Geologic evidence for two pre-2004 earthquakes during recent centuries near Port Blair, South Andaman Island, India

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ABSTRACT

Coastal stratigraphy near Port Blair, Andaman Islands, where the A.D. 2004 Sumatra-Andaman earthquake was accompanied by ~1 m of subsidence, provides evidence for two prior earthquakes, perhaps both from the past 400 yr. The first of these (event I) is marked by an abrupt mud-over-peat contact best explained by subsidence similar to that in 2004. Event II is evidenced by an overlying chaotic layer composed of mud clasts in a sandy matrix that is connected with feeder dikes. These mud clasts, probably produced by liquefaction, are capped by laminated sand and mud that we ascribe to an event II tsunami. Radiocarbon ages of plant remains in the peat give discordant ages in the range 100 B.C. to A.D. 1950. Event I probably resembled the 2004 Sumatra-Andaman earthquake in that it was accompanied by subsidence (as much as 1 m) but not by strong shaking near Port Blair. If event II was the A.D. 1762 Arakan earthquake, the laminated sand and mud provide the first evidence that this earthquake was associated with a tsunami.

INTRODUCTION

The giant Sumatra-Andaman earthquake (Mw 9.3) occurred on 26 December 2004 at 00:58:53 Universal Time (06:28:53 a.m. Indian Standard Time) and resulted in a very large fault rupture of ~1300 km (Ammon et al., 2005; Lay et al., 2005; Subarya et al., 2006) that occurred along the plate boundary marked by subduction zone between the Indian plate and the Sunda microplate (a part of the Eurasian plate) (Fig. 1A). Along with the destruction caused by the tsunami, coseismic deformation resulted in land-level changes along the Sumatra-Andaman arc (Malik and Murty, 2005; Meltzner et al., 2006; Tobita et al., 2006; Singh et al., 2006; Kayanne et al., 2007), with significant uplift and subsidence along the west and east coasts, respectively, at various locations in the Andaman and Nicobar Islands (Malik and Murty, 2005).

Few candidates for giant pre-2004 earthquakes have been documented from the vicinity of the Andaman and Nicobar Islands (Fig. 1A). Large earthquakes in A.D. 1881 and 1941 were accompanied by land-level changes in the islands (Ortiz and Bilham, 2003; Bilham et al., 2005; see the GSA Data Repository[1]). The region's written history, which can be traced back to A.D. 1600 (Iyengar et al., 1999), probably postdates the 2004 earthquake's most recent giant predecessor, which occurred soon after A.D. 1300–1450, according to interpretation of tsunami deposits in Thailand (Jankaew et al., 2008).

Here we present geologic evidence for two pre-2004 earthquakes along a northern part of the 2004 rupture (Figs. 1A–1D). Previous work shows that the area contains stratigraphic evidence for subsidence 656 ± 141 cal. (calibrated) yr B.P. near Port Blair, and marine terraces suggestive of uplift 500–600 yr ago, and another 900 yr ago (Rajendran et al., 2008). Our new evidence, the east side of South Andaman Island near Port Blair, suggests coseismic subsidence from one earthquake, and both shaking and a tsunami from another.

GEOLOGIC SETTING

The 2004 earthquake at Port Blair was accompanied by weak shaking and tectonic subsidence; however, no prominent liquefaction was reported, except the occurrence of lateral spreading at few places around Sippyghat (Malik and Murty, 2005; Singh et al., 2006). Subsidence of ~1 m caused inundation of the paddy field and several residential areas were affected (Malik and Murty, 2005). The ensuing tsunami reached heights of 3.0–3.5 m near Port Blair; no significant tsunami deposit was reported.

Our study area, Mitha-Khadi, is a lowland northwest of Port Blair on the west side of Flat Bay (Figs. 1B and 1C). Historically this lowland may have been a mangrove swamp behind beach ridges; these ridges, ~0.5 m high, trend north-south beside a shoreline to the east (Figs. 1D and 2). The lowland was farmland at the time of the 2004 earthquake. An artificial levee 1.0–1.5 m high kept out the tides, which have a range of 2 m. The levee has been raised another meter to permit continued farming since 2004.

