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LETTERS

A 1,000-year sediment record of tsunami recurrence in northern Sumatra

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The Indian Ocean tsunami of 26 December 2004 reached maximum wave heights of 35 m in Aceh, the northernmost province of Sumatra[1,2]. Both the tsunami and the associated Sumatra–Andaman earthquake were unprecedented in Acehnese history[3,4]. Here we use sand sheets to extend tsunami history 1,000 years into Aceh's past. The 2004 tsunami deposited a sand sheet up to 1.8 km inland on a marshy beach ridge plain. Sediment cores from these coastal marshes revealed two older extensive sand sheets with similar sediment characteristics. These sheets, deposited soon after AD 1290–1400 and AD 780–990, probably resulted from earlier tsunamis. An additional sand sheet of limited extent might correlate with a documented smaller tsunami of AD 1907. These findings, a first step towards a palaeotsunami record for northern Sumatra, suggest that damage-causing tsunamis in Aceh recur infrequently enough for entire human lifetimes to typically elapse between them. Such recurrence adds to the challenge of preparing communities along the northern Indian Ocean shorelines for future tsunamis.

Aside from the 2004 tsunami and its successor in 2005, few tsunamis are documented in 400 years of Indonesian history to have reached or approached Aceh (Fig. 1a)[3–6]. The largest of these, in 1907, devastated the west coast of Simeulue Island and extended more than 950 km along the northwestern coast of Sumatra[4]. Run-up heights in Aceh are uncertain but, as estimated from interviews with inhabitants, they were far from reaching the extreme wave heights of the 2004 tsunami (Supplementary Note 1). Previously, in 1861, Aceh apparently sustained little or no damage from a documented west Sumatran tsunami[4] associated with a likely predecessor of the Nias earthquake (moment magnitude (M_w) = 8.7) in March 2005 (ref. 7). The latter caused a tsunami that reached heights of 1–4 m in Aceh[8].

We sought geological evidence for past tsunamis on a marshy plain along 4 km of coast north of Meulaboh (Fig. 1a, Me). Marshes have previously yielded geological histories of tsunamis in the northwestern United States[9], Kamchatka[10], Japan[11] and Chile[12]. In Aceh, the marshy plain shows a characteristic ridge and swale topography that is formed by rapid shoreline progradation. Individual beach ridges, which mark former positions of the shoreline, run parallel to the coast for several kilometres (Fig. 1b and Supplementary Fig. 1). They are separated by swales where peaty marsh deposits accumulate.

The sequence of ridges builds progressively seaward at a rate that can be determined from the ages of deposits on the beach ridge plain: the oldest deposit in a swale ~1,800 m distant from the current coastline is dated at between AD 780 and 990, or between 1,230 and 1,020 years ago (Fig. 2a, c). Assuming that at the time of its deposition the coastline was located at the foot of the beach ridge immediately before it—that is, at a distance of ~1,600 m from the current coastline—the average coastal progradation rate can be estimated to lie between 1.3 to 1.6 m yr^{-1}. Such a range has been described for similar beach ridge plains elsewhere[13,14].

In swales between beach ridges we took more than 100 auger cores along four transects running perpendicular from the coast up to 2 km inland (Fig. 1b and Supplementary Fig. 1). Wet ground and partly submerged areas limited access and precluded trenching (Supplementary Fig. 1). The coring in the swales was limited to depths of 1–2 m by compact grey-greenish, fine to medium shoreface sand extending beneath the beach ridge plain (Fig. 2 and

