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Crustal Deformation and Seismic History Associated with the 2004 Indian Ocean Earthquake: A Perspective from the Andaman–Nicobar Islands

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Abstract The Indian Ocean earthquake of 26 December 2004 led to significant ground deformation in the Andaman and Nicobar region, accounting for ~800 km of the rupture. Part of this article deals with coseismic changes along these islands, observable from coastal morphology, biological indicators, and Global Positioning System (GPS) data. Our studies indicate that the islands south of 10° N latitude coseismically subsided by 1–1.5 m, both on their eastern and western margins, whereas those to the north showed a mixed response. The western margin of the Middle Andaman emerged by >1 m, and the eastern margin submerged by the same amount. In the North Andaman, both western and eastern margins emerged by >1 m. We also assess the pattern of long-term deformation (uplift/subsidence) and attempt to reconstruct earthquake/tsunami history, with the available data. Geological evidence for past submergence includes dead mangrove vegetation dating to 740 ± 100 yr B.P., near Port Blair and peat layers at 2–4 m and 10–15 m depths observed in core samples from nearby locations. Preliminary paleoseismological/tsunami evidence from the Andaman and Nicobar region and from the east coast of India, suggest at least one predecessor for the 2004 earthquake 900–1000 years ago. The history of earthquakes, although incomplete at this stage, seems to imply that the 2004-type earthquakes are infrequent and follow variable intervals.

Introduction

Earthquake generation in subduction zones varies from one to another, in terms of their spatial and temporal patterns (Ruff and Kanamori, 1980; Kanamori and McNally, 1982; Byrne *et al.*, 1992; Nanayama *et al.*, 2003). While some margins are known to produce frequent moderate to large earthquakes (e.g., parts of the Mexican subduction zone), others experience occasional great events separated by periods of little moderate activity (e.g., southern Chile). There are also subduction zones that have not experienced any great earthquakes during the recent history, but have produced such megaevents in the past (e.g., Cascadia). As for the Andaman–Sumatra subduction zone, the southern Sumatra region had generated several large and great earthquakes, but the overall seismicity of the Andaman and Nicobar segments is comparatively low, involving a few large earthquakes and rupture lengths of 200–300 km (Ortiz and Bilham, 2003). The M_w 9.3 2004 earthquake broke ~1300 km of the plate boundary (Ammon *et al.*, 2005), including portions that have ruptured in the recent past (e.g., 1881 and 1941).

The 2004 event is the first giant earthquake to have occurred since the advent of broadband seismometry and space-based geodesy. It attracted global attention also because of the devastating tsunami that affected the Indian Ocean rim countries—an unprecedented experience for people living in these regions. Many issues concerning this earthquake continue to be debated; for example, was this a single or a compound earthquake, consisting of multiple ruptures? Was there a component of slow slip anytime during its rupture propagation? What can be said of the strain accumulation before this earthquake and how would the segments to the north and south behave in terms of future seismic productivity? These issues are discussed in many articles (Ammon *et al.*, 2005, Ishii *et al.*, 2005; Lay *et al.*, 2005, Meltzner *et al.*, 2006; Subarya *et al.*, 2006;). From the point of future regional hazard the challenging issue is to understand if there was a predecessor to this event, an issue that can be addressed through paleoseismological/tsunami geology investigations.

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Our studies in this region started in 2002, using a few campaign-mode stations and selecting locations where microatolls can be used as paleogeodetic indicators as done in the Sumatra Coast (Zachariasen *et al.*, 2000). While these efforts were continuing (although the coral studies did not advance much, because of sampling restrictions), the earthquake occurred, providing some pre-earthquake Global Positioning System (GPS) data (Earnest *et al.*, 2005b). Post-earthquake investigations involved mapping coseismic deformation and obtaining paleoseismological/tsunami evidence in an attempt to reconstruct the earthquake history. Constrained by logistics and entry restrictions to tribal reserves, our surveys could not adequately cover the entire stretch of the islands; nevertheless, observations presented in this article provide the basis for a variety of future investigations.

Historical Seismicity along the Andaman–Nicobar Arc

The Andaman–Nicobar part of the interface between the Indo-Australian plate and the Burma microplate is known to have experienced only a few large earthquakes during recent and historic times (Fig. 1, Table 1). Among the earlier earthquakes, only those in 1881 (M_w 7.9) and 1941 (M_w 7.7) are significant (Bilham *et al.*, 2005). The 26 June 1941 earthquake is reported to have caused an uplift of $\sim$1.5 m along the western margin of the Middle Andaman and subsidence of the same magnitude along the eastern margins, an observation not validated by any direct measurement (Jhingran, 1953). There are no reports of any tsunami impact either from the Andaman and Nicobar islands or from the east coast of India (*Times of India*, Bombay, 28 June 1941; eyewitness accounts of surviving senior citizens at Port Blair). The only tidal chart available from the Calcutta port (source: Survey of India) also does not indicate any notable sea surges subsequent to this earthquake (Rajendran *et al.*, 2005). Another large earthquake is reported to have occurred in the middle/north Andaman on 28 January 1679 (Iyengar *et al.*, 1999). Felt reports from the Burmese coast, as well as parts of the east coast of India (Temple, 1911), suggest this is comparable to the 1941 earthquake in magnitude and rupture extent. An earthquake also occurred in the Arakan Coast of Burma (Myanmar) on 2 April 1762 (Oldham, 1883; Chhibber, 1934); from the description of felt effects in the northern part of the Bay of Bengal and Arakan, it appears that the event was close to the Irrawady delta (Fig. 1). This earthquake elevated the Arakan coastal tract (Terribles to Foul Island in the south) 3–6 m and also probably generated a tsunami that affected the coast of Bengal, including the city of Calcutta and Chittagong (Oldham, 1883). The 1881 earthquake, significant among the past earthquakes, caused a tsunami surge not exceeding 0.75 cm at Car Nicobar (Rogers, 1883); wave, height of 0.25 m was measured from the tide gauge stations at Madras (Chennai) on the east coast of India (Ortiz and Bilham, 2003). The historical records, therefore, show that the 26 December 2004 event has no known historical precedence in the region by virtue of its magnitude, rupture length, and tsunamigenic potential.

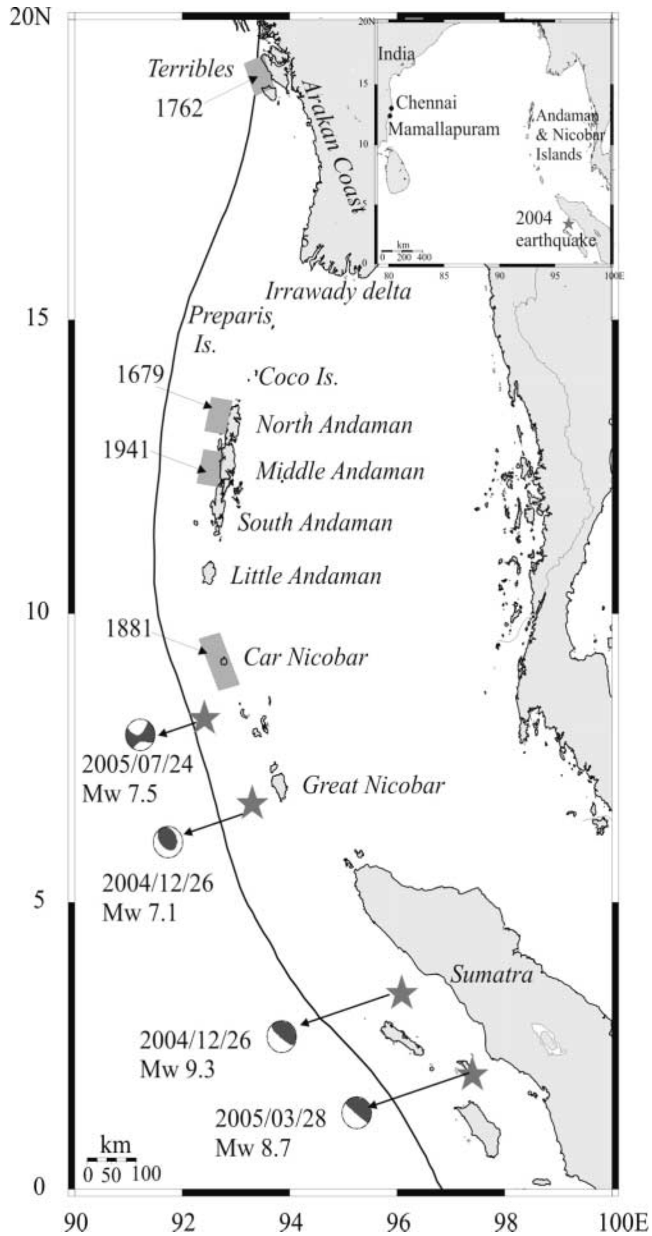

Figure 1. Location of the 26 December and some of the larger aftershocks (source: National Earthquake Information Center [NEIC]). Rupture areas of the 1881 and 1941 earthquakes are from Ortiz and Bilham (2003); rupture area for 1679 is inferred from felt reports in comparison with the 1941 event. (Inset) index map of the region, also showing Mamallapuram on the east coast of India.

