# Landscape Changes in the Andaman and Nicobar Islands (India) after the December 2004 Great Sumatra Earthquake and Indian Ocean Tsunami

**Javed N. Malik,[a) ] C.V.R. Murty,[a) ] M.EERI, and Durgesh C. Rai,[a) ] M.EERI**

Plate tectonics after the 26 December 2004 Great Sumatra earthquake resulted in major topological changes in the Andaman and Nicobar islands. Aerial and land reconnaissance surveys of those islands after the earthquake provide evidence of spectacular plate tectonics that took place during the earthquake. Initial submergence of the built environment and the subsequent inundation upon arrival of the tsunami wave, as well as emergence of the new beaches along the islands—particularly on the western rims of the islands and in the northern islands—are the major signatures of this $M_w$=9.3 event.
[DOI: 10.1193/1.2206792]

## INTRODUCTION

The Andaman and Nicobar (A&N) islands southeast of mainland India are the Indian land masses closest to the epicenter of the 26 December 2004 Great Sumatra earthquake ($M_w$=9.3). They consist of a narrow broken chain of about 572 picturesque islands, islets, and rocks extending along a general north-south direction between 14° N and 6.5° N latitude in the southeastern part of the Bay of Bengal (Figure 1). Of these, only about 36 islands are inhabited. The islands are grouped into two sets, with the 10° N international shipping channel as the divider; islands north of the 10° N latitude are called the Andaman Islands, and those south of the 10° N latitude are called the Nicobar Islands. The North, Middle, South, and Little Andaman islands are the most populated of the former islands; Car Nicobar, Great Nicobar, Katchaal, and Kamorta are the most populated of the latter islands. According to the 2001 census, the total population of the A&N islands is about 356,152; about 314,084 people live on the Andaman Islands, and about 42,068 live on the Nicobar Islands.

The region of the A&N islands is in seismic zone V outside the Himalayan belt and has experienced several earthquakes of moderate-to-large magnitude during the historic and recent past. The A&N region provides an ideal tectonic setting for the occurrence of megathrust earthquakes and particularly for the effects of the tsunami waves triggered by such events (Rajendran et al. 2003). The area is at risk not only from tsunamis generated by earthquakes from nearby sources along the Andaman arc but also from adjacent regions such as Indonesia, as in the 2004 Great Sumatra earthquake. Literature suggests that the A&N islands have experienced several other large-magnitude earthquakes—in

[a)] Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India


*Earthquake Spectra,* Volume 22, No. S3, pages S43–S66, June 2006; © 2006, Earthquake Engineering Research Institute