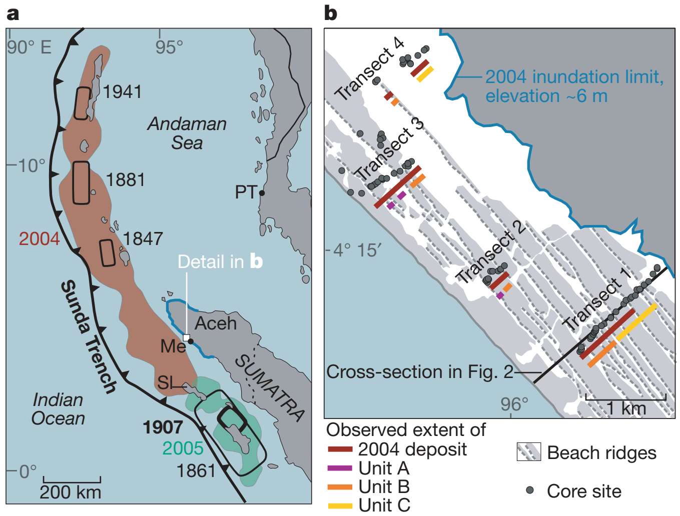

Figure 1 | Index maps. a, Northern Sunda margin and vicinity. The red patch denotes the area of seismic slip during the 2004 Sumatra–Andaman earthquake of magnitude 9.2 (ref. 26). The green patch indicates the area of seismic slip during the March 2005 earthquake[7]. Rectangular patches outlined in black mark inferred rupture areas of historically reported earthquakes[3–6,26]. The blue line denotes Acehnese coast damaged by the 2004 tsunami. SI, Simeulue Island; Me, Meulaboh; PT, Phra Thong Island, Thailand. **b**, Locations of sample sites and extents of sand sheets A, B and C along shore-normal transects. The beach ridges, sketched from aerial photographs (Supplementary Fig. 1), mark former shorelines from the past 1,000 years or more. The 2004 tsunami inundation is mapped from the extent of dead trees in Supplementary Fig. 1.

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Supplementary Fig. 2). Because swale age increases inland, however, coring progressively farther from the modern beach allowed us to extend the sedimentary record about 1,000 years into the past.

North of Meulaboh the 2004 tsunami reached wave heights of between 9 and 14 m (ref. 15) and inundated the area to a distance of 2.0–2.5 km inland (Fig. 1b and Supplementary Fig. 1). The tsunami deposited a sand sheet that can be followed up to 1.8 km inland, and shows overall landward thinning from ~50 cm near the shoreline to a few millimetres farther inland (Fig. 2 and Supplementary Fig. 2). A continuous sand sheet can be found in swales up to 800 m inland, whereas farther away from the shoreline the deposit becomes patchy. Although typically without obvious internal structure, in some locations the 2004 sand sheet shows normal grading with as many as three normally graded layers (Supplementary Fig. 3). Near the present shore the 2004 deposit consists of moderately-to-well-sorted medium sand dominated by silicate grains. Farther inland the sorting becomes poor; the mean grain size diminishes to fine sand (Supplementary Fig. 4), and the sand grains are mixed with soil fragments and plant debris. Microscopic fossils in 2004 deposits include pollen grains and diatoms. Although the diatoms are mostly of freshwater origin, one sample abounds in *Nitzschia salinicola*, a species that can grow in brackish water and is associated with sand grains (Supplementary Fig. 2 and Supplementary Table 1).

Sediment cores from the swales revealed three older sand beds, a few millimetres to 25 cm thick, that are intercalated with peaty marsh deposits (units A, B and C in Fig. 2, and Supplementary Fig. 2). We correlated them both between cores along shore-normal transects and between transects connected by shore-parallel beach ridges (Figs 1b and 2, and Supplementary Figs 1 and 4). Though nowhere encountered in vertical stratigraphic succession, the three units are superposed geomorphically: in keeping with the progressive seaward shift in shoreline, the oldest of the three units (C) is the farthest inland, and the youngest unit (A) the closest to the modern shoreline. The three units can be distinguished not just by geomorphic position on the beach ridge plain but also by landward fining along transects (Supplementary Fig. 4) and by radiocarbon ages (Supplementary Table 2).

Among the three pre-2004 sand sheets, unit A was found in just a few places 300–500 m from the modern beach, whereas units B and C extend more widely. Along transect 1 we found them 700–1,100 m inland and 1,200–1,800 m inland, respectively (Figs 1b and 2). All three units resemble the 2004 tsunami deposit compositionally: they are composed of grey-brown, silicate-rich, fine to medium sand rich in pollen grains and plant debris. Individual units become more fine-grained and less well sorted with increasing distance to the shoreline (Supplementary Fig. 4). Also like the 2004 deposit, the sand layers are typically massive but might show normal grading. Unit B contains two depositional units locally (Fig. 2d).

Among 14 microfossil samples, only 8 yielded diatoms (Supplementary Fig. 2). These are dominated by freshwater species (Supplementary Fig. 2 and Supplementary Table 1) except in one sample containing marine valves of *Actinoptychus* and *Diplomenora* (Fig. 2e, Supplementary Fig. 2 and Supplementary Table 1). We infer that the overall scarcity of diatoms in the pre-2004 sand units results from the dissolution of diatom silica at high temperatures and within an organic-rich environment[16].