Coseismic Ground Level Changes along the Andaman and Nicobar Islands

The 2004 earthquake generated a variety of land level changes reflected on the coastal features, microatolls, and

Table 1
Significant Earthquakes That Occurred in the Past in Andaman and Nicobar Islands

No.	YYYY/MM/DD	Latitude (° N)	Longitude (° E)	Magnitude	Geographic Location
1	1679/01/28	12.50	92.50	7.5?	Middle/North Andaman (Iyengar *et al.*, 1999)
2	1762/04/02	?	?	?	Arakan Coast (Chhibber, 1934)
3	1847/10/31	?	?	?	Nicobars (Imperial Gazetteer of India, 1909)
4	1881/12/31	9.25 ± 0.75	9.25 ± 0.3	M_w 7.9	North-northwest of the Andaman Islands (Ortiz and Bilham, 2003)
5	1914/11/16	12.00	94.00	M_s 7.2	Southwest of Barren Island
6	1925/06/28	11.0	93.00	6.5	Little Andaman Island
7	1929/08/01	10.0	93.00	M_s 6.5	Nicobar region
8	1929/12/09	04.90	94.80	m_b 6.7, M_s 7.2	Sumatra, Indonesia
9	1936/03/19	10.50	92.50	M_s 6.5	Little Andaman Island
10	1939/09/14	11.50	95.00	M_s 6.0	Andaman Sea, east of Car Nicobar Island
11	1941/06/26	12.50	92.50	M_s 8.1	West of Middle Andaman Island
12	1945/08/08	11.00	92.50	M_s 6.8	North of Little Andaman
13	1949/01/23	09.50	94.50	M_s 7.2	Andaman Sea, East of Car Nicobar Island
14	1955/05/17	06.70	93.70	M_s 7.3	Off the east coast of Great Nicobar Island
15	1957/06/18	14.50	95.70	M_s 6.7	Bay of Bengal
16	1967/02/14	13.70	96.50	M_s 6.8	Andaman Sea, West of the Mergui Archipelago
17	1982/01/20	06.95	94.00	M_w 6.2	8.5 km east of Banaga, Great Nicobar Island (NEIC)
18	1982/01/20	07.12	93.94	M_w 6.1	8 km southeast of Laful, Great Nicobar Island (NEIC)
19	2002/09/13	13.08	93.11	M_w 6.5	23.6 km south-southeast of Diglipur (North Andaman) (NEIC)

The magnitudes of the noninstrumented earthquakes are estimated using damage and felt records (Bapat *et al.*, 1983, and references therein).

mangroves; it also caused ground cracking, liquefaction, and sand blows. These features serve as indicators of coseismic deformation; they also provide telltale evidence of similar events in the past. Some of these features along the Andaman and Nicobar Islands are discussed here, with their locations keyed to Figure 2, and the elevation changes summarized in Table 2. Further, campaign-mode GPS surveys at eight control points provide data on the coseismic changes (Table 3; Fig. 3). In the next section, we present the elevation changes observed in the field, followed by GPS-based constraints. Then, we compare the observed values with the slip-model predictions.

Uplift in the North Andaman

Coseismic ground deformation in the northern part of the rupture zone was characterized by uplift of the land, both along its western and eastern margins. This is manifested mostly in the form of elevated shore lines, uplifted coral beds, emerged mangrove swamps, and recession of water marks showing the pre-earthquake survival levels of mussels and barnacles. Uplift of the coast caused withdrawal of the sea by about 60–80 m, as observed at Ariel Bay, east coast of Diglipur (Fig. 4a). Change in elevation of land was also evident at Mayabandar, about 80 km south of Diglipur, where lines of mussels occur >50 cm above the postearthquake high tide (Fig. 4b). Rise in the ground level was evidenced by the emergence of mangrove swamps, with roots exposed 50–60 cm above the postearthquake high-tide level (Fig. 4c). The beaches of Avis Island, located on the eastern margin of the North Andaman, were uplifted by ~1 m, as evident from the raised beach.

Coseismic ground uplift appears to have progressed to the northern limits of the islands, the farthest we could observe was at the Landfall Island, about 40 km north of Diglipur, where microatolls are elevated by 0.6 m above the present high tide (Fig. 4d). Based on remote sensing data, Meltzner *et al.* (2006) have reported minor uplift of 20–30 cm at Preparis Island (see Fig. 1 for location).

Uplift along the Western Margins

Most parts of the western Andaman Islands are tribal reserves where entry is restricted and the land surveys were confined to a few accessible islands. Aerial surveys done soon after the earthquake have reported uplift of ~1 m, along the western Andaman coast, based on the raised watermarks (Malik and Murty, 2005). The Coast Guard crews reported emergence of new beaches and elevated coral beds along the western part of North Sentinel Island. Along the accessible margins of North Andaman, we noted uplifted mangrove swamps, with their roots exposed 50–60 cm, above the pre-earthquake high tide.

We documented evidence of uplift along the western margin of Interview Island, about 200 km north of North Sentinel, where microatolls remain exposed 1–1.5 m above the present low-tide level. Microatolls are known to grow up to a certain elevation with respect to the annual lowest tides; this is known as the highest level of survival (HLS) above which the they cannot survive and grow (Taylor *et al.*, 1987). Thus, the height to the top of the microatolls is taken as a good indicator of the pre-earthquake low-water level, and the change in elevation is measured with respect to the present low-water level. We have not attempted to conduct any cross-sectional study of the coral head, but only recorded their morphology with reference to the annual low-

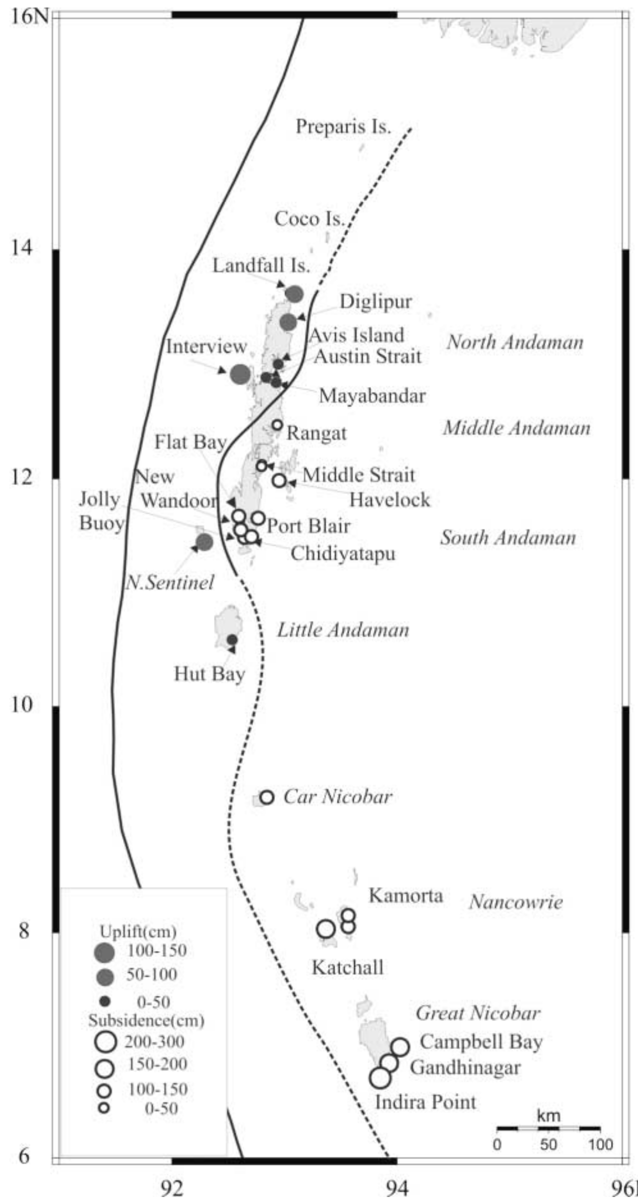

Figure 2. Map of the Andaman and Nicobar region showing areas of uplift and subsidence, based on field observations; also shown is the pivot line: solid line denotes regions where sense of movement is tightly constrained; dashed lines indicate poorly constrained parts of movement.

est tide (see footnotes in Table 2). Our measurements of emerged microatolls suggested an elevation change of 1.5 m; this was confirmed from beach profiles taken by using a digital theodolite. An independent survey by Kayanne *et al.* (2005) conducted on the west coast of Interview Island suggested a change in elevation of 1.53 m based on the emergence of microatolls.

Subsidence at Port Blair

Although most parts of South, Middle, and North Andaman showed evidence of coseismic emergence, Port Blair, located on the eastern margin of South Andaman, subsided by >1 m. The pre- and postearthquake tide gauge record at Port Blair indicated a shift of 1.0 m between their respective diurnal levels (Fig. 5a). Subsidence of land was significant at Sipighat, close to Port Blair, where many houses remain submerged to the level of windowsills; the area remains flooded even during low tides (Fig. 5b). At Mundapahar, located on the east coast, mangrove forest remained waterlogged eight months after the earthquake (Fig. 5c). Whereas this region subsided by >1m, western, margins of the south Andaman showed submergence of relatively smaller magnitude. For example, Jolly Buoy and New Wandoor, both located on the western margin registered only 0.6 m of subsidence, compared with locations on the east at the same latitude (Fig. 2). However, at Havelock Island, located farther east of the arc, the subsidence was smaller (0.3–0.5 m) than the preceding locations (Table 2); this site is located >100 km from the subduction front.

Subsidence in the Southern Islands

The southern islands constituting the Car Nicobar, Nancowrie group, and Great Nicobar showed maximum effects of subsidence. Malik and Murty (2005) reported maximum subsidence (3 m) at Great Nicobar, a measurement based on the pre- and postearthquake positions of the basement of a submerged lighthouse (Fig. 5d). Submergence of land leading to permanent water logging was observed also at Campbell Bay and Gandhi Nagar, in the Great Nicobar. Because the whole area had submerged, measurements are largely based on pre- and postearthquake high-tide watermarks on buildings. Submergence of the Kamorta jetty by >1 m was reported by Thakkar and Goyal (2006). The amount of submergence varies from one site to another, based on the nature of the site, slumping, and other secondary effects.

Submergence of Katchall Island is evident from the beach level changes observed from the pre- and postearthquake satellite images as well as field observations. Satellite images reveal maximum subsidence along the west coast of the island, which is more or less flat land of low relief and covered by dense mangrove forests, compared with the east coast, where island hills in general start 300–700 m from the coast (Thakkar, 2005). Field observations of elevation changes summarized in Table 2 compare reasonably well with the coseismic slip-model predictions (Freymueller *et al.*, 2006), discussed in the next section.