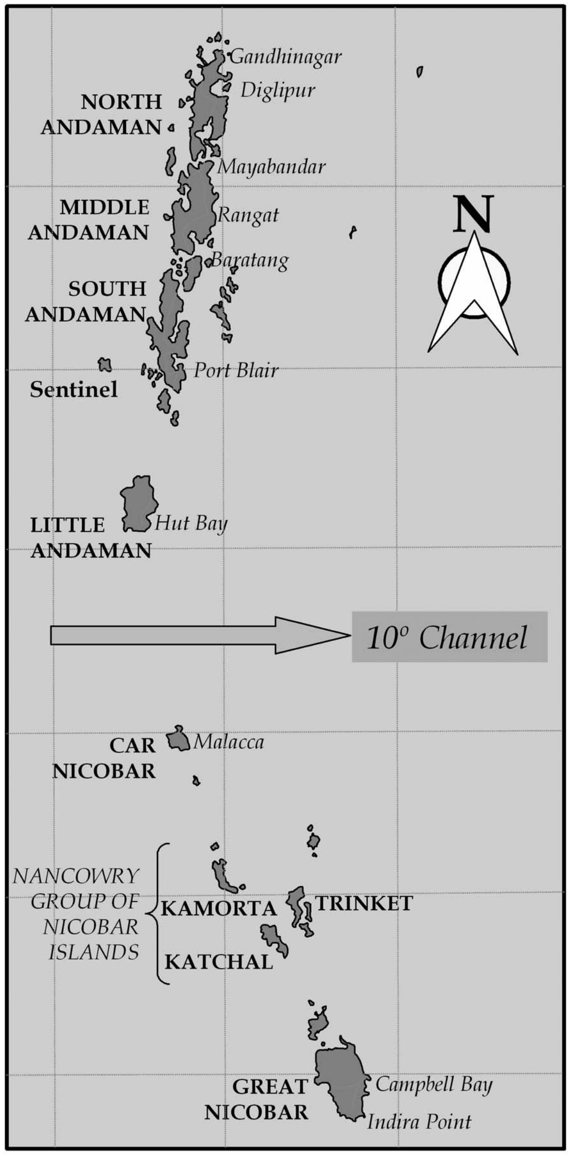



**Figure 1.** The A&N islands region, including some of the larger islands.

1847 ($M_w$=7.5), in 1881 ($M_w$=7.9), and in 1941 ($M_w$=7.7); also, the latter two earthquakes reportedly triggered tsunamis that caused runup in the A&N islands as well as along the eastern coast of the Indian mainland (Bilham et al. 2005, Rajendran et al. 2005).

## SEISMOTECTONICS OF THE A&N ISLANDS REGION

For several decades, the seismotectonics of the region have been studied in great detail (e.g., Fitch 1970, Curray et al. 1979, Dasgupta and Mukhopadhyay 1992). Excellent information about this region is available in a seismotectonic atlas published by the Geological Survey of India (GSI 2003), which provides regional information on the tectonic and geological setting of the A&N islands. The sections below are an attempt to provide an overview of these aspects from the GSI atlas and from published literature.

### TECTONIC SETTING AND GEOLOGY

The regional tectonic setting of the northeast Indian Ocean is very complex (Figure 2). The subduction of the major plates with respect to one another has resulted in the formation of a deep trench, a back-arc island and basins, and a spreading center. This convergent margin is one of the most prominent tectonic features in the region marked by the Sunda-Andaman trench, which has resulted from the subduction of the Indo-Australian plates below the Eurasian plate. Other names have been assigned to this sinuous-arcuate trench through the Sunda trench or Java trench along the Java-Sumatra islands; for example, it has been called the Andaman trench along the A&N islands and the Burma trench in the north along the Indo-Burma ridges. The A&N islands north of the 90° E ridge are aligned in a north-south direction in an arcuate shape, which separates the Indian and Sunda plates (Fitch 1970, Curray et al. 1979, Dasgupta and Mukhopadhyay 1993, Rajendran and Gupta 1989, Curray 2005). The A&N islands are bounded by the Andaman trench to the west and by the Sunda fault system to the east along with the Andaman spreading zone between latitudes 10° N and 12° N. The Andaman trench marks the active subduction zone where the northeast-moving Indian plate is subducting below the Eurasian plate. This island chain acts as a small tectonic plate that has also been referred as the Burma microplate (Dasgupta and Mukhopadhyay 1993, Ortiz and Bilham 2003, Kayal et al. 2004). The Andaman Sea to the east of these islands represents the back-arc basin characterized by a complex arc spreading center (the Andaman spreading center), which connects to the south with the Sunda fault and to the north with the major transform fault in Burma (Ortiz and Bilham 2003). This tectonic setting has resulted in the development of several thrust and strike-slip faults. Among these, the West Andaman fault (WAF) is the most prominent right-lateral strike-slip fault that has continuity all along the islands. This fault appears to extend from Sumatra in the southwest up to the Burma microplate in the north (Figure 2).

The Andaman outer arc ridge, the right-lateral WAF, and the Barren volcano are the major tectonic features in the region. The trench along the margin in the west of the A&N islands is as deep as 3,000–3,500 m. The ridges, indicative of a topographic high, consist of scrapped accretion oceanic sediments, which were uplifted during the Oligocene epoch. The eastern part of the Andaman Islands is made up of highly deformed rocks (ophiolites from the oceanic floor) of Cretaceous-Early Eocene ultrabasic/volcanic/pelagic sediments along with older metamorphics. The western part of the islands is occupied by sediments that belong to an accretionary prism consisting of Eocene-Oligocene flysch-sandstone/siltstone with conglomerates along with Mio-Pliocene calcareous sediments. Like the WAF, the Eastern Boundary thrust (EBT) is also