We obtained AMS radiocarbon ages on pieces of wood and other plant debris, all probably detrital, from below and above sand beds. We interpret the lower dates as maximum ages and the upper ones as minimum ages for the times of sand-sheet deposition (Supplementary Table 2). The resulting age estimates, with ranges at two standard deviations, are younger than 1640–1950 AD for

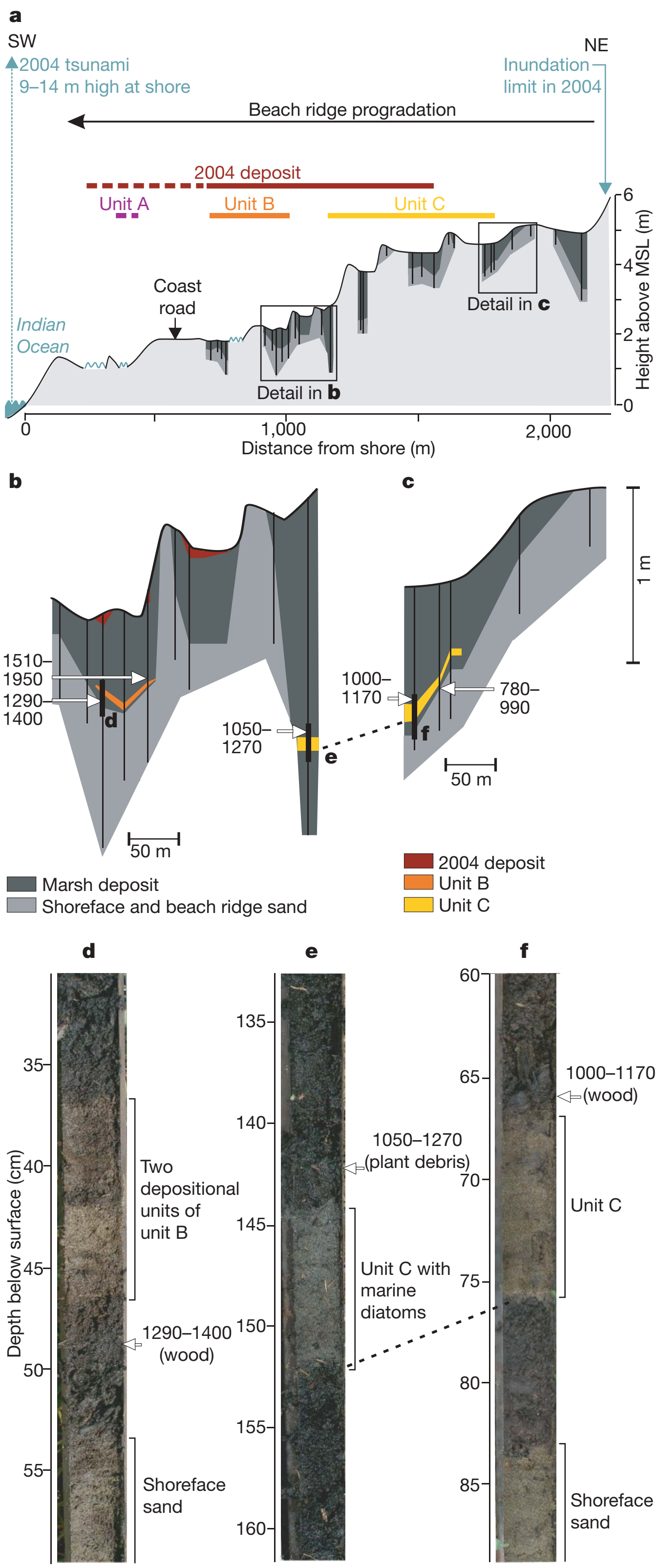

Figure 2 | Examples of sand sheets near Meulaboh. a, Topography of the beach ridge plain along shore-normal transect 1 (location shown in Fig. 1b), obtained by auto-level surveying, field observations, aerial photographs and a digital elevation model from helicopter surveys[27]. Cores are shown by vertical lines. The observed extents of the 2004 sand sheet and of three earlier sheets (units A, B and C) are plotted above profile. Stippled lines mark the extent of sand sheets projected from near shore transects 2 and 3. The vertical elevation has been magnified 125-fold. MSL, mean sea level. **b**, **c**, Generalized stratigraphy and radiocarbon ages (in years AD at two standard deviations) along two parts of transect 1 indicated in **a**. **d**–**f**, Photographs of auger core samples from sand units B and C. Locations are shown in **b** and **c**.

unit A, between 1290–1400 and 1510–1950 AD for unit B, and between 780–990 and 1000–1170 AD for unit C.