METHODS

Subduction zone earthquakes result in sudden changes in land level (uplift or subsidence), shaking-induced liquefaction, or tsunami sediment transport, which are preserved in the sediments or landforms (e.g., McCalpin, 1996) and hence can be extracted from stratigraphic records and by studying landforms (e.g., Atwater et al., 2005; Cisternas et al., 2005; Satake and Atwater, 2007).

We excavated trenches and also obtained geoslices from depths of more than 1.5 m. In this paper we discuss common features across five trenches (four north trenches, T1–T4, and one south trench, T5) and five geoslice sections (M1–M5) from Mitha Khadi (Figs. 1D and 2). Diatoms provided paleoecological information for one of the field locations (M4 in Fig. 2).

We obtained 15 radiocarbon (accelerator mass spectrometer, AMS) ages by dating charred plant material, rhizomes, and shell material (Fig. 2). More details of site description and methods are given in the GSA Data Repository[1] (Item DRII, with a full description of each trench and geoslicer section with figures, and all the dating data [Table DR1] are provided in DRIII).

STRATIGRAPHY AND PALEOECOLOGY

Based on the sedimentary characteristics, sedimentary structures, grain size, and nature of contacts (depositional and/or erosional), the lithological sections of the trench and geoslice sites were classified into six units (a–f, from top to bottom).

Unit f, the oldest unit, consists of dark gray, silty, medium to fine sand with shell fragments low in the unit and peaty material (Figs. 2 and 3C). Laminae of mud and peaty material were observed in the upper portion. It shows poor preservation of fossil diatoms, but we infer that

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[1]GSA Data Repository item 2011178, past and present seismicity and crustal deformation, details of the study site and method, descriptions of geoslice and trench samples, and radiocarbon dates, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

