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Shallow megathrust earthquake ruptures betrayed by their outer-trench aftershocks signature

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ABSTRACT

For some megathrust earthquakes, the rupture extends to the solid Earth's surface, at the ocean floor. This unexpected behaviour holds strong implications for the tsunami potential of subduction zones and for the physical conditions governing earthquakes, but such ruptures occur in underwater areas which are hard to observe, even with current instrumentation and imaging techniques. Here, we evidence that aftershocks occurring ocean-ward from the trench are conditioned by near-surface rupture of the megathrust fault. Comparison to well constrained earthquake slip models further reveals that for each event the number of aftershocks is proportional to the amount of shallow slip, a link likely related to static stress transfer. Hence, the spatial distribution of these specific aftershock sequences could provide independent constrains on the coseismic shallow slip of future events. It also offers the prospect to be able to reassess the rupture of many large subduction earthquakes back to the beginning of the instrumental era.

1. Introduction

Subduction zones generate the largest earthquakes and are the main source of tsunami waves. The rupture of these earthquakes is generally assumed to stop several kilometres below the surface because of the presence of poorly consolidated materials (Kanamori, 1972; Moore and Saffer, 2001; Wang and Hu, 2006). However, this conceptual model is challenged by several observations such as the occurrence of slow "tsunami-earthquakes" along the shallowest parts of the megathrust (Kanamori, 1972) or the evidence that the 2011 Mw9.0 Tohoku earthquake, Japan, has ruptured the megathrust up to the surface (Fujiwara et al., 2011). But near-field measurements of a shallow rupture are scarce as existing seafloor technologies remain too costly for widespread seafloor deployment, and alternative technologies are awaited (Newman, 2011). Pending a technological breakthrough in the direct instrumentation of shallow subduction zones, an indirect approach is needed. Since the 1980s, the slip distribution of large subduction earthquakes is most often inferred from land-based seismology and/or geodesy. But these approaches are rarely an effective alternative. As attested by simple resolution tests (Bletery et al., 2014) or by the variability between independent studies of the same event, land-based seismology and geodesy fail at resolving in a robust manner any slip happening more than 50 km away from the coasts. This lack of resolution is even more acute for slip happening near the trench as the signal could be masked by slip patches in the seismogenic zone, hence closer to the coast and the instruments.

In summary, the extremely limited number of documented earthquake ruptures near the trench does not allow us to answer the question of whether the shallow portion of all megathrusts can slip, accumulate stresses, rupture or just slip aseismically (Scholz, 1998; Wang and Kinoshita, 2013). This lack of information remains a major limitation for the evaluation of seismic and tsunami potential along subduction zones, and more fundamentally for the inference of the physical laws governing the nucleation and propagation of earthquakes. There are hints that both seismic and aseismic behaviours exist (Sugioka et al., 2012), and might even coexist (Villegas-Lanza et al., 2016), but further progress is hindered by very limited observations and documented cases.

A traditional, yet indirect, way to track processes in subduction zones is offered by the study of seismicity. For all subduction zones, seismicity is fairly well characterized down to magnitude M3-4, since the 1980s. In particular, it has been long recognized that following major megathrust earthquakes, large sequences of aftershocks can be triggered ocean-ward of the trench, in a zone otherwise characterized by scarce seismicity (Astiz and Kanamori, 1986; Christensen and Ruff, 1983; Lay et al., 1989; Stauder, 1968). It follows that these so-called outer-rise, or outer-trench slope earthquakes are not solely controlled by the long term ambi-

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ent stress field, but are also highly influenced by the temporary stress perturbations caused by the large nearby subduction earthquakes (Christensen and Ruff, 1983; Dmowska and Lovison, 1992; Lay et al., 2009). The nature of this interaction remains unclear but the proximity between the shallow portion of the megathrust and the outer-rise aftershocks suggests a possible link. Several mechanical models (Dmowska et al., 1988; Dmowska and Lovison, 1992; Lin and Stein, 2004) have been proposed to explain the triggering of outer-rise seismicity. But, again, the limited knowledge on the details of large historical megathrust has precluded a detailed analysis. For instance, no explanation has been proposed as to why some major subduction thrust events (Mw $>$ 8) would not trigger noticeable increase of outer-rise seismicity.

Instrumentation progress and the occurrence of a number of large earthquakes in recent decades, makes it possible to isolate a number of large megathrust fault events for which we know that they have reached the near-surface or, on the contrary, that their rupture stopped far away from the trench. In this study, we carefully investigate these events and analyse the corresponding outer-rise aftershocks sequences. We find that the occurrence of outer-rise aftershocks sequences is strictly conditioned by a near-surface rupture of the megathrust fault, and their distribution modulated by the amount of shallow slip along the trench.