Deformation Constraints from GPS

GPS work in the Andaman and Nicobar region started in 2002, with three control points at Port Blair (PBLR), Havelock (HVLK), and Barren Island (BRRN). During our subsequent survey in 2003, we reoccupied PBLR and added Diglipur (DGLP), Car Nicobar (CARN), and Chatham (CHAT). During the 2004 campaign, which ended three months before the earthquake, two more stations were

Table 2
Summary of Field Observations on Coseismic Changes*

Location	Longitude (° E)	Latitude (° N)	Features†	Up/Dn (±m)	Q‡	Source§	Slip Model (m)
Indira Point (Great Nicobar)	93.85	6.80	Submerged lighthouse	>3.0	G	M	−2.8052
Campbell Bay (Great Nicobar)	93.95	6.92	Submerged houses	1–1.5	A	RR	−1.7787
Gandhinagar (Great Nicobar)	93.92	6.89	Submerged beach	1.8–2.5	G	T	−2.0824
Katchall Island	93.40	7.99	Submerged beach	1.5–2.0	G	T	−1.4055
Nancowrie Island	93.52	8.00	Submerged beach	1.0	G	T	−0.9102
Kamorta Island	93.54	8.15	Submerged jetty	1.0–1.1	G	T	−0.6471
Car Nicobar	92.85	9.26	Submerged tourist bungalow	1.0–1.2	G	M	−1.8760
Malacca East Car Nicobar			Submerged temple	1.25	G	R	
Hut Bay	92.54	10.58	Uplifted coral bed	0.30	G	RR	0.2256
North Sentinel	92.26	11.47	Uplifted beach	1.0	A	CG	0.7146
Port Blair	92.70	11.48	Submerged mangroves	1.0	G	RR	−1.0319
Port Blair	92.76	11.68	Tide gauge	1.10	E	NT	
Jolly Buoy	92.68	11.50	Submerged corals	0.63 ± 6.4 cm (N:10)	A	RR	−1.1193
New Wandoor	92.61	11.58	Submerged coast	0.8	G	T	−1.6679
Middle Strait	92.75	12.16	Submerged mangroves	0.5	A	RR	−0.9682
Amkunj (Rangat)	92.95	12.47	Submerged beach	0.1–0.2	G	T	−0.2532
Mayabandar	92.93	12.85	Uplifted mussels	0.62 ± 12 cm (N:12)	A	RR	1.1118
Mayabandar			Uplifted microatolls	0.69 ± 10.3 cm (N:14)	A	RR	
Avis Island	92.95	12.94	Uplifted beach	1.0	G	RR	0.9118
Interview Island (west)	92.66	12.89	Uplifted coast	1.4	G	RR	1.5058
Interview Island (west)			Emerged microatolls	1.5 ± 5 cm	G	K	
Diglipur	93.06	13.35	Raised beach	0.63	G	RR	0.3430
Landfall Island	93.05	13.62	Emerged microatolls	0.65 ± 6.16 cm (N: 7)	G	RR	0.6381
Landfall Island			Emerged mangrove swamps	0.65 ± 6.04 cm (N: 15)	G	RR	

*Model predictions are from the coseismic slip model of Freymueller *et al.* (2006). These field observations were not used in deriving the model, except for the observation that uplift was observed on the west coast of Middle and South Andaman and at Sentinel Island. The model predictions generally agree with the observations; some discrepancies probably arise from site dependency (west or east coast of an island) as well as wedge deformation.

†Methodology followed for biological markers: For the biological markers (microatolls, mussels, mangroove roots, etc.), we made multiple measurements at the time of the low tide and repeated the observations wherever possible on the following day. A mean of these values (N, number of observations) was used to compute the elevation change, their standard deviation taken as the limit of error. As for the tidal corrections, in the absence of local tide gauge data, we use the tidal corrections provided by Meltzner *et al.* (2006) for this region. The residuals obtained by Meltzner *et al.* (2006) for Port Blair indicate a regional tidal correction of 2–4 cm during 2005. For want of a better value for the specific sites in our study area, we follow the same corrections, the upper limit of which is added to the standard errors in observation. Because of their larger uncertainties compared with other measured values, these observations are treated as of average quality. Corrections have been applied only to the observations made in this study.

‡*Q* (Quality of observations): These observations have been graded based on their quality. E, excellent, based on exact measurement. Here we have only one such value, based on the tide gauge at Port Blair. G, good, based on multiple data and multiple observation uncertainties within 12 cm. Elevation changes measured by us using digital theodolite quality are treated as good. A, average, based on biological markers and treated as of average quality.

§K, Kayanne *et al.*, 2005; M. Malik and Murty, 2005; T. Thakkar, 2005; R. Ramesh *et al.*, 2006; RR, this study; N, National Institute of Ocean Technology (NIOT); CG, Coast Guard.

Table 3
History of Occupation of Control Points in the Andaman–Nicobar Region and Coseismic Offsets

Station ID	2002	2003	2004	2005	East	North	Vertical	E sig	N sig	V sig
DGLP	–	2	3	2	−3.987	−2.680	0.601	0.004	0.002	0.013
PBLR	4	5	26	12	−2.962	−1.041	−0.841	0.001	0.001	0.002
HVLK	1	–	–	2	−1.322	−1.018	0.072	0.006	0.003	0.008
HBAY	–	–	3	1	−3.577	−2.916	0.342	0.004	0.002	0.010
CHAT	–	3	–	–	–	–	–	–	–	–
BRRN	1	–	–	–	–	–	–	–	–	–
CARN	–	2	2	2	−5.742	−2.973	−1.122	0.006	0.004	0.012
CBAY	–	–	3	2	−4.145	−2.377	−1.386	0.003	0.003	0.011

All displacements and uncertainties are given in meters (Earnest *et al.*, 2005b; Freymueller *et al.*, 2006).

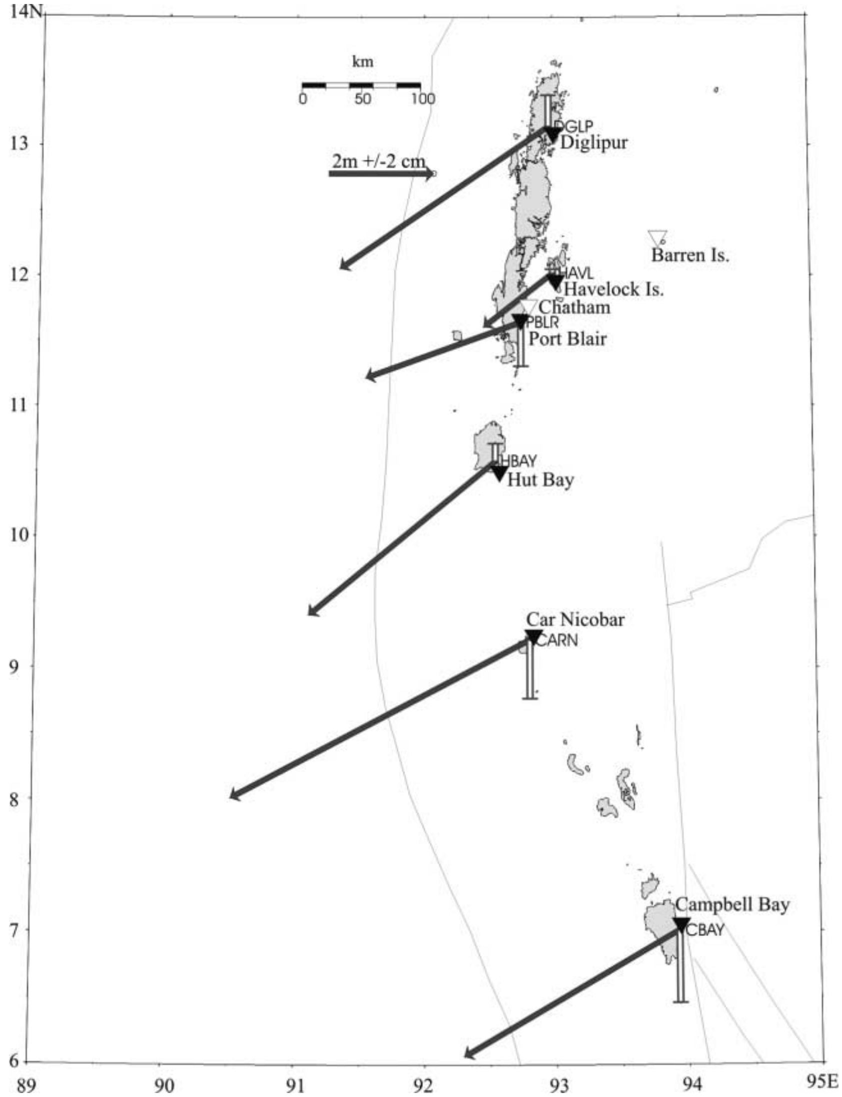

Figure 3. Map of the Andaman–Nicobar region showing GPS points occupied after the 2004 earthquake (filled triangles); open triangles indicate points not occupied after the 2004 event. Arrows show coseismic displacements computed from pre-earthquake observations; vertical displacement (up/down) is also shown (Freymueller *et al.*, 2006). Error estimates are given in Table 3. GPS stations at Diglipur, Hut Bay, and Car Nicobar are now running on a continuous mode.

added, at Hut Bay (HBAY) and Campbell Bay (CBAY). Five of these stations could be occupied soon after the earthquake; Havelock has been occupied since June 2005 and CHAT and BRRN could not be occupied because of logistical problems (see Table 3 for occupational history). Earnest *et al.* (2005b) present the initial results of coseismic offsets based on these surveys; an updated version is given in Figure 3.

Analysis of coseismic GPS data from regional permanent GPS stations indicates that the earthquake affected an area extending at least 4000 km from the source zone and that the South Indian shield shifted eastward by 10–16 mm (Banerjee, 2005). Near-field GPS data obtained from our pre- and postearthquake campaigns suggest that the coseismic displacement was nonuniform along the arc, Car Nicobar having registered the maximum horizontal shift of 6.46 m in the southwest direction (Fig. 3, Table 3).

Because pre-earthquake GPS operations were in a campaign mode, we could not use these data to detect for any precursory deformation. However, we noted some evidence of interseismic emergence from the microatolls in the eastern margin of Andaman Island and Car Nicobar. During the September 2003 surveys, we documented that microatolls emerge by 10 cm above HSL at Port Blair, South Andaman (Fig. 6a) and Diglipur, North Andaman (Fig. 6b). Emergence of microatolls by 20 cm was also observed in the Car Nicobar region during the same period (Fig. 6c). These regions, located on the downdip side of the subduction front are expected to show pre-earthquake emergence and post-earthquake submergence (Spence, 1987), both of which were observed, except in Diglipur.