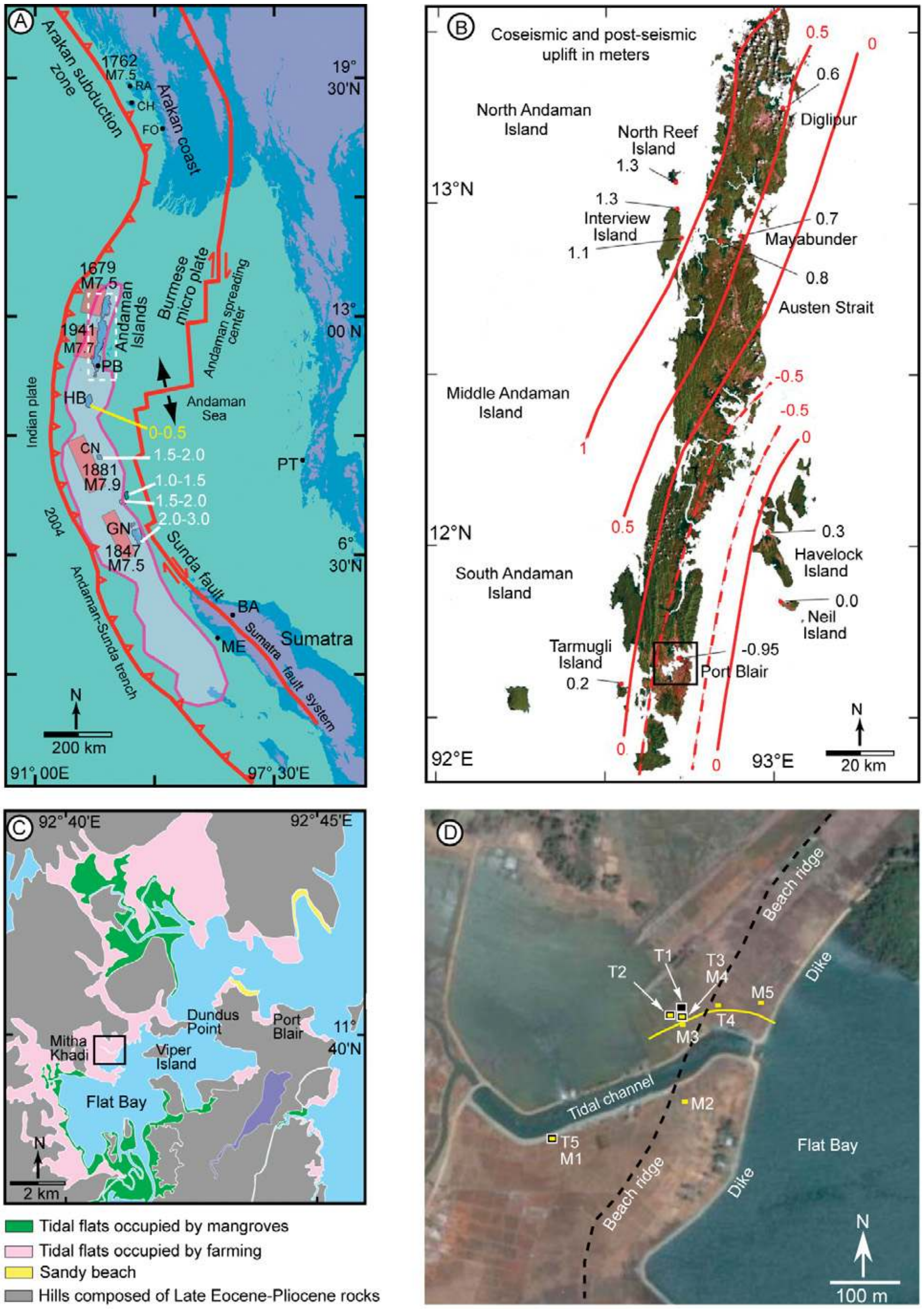


Figure 1. A: Generalized plate tectonic map of Sumatra-Andaman and Arakan arc with past seismicity. Purple area marks source fault of A.D. 2004 Sumatra-Andaman earthquake (from Monecke et al., 2008). White box with broken line shows location of B. Yellow numbers indicate uplift and white shows subsidence during 2004 earthquake. RA—Ramree; CH—Cheduba; FO—Foul; PB—Port Blair; HB—Hut Bay; CN—Car Nicobar; GN—Great Nicobar; BA—Band Aceh; ME—Meulaboah; PT—Phra Thong. B: Map of Andaman Islands showing areas of uplift and subsidence triggered by 2004 event (after Kayanne et al., 2007). Black box shows location of C. C: Generalized geomorphic map of area around Port Blair and Flat Bay in South Andaman. Black box shows location of D. D: Google Earth™ image showing locations of trenches (T) and geoslice sampling (M) collected from 2005–2006 fieldwork. Yellow bold line—transect of total station profile. Black dotted line—location of beach ridge.

brackish or marine conditions account for the shell fragments.

Unit e is made up of peaty silt, and is occasionally laminated; it changes upward from very dark brown to light brown. Prominent buried rhizomes and charred plant material were observed in the M3 and M4 sections (Figs. 2 and 3C). We infer that the peat represents a vegetated wetland, and that rhizomes, which do not extend above unit e, represent plants that lived in this wetland. The unit has a gradational contact with underlying unit f but a sharp contact with overlying unit d (Fig. 3C). Fossil diatom assemblages are dominated by a few brackish and marine species (*Pseudopodosira westii*, *Tryblionella cocconeiformis*, and *T. compressa*) low in unit e, by other brackish species (*Caloneis lineariz* and *Diploneis suborbicularis*) in the middle, and by freshwater and brackish-water taxa in the upper part (*Diadesmis contenta*, *Pinnularia* spp., and *Cosmioneis pusilla*). This vertical change in diatom assemblages implies that a vegetated wetland became mostly emerged from tidal water during the deposition of unit e.

