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Tsunamigenic potential due to frontal rupturing in the Sumatra locked zone

Alvina K. Kuncoro [a], Nadaya Cubas [a,*], Satish C. Singh [a], Marie Etchebes [b], Paul Tapponnier [b]

[a] Laboratoire Géosciences Marines, Institut de Physique du Globe (CNRS, Paris Diderot, Sorbonne Paris Cité), 1 rue Jussieu, 75238 Paris Cedex 05, France
[b] Tectonics Research Group, Earth Observatory of Singapore, Nanyang Technological University, N2-01A-10B, 50 Nanyang Avenue, Singapore 639798, Singapore

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ABSTRACT

The Sumatra subduction zone is one of the most seismically active subduction zones. Although there have been three $M_w \geq 8.4$ earthquakes in the region, including the disastrous 2004 $M_w = 9.2$ Sumatra–Andaman earthquake, a 500 km long patch around Mentawai Islands is still locked and could produce a large megathrust earthquake. If the rupture propagates to the subduction front, as it most likely occurred during the 2004 earthquake, it may lead to a devastating tsunami. Here, we present high-resolution reflection seismic data from the Sumatra locked zone that shows the subduction interface down to 20 km depth. The seismic data also show that the wedge is composed of two layers: a shallow layer formed by mixed to landward vergent thrusts, termed as pop-ups, and a deeper layer showing sub-horizontal reflectors. The lower layer is most probably formed by duplexes, whose roof serves as a pseudo-décollement for the mixed to landward thrust systems. Based on the seismic results, we perform mechanical modeling in order to understand the formation of these structures and to retrieve the associated frictional properties. We first show that the activation of the pseudo-décollement requires (1) either a sudden increase of effective friction along the plate interface or an irregular geometry of the plate interface, (2) a lower effective friction along the pseudo-décollement than along the plate interface. We then show that low effective frictional values (≤ 0.1) are required to reproduce the observed frontal structures. The low effective friction along the pseudo-décollement could either be due to the presence of a long-term high pore pressure layer or to dynamic weakening associated with earthquakes. Since similar structures are present in the 2010 tsunami earthquake area, we favor the dynamic weakening hypothesis. According to the mechanical modeling, if the next rupture propagates up to the toe rupturing the three most frontal pop-up structures, we could expect at least 5.5 to 9.2 m of frontal horizontal displacement and a frontal uplift of 2 to 6.6 m along the frontal thrusts. This would amplify the uplift of the water column and, as a consequence, generate a large tsunami.

1. Introduction

The Sumatra subduction zone is known as one of the most seismically active zones in the world, where the Indo-Australian plate subducts beneath the Sunda plate at a 10° azimuth leading to an increasing obliquity towards the north and a decrease of the convergence rate from 60 mm/yr near the southern Sumatra to 52 mm/yr in the northern Sumatra (Prawirodirdjo et al., 2000) (Fig. 1a). This obliquity leads to a slip partitioning into a pure thrust motion along the plate interface and a strike-slip motion along the Great Sumatra Fault, which traverses the continental block of the main land Sumatra (McCaffrey, 1992). It has been suggested that a part of the strike-slip motion is also accommodated along a strike-slip fault system (West Andaman Fault and Mentawai Fault) (e.g. Martin et al., 2014) between the trench and the Great Sumatra Fault, but deep seismic reflection data indicate that these fault systems are dominantly backthrusts (Singh et al., 2011b, 2013; Mukti et al., 2012).

During the last decade, the Sumatra subduction zone has experienced the most intense sequence of earthquakes ever recorded (Fig. 1a). The sequence started with the third largest recorded event, the $M_w \sim 9.2$ Sumatra–Andaman earthquake of December 26th, 2004 that ruptured over 1300 km of the subduction zone propagating from northwest Simeulue Island to northern Andaman Island (Lay et al., 2004; Ammon et al., 2005; Singh et al., 2008). The earthquake generated a devastating tsunami with

* Corresponding author. Now at: Sorbonne Universités, UPMC Univ Paris 06, CNRS, Institut des Sciences de la Terre de Paris (iSTeP), 4 place Jussieu, 75005 Paris, France.
E-mail address: nadaya.cubas@upmc.fr (N. Cubas).

