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The effect of compliant prisms on subduction zone earthquakes and tsunamis ☆

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ABSTRACT

Earthquakes generate tsunamis by coseismically deforming the seafloor, and that deformation is largely controlled by the shallow rupture process. Therefore, in order to better understand how earthquakes generate tsunamis, one must consider the material structure and frictional properties of the shallowest part of the subduction zone, where ruptures often encounter compliant sedimentary prisms. Compliant prisms have been associated with enhanced shallow slip, seafloor deformation, and tsunami heights, particularly in the context of tsunami earthquakes. To rigorously quantify the role compliant prisms play in generating tsunamis, we perform a series of numerical simulations that directly couple dynamic rupture on a dipping thrust fault to the elastodynamic response of the Earth and the acoustic response of the ocean. Gravity is included in our simulations in the context of a linearized Eulerian description of the ocean, which allows us to model tsunami generation and propagation, including dispersion and related nonhydrostatic effects. Our simulations span a three-dimensional parameter space of prism size, prism compliance, and sub-prism friction – specifically, the rate-and-state parameter $b - a$ that determines velocity-weakening or velocity-strengthening behavior. We find that compliant prisms generally slow rupture velocity and, for larger prisms, generate tsunamis more efficiently than subduction zones without prisms. In most but not all cases, larger, more compliant prisms cause greater amounts of shallow slip and larger tsunamis. Furthermore, shallow friction is also quite important in determining overall slip; increasing sub-prism $b - a$ enhances slip everywhere along the fault. Counterintuitively, we find that in simulations with large prisms and velocity-strengthening friction at the base of the prism, increasing prism compliance reduces rather than enhances shallow slip and tsunami wave height.

1. Introduction

Tsunamis induced by subduction zone earthquakes can be incredibly destructive events. Within the past few decades, tsunamis have been among the deadliest and costliest natural hazards (Smith, 2013), killing hundreds of thousands of people and doing billions of dollars of damage. Our study addresses tsunamigenic earthquakes by using dynamic rupture models to explore how the unique shallow structure of subduction zones, specifically sedimentary prisms, influences the rupture process and tsunami generation. To motivate this effort, we provide a brief overview of tsunamigenic earthquakes, as well as the current understanding of the material structure near the trench and frictional properties of the shallow plate interface, particularly as these relate to tsunami generation.

Tsunamigenic earthquakes can be broken into two major categories: great megathrust events and tsunami earthquakes (Kanamori, 1972). The former category includes the 26 December 2004 Sumatra earthquake (Stein and Okal, 2005) and the 11 March 2011 Tohoku-Oki earthquake (Simons et al., 2011), both M_w 9.0+ earthquakes that generated large amounts of coseismic slip. The latter category includes events like the 17 July 2006 Java earthquake (Ammon et al., 2006) and the 25 October 2010 Mentawai earthquake (Lay et al., 2011), which excited unusually large tsunamis for their body- and surface-wave magnitudes.

Coseismic slip during the Tohoku-Oki event displaced the seafloor near the Japan Trench by about 50 m, according to bathymetric surveys, GPS measurements, and acoustic ranging data (Fujiwara et al., 2011; Sato et al., 2011). Seismic reflection data recorded days after the earthquake showed deformation in the

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sediments near the trench, indicating that fault rupture reached all the way to the seafloor (Kodaira et al., 2012). Numerical modeling results indicate that rupture to the trench could occur even with shallow frictional conditions unfavorable to earthquake nucleation (Kozdon and Dunham, 2013). It is less clear that the Sumatra earthquake ruptured to the seafloor, as slip inversions with primarily deeper slip patches fit the sparse seismic and geodetic data reasonably well (Chlieh et al., 2007; Pietrzak et al., 2007). However, any slip that did occur near the trench could have contributed substantially to the resulting tsunami (Gulick et al., 2011; Hubbard et al., 2015).

Tsunami earthquakes, first identified by Kanamori (1972) in reference to the 1896 Sanriku, Japan, earthquake and the 1946 Aleutian Islands earthquake, also exhibit coseismic rupture through the shallow parts of subduction zones. Polet and Kanamori (2000) identified several additional characteristics that tsunami earthquakes share: a slow rupture velocity that inefficiently releases high-frequency energy, a large distance between the earthquake source and the land, a subducting sedimentary layer with a small (under 40 km downdip width) accretionary prism at the trench, and rupture that propagates to very shallow depths. The most common explanation for the occurrence of tsunami earthquakes invokes the ease of deforming compliant accretionary prisms and subducted sediments, which are often present at subduction zone trenches (Kanamori and Kikuchi, 1993; Polet and Kanamori, 2000; Tanioka and Sataka, 1996).

Generally speaking, the mechanism behind enhanced deformation in a compliant zone is that, in accordance with Hooke's Law, a given earthquake-induced stress change will cause greater strain and hence greater displacement in a more compliant material. In addition to the increased strain expected in the compliant prism, normal stress changes due to the presence of a bimaterial interface can affect the rupture process and facilitate unstable slip (Andrews and Ben-Zion, 1997; Weertman, 1980). Ma and Beroza (2008) found that normal stress variations on a dipping thrust fault due to free surface and bimaterial effects can create larger-than-normal stress drops when the hanging wall material is more compliant. However, material properties may not be solely responsible for large tsunamis; Bilek and Lay (2002) pointed out that tsunami earthquakes have occurred both in regions with and without large sedimentary prisms, suggesting that frictional properties on the plate interface may also influence the rupture process.