Unit d is massive, bluish-gray clayey silt (Figs. 2 and 3A–3D) that has a sharp contact with unit c (Fig. 2); in places unit c is intruded by fine silty sand dikes (Figs. 3A and 3B). Multiple intrusions of dikes and sills have resulted in development of a blocky structure. Approximately 4 cm above the lower contact, a sample includes many brackish-marine diatom species (*Diploneis suborbicularis*, *Lyrella lyra*, and *Tryblionella cocconeiformis*) (Fig. 2). This probably indicates that the area was submerged to intertidal depths.

Unit c shows chaotic nature, with a matrix of silty sand and clasts of mud and peat (Fig. 2; Fig. DR4b). It is indistinctly layered in trench T1 (Fig. 3A). The mud and peat clasts were likely derived from unit d during strong shaking.

Unit b comprises parallel, well-laminated fine to medium yellowish sand and silt. Well-preserved inclined stratification (toward land), along with rip-up mud clasts, were observed (Fig. 2). The lower contact is erosive with unit c. Grain size and thickness decrease inland; coarse and thick sand was observed near the bay and fine and thin sand was observed inland (Fig. 2A). The south trench (T5) exhibits prominent fine laminated sand with fine silt; however, it does not show any indication of bioturbation in all trenches (Fig. 2). Based on the criteria suggested by Morton et al. (2007), the inclined stratification, lack of bioturbation, landward thinning, lateral variation in grain size, presence of mud clasts, and sharp and erosive contact suggest that unit b was associated with a tsunami.

Unit a, with grayish-black humic fine silty sand, is the topmost, youngest unit. It shows an irregular contact with unit b. This unit suggests probable deposition under an intertidal environment. The primary sedimentary structures were possibly destroyed by farming.

PALEOSEISMOLOGICAL INTERPRETATION

We infer two paleoseismic events predating A.D. 2004 in the trench and geoslicer stratigraphy. Diatoms in the peaty layer (unit e) indicate a freshwater-brackish marshy environment at the top of the unit, whereas diatoms in the overlying

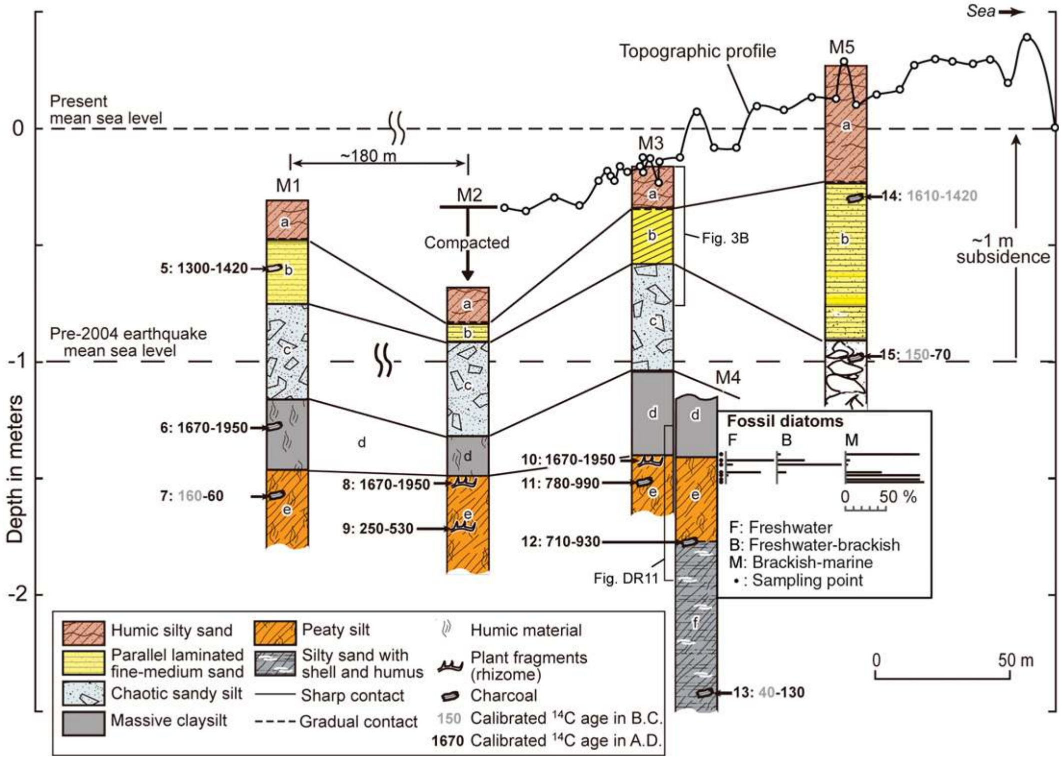
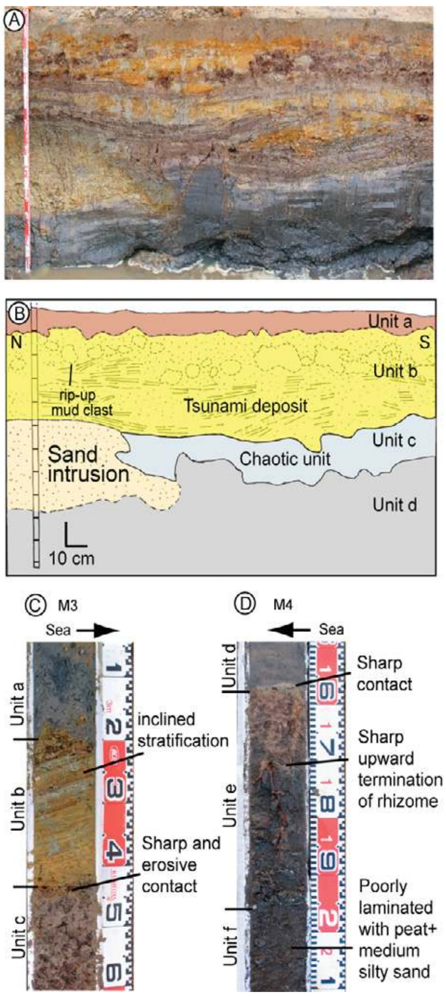