Coseismic Slip Model Predictions

The coseismic slip model of Freymueller *et al.* (2006) was developed to fit the horizontal and vertical GPS data. The agreement with model predictions is quite good for the southern group of islands, especially for Great Nicobar, Katchall, and Nancowrie Islands. Vertical deformation at Hut Bay, Little Andaman, a site that registered an uplift of

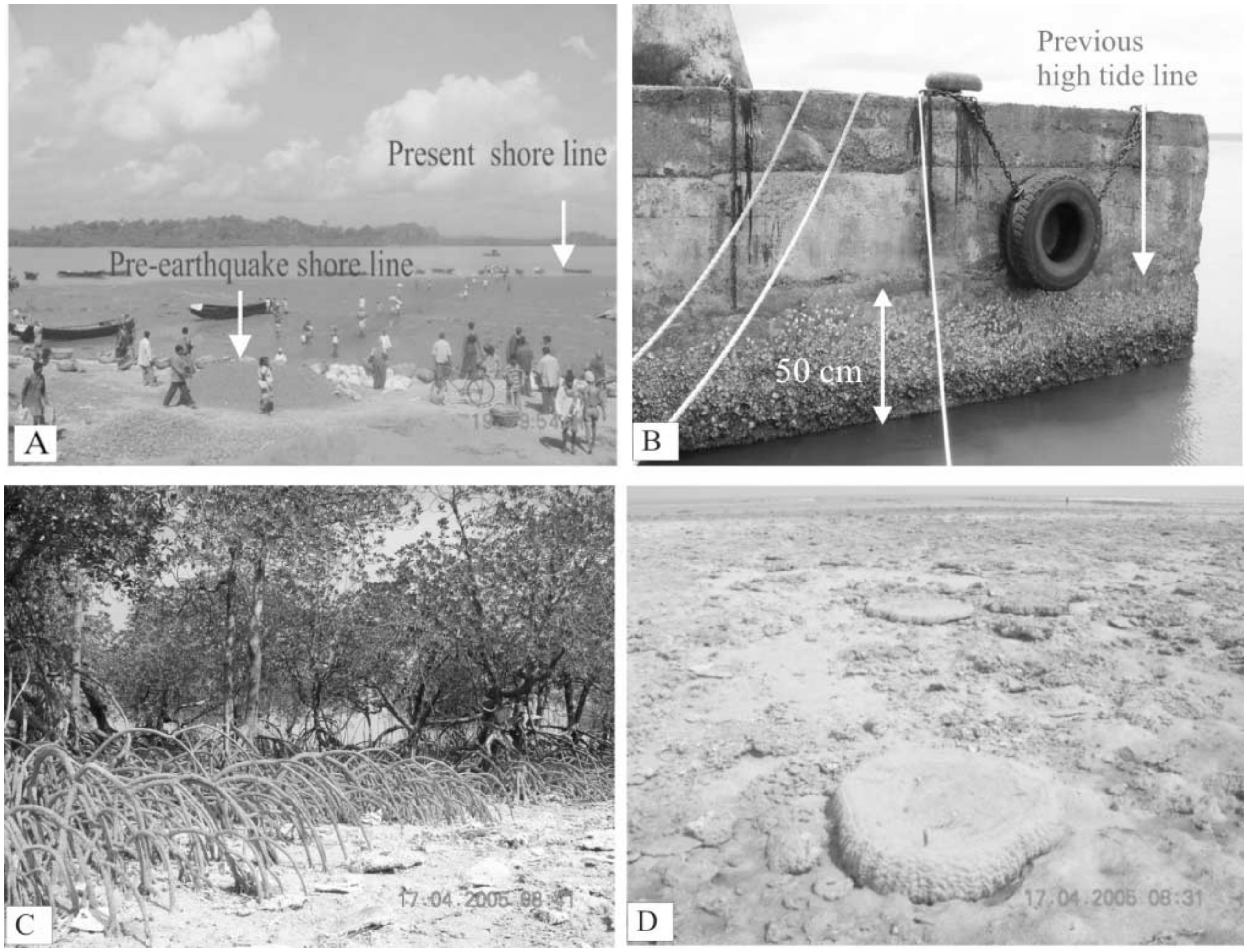

Figure 4. Uplift in Northern group of islands. (a) Recession of sea by 60–80 m from the previous shoreline near Ariel Bay (13°16.864′N, 93°01.509′E), Diglipur. (b) Line of mussels exposed 50 cm above the current high-tide level at Mayabandar (12°55.604′N, 92°54.000′E). (c) Exposed roots of mangroves ~50 cm above the post-earthquake ground level(13°38.594′N, 92°59.604′E). (d) Coral heads elevated ~60 cm in the Landfall Island.

only 0.3 m, agrees well with the model prediction. Subsidence observed at Port Blair is well constrained through higher-quality tide gauge data, and is in perfect agreement with the model predictions. However, for points located in the middle (Middle Strait) and on the western margins of South Andaman (Jolly Buoy and New Wandoor), the agreement is not as good. We suspect this could be due to their relative proximity to the updip side of the fault and/or to influence by the wedge deformation. Similar disagreements are observed for Diglipur, located on the eastern margin of the North Andaman where the model underpredicts the uplift by about 50%. It is possible that the remarkable uplift observed along the eastern margin of North Andaman is the result of wedge deformation. However, this does not seem to be true for Avis Island (Fig. 2) where the field observations are comparable to the model predictions, despite the fact that it is located along the same longitude and is only about 50 km south. The predicted values are in good agreement also for Landfall Island, located in the northern limits of our study area. The model results also agree for the available observations at Interview Island and North Sentinel, the former being a better-constrained value, based on multiple measurements.

One point that must be considered here is the relative postearthquake recovery along these islands. Most of the observations presented in this report were made one to two months after the earthquake; some were made as late as eight months after. Depending on their relative position with respect to the source of the earthquake as well as the distance from the subduction interface, these islands are likely to go through a postearthquake relaxation. For example, analysis of limited postearthquake GPS data suggest that Car Nicobar and Port Blair emerged by 54 mm and 40 mm, respectively, during May–October 2005. On the other hand, Diglipur,

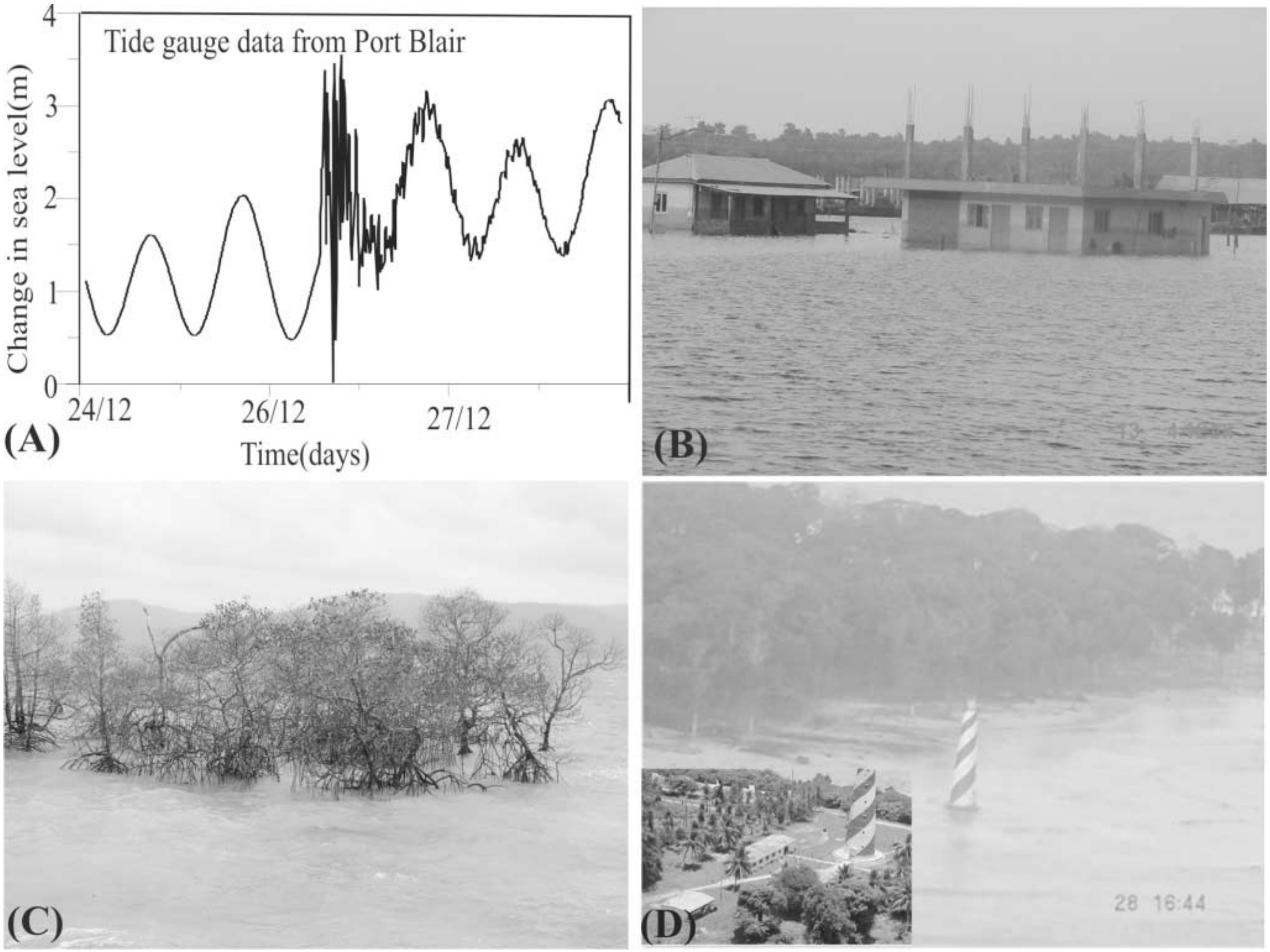

Figure 5. (a) Tide gauge data from the Port Blair station (11°41′N, 92°46′E) recorded by National Institute of Ocean Technology (NIOT), India, showing the subsidence of the pier and ~1-m change in the postearthquake datum. (b) Submerged houses in Sipighat area (11°36.583′N, 92°41.640′E), Port Blair. (c) Submerged mangroves in Mundapahar (11°30.108′N, 92°42.111′E), Port Blair. (d) Base of lighthouse at Indira point (6°45.340′N, 93°49.694′E), Great Nicobar submerged by more than 3 m. (Inset) View of the lighthouse before the earthquake.

which was uplifted coseismically, continued to emerge at a lower rate of 14 mm, based on the GPS observations taken during the same period (Shuler *et al.*, 2005). Thus, models based on observations taken along a stretch of about 800 km, over a period of several months after the earthquake, must consider this aspect. These limitations notwithstanding, we believe that the ability to compare field evidence of ground level changes with a coseismic slip model for great subduction earthquakes is an unusual opportunity.

Liquefaction and Ground Failure

The earthquake produced significant liquefaction at many locations, notably around Diglipur. We observed sand blows (maximum diameter, 20–30 cm), and sand boils and ground cracks (10–15 cm wide) at many locations. A few other smaller-scale features were also reported from middle Andaman and Port Blair (Dasgupta, 2006). Water spouting resulting from intense ground shaking was reported from many parts of Car Nicobar. Note that such features are more profuse in the northern part of the rupture zone, probably because of the relative availability of liquefiable sand and sediment thickness.