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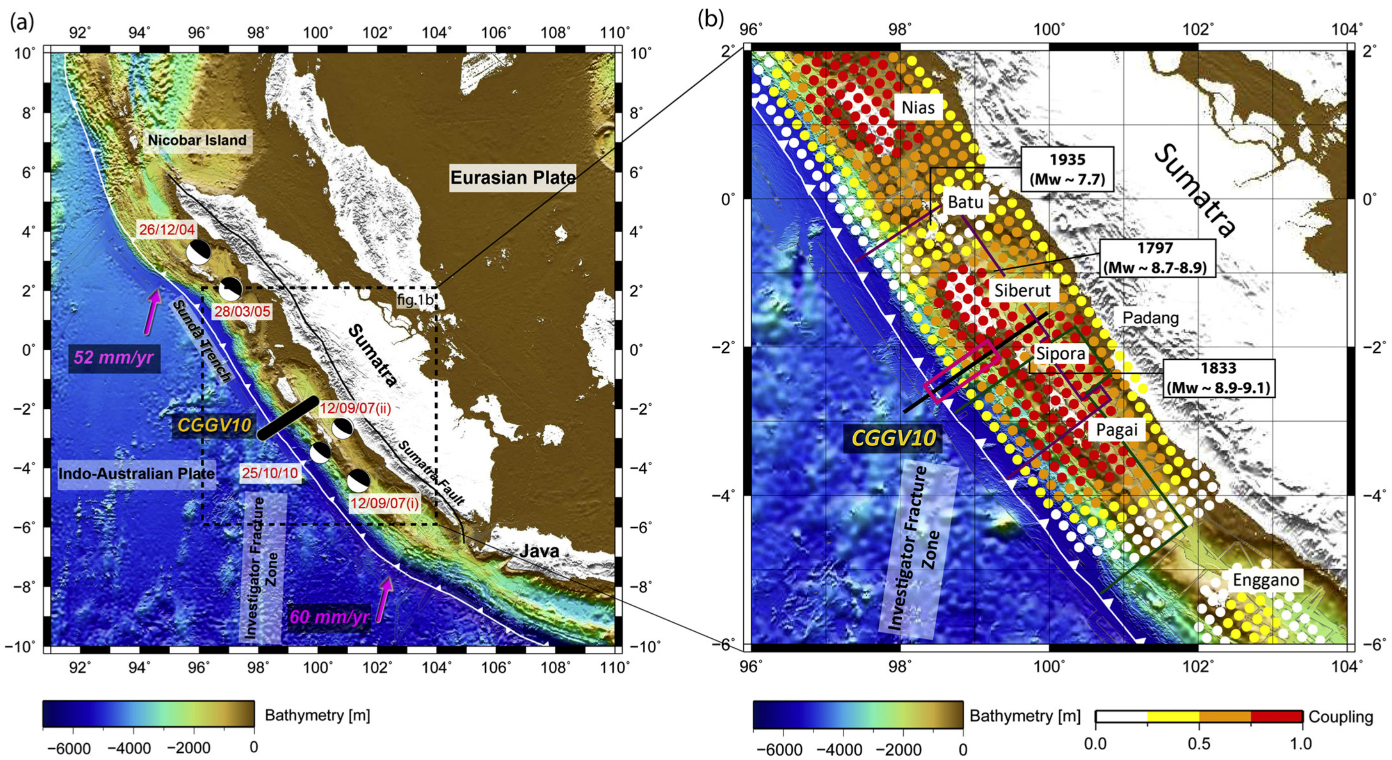