Figure 2. Lithological sections collected by geoslicer at Mitha Khadi site. Geoslices M1–M5 were collected to identify evidence of past earthquakes preserved in sediment record (see Fig. 1C for location).



silty clay layer (unit d) show a brackish-marine environment. A sharp contact between units d and e suggests a sudden submergence at the time of the contact (event I; older event). The chaotic nature and the dikes that probably fed it (unit c) indicate liquefaction, and the laminated unit b indicates an ensuing tsunami, both produced by event II.

The radiocarbon (AMS) ages, obtained by dating charred material, rhizomes of vascular plants, and shell fragments, ranged from 60 to 3870 ^{14}C yr B.P. (Fig. 2). In situ rhizomes from the upper part of unit e from M2 and M3 gives an age of A.D. 1670–1950 (samples 8 and 10: Fig. 2). Because the detrital charred material from unit d gives an age of A.D. 1672–1950, the transition from unit e to unit d is well constrained as ca. 130 yr ^{14}C B.P., which corresponds to calibrated ages of A.D. 1670 or later. Relatively older ages found in the younger stratigraphic units, for example A.D. 1300–1420 (sample 5; see Fig. 2) or 3220 ± 40 ^{14}C yr B.P. (sample 14 see Fig. 2) in unit b, or charred material dated as 150 B.C. to A.D. 70 (sample 15, Fig. 2), are considered as due to reworked material.

Figure 3. A: East wall of north trench (T1). Prominent sand intrusion in unit d was observed in lower left side of trench. Unit b shows erosive and sharp contact with unit c, abundant reworked mud clasts near top, is devoid of bioturbation, and inclined stratification indicates probable tsunami deposit. Scale is 1.2 m. B: Sketch of east wall of north trench. C: Upper section of geoslice M3 shows inclined stratification toward land and sharp to erosive contact with unit c. Unit b is interpreted as tsunami deposit. (For location, see Fig. 2, column M3.) D: Close-up view of upper part of geoslice M4 (peel sample) showing prominent change in sedimentary facies from massive clay (unit d) and underlying peaty soil (unit e). (For location, see Fig. 2, column M4.) This change is well marked by sharp contact between units d and e. Sharp termination of rhizome was observed in unit e.