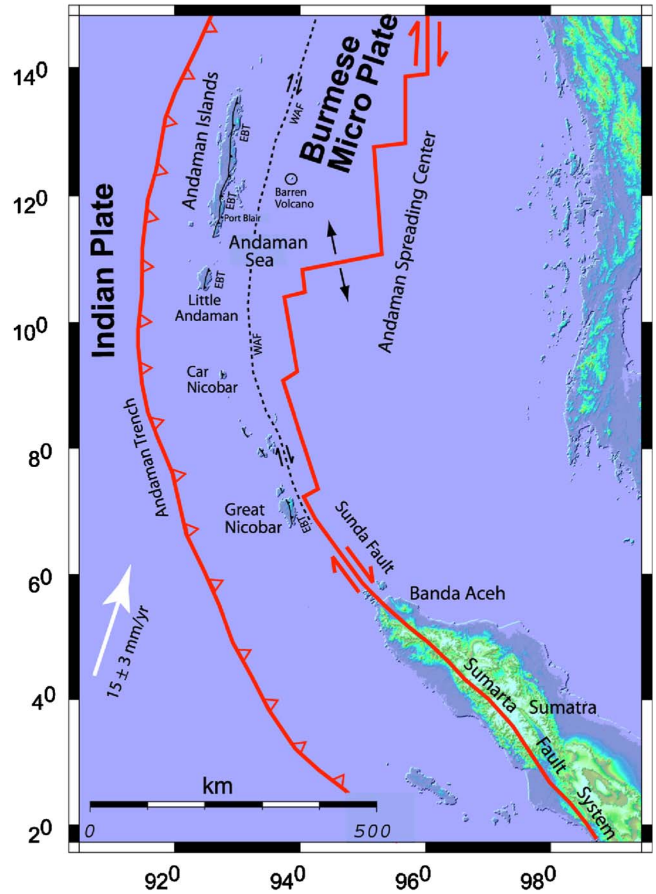



**Figure 2.** Generalized tectonic map of the A&N islands and the adjacent region. The thick line with triangles marks the Andaman-Sunda trench (the subduction zone between the Indian plate and the Burmese/Sunda plate). The thick line without triangles marks the Sumatra fault system and the Andaman spreading center. The white arrow shows the direction of the movement of the Indian plate.

an important fault, which extends regionally from Burma in the north and Sumatra in the south. The EBT marks the contact between the western accretionary prism and the eastern ophiolite-bearing accretionary complex (Figure 2).

## PAST AND PRESENT SEISMICITY

The region of the A&N islands has experienced several large-magnitude earthquakes in recent history. These were mainly thrust earthquakes, such as those in 1847, 1881, and 1941, which appear to have occurred in this region (Rajendran et al. 2003, Bilham et al. 2005). Recent global plate reconstruction data suggest that the northeast-moving Indian plate converges obliquely at 54 mm/yr with respect to the Eurasian plate (DeMets et al.

1994). Also, the GPS observations between Bangalore and Port Blair (the capital of the A&N islands) suggest that the Indian plate is approaching the Burma plate at a rate of $15.3 \pm 3$ mm/yr (DeMets et al. 1994, Paul et al. 2001, Ortiz and Bilham 2003). The GPS measurements suggest that great earthquakes with slip that is similar to the 2004 event cannot occur more frequently than once every 1,000 years; a shorter recurrence interval of 400 years has been calculated for the epicentral region, where convergence rates are higher (Bilham et al. 2005).