We used some of these features in Diglipur as pointers to search for past liquefaction events that may have affected this region. It is not easy to distinguish the size of the causative earthquake that generated the older sandblows. It is equally possible that any of the lesser-magnitude earthquakes (e.g., 1941 or 1679) in the past could have generated these features. Our approach is to document as many features as possible along the arc and examine if contemporaneous features exist at multiple locations. Thus, the results we present here on paleoliquefaction must be treated as tentative and only as a part of the future database. Excavations carried

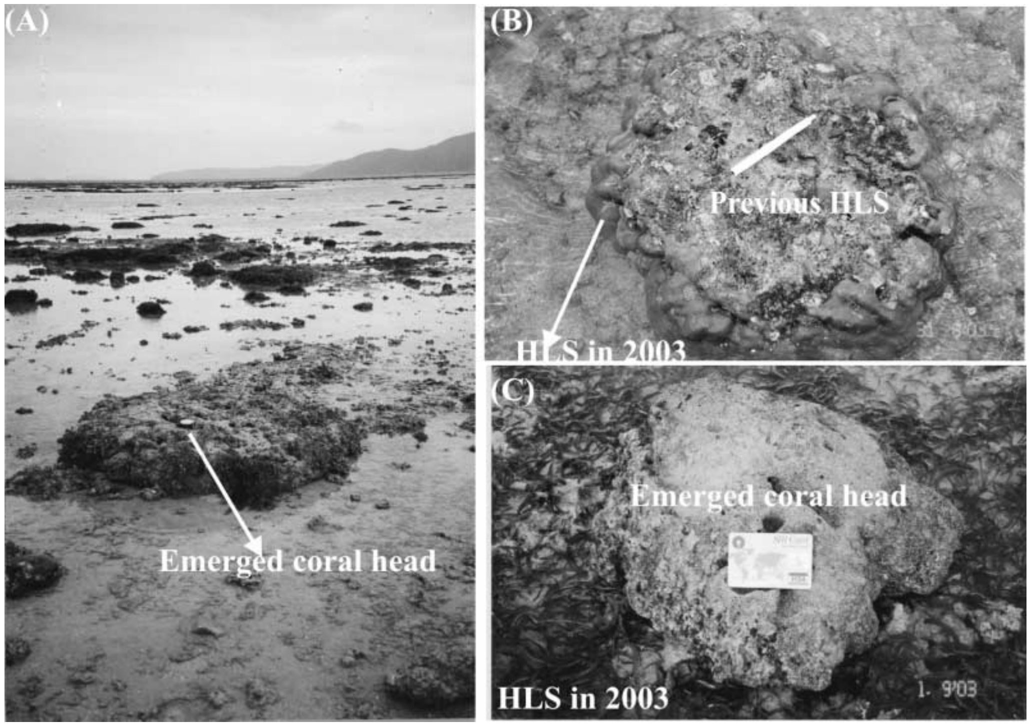

Figure 6. (a) Interseismic emergence of microatolls near Mundapahar (11°30.108′N, 92°42.111′E), Port Blair, by ~10 cm. (b) View of the coral head at Diglipur (13°17.120′N, 93°01.410′E) where the emergence is estimated to be ~10 cm. (c) Interseismic uplift of corals at Arong (9°09.789′N, 92°43.146′E), Car Nicobar, where the coral heads uplifted by ~20 cm. Photographs taken at low tide during September 2003.

out at three locations around Diglipur revealed possible evidence for previous liquefaction events. Here, we present observations from one of the trenches cut on the west bank of Magar Nalla River (Fig. 7). The 1.5-m-thick patch of alluvium preserved on the bank of the river exposed two discordant layers of fine sand, which we interpret as sills, formed by liquefaction (Obermeier and Pond, 1999). The oxidized, clay-rich sand is disturbed by the injection of the sill, but we could not trace the source of the sand. The trench bottomed in a pebble bed, which is being actively eroded during the high tide. Peat samples taken from the top layer of liquefied sand provided a date of 1050 ± 100 yr B.P. The age remains to be constrained by dating more samples; we also need to expand our search to other areas. We report this because its age is comparable to that of other features observed elsewhere in the study area.

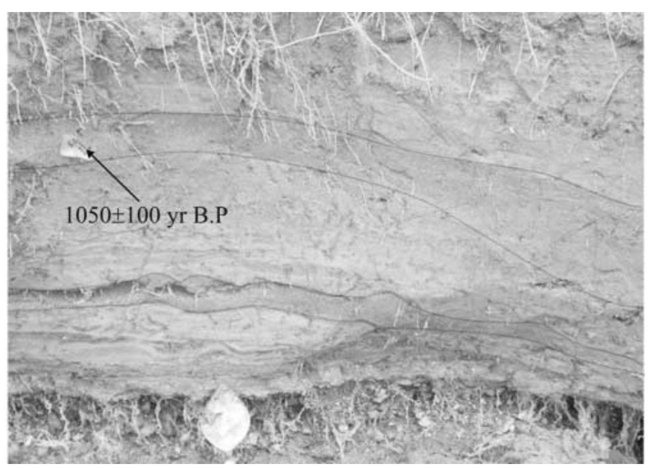

Figure 7. Liquefaction feature exposed on the west bank of Magar Nalla River (13°15.673′N, 92°59.534′E), Diglipur. Multiple injections of fine silty sand are observed on the trench walls; sample location for radiocarbon dating is also shown.

Search for Past Deformation

Evidence for Long-Term Uplift

In general, the regions where coseismic uplift occurred in 2004 are associated with receded marine terraces, useful to compute the long-term uplift rate. We took more than ten profiles of varying lenght (up to 500 m) wherever the beaches were accessible. These profiles indicate elevation changes on the order of 10–30 m, over distances of 100–150 m, often exhibiting steplike features, representative of episodic uplift (Fig. 8a). Here, we use a profile across the western coast of Interview Island where five older terraces are observed. We have dated the coral samples from four

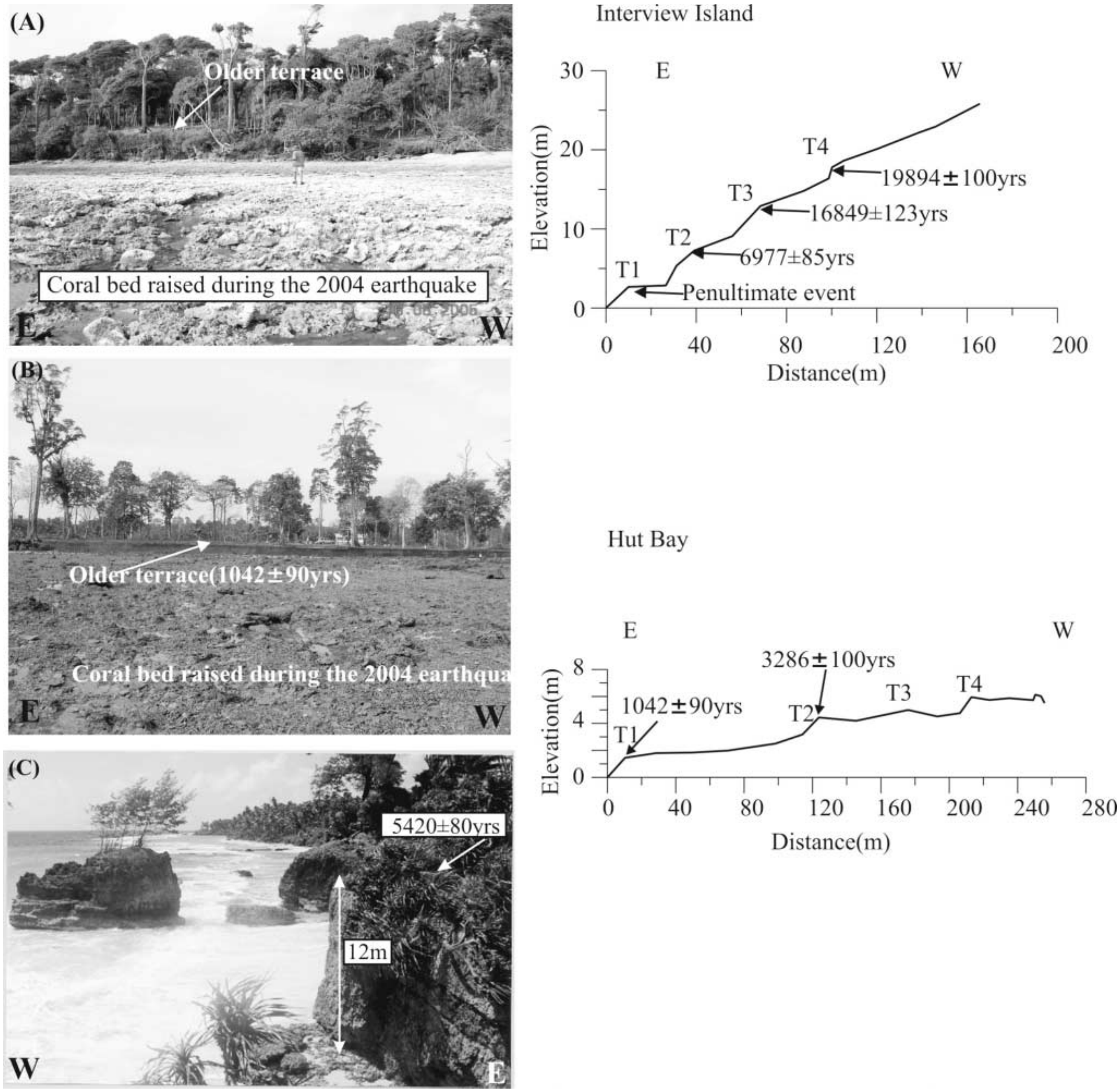

Figure 8. (Left) Coral terraces at Interview Island (12°54.471′N, 92°40.268′E) (a), Hut Bay (10°35.410′N, 92°33.064′E), Little Andaman (b), and Mus (9°14.128′N, 92°46.414′E), Car Nicobar (c) representing coastal uplift. (Right) Elevation profiles for Interview Island and Hut Bay.

terraces and computed the uplift rate during each episode using the global sea level curves (Bloom *et al.*, 1974; Pinter and Gardner, 1989). We do not have the age data for the youngest terrace (T1); ages for the older terraces are given in Table 4. Our observations suggest an uplift rate of 1.75 mm/yr for terrace 2 and an average uplift rate of 6.97 mm/yr for the older terraces. Whether the nonuniform rate of uplift is real or if there is any contamination due to recrystallization in the coral samples for older terraces cannot be ruled out (we still need to examine these samples by quantitative X-ray diffraction to assess the mineralogy). Further work on dating of samples from this region is in progress and we hope to refine these estimates.