The two paleoseismological events are significantly different in terms of age and paleoseismological characteristics. Event I occurred ca. A.D. 1670 or later, based on the calibrated radiocarbon ages of in situ plant material and detrital charcoal from the peaty layer. Event II, with liquefaction and a tsunami, occurred after event I. While event I has no evidence for strong ground motions and was associated with clear geological evidence of sudden subsidence, event II was associated with strong ground shaking and a tsunami. The A.D. 2004 event was not accompanied by strong shaking, but did involve a tsunami and subsidence.

We estimate that the amount of subsidence during event I was as much as 1 m. The peaty unit e was deposited in a marshy environment, whereas unit d, with a sharp bottom contact, was deposited in a deeper (probably marine) environment. This height range is approximated by the difference in habitats of diatom species. The dominant diatom species show that the environment was a freshwater or slightly brackish water marsh before the event, while two of marine taxa (*Diploneis suborbicularis* and *Tryblionella cocconeiformis*) suggest that it became marine between high and mean tides (Kosugi, 1987) after the event. As the present tidal range is 2 m, we approximate the amplitude of submergence to be as much as 1 m.

DISCUSSION AND CONCLUSION

Event I may be correlated with an earthquake on 28 January 1679, among the large earthquakes known from written records in India. The 1679 earthquake was widely felt in the regions from Arakan (Burma), Bengal (Bangladesh), and along the eastern coast of India along Coromandal and Madras (now known as Chennai) (Iyengar et al., 1999), indicating that it was large magnitude (M ~7.5). It is ambiguous whether this earthquake generated any tsunami around the southern Andaman area (Rajendran et al., 2008).

Event II may be related to a large earthquake on 2 April 1762 in Arakan, as reported in historical records from the coastal region of Myanmar (Cummins, 2007). It has been suggested that this earthquake resulted in uplift of ~3–7 m along the coasts of Ramree, Cheduba, and Foul Islands, located offshore of the Arakan coast of Myanmar (Aung et al., 2008). However, there is no written record of a tsunami.

Studies of tsunami deposits in Thailand have revealed tsunami sand layers dated as ca. 550–700 ^{14}C yr B.P. (ca. A.D. 1300–1450; Jankaew et al., 2008; Fujino et al., 2009). From the sediment stratigraphy, it is suggested that this event was similar to the 2004 Sumatra-Andaman earthquake, and no such event has occurred since then. Also, evidence of past earthquakes, ca. A.D. 1640–1950, has been reported from Aceh, northwestern Sumatra, and another after A.D. 780–990 (Monecke et al., 2008). Event I in Port Blair may be correlated with penultimate tsunami in Sumatra, but not in Thailand. Event I and the A.D. 2004 earthquake had similar effects in Port Blair; however, their sources may be different because they produced different tsunami effects in Thailand.

While no evidence of coseismic land-level change associated with event II was found, it is possible that the area underwent either coseismic or postseismic uplift. If the uplift was not coseismic, it must have been transient in the postseismic period. It did not continue during the entire interseismic period, because the tide gauge data at Port Blair indicates subsidence at a rate of 2.2 mm/yr since A.D. 1916. The reasons to envisage the uplift are (1) the area after event I was under subtidal conditions, as indicated by unit d, and (2) the area was ~1 m above mean sea level before the 2004 Sumatra-Andaman earthquake, as suggested from the uppermost unit a and the subsidence of 1 m during the 2004 earthquake. Thus, it is inferred that the area underwent subsidence of ~1 m during event I, and possibly an uplift of ~1 m between event I and 2004, either coseismic with event II or during the postseismic period, then subsided by ~1 m in 2004. It is also suggested that the uplift could have been the result of slip in the deeper part of the subducting plate farther eastward, resulting in a different pattern of deformation compared to event I and the 2004 Sumatra-Andaman earthquake. Slip along the deeper section might have resulted in uplift of the area around Port Blair and subsidence farther east.

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Notes