Fig. 1. a. Geodynamic setting and last major earthquakes of the Sumatra subduction zone (epicenters from USGS combined with GCMT focal mechanisms, high resolution bathymetry from GEBCO and a compilation of German data set (Ladage et al., 2006) recorded during the SeaCause cruises (Mukti et al., 2012). The CGGV10 deep seismic reflection profile acquired by CGGVeritas in 2009 in the northern Mentawai gap is shown in black. **b.** Slip deficit from Chlieh et al. (2008) and Konca et al. (2008). We can observe two highly coupled zones: one below Nias island, another along the Mentawai islands. Purple and green boxes show the 1833 and 1797 historical ruptures of the Mentawai segment (Chlieh et al., 2008). Pink box shows location of Fig. 2 profile. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

run-up height up to 30 m (Geist et al., 2006) causing enormous causalities. This event was followed by the $M_w = 8.7$ Nias earthquake in March, 2005, which ruptured a 350 km long patch located south of the 2004 rupture producing only a minor tsunami (Hsu et al., 2006). The sequence resumed in 2007 along the southern Mentawai area with two successive major earthquakes within a range of twelve hours. The first one, the $M_w = 8.4$ event, ruptured a patch located beneath the southern Mentawai islands while the second one with $M_w = 7.9$ occurred beneath the forearc basin at $\sim$40 km depth (Konca et al., 2008). The last big event, presumably a consequence of the previous twin earthquakes, occurred in 2010 and ruptured the up-dip portion of the Mentawai earthquakes region of 2007 with a magnitude of 7.8 (Singh et al., 2011a). This event, qualified as a tsunami earthquake, characterized by moderate shaking but a large tsunami (Kanamori, 1972), generated tsunami run ups up to 9 m on Pagai Island (Lay et al., 2011; Hill et al., 2012).

Coupling models obtained from geodetic and paleogeodetic data for interseismic strain estimates show a heterogeneous coupling along the Sumatra subduction zone (Chlieh et al., 2008; Konca et al., 2008) (Fig. 1b). Two main areas appear to be highly locked: the first one is located in the 1805 earthquake, which ruptured completely during the 2005 $M_w = 8.7$ Nias earthquake, and the second is located beneath the Mentawai islands in the area of the historical earthquakes rupture zones of the 1797 $M_w \sim 8.7$–8.9 and the 1833 $M_w \sim 8.9$–9.1. The 2007 and 2010 events only ruptured parts of the southern area of the second locked segment, leaving a 500 km long northern Mentawai segment still fully locked. According to geodetic and paleogeodetic measurements, the recurrence time of those Mentawai earthquakes is of 250 yrs (Natawidjaja et al., 2006; Sieh et al., 2008). The northern Mentawai segment is thus ready for a new rupture and a slip deficit of 8 to 10 m has been accumulated since the 1797 and 1833 earthquakes (Chlieh et al., 2008). From historical records, we also know that the 1797 earthquake produced a devastating tsunami in Padang area with a run-up height of more than 10 m. The northern Mentawai segment might produce again a great earthquake, and possibly a tsunami, which could be devastating for the coastal region of central and southern Sumatra. Therefore, it is important to assess the earthquake and tsunami risk in this region.

Since frontal sections of megathrust are composed of unconsolidated sediments characterized by a rate-strengthening behavior (Byrne et al., 1992; Oleskevich et al., 1999; Scholz, 1998), they were supposed to slip aseismically. However, the 2011 M_w 9.0 Tohoku-Oki earthquake has challenged this classical view. The earthquake produced exceptionally large shallow slip generating a major tsunami (Bletery et al., 2014; Ide et al., 2011; Ozawa et al., 2011). The rupture propagated all the way to the trench, with the shallow-portion displacement of 15 to 40 m as attested from the displacement of ocean-bottom pressure gages (Ito et al., 2011) and comparison of bathymetric profiles measured in 1999 and after the earthquake in March 2011 (Fujiwara et al., 2011). Up-dip rupture has also been suggested for the 2004 Sumatra–Andaman earthquake from co-seismic models (Ishii et al., 2007; Ammon et al., 2005; Chlieh et al., 2007), and from the aftershock pattern (Tilmann et al., 2010).

Assessing the potential for frontal rupturing of a megathrust earthquake remains difficult because of the very poor sensitivity near the trench of geodetic model based on inland GPS stations (Loveless and Meade, 2011; Hill et al., 2012). One way to overcome this problem is to study the accretionary wedge structure to determine if the deformation might have been acquired during co-seismic slip. For instance, based on mechanical modeling of deformation, Cubas et al. (2013b) find two regimes of defor-