A similar profile taken on the east coast of Hut Bay (the western parts are generally inaccessible), where the 2004 coseismic elevation changes, was marginal compared with the measurements from Interview Island. We identified four coral terraces, and dated two of them (Table 4). The age data indicate that two terraces were formed at about 3000 yr B.P. and 1000 yr B.P., respectively. Age data for two of the

Table 4
Ages of the Coral Terraces at Interview Island, Little Andaman, and Car Nicobar

Station No.	Location	Sample ID	Lab No.	Elevation (m)	C14 Years B.P.*	Remarks
Interview Island						
1	Interview Island	IN/TOP/A	R29033/2	50	30,880 ± 300	Coral fragment from the highest point of the island (Fig. 8a).
2	Interview Island	T5/IN/D/P1/A	R29033/3	26	22,890 ± 120	Coral fragment from the fifth terrace on the island ~160 m from the sea (Fig. 8a).
3	Interview Island	T4/IN/D/P1/A	R29033/4	18	19,894 ± 100	Coral fragment from the fourth terrace of the island ~100 m from the sea (Fig. 8a)
4	Interview Island	T3/IN/D/P1/A	IP322	13	16,849 ± 123	Coral fragment from the third terrace of the island ~70 m from the sea (Fig. 8a)
5	Interview Island	T2/IN/D/P1/A	IP320	7	6977 ± 85	Coral fragment from the second terrace ~40 m from the sea (Fig. 8a)
Hut Bay (Little Andaman)						
1	Hut Bay	HB/L2/CP	—	4	3286 ± 100	Coral fragment obtained ~100 m from the sea (Fig. 8b)
2	Hut Bay	HB/L1/CP	—	1.5	1042 ± 90	Coral fragment obtained ~10 m from the sea (Fig. 8b)
Car Nicobar						
1	Car Nicobar	CN/TC/1	BS2258	12	5420 ± 80	Coral fragment from the cliff ~5 m from the sea (Fig. 8c)

*Measurements for C14 dating of the coral samples were done at the Rafter Radiocarbon Laboratory, New Zealand, Birbal Sahni Institute of Palaeobotany, Lucknow, India, and Institute of Physics, Bhubaneswar, India. Ages of calcareous samples are estimated assuming ΔR (difference in reservoir age of local region compared with model ocean) to be zero. Half-life for C14 taken as 5570 ± 30 yr B.P. at the Birbal Sahni Institute of Palaeobotany, 5568 yr B.P. at the Institute of Physics, and 5730 yr B.P. at Rafter Radiocarbon Laboratory, New Zealand.

younger terraces suggest a much slower uplift rate of 1.54 mm/yr, implied also by the subdued topography (Fig. 8b).

The date from Car Nicobar region provides the age of an elevated terrace (profiled in 2003), located 12 m above sea level (Table 4, Fig. 8c). We computed an uplift rate of 3.14 mm/yr. The limited age data available for the three locations along the islands seem to imply variable rates of uplift, evident also from the pattern of coseismic elevation changes. The coseismic emergence at Interview Island and Hut Bay are compatible with the trend of long-term uplift observed at these locations. The deformation at Car Nicobar, however, seems to be characterized by long-term uplift and large coseismic subsidence. The long-term uplift rate at Car Nicobar shows that over the seismic cycle uplift exceeds subsidence, and a permanent uplift component of the postseismic and interseismic deformation field is required.

Evidence for Previous Subsidence Events

Coastal coseismic subsidence is known to occur in association with great subduction zone earthquakes (Atwater, 1987; Leonard *et al.*, 2004, Cisternas *et al.*, 2005). Stratigraphic sequences characterized by peat-mud couplets are considered representative of various cycles of coseismic subsidence and interseismic shoaling in these settings (Atwater, 1987, 1992; Cisternas *et al.*, 2005). With a coseismic subsidence of ~1 m, we focused our studies around Port Blair to identify events of past subsidence. We started our analysis with cores from 30- to 60-m-deep bore holes drilled in various locations at Port Blair (6 September 2005). Stratigraphy reconstructed from three cores selected from this region is presented in Figure 9. All of the three boreholes bottomed on hard basement at depths of 30–40 m from the surface. Sediment layers are mostly composed of sequences of silty/sandy clays with shells. The logs also showed intervening layers (1–2 m) containing decayed wood at depths ranging from 2 to 26 m from the present MSL. Two of the three wells examined here, from Flat Bay (A-1, FB-2, and FB-3), showed continuity in the wood-rich layer at depths of 2–5 m and 11–15 m. A third layer rich in decayed wood was observed at 25 m at FB-2 and 19 m at FB-3, but was absent from A-1 (Fig. 9). The plant material and shells at 4–5 m depth from FB-3 yielded radiocarbon ages of 5903 ± 35 yr B.P. and 6283 ± 25 yr B.P., respectively. Whether these layers resulted from tectonic subsidence needs to be resolved in future investigations.

Some complimentary evidence for past submergence comes from the mangrove swamps at Rangachanga, about 8 km from Port Blair, and 12 km from the location of the wells discussed earlier. This region subsided by 1 m during the 2004 earthquake, and rich mangrove forests subsided by about 1 m. Along the banks of a creek leading to the mangrove swamps, we noted a prominent line of dead tree trunks at 1 m depth, some of which are jutting out into the creek (Fig. 10a). Because this location is in the proximity of a mangrove swamp that coseismically subsided in 2004, we take this as direct evidence for a previous subsidence event. We dated three samples, one from the line of tree trunk and the other two from layers of peat below. The tree trunk was dated at 740 ± 100 yr B.P. and the peat layers yielded ages of 3070 ± 120 yr B.P. and 4320 ± 130 yr B.P. (Table 5). The older dates appear less reliable possibly because of the reworking of sediments. The younger date obtained for the tree trunk is comparable to dates obtained elsewhere, dis-

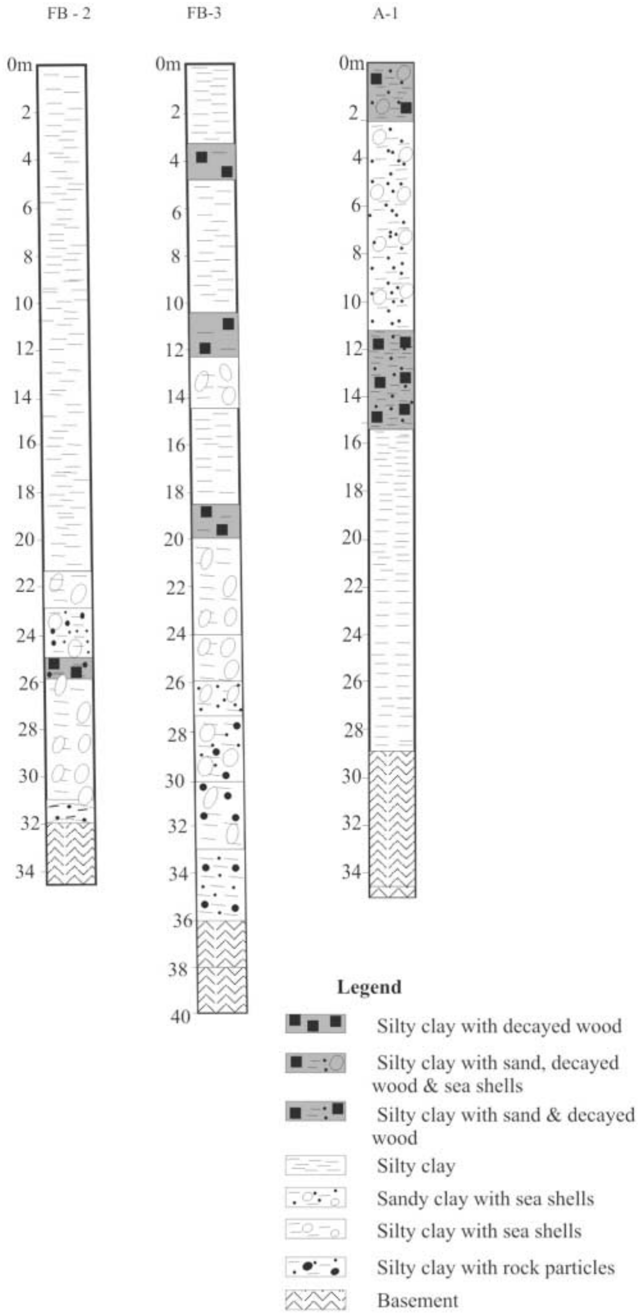

Figure 9. Shallow stratigraphy derived from three boreholes close to Port Blair. Silty clay with plant material and shells observed at different levels in these boreholes indicating possible episodic subsidence in the past.

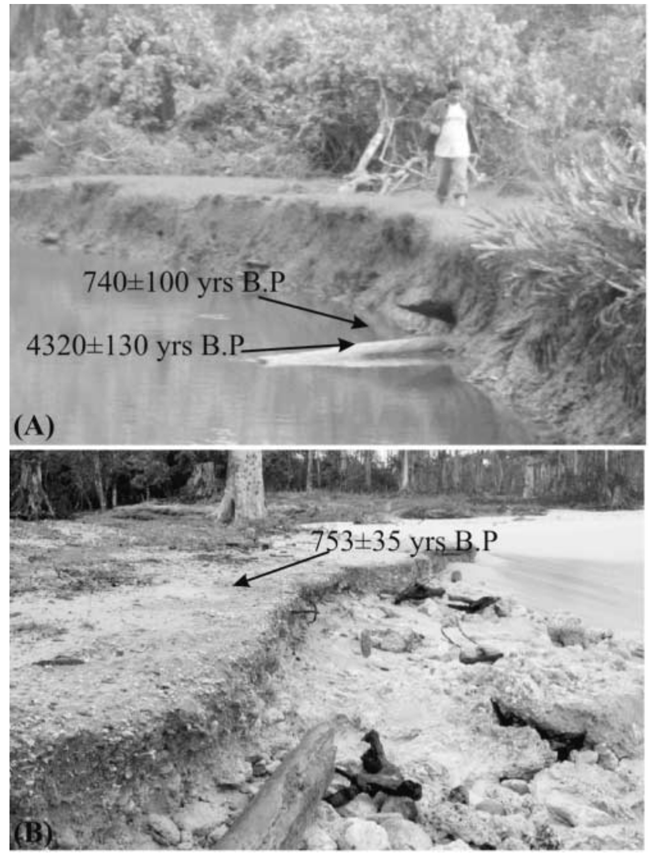

Figure 10. (a) Submerged mangroves observed along a creek near Rangachanga (11°24.575′N, 92°37.443′E), Port Blair (~1 km from the sea front). Note the tree stumps exposed in the creek. The peat layer is dated at 4320 ± 130 years and the tree trunk is 740 ± 100 years old. (b) Semiconsolidated shelly sand and coral rubble deposit overlying an older terrace along the banks of a narrow creek at Hut Bay (10°35.305′N, 92°33.395′E), Little Andaman. The shells have been dated at 753 ± 35 yr. B.P. The coral fragment from the deposit is dated at 5623 ± 35 yr B.P.

cussed later in the text in the context of the past major event that may have affected this region.

