Quaternary Science Reviews 122 (2015) 258–281

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Time-varying interseismic strain rates and similar seismic ruptures on the Nias–Simeulue patch of the Sunda megathrust

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ARTICLE INFO

Article history:
Received 11 March 2015
Received in revised form
22 May 2015
Accepted 4 June 2015
Available online 17 June 2015

Keywords:
Subduction zone
Paleoseismology
Paleogeodesy
Sumatra
Coral microatolls
Earthquake recurrence
Interseismic deformation
Slow slip events

ABSTRACT

Fossil coral microatolls from fringing reefs above the great (M_W 8.6) megathrust rupture of 2005 record uplift during the historically reported great earthquake of 1861. Such evidence spans nearly the entire 400-km strike length of the 2005 rupture, which was previously shown to be bounded by two persistent barriers to seismic rupture. Moreover, at sites where we have constrained the 1861 uplift amplitude, it is comparable to uplift in 2005. Thus the 1861 and 2005 ruptures appear to be similar in both extent and magnitude. At one site an uplift around AD 1422 also appears to mimic the amount of uplift in 2005. The high degree of similarity among certain ruptures of this Nias–Simeulue section of the Sunda megathrust contrasts with the substantial disparities amongst ruptures along other sections of the Sumatran portion of the Sunda megathrust. At a site on the northwestern tip of Nias, reefs also rose during an earthquake in AD 1843, known historically for its damaging tsunami along the eastern coast of the island.

The coral microatolls also record interseismic vertical deformation, at annual to decadal resolution, spanning decades to more than a century before each earthquake. The corals demonstrate significant changes over time in the rates of interseismic deformation. On southern Simeulue, interseismic subsidence rates were low between 1740 and 1820 but abruptly increased by a factor of 4–10, two to four decades before the 1861 rupture. This may indicate that full coupling or deep locking of the megathrust began only a few decades before the great earthquake. In the Banyak Islands, near the pivot line separating coseismic uplift from subsidence in 2005, ongoing interseismic subsidence switched to steady uplift from 1966 until 1981, suggesting a 15-year-long slow slip event, with slip velocities at more than 120% of the plate convergence rate.

1. Introduction

Assessing future earthquake hazard relies upon an appreciation for the range of earthquake scenarios that are plausible for a particular fault and an understanding of the strain accumulation history along that fault. The better we can characterize the earthquake recurrence in a region, the more that region can prepare for the hazards it faces. And the more complete we can make our picture of strain accumulation, and how strain accumulation varies over time, the better our chances for accurately identifying faults that are likely to rupture in the near future.

There have been limited efforts to apply earthquake recurrence models to subduction megathrusts. Few long paleoseismic records exist for subduction zones with which to rigorously test these models, and the inaccessibility of megathrusts hinders attempts to compare displacements at a point along the fault from one event to

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http://dx.doi.org/10.1016/j.quascirev.2015.06.003

the next. In Sumatra, prior studies identified two persistent barriers to rupture, under the Batu Islands (Natawidjaja et al., 2006) and under central Simeulue (Meltzner et al., 2012) (Fig. 1). These two barriers, which align with fracture zones in the subducting slab, divide the Sumatran portion of the Sunda megathrust into at least three segments with independent rupture histories. North of the northern barrier (on the Aceh segment) and south of the southern barrier (on the Mentawai segment), paleoseismic evidence suggests that ruptures vary considerably: no two ruptures in the available paleoseismic, historical, or modern records even vaguely resemble one another (Meltzner et al., 2010; Philibosian et al., 2014). The 28 March 2005 M_W 8.6 rupture spanned the full distance between these two barriers, and since both rupture endpoints appear to have been structurally controlled, we speculate that earthquakes like 2005 may be a common feature of this portion of the megathrust.

As for fault behavior between earthquakes, researchers generally believed until recently that interseismic motions are roughly linear over time, punctuated only by sudden earthquakes and postseismic deformation that follows the earthquakes (Savage and Thatcher, 1992). Although postseismic transients in deformation have been widely documented (e.g., Melbourne et al., 2002; Zweck et al., 2002; Hu et al., 2004; Sawai et al., 2004; Hsu et al., 2006; Pollitz et al., 2008; Perfettini et al., 2010; Hu and Wang, 2012) and result from a variety of processes during the post-earthquake deformation phase of the earthquake cycle (Perfettini et al., 2005; Wang et al., 2012; Bürgmann and Thatcher, 2013; Sun et al., 2014), they are commonly observed to decay, over a period of years to decades, to a "background" interseismic rate. The belief was that, subsequently, this "background" interseismic strain rate (or pattern of interseismic deformation) remained steady over most of the seismic cycle (Savage and Thatcher, 1992). More recently, researchers discovered processes and phenomena previously unappreciated along subduction zones. Numerous studies have explored slow slip events (SSEs) at a range of timescales, in a number of settings (Beroza and Ide, 2009; Gomberg and The Cascadia 2007 and Beyond Working Group, 2010; Peng and Gomberg, 2010). Multiple large SSEs, with durations of 2–4 years, and a series of abrupt changes in the width of the locked region, have now been documented in southern Alaska (Fu and Freymueller, 2013; Freymueller et al., 2014; Fu et al., 2014). In the Tokai region of Japan, a 5-year-long SSE occurred between 2000 and 2005, and longer-term changes in plate coupling have been observed (Ochi and Kato, 2013). Changes in plate coupling over time have also been proposed elsewhere (Nishimura et al., 2004; Prawirodirdjo et al., 2010; Ozawa et al., 2012; Uchida and Matsuzawa, 2013; Mavrommatis et al., 2014; Philibosian et al., 2014; Yokota and Koketsu, 2015).