2. Methods

2.1. Identifying known sub-surface ruptures

We used the gCMT catalogue (ww.globalcmt.org) to identify all megathrust earthquakes between 1990 and 2012 with a magnitude Mw $>$ 7.5 and shallower than 60 km. For each of these individual events (more than 35), we then attempted a global survey of the literature to find whether geophysical data allowed to robustly constrain the details of their slip distribution (finite-fault models), and in particular the offshore extension of the rupture. For this compilation work, we had to exclude events constrained only by seismology because trade-offs between rupture velocity, slip history and depth make the solution potentially very non-unique (Christensen and Ruff, 1985; Wagner and Langston, 1989). Static geodetic data, because they are independent of the rupture history, tend to provide more reliable solutions of the final slip distribution. Yet, the gradient of surface deformation, measured by the geodetic instruments, decreases rapidly with distance from the source so it becomes difficult to resolve the details of a slip distribution for ruptures more than 40–50 km away from the coast (Bletery et al., 2014). Also, the complexity of the recorded surface deformation will be dominated by any slip in the nearby/down-dip part of the rupture, further limiting the resolution of any slip happening up-dip and closer to the trench. Nevertheless, they are a few settings which have allowed to deploy geodetic instruments on top of the seismogenic zone, close enough to the trench to resolve shallow slip. This is the case of Sumatra subduction zone, where the alignment of islands in the fore-arc allowed to image the rupture of the 2005 Mw8.6, 2007 Mw8.4 and Mw7.9, and 2010 Mw7.8 earthquakes (Konca et al., 2007, 2008; Yue et al., 2014b) with continuous GPS stations. Beyond the special case of the Sumatra subduction, source models of megathrust fault events are considered well constrained if they occurred either sufficiently close to the coast and far away from the trench to be unambiguously resolved by geodesy (e.g. the 2007 Mw7.7 Tocopilla earthquake, Chile, Fig. 1B), or if they were recorded by deep-ocean tsunami sensors. Several reasons explain why the deep-ocean tsunami records are so unique in their ability to resolve offshore ruptures: 1) the stations are usually located seaward of the rupture which greatly complements the azimuthal coverage land instrumentation, 2) the assumptions of elastic deformation and shallow-water tsunami propagation allow to directly relate tsunami waveforms to slip on the fault, 3) the propagation speed is well known (to within a few percent) so that even distant records ($>$1000 km) can be exploited, and 4) the influence of rupture velocity is very small which allows to treat the inversion as a static problem, independent of the rupture history (the seismic rupture propagates one order faster than the tsunami waves). The development of this instrumentation after the 2004 Mw9.2 Sumatra earthquake has allowed to significantly increase the number of events with a robust inference of their shallow extent. Finally, the recent rediscovery of long wavelength dispersion effects, due to elastic loading of the Earth and stratification of the water column, has reduced the uncertainties on tsunami predictions to less than 1–2% of the total travel time. These refinements allow the characterization of large earthquakes even if the associated tsunami was only recorded by very distant sensors (Allgeyer and Cummins, 2014; Nakamura, 1961; Tsai et al., 2013; Watada, 2013; Watada et al., 2014). This improvement was critical to evidence that the February 2010 Mw8.8 Maule earthquake Chile, did reach the trench (Yoshimoto et al., 2016; Yue et al., 2014a) after several previous studies had concluded otherwise (Delouis et al., 2010; Lin et al., 2013; Vigny et al., 2011). The result was later confirmed by differential bathymetry (Maksymowicz et al., 2017). Yet, the tsunami observations for this event are from stations to the northwest implying that the inversion cannot be “tightly bound shallow slip in the south” (Yue et al., 2014a). This lack of good azimuthal coverage of tsunami observations probably explains the differences between the two updated slip models in the southern part of the rupture (Yoshimoto et al., 2016; Yue et al., 2014a) and why there is no strict correspondence with the outer-rise aftershock distribution there. Although preceding the development of deep-ocean tsunami sensors, we included the 1992 Mw7.6 Nicaragua earthquake in our analysis. This landmark tsunami-earthquake (Kanamori and Kikuchi, 1993) occurred right along the trench as attested from the distribution of aftershocks (land-ward of the trench) and its moderate spatial extent could be fairly well constrained by the tsunami data-set composed of five near-field tide gauges and a tsunami inundation profile, all along the directly impacted coast (Piatanesi et al., 1996).

2.2. Outer-rise aftershock analysis

To investigate the relationship between the main shocks and their associated outer-rise aftershocks, we extract the outer-rise earthquakes locations from the ISC bulletin (www.isc.ac.uk), a global catalogue of seismicity, probably the most comprehensive available up to date because it also include solutions obtained from most seismic regional networks worldwide. The magnitude of completeness was estimated for each outer-rise region studied, and is in the range $Mc = 3.0$–3.8, and around $Mc = 3.6$ in most cases (Fig. S1). The outer-rise events we kept are over this magnitude of completeness at less than 100 km from trench and from 48 h to 30 days after the main shock.

3. Results

A review of fault slip models for megathrust earthquakes of Mw $>$ 7.5 between 1990 and 2012 in the gCMT catalogue has led us to identify 7 events with robust inference of surface rupture, or at least near-surface rupture, and 6 events with clear evidence that their rupture did not reach the trench (Table 1). We compare these 13 events to their first 2 days (48 h) of outer-rise seismic activity as reported in the ISC bulletin.

The comparison reveals that outer-rise aftershocks are only triggered in the case of megathrust ruptures reaching the near-surface