The seismicity of the A&N region is marked by several small-, moderate-, and large-magnitude earthquakes with $M = 4-8$. Most of the earthquakes in this region show thrust and strike-slip faulting associated with oblique subduction of the Indian plate, along with some faulting associated with extensional stresses in the northern Andaman Sea (Eguchi et al. 1979). Several reports and other published data suggest that some of the events that occurred in the vicinity of the A&N island chain were as shallow as 10 km or less, and some were deeper than 250 km (e.g., Mukhopadhyay 1984, Eguchi et al. 1979, Banghar 1987, Ortiz and Bilham 2003, Kayal et al. 2004, GSI 2003). These earthquakes were mostly concentrated on the east and west of the islands along the trench and along the spreading center, respectively, barring some on the mainland. The shallow-to-intermediate thrust earthquakes are the result of the Indian plate thrusting under the Burma microplate, along with several events showing a prominent strike-slip mechanism with some component of thrust inferred to be associated with oblique subduction between the Indian plate and the Burma plate (Banghar 1987). The normal faulting events associated with shallower depth are the result of the bending of the plate below the island arc (Banghar 1987). It has also been noted that the focal depth decreases as a function of latitude from south to north.

## THE 26 DECEMBER EARTHQUAKE

The great megathrust earthquake of 26 December occurred at 7:58:53 A.M. Indonesian local time (00:58:52 UTC, 06:28:53 A.M. IST) west of Sumatra. This was the world's most devastating earthquake in the last two centuries; by comparison, other great earthquakes include Kamchatka 1952 ($M = 9.0$), Alaska 1964 ($M = 9.1$), and Chile 1960 ($M = 9.5$).

The 26 December earthquake, which is the second largest in magnitude in 200 years, occurred along the plate boundary marked by the subduction zone between the Indian plate and the Burmese plate (a part of the Eurasian plate) which are shown at right in Figure 3. The rupture was about 1,200 km along the subduction plate boundary in the Sumatra and A&N region, registering a slip of about 20–25 m. On the basis of the distribution of moderate-to-large-magnitude aftershocks that occurred just after the main shock, it has been suggested that the rupture did not occur instantaneously, but rather in two phases. Seismic data indicate that in the first phase a rupture about 400 km long occurred, 30 km beneath the seabed, along the coast of Banda Aceh in the epicentral area. In the second phase, a rupture about 600 km long occurred along the Andaman Islands. The main shock focal mechanism suggests a thrust motion with a gently dipping plane toward the northeast. The swarm of aftershocks propagated northward from Sumatra along the Andaman arc, where one of the aftershocks was of magnitude M