What if a fault system can appear for decades to be uncoupled and then suddenly start accumulating strain that could lead to seismic rupture? If this could happen, it would have profound implications for hazards along subduction zones and other faults that are not currently considered highly seismogenic. Interseismic deformation rates, long assumed to be steady over time, may instead be a function of time. Most modern geodetic networks have not been in operation for sufficiently long durations to address this question. The geological record may provide unique insight.

In this paper, we explore the recent paleoseismic (earthquake) histories of sites on Nias, Bangkaru, and southern (eastern) Simeulue islands, which lie above the 28 March 2005 M_W 8.6 rupture patch (Briggs et al., 2006) (Figs. 1–2). We combine historical records with geological observations from in situ preserved coral colonies—namely coral microatolls—to determine details of the timing, extent, and magnitude of past coseismic deformation. These data elucidate similarities and differences between various past earthquakes, including notable similarities between earthquakes in 1861 and 2005. We also explore the recent paleogeodetic (interseismic deformation) histories of these sites. The coral microatolls provide information on gradual relative sea-level (RSL) change (hence land-level change) between earthquakes, which we

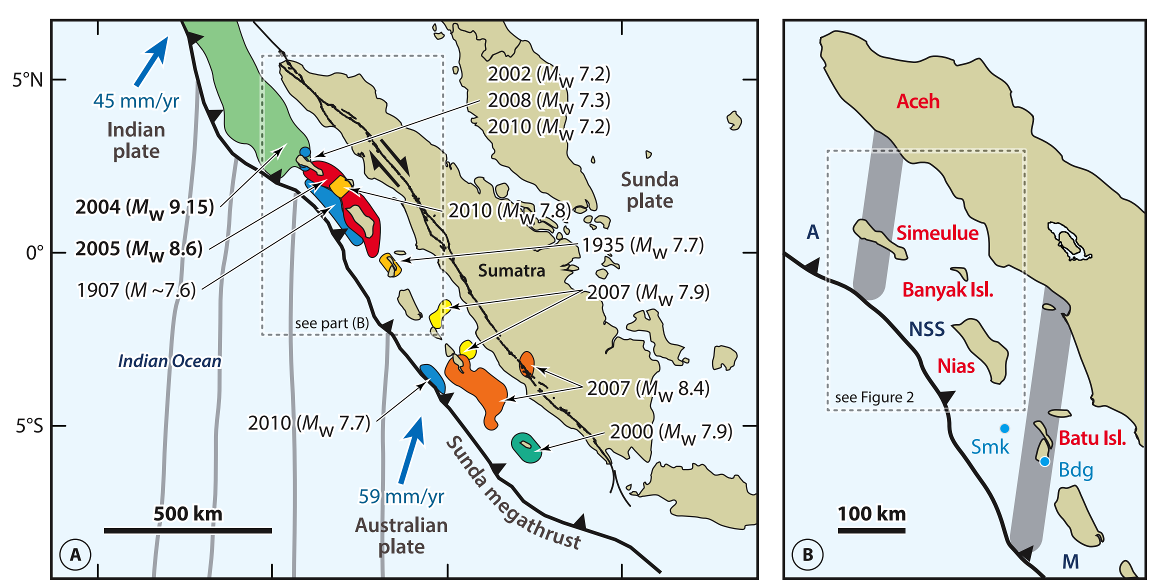

Fig. 1. (a) Regional map of the Sunda megathrust and large megathrust ruptures since AD 1865. Rupture locations and magnitudes are from Briggs et al. (2006), Konca et al. (2008), Meltzner et al. (2010), Hill et al. (2012), and references therein; the 1907 location is speculative. Relative plate motions from Shearer and Bürgmann (2010). Black lines are faults; gray lines are fracture zones. (b) The 2005 rupture spanned the Nias–Southern Simeulue segment of the megathrust (NSS), which is bounded by persistent rupture barriers (gray bars). Ruptures to the north on the Aceh segment (A) and to the south on the Mentawai segment (M) have been highly variable, but there may be a higher degree of similarity among the largest ruptures along the Nias–Southern Simeulue segment. Bdg, Badgugu; Smk, Simuk Island.