Frictional properties are an important factor in determining rupture behavior on faults, but the frictional properties of the materials beneath subduction zone prisms are not fully understood. The conventional view of plate interfaces is that they are seismogenic only below a depth of about 5–10 km (Hyndman et al., 1997). Below this depth, fault materials have velocity-weakening properties (they decrease in strength with increased slip velocity) and earthquakes can nucleate; above, unconsolidated clay-rich fault gouge is thought to be velocity-strengthening, inhibiting unstable slip. Our understanding of the upper limit of unstable slip is based in part on experiments showing that smectite-rich clay sediments dehydrate to form illite-rich material at $\sim$150 °C (Hower et al., 1976). But experiments have shown that illite fault gouge may have velocity-strengthening properties (Saffer and Marone, 2003). Ultimately, it is likely that the depth range of velocity-weakening behavior is controlled by a combination of sediment composition, temperature, pore fluid pressure, and effective normal stress (den Hartog and Spiers, 2013). As a practical example from a real subduction zone, laboratory experiments on samples from the pelagic clay-based fault zone gouge of the Japan Trench found them to be predominantly velocity-strengthening, but with some amount of velocity-weakening and velocity-neutral behavior (Ikari et al., 2015).

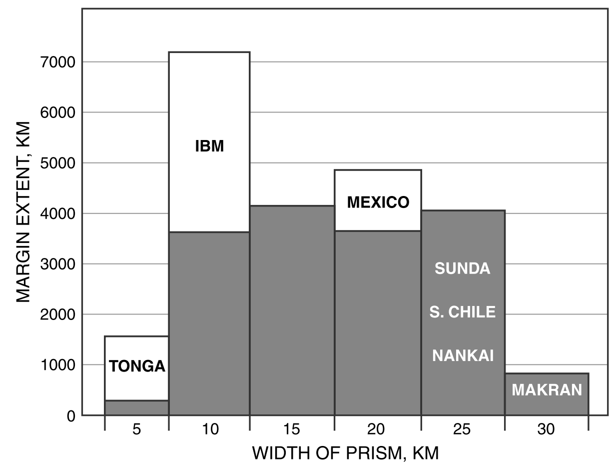

Fig. 1. Histogram of prism widths in global subduction zones, compiled from seismic images of about 48% of the world's convergent margins. Unshaded areas (e.g., Tonga) represent prisms whose widths are uncertain due to poor seismic image quality. IBM refers to the Izu–Bonin–Mariana margin. After von Huene et al. (2009).

The Japan Trench samples were also found to have low absolute friction coefficients (f_0) between 0.20 and 0.26 for the fault zone (Ikari et al., 2015). These were comparable to measurements from other clay-rich subduction zone boundaries, including Nankai (Kopf and Brown, 2003), Barbados (Kopf and Brown, 2003), and Costa Rica (Ikari et al., 2013). In this study, we focus mainly on the rate-dependence effect of friction and not absolute friction (which we keep fixed at $f_0 = 0.6$, except in a set of simulations utilizing $f_0 = 0.2$), recognizing that the latter is important in determining the sensitivity of fault shear strength to changes in effective normal stress.

We return our discussion now to material structure, in order to justify the range of prism geometries and material properties to be explored in our simulations. Wide-angle seismic reflection surveys and potential-field modeling have imaged the structure of subduction zone boundaries in northern Japan (Miura et al., 2005; Nakamura et al., 2014), Nankai (Kodaira et al., 2002; Nakanishi et al., 2008), Sunda (Klingelhoefer et al., 2010; Kopp and Kukowski, 2003), Cascadia (Fleming and Tréhu, 1999; Flueh et al., 1998), Chile (Krabbenhöft et al., 2004; von Huene et al., 1996), and elsewhere. From a structural perspective, convergent margins are complex, and no simple model can explain them all. About 25% of the global span of major subduction zones are accreting margins, which widen over geologic time scales as lower-plate sediments transfer to the inner rock framework of the upper plate. Nonaccreting margins, identified by a trench axis that moves landward and a bedrock framework that extends offshore to within a few tens of kilometers of the trench, make up the other 75% (Scholl and von Huene, 2007). Despite the differences in tectonic setting, geophysical data show that both accreting and nonaccreting margins have frontal prisms made up of actively deforming sedimentary material. The frontal prism is underlain by a sedimentary apron of shelf-slope deposits, which can include significant amounts of mass wasting debris (von Huene and Ranero, 2003). Frontal prisms are typically 5–30 km wide and can be several kilometers thick (Fig. 1) (von Huene et al., 2009). The landward boundary of a frontal prism is defined by a mechanical backstop, a transition to a little-deforming middle prism (in the case of an accreting margin) or to a section of fragmented inner prism bedrock (in a nonaccreting margin) (Scholl and von Huene, 2007). Our simulations span the typical width range of frontal prisms and ignore structural differences between accreting and nonaccreting margins.

Frontal prisms are composed of sedimentary materials that are more compliant than the surrounding bedrock framework. Mod-