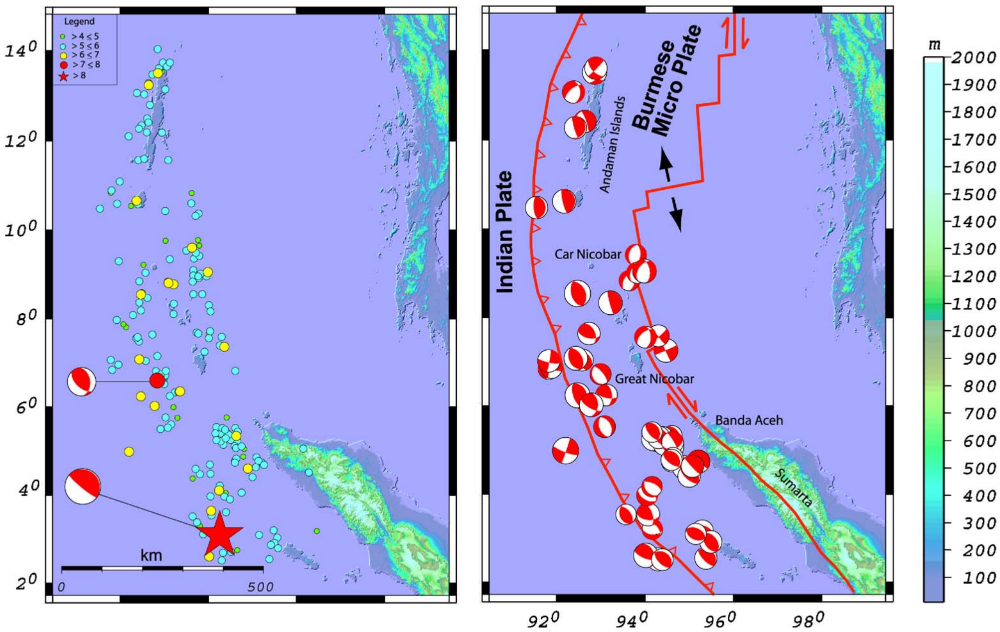



**Figure 3.** (a) Epicenters of the earthquakes (including the main shock and aftershocks) that occurred from 17 November 2004 to 12 January 2005. The solid black dot shows the location of an M=7.3 earthquake that occurred just after the main event, and the star shows the location of the 26 December earthquake. The focal mechanisms of both these earthquakes are shown. (b) Major tectonic features and focal plane mechanisms of the earthquakes that occurred from 17 November 2004 to 12 January 2005. The locations of earthquake epicenters were obtained from the India Meteorological Department, New Delhi; the U.S. Geological Survey (USGS); and Harvard University. Focal plane mechanisms were obtained from the Harvard Seismology Center Moment Tensor Catalog.

=7.3 with a strike-slip component. In general, most of the aftershocks were dominated by a thrust and strike-slip fault mechanism, along with some that showed normal faulting in the back-arc region (at left in Figure 3).

## COSEISMIC LAND-LEVEL CHANGES AND TSUNAMI EFFECTS

To understand the overall pattern of geomorphological changes and the effects of tsunami waves, aerial and field surveys were carried out along most of the A&N islands, whereas the field investigations were restricted to the North, Middle, South, and Little Andaman islands and the Great and Car Nicobar islands. Most of the damage and loss of life was caused by the giant tsunami waves generated by the 26 December earthquake. Earthquake-related ground shaking was observed all along these islands; however, the intensity of shaking was too low to expect significant liquefaction along the coastline of the A&N islands. Evidence of liquefaction was not available at most places on the

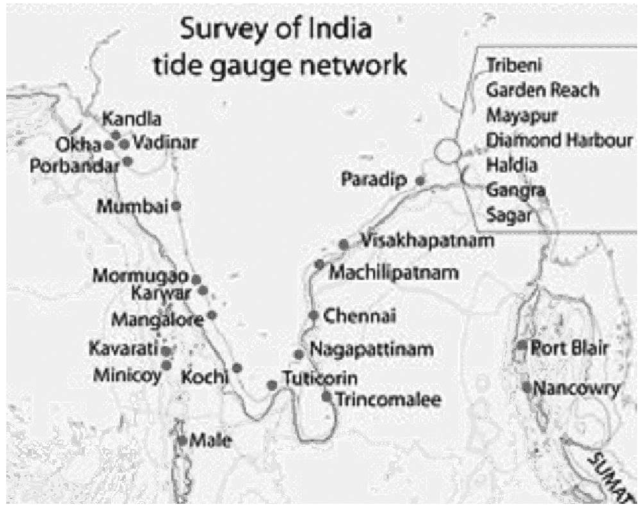



**Figure 4.** Location of tide gauges in India along the mainland coast and in the A&N islands (source: www.nio.org).

ground surface, because the high-energy tsunami waves followed by shaking carried away large amounts of debris and topsoil and redeposited them in many regions along the coastline.

The Survey of India maintains a network of analog tide gauges along the coast of India at 26 major and significant ports (Figure 4), including one each at Port Blair and Nancowry in the A&N islands. During the 26 December event, the Survey of India tide gauges at Port Blair, Nancowry Island, and Nagapattinam were inundated and thus provided no recording. The only record available from the A&N islands is from the digital gauge operated by the Integrated Center for Marine Area Management (ICMAM) in the Port Blair area. This record indicates a sharp change in the mean sea level of about 1.2 m after the earthquake (Figure 5).

## Great Nicobar Island

Great Nicobar Island marks the southernmost tip of India (7° N), about 700 km north of Sumatra, and is closest to the epicenter of the 26 December earthquake. There was not much damage related to ground shaking, barring some cracks in light tin-roofed and two-story buildings in the army area. Mainly, the damage along the coastline was caused by tsunami waves. Lightweight huts made from wood and coconut leaves were affected. Severe damage was caused to the jetty of the Andaman Harbor Works, where a portion of the jetty was washed away by the tsunami. At the main harbor works office, a thin layer of sand deposit (6–8 cm) was observed. According to a local army officer (Captain Mahabir Singh), the shaking was felt at about 06:28 A.M. (IST), followed by a tide surge within 5 minutes, resulting in major flooding in the area. This tide surge is indicative of subsidence of the area during the earthquake. At about 6:50 A.M., after the