Units A, B and C are best explained by tsunamis that ran onto the beach ridge plain and deposited sand on top of peaty marshes. Architecturally the three units resemble tsunami sand sheets described elsewhere: the sand extends hundreds of metres inland and rarely exceeds 25 cm in thickness[17]. Massive or normally graded beds and the lack of bed-load transport structures further indicate settling from suspension, which is characteristic of tsunami deposition[17,18]. Finer-grained and less well sorted deposits with increasing distance from the shoreline have been observed in other tsunami deposits[17] and point towards waning flow velocities and towards the incorporation of plant debris and soil into the flow during the landward passage of a tsunami. Despite the meagre microfossil evidence of a marine origin of the sand layers, we rule out flood deposition because most of our sampling sites are located a few kilometres south of the nearest (Woyla) river (Supplementary Fig. 1). Furthermore, villagers report that river floods during the monsoon season have not reached our sampling sites.

Sumatra's geographical setting probably excludes the deposition of the sand beds by storms. The island is located within the equatorial zone where tropical cyclones rarely occur for lack of sufficient Coriolis Force[19]. One exception was Typhoon Vamei in 2001, which formed in the South China Sea, proceeded westward and eventually passed over Sumatra, 100 km south of Meulaboh, before dissipating over the Indian Ocean[20]. The storm weakened during its passage over Sumatra and caused no reported storm surge on the island's west coast[21].

How might the three pre-2004 sand units correlate with the written and geological records in the Indian Ocean region? Unit A, being younger than AD 1640–1950 and limited to a narrow area, might represent the documented smaller tsunami of AD 1907. Unit B, if deposited shortly after AD 1290–1400, may correlate with the youngest pre-2004 tsunami deposit inferred from sand sheets of Phra Thong Island, Thailand (Fig. 1a), dated to soon after AD 1300–1450 (ref. 22). Unit C, deposited after AD 780–990, has no dated equivalent in Thailand. However, marine terraces in the Andaman Islands, the northern part of the 2004 rupture area (Fig. 1a), have been dated to AD 1170–1600 and AD 550–1330 and have been interpreted as evidence for subduction earthquakes[23]. Acehnese units B and C might correlate with these terraces.

The combined evidence from Meulaboh and Phra Thong, although correlated tentatively, suggests that recurrence intervals of destructive tsunamis from Sumatra–Andaman sources can span centuries, with the 2004 Indian Ocean tsunami separated from its youngest full predecessor by perhaps 600 years. Such a long recurrence interval, which exceeds Indonesian tsunami records by about 200 years, would explain not just the lack of historical data but also the enormity of the 2004 Sumatra–Andaman earthquake[24].

Infrequent tsunami recurrence poses a dilemma for communities devastated by the 2004 tsunami. What balance should survivors seek between the risks of the next tsunami that might not return for a few generations, and the benefits of living close to sea? A partial solution is to ensure that communities sustain awareness of tsunami hazards. Such awareness saved thousands of lives on Simeulue Island (Fig. 1a), where people knew to interpret the severe ground shaking of the 2004 earthquake as a natural tsunami warning[25]. This knowledge, derived from Simeulue's great losses to the 1907 tsunami, led the island's residents flee to high ground in time to escape the 2004 tsunami. On the Sumatran mainland, a large fraction of the tsunami's victims may have survived in this fashion had the area's history of recurring tsunamis been detected and communicated in time.