Search for Paleotsunami Deposits

Reconnaissance Surveys Close to the Source

Sedimentary deposits of modern tsunamis provide useful recognition criteria for similar past events (Atwater *et al.*, 2005; Cisternas *et al.*, 2005). The 2004 tsunami impacted both near-source and far away locations, more than 2000 km away from the source. It left sand deposits as thick as 70 cm in some locations of the Andaman and Nicobar Islands, and much thinner deposits (~10 cm) along parts of the east coast of India. The deposits varied in composition and thickness but were not as profuse as one would have expected, probably because of the lack of availability of sand. We surveyed three sites at Car Nicobar, Hut Bay (Little Andaman), and Port Blair; at Car Nicobar the maximum thickness of the tsunami sand deposit was about 60–70 cm thick and was characterized by coarse carbonate gravel, with abundant coral fragments and broken shells. Partial grading was evident, with a fining upward sequence; layers formed by multiple waves could also be observed from this deposit (an eyewitness account suggests at least three pulses of tsunami

Table 5
Radiocarbon Dates from Various Locations in the Andaman and Nicobar Islands

No.	Location	Sample ID	Lab. No.	C14 years B.P.*	Remarks
1	Panchavadi (Middle Andaman)	PA/Peat/1	BS2505	1490 ± 140	Roots of old mangrove traces preserved in the elevated coastal sections
2	Rangachanga (near Port Blair)	RG/Peat/2	BS2511	4320 ± 130	Peat from stream bank (Fig. 10a)
3	Rangachanga (near Port Blair)	RG/Wood/1	BS2530	740 ± 100	Wood sample from stream bank (Fig. 10a)
4	Magar Nalla (near Diglipur)	MN/Sill1/S3	BS2521	1050 ± 100	Peat taken from the top of the liquefied layer (Fig. 7)
5	Hut Bay (Little Andaman)	GS/HUT/OT	R29033/8	753 ± 35	Gastropod shells from rubble deposits from the older terrace (Fig. 10b)
6	Hut Bay (Little Andaman)	CS/HUT/OT	R29033/7	5623 ± 35	Coral fragment from the rubble deposit

*Measurements for C14 dating of the coral samples were done at the Rafter Radiocarbon Laboratory, New Zealand, Birbal Sahni Institute of Palaeobotany, Lucknow, India, and Institute of Physics, Bhubaneswar, India. Ages of calcareous samples are estimated assuming ΔR (difference in reservoir age of local region compared with model ocean) to be zero. Half-life for C14 taken as 5570 ± 30 yr B.P. at the Birbal Sahni Institute of Palaeobotany, 5568 yr B.P. at the Institute of Physics, and 5730 yr B.P. at Rafter Radiocarbon Laboratory, New Zealand.

waves affected the area). The deposit at Port Blair is composed mostly of coarse-to-fine grained and better-sorted sand, probably remobilized from the beach itself. However, Moore *et al.* (2006a), based on their work in Sumatra, suggests a complex stratigraphy and distinct changes in the composition of the sand deposits, which varies based on the location of the site with respect to the inundation zone and ocean front.

On the east coast of Hut Bay (Little Andaman), the tsunami waves traveled ~1 km inland through a creek, the effects of which are evident from the scouring and deposition of fresh sands and debris (Ramanamurthy *et al.*, 2005). We observed huge blocks of microatolls carried from the seaside, about 300 m to the west of the seashore, brought inland by the 2004 tsunami. Along margins of this creek, about 500 m inland, we noted patches of semiconsolidated deposit (~50 cm thick) consisting of assorted shells and poorly sorted coralline sands, overlying an older terrace (Fig. 10b). From the composition of the deposits, which included shells such as gastropods, and its occurrence as a narrow band (~100 m wide) along the banks of the creek, it is logical to trace its origin to a huge sea surge, possibly an earlier tsunami. Gastropod shells and coral fragments from this deposit yielded dates of 753 ± 35 yr B.P. and 5623 ± 35 yr B.P., respectively (Table 5). It is likely that the age of the gastropod represents the timing of the sea surge. We are exploring the region for more such deposits to establish their diagnostics and to develop better age constraints, to check whether there is a regional pattern and consistency in the ages of these deposits.

Reconnaissance Surveys along the East Coast of India

The 2004 tsunami has no known predecessors in the east coast of India; thus, no effort was made in the past to search for paleotsunami deposits. Open beach conditions characterized by a high rate of erosion, combined with the anthropogenic activity, contribute to the poor preservation of deposits, if any. Despite these adverse conditions, any positive evidence pointing to a paleotsunami can be used to recognize past events. We started our search from locations that had been affected by the 2004 tsunami, also seeking favorable sites that could offer reliable historical and archaeological constraints.

Chadha *et al.* (2005) reported run-up elevation of 2.5 to 5.2 m and lateral inundation up to 430 m along the east coast of India, south of 14° N. They also noted tsunami sand deposits (1 cm to several tens of centimeters thick) with fining-upward sequences, transported 100 m inland. Here we report results of our investigations at Mamallapuram, an important port under the Pallava Kings built about 1000–1300 years ago (see Keay [2000] for historical details on the Pallava dynasty) and a prominent heritage site. Chadha *et al.* 2005 had not surveyed this location, but from locations immediately north, they reported an inundation distance of 360 m and run-up elevation of 4.1 m. Based on surveys along 60 km length of the beaches south of Mamallapuram, Seralathan *et al.* (2006) reported tsunami sands varying in thickness from 0.5 to 45 cm, fining-upward sequences thinning out within 15 m of the limit of inundation.

The 2004 tsunami stripped beaches and created scour ponds along the Mamallapuram Coast and exposing the basement of buried cultural settlements, which were subsequently excavated by the Archaeological Survey of India (ASI). Here we report results from a site that exposed ruins of ancient temples dating to seventh to eighth century A.D. From the descriptions of the early navigators, Mamallapuram is known as a town of seven pagodas (turrets of the Hindu temples); the only surviving structure is the Shore Temple—a world heritage site that escaped the scouring action of the tsunami because it stands on a rock outcrop and is further reinforced by a shore protection wall. Other temples are submerged but their top parts were visible a few centuries ago (Chambers, 1788). Mamallapuram has a history of submergence and episodes of flooding (Raman, 1998); William Chambers, an early British explorer, attributed part of the submergence to "overflowing sea" caused by an earthquake (1788; page 154). The scouring during the 2004 tsunami exposed some archaeological artifacts at two sites in the Mamallapuram beach. Excavations by the ASI at these sites revealed cultural settlements and associated sedimentary horizons dating to the fourth to ninth century A.D. We observed two anomalous sand deposits trapped above successive brick foundations, presumably destroyed by a sea surge; the latter destruction around ninth century A.D. From the nature and context of these deposits, it appears that a major sea surge, possibly a tsunami, was responsible for the destruction, the younger event dated around 900–1000 yr B.P. and the older one at about 1400 yr B.P. Comparable ages obtained for the paleoliquefaction feature at Diglipur, subsided tree trunk at Rangachanga, and gastropods from the suspected paleotsunami deposit at Little Andaman provide complimentary evidence for a megathrust earthquake, a predecessor of the 2004 event.

Excavations at Saluvankuppam

Excavations at Saluvankuppam, near Mamallapuram, revealed an ancient temple complex representing three phases, spanning from early fourth century to ninth century A.D. Structures belonging to the two earlier phases are built in bricks; during the latest phase, before the use of granite had come in vogue. Apparently, each of these three settlements was destroyed; the last phase of destruction is evident also from the granite pillars strewn around on the western side of the temple. Why the resident community abandoned such a well-developed cultural habitat, especially a place of worship, is not evident. Is it possible that successive sequences of sea surges could have destroyed each of these constructions and the site was ultimately abandoned? Given the 400–600 m inland invasion of the recent tsunami along this coast, it is reasonable to assume that repeated inundation and destruction along the previously extended coast must have prompted the ancient settlers to abandon the site after the last phase of destruction, at about A.D. 925 (Rajendran *et al.*, 2006).

The western and eastern walls of the excavated site consist of several layers of sand, mixed with brick debris, shells, and pottery shards. We noted three layers of highly compacted sand, consisting of brick debris, plaster, and shell remains, representing various phases of construction (L1, L2, and L3 in Fig. 11a). These layers observed only on the seaward side must have been used to stabilize the ground as well as to provide protection from the sea. Sandwiched within the top layer of brick debris, we found a thin layer of sand, which we believe is a paleotsunami deposit. Because of the infrequency of tsunami events, little or no effort has gone toward characterizing tsunami deposits along the coasts of the Indian Ocean countries.

