seismic waves in a faster accelerating wedge might impact part of our results, as shown in terms of rupture styles[30]. On the other hand, events in our numerical model have similar properties to events in the laboratory model[8] and our results agree in general with results from dynamic rupture simulations[22,23].

Code availability. We have opted not to make the computer code associated with this paper available.

Data availability. Data produced by our computer code and post-processing scripts to plot related figures are available at https://www.dropbox.com/sh/dd2d0uj3c2mybp1/AAAU9fFOdG8ITY0Kb_RLRC7ua?dl=0.

Analysed functions and parameters. We evaluate different models using functions and parameters, averaged over the width of the seismogenic zone: cumulative sum of displacements tracks the evolution of elastic strain, strength excess depicts the stress state and the S parameter is the ratio of initial strength excess and stress change for each event. Furthermore, we calculate the average recurrence interval of superevents, from which the average number of events per supercycle is determined (for more details see Supplementary Methods 4). The event selection algorithm is described in Supplementary Methods 3.

Rupture styles and nucleation size. In our model, we qualitatively analysed rupture styles. Pulse-like ruptures are distinguished from crack-like ruptures by identifying the existence of significant healing (that is, increase of the yield strength) after the passage of the rupture front and short local duration of coseismic displacements compared to the entire rupture duration. In crack-like ruptures, including transitional styles between pulses and cracks, the yield strength drops down to a low value and coseismic displacements occur at the same time in the entire seismogenic zone. Furthermore, subcritical ruptures are defined as those events that fail to propagate a long distance from the nucleation region. The nucleation region has an approximate upscaled size of 6 km.

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