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1. Tsuji, Y. *et al. Distribution of the tsunami heights of the 2004 Sumatra tsunami in Banda Aceh measured by the tsunami survey team* 〈http://www.eri.u-tokyo.ac.jp/namegaya/sumatera/surveylog/eindex.htm〉 (2005).
2. Yalciner, A. C. *et al. December 26, 2004 Indian Ocean tsunami field survey (Jan. 21–31, 2005) at north of Sumatra Island* 〈http://ioc.unesco.org/iosurveys/Indonesia/yalciner/yalciner.htm〉 (2005).
3. Hamzah, L., Puspito, N. & Imamura, F. Tsunami catalogue and zones in Indonesia. *J. Nat. Disast. Sci.* **22,** 25–43 (2000).
4. Newcomb, K. R. & McCann, W. R. Seismic history and seismotectonics of the Sunda Arc. *J. Geophys. Res.* **92,** 421–439 (1987).
5. Bilham, R., Engdahl, R., Feldl, N. & Satyabala, S. P. Partial and complete rupture of the Indo-Andaman plate boundary 1847–2004. *Seismol. Res. Lett.* **76,** 299–311 (2005).
6. Ortiz, M. & Bilham, R. Source area and rupture parameters of the 31 December 1881 $M_w = 7.9$ Car Nicobar earthquake estimated from tsunamis recorded in the Bay of Bengal. *J. Geophys. Res.* **108,** 1–16 (2003).
7. Briggs, R. W. *et al.* Deformation and slip along the Sunda megathrust in the great 2005 Nias–Simeulue earthquake. *Science* **31,** 1897–1901 (2006).
8. U.S. Geological Survey. *Notes From the Field ... USGS Scientists in Sumatra Studying Recent Tsunamis: Leg 2 Reports, 12 April to 30 April 2005* <http://walrus.wr.usgs.gov/news/reports.html> (2005).
9. Atwater, B. F. & Moore, A. L. A tsunami about 1000 years ago in Puget Sound, Washington. *Science* **258,** 1614–1617 (1992).
10. Pinegina, T. K. & Bourgeois, J. Historical and paleo-tsunami deposits on Kamchatka, Russia: long-term chronologies and long-distance correlations. *Nat. Hazards Earth Syst. Sci.* **1,** 177–185 (2001).
11. Nanayama, F. *et al.* Unusually large earthquakes inferred from tsunami deposits along the Kuril trench. *Nature* **424,** 660–663 (2003).
12. Cisternas, M. *et al.* Predecessors of the giant 1960 Chile earthquake. *Nature* **437,** 404–407 (2005).
13. Anthony, E. J. Beach-ridge development and sediment supply: examples from West Africa. *Mar. Geol.* **129,** 175–186 (1995).
14. Tanner, W. F. Origin of beach ridges and swales. *Mar. Geol.* **129,** 149–161 (1995).
15. Kongko, W., Istiyanto, D. C. & Irwandi, I. *Tsunami Modeling and Field Observations of December 26 2004 Indian Ocean Earthquake* (Technical Report, Coastal Dynamic Research Center (BPPT), Jogjakarta, 2006).
16. Bennett, P. C., Siegel, D. I., Hill, B. M. & Glaser, P. H. Fate of silicate minerals in a peat bog. *Geology* **19,** 328–331 (1991).
17. Morton, R. A., Gelfenbaum, G. & Jaffe, B. E. Physiacal criteria for distinguishing sandy tsunami and storm deposits using modern examples. *Sedim. Geol.* **200,** 184–207 (2007).
18. Goff, J., McFadgen, B. G. & Chagué-Goff, C. Sedimentary differences between the Easter storm and the 15th century Okoropunga tsunami, southeastern North Island, New Zealand. *Mar. Geol.* **204,** 235–250 (2004).
19. Anthes, R. A. *Tropical Cyclones: Their Evolution, Structure and Effects* (Am. Meteorol. Soc., 1982).
20. Chang, C.-P., Liu, C.-H. & Kuo, H.-C. Typhoon Vamei: An equatorial tropical cyclone formation. *Geophys. Res. Lett.* **30,** 1151–1154, doi:10.1029/2002GL016365 (2003).
21. Grandau, F. & Engel, G. *2001 Annual Tropical Cyclone Report*. (U.S. Naval Pacific Meteorology and Oceanography Center/Joint Typhoon Warning Center, 2002).
22. Jankaew, K. *et al.* Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand. *Nature* doi:10.1038/nature07373 (this issue).
23. Rajendran, K. *et al.* Age estimates of coastal terraces in the Andaman and Nicobar islands and their tectonic implications. *Tectonophysics* **455,** 53–60 (2008).
24. Stein, S. & Okal, E. A. Ultralong period seismic study of the December 2004 Indian Ocean earthquake and implications for regional tectonics and the subduction process; The 2004 Sumatra–Andaman earthquake and the Indian Ocean tsunami. *Bull. Seismol. Soc. Am.* **97,** 279–295 (2007).
25. McAdoo, B. G., Dengler, L., Prasetya, G. & Titov, V. Smong: How an oral history saved thousands on Indonesia's Simeulue Island during the December 2004 and March 2005 tsunamis. *Earthq. Spectra* **22,** 661–669 (2006).
26. Chlieh, M. *et al.* Coseismic slip and afterslip of the great M_w 9.15 Sumatra–Andaman earthquake of 2004. *Bull. Seismol. Soc. Am.* **97,** 152–173 (2007).
27. Siemon, B., Steuer, A., Voss, W. & Rehli, H. J. *Helicopter-Borne Geophysical Investigation in The Province of Nanggroe Aceh Darussalam, Northern Sumatra, Indonesia. Survey area Calang-Meulaboh* (Technical Report, Federal Institute for Geosciences and Natural Resources (BGR), Hanover, 2006).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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