The suspected tsunami deposit reported by us occurs as a thin layer of sand of varying thickness (14–10 cm) sandwiched between two layers of compacted brick debris extending from the south to the east wall, finally tapering (1–2 cm) on the northern wall (Fig. 11a). This anomalous sand layer is characterized by flow structures, laminations, and thinning upward sequences, typical of tsunami deposits (Moore *et al.*, 2006b and references therein). Small fragments of bricks and clasts, probably derived from the brick debris are embedded within this layer. The constitution of the brick debris above and below the sand layer appears to be different, which we attribute to reinforcement of the original layer after the sea surge (see Rajendran *et al.* [2006] for details). Charcoal pieces obtained from the sand layer (S1) provided an age of 955 ± 30 yr B.P. (A.D. 1019–1161), and probably postdates the construction of the stone temple. The flooding event may have occurred between the inscriptional

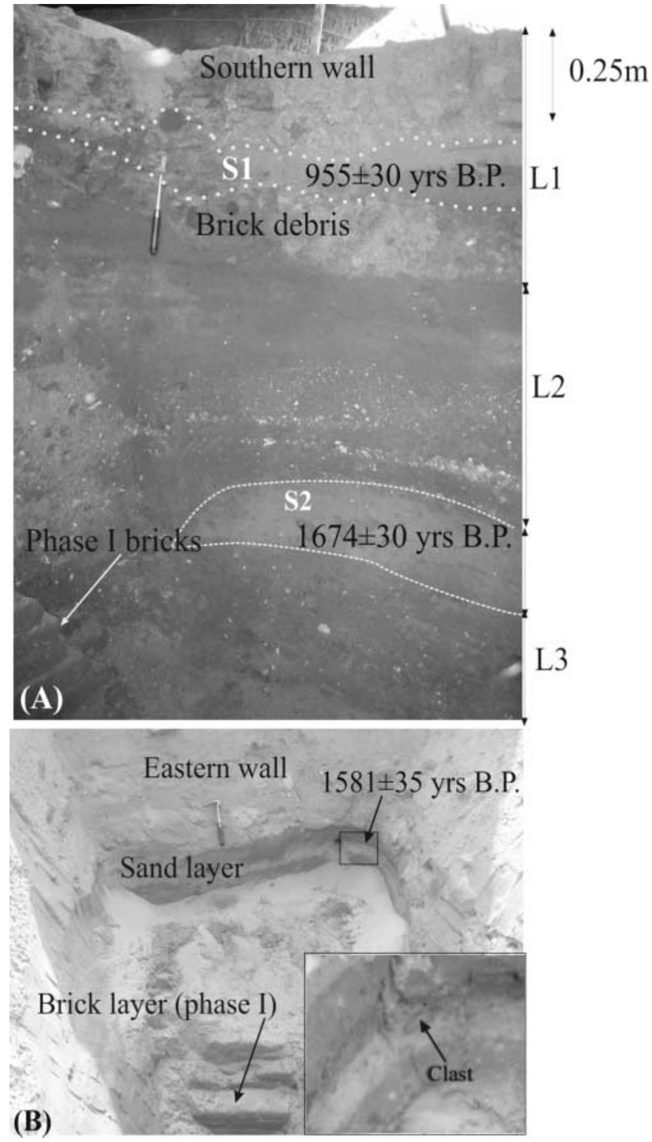

Figure 11. (a) Stratigraphy of the eastern wall of the ASI excavation at Saluvankuppam (12°39.578′N, 80°12.625′E). The anomalous sand layer marked as S1 sandwiched between the brick debris is considered as a paleotsunami deposit; S2 represents another layer of anomalous sand at a lower level. (b) Stratigraphy of the eastern wall of the trench excavated close to the ASI site. Extension of the layer S2 in the ASI site is traced above the older layer of bricks; laminations and clasts in close view (inset).

age of A.D. 925 and the calibrated charcoal date of A.D. 1161 (see Table 5 for comparison). At deeper levels, we logged another layer of fine-grained sand (10 cm), possibly of marine origin at a depth of 3.0 m from the surface (S2 in Fig. 11a). This discontinuous layer of sand occurs above the ruins of the oldest brick structure (phase I) and as in the case of S1, this one is also prominent only on the southern wall, with a slimmer eastward extension.

Another trench, located 10 m south of the ASI site revealed a discordant layer of sand occurring over a brick basement, believed to be the oldest structure in this temple complex (Fig. 11b). The layer of sand, ~10 cm thick exposed in the southeastern corner of the trench is made of a fining-upward sequence of sand with clasts derived from the underlying layer. This layer also shows horizontal layering and laminations with thin intercalations of clay. Its occurrence above a cultural level is suggestive of its origin to an unusual sea surge. Charcoal samples yielded a date of 1581 ± 35 yr B.P. (A.D. 405–564). We believe that this layer may be comparable to the lower layer of sand observed in the ASI site, which gave a similar age 1674 ± 30 yr B.P. (A.D. 321–427). The anomalous sand layers described previously seem to suggest the possibility of at least two of sea floods at this site: one event around the tenth century A.D. and the other between the fourth and sixth century. Despite occasional minor storms, compared with other areas of the eastern coast, the Mamallapuram Coast has generally been sheltered from the region's large cyclones and the patterns have not shifted much over time (Mascarenhas, 2004). Based on these observations we infer that the east coast of India must have been affected by one or maybe two tsunamis in the past, the later event implied as an earthquake-related sea surge by Chambers (1788).

The anomalous sand layers reported from both the trenches contained significant quantity of foraminifera such as *Ammonia dentatus*, a species that lives in shallow neritic zone (40–50 m) (S. Sreenivasalu, Anna University, India, personal comm.). Similar species are reported also from the foram assemblages found in the 2004 tsunami deposit from the Nagapattinam coast (Nagendra *et al.*, 2005), located 250 km south of this site, where the tsunami deposited several thin patches (3–5 cm) of sands along the beach. The suspected tsunami deposits from the ASI trench also yielded fragments of oceanic diatom species like *Navicula* and *Coscinodiscus* (Prema Paul, personal comm.). The probability of these being brought by storms was also considered. The maximum storm height along this coast is 7.94 m (Sanil Kumar *et al.*, 2003), not sufficient to churn sediments deeper than 20 m and thus, making their storm-related origin rather unlikely.

Discussion

Preseismic and Coseismic Deformation

The coseismic deformation of the upper plate has in general been modeled using an elastic slip-dislocation model (e.g., Plafker and Savage, 1970; Plafker, 1972). In this model, the portion of the upper plate overlying the locked subduction interface in general is depressed during the interseismic period, while the region landward of the locked fault zone arches upward. During the earthquake, the region above the updip portion of the rupture recovers the elastic strain and experiences sudden coseismic uplift while the regions above the downdip end of the rupture will subside. Our observations of preseismic emergence are restricted to three observation points at Car Nicobar (~20 cm from coral head), Port Blair (~10 cm from microatolls), and Diglipur (~10 cm from microatolls), all of them falling in the landward part of the locked fault zone. Both Car Nicobar and Port Blair subsided by more than 1 m, coseismically, but the Diglipur site showed uplift. The predictions of the model are in general agreement with the field observations, except in the North Andaman (Diglipur). Located on a structural forearc high, it is quite possible that the general uplift here is more related to the deformation of the wedge rather than to the earthquake cycle.

Postseismic observations as well as the GPS data suggest varying rate of deformation along the arc, evident also from the seismologic data (Ammon *et al.*, 2005; Earnest *et al.*, 2005a). Subarya *et al.* (2006) estimate that the pivot line lies less than 150 km from the trench in the Nicobar region. Our observations suggest that the pivot line separating areas of coseismic uplift and subsidence lies about 100–150 km east of the trench. In the north Andaman and Nicobar region, it lies ~120 km away from the trench, whereas it is within 100 km in the Middle Andaman region. It takes a swing in the northern part of the rupture zone, where the distance from the subduction front is maximum (Fig. 2).

Both interseismic and coseismic uplift was observed at Diglipur, close to the northern limits of the rupture (Ammon *et al.*, 2005). No historical earthquakes have been reported from this region (Rajendran *et al.*, 2003); the current seismicity is also generally low here. It is tempting to conclude that the large thickness of the Bengal fan sediments (6–7 km) may play an important role in arresting the rupture here (due to the velocity-strengthening behavior in unconsolidated sediments). The profusion of liquefaction features and ground fissures in this part of the rupture zone would indicate a relatively higher ground shaking.

The historical data are suggestive of a minimum recurrence interval of about 250 years for the large earthquakes in the Andaman segment. For the Nicobar segment, Ortiz and Bilham (2003) made a comparable estimate. That the 1941 and 1679 earthquakes in the Andaman segment did not generate perceptible tsunamis suggesting that the vertical displacement probably was small. It is possible that these earthquakes occurred at greater depth and the displacement at the shallower part of the subduction interface was mostly aseismic (see Freymueller *et al.*, 2006).

The 1300-km-long rupture associated with the 2004 earthquake occurred within 8 mins (Ishii *et al.*, 2005). The 2004 mainshock was followed by a large aftershock (close to Car Nicobar), at a location close to the 1881 source. Two large earthquakes that followed on 28 March (M_w 8.7) and 24 July (M_w 7.5) deserve attention. The March earthquake occurred south of the 2004 rupture, breaking about 300 km length along northern Sumatra (Lay *et al.*, 2005). However, the 24 July earthquake was rather unexpected at a location that had already had a large earthquake in the recent history (1881; M_w 7.9) and a large aftershock (M_w 7.1, 26 January 2004). Also, note that both the vertical and horizontal components of deformation are the largest in this part of the subduction front (Earnest *et al.*, 2005b; Freymueller *et al.*, 2006) suggestive of an anomalous strain buildup in this region.

Earthquake Recurrence

Although large earthquakes have occurred along the Andaman and Sumatra segments of the plate boundary, only the Sumatra part has been studied extensively (Zachariasen *et al.*, 1999, 2000; Natawidjaja *et al.*, 2004). The submergence/emergence history of microatolls has been used here to develop paleogeodetic models and to identify potential segments of future rupture. However, the 2004-type earthquakes that involve rupture of multiple segments are not restricted to the past rupture histories. A varying rate of deformation along the subduction boundary seems to be another distinctive characteristic of the subduction front. Such variability in deformation may be the reason for the persistent occurrence of such earthquakes in some segments and the prolonged quiescence in others. The 2004-type earthquakes seem to break all of these patches as well as the previously unbroken/slow deforming ones, following a different calendar of recurrence and also seeking a unique explanation.

Persistent recurrence of single-segment earthquakes along subduction boundaries that generate multiple-segment events has been reported elsewhere, for example, at the Kurile Trench (Nanayama *et al.*, 2003). As noted by these authors, this variable mode rupture and the interseismic interval between larger ruptures may be characteristic of a subduction zone. With limited historical and prehistorical evidence (unlike for the Kurile trench), it is not yet clear whether this model applies to the Andaman trench. From a regional earthquake/tsunami hazard perspective, it is important to understand the pattern of recurrence of such megathrust events. Our available data from the east coast of India imply that at least two large events of coastal flooding occurring around A.D. 1000 and A.D. 400 may have been triggered by megathrust earthquakes. The evidence from ancient coral rubble and drowned vegetation from some sites in the Andaman Islands, both dating to about 750 years and a relatively younger coastal terrace of 1000-year vintage from Little Andaman suggest that the penultimate megathrust earthquake may have occurred 900–1000 years ago.

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