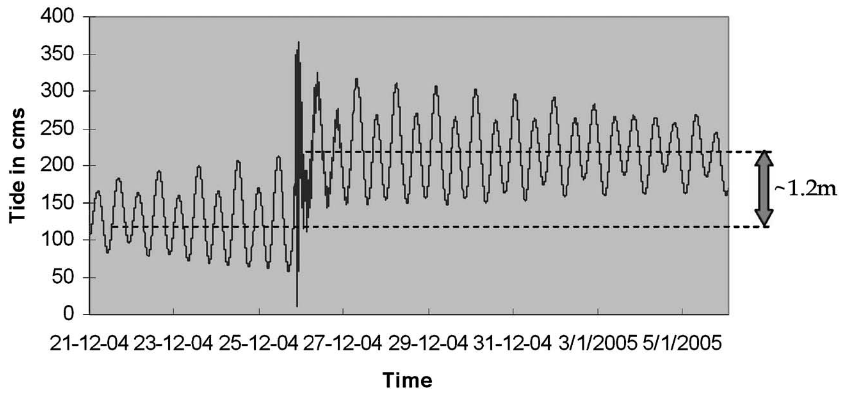



**Figure 5.** Arrival of tsunami waves, indicated by a sudden rise in seawater level as recorded by the tide gauge at Chatam Island, South Andaman Island (source: ICMAM).

shaking, a tsunami wave about 6 m high was observed. This shows that the expected negative wave on the Burma microplate caused by the tectonic movement was not experienced by the people in the Campbell Bay area, possibly because of the dominance of the submergence effects.

The tsunami wave was less than the ~10-m height observed by people in other islands, such as Car Nicobar, Little Andaman, and Main Andaman (including the North, Middle, and South Andaman islands). This could be because of the local topographic variations of the islands and the distance from where the tsunami originated. Great Nicobar is characterized by hilly terrain with a maximum elevation of 600 m. The lower-elevation hills (300–400 m) along the coast might have reduced the impact of the tsunami. The coastal road encircling the island was badly affected—it was damaged and submerged at several locations by the tsunami (Figures 6 and 7). The waves traveled about 1.5–2 km, inundating most of the low-lying areas inland. The effect of the wave as it traveled inland was indicated by the scattered tar barrels that were dragged about 200–300 m away from their original location at the Andaman Public Works Division office, which is ~1 km from the coast. Compound or boundary walls encircling several buildings inland were toppled by high-energy tsunami waves. At the Coast Guard Headquarters building in Campbell Bay, the average water level increased after the earthquake by about 2 m, as demonstrated by the ocean water lashing the floor of the building located a few meters from the sea. According to the Coast Guard officer, during the high tides prior to the earthquake, at least 25–30 m of beach used to be exposed in front of the building, and during low tide, more than 100 m was exposed. In contrast, now no beach can be seen. Such submergence is also observed at Indira Point, the southernmost tip of Great Nicobar Island. Here, the base of the 23-m-high lighthouse tower is now submerged in at least ~3 m of water; several houses, the helipad, and vegetation near the lighthouse have been washed away by the tsunami (Figure 8).

With respect to the overall damage and landscape, it is suggested that the ground

(a)

(b)

**Figure 6.** (a) Inundation and submergence of the area along the eastern coastline of Great Nicobar Island because of subsidence caused by the 26 December earthquake. (b) A coastal road encircling the island was damaged and submerged due to subsidence (photos: J. Malik).

shaking might have resulted in some liquefaction in the coastal area; however, damage was mainly due to the high-energy tsunami waves. The liquefaction might have also facilitated the easy erosion of concrete and masonry structures, which is well exemplified by the washed-out portion of the jetty and houses at Indira Point. With respect to the high water level around the Coast Guard office area and the submerged lighthouse tower at Indira Point, it seems reasonable to suggest that the coastline has subsided by about 2.5–3.0 m at the southern portion of Great Nicobar Island.

**Figure 7.** The eastern coastline at Campbell Bay (part of Great Nicobar Island) is now permanently inundated; the normal coastal waves cross over the tree line (photo: C. Murty).

## Car Nicobar Island

Similar evidence was also observed at Car Nicobar Island. Car Nicobar (9.2° N) is the northernmost island that belongs to the Nicobar group. This island suffered the worst damage and loss of life. Several buildings were toppled, and huge tanks containing petroleum products were carried away up to 1 km inland by the powerful wave. Topographically, this island is characterized by almost flat terrain, with a maximum elevation of about 70 m to the west. The eastern coast was destroyed; the Indian Army and Air Force township adjacent to the airstrip and the civilian township at Malacca were swept away.

According to an officer of the Indian Air Force at Car Nicobar, after shaking at ~6:35 A.M. (IST), 20 minutes later the tsunami arrived with a wave height of about <1 m, which resulted in local flooding. This suggests that the inundation from the first wave as noted by local residents had occurred because of subsidence of the area, which occurred 20 minutes after the main shock; this effect is also consistent with the slow rupture propagation model suggested by many researchers. According to a survivor, the wave following the initial submergence was higher. He also recalled that the seawater receded after the initial submergence, exposing the sea floor (coral beds) by about >1 km. The next wave was the highest—about 10 m high, which caused massive destruction. The height of that wave can well be judged from the remnants of clothes and

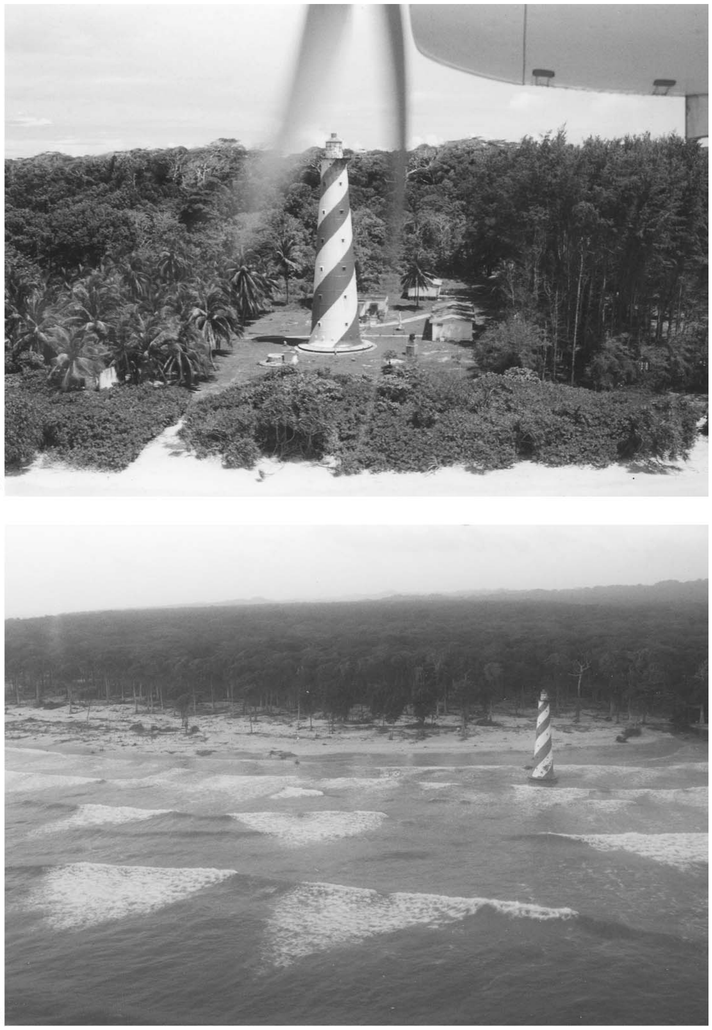

(a)
(b)

**Figure 8.** (a) The lighthouse tower at Indira Point in Great Nicobar Island before the 26 December earthquake. The tower is surrounded by lavish green grass, residences are at the base, and a sandy beach is in the foreground. (b) Flooding of the lighthouse base because of land subsidence. The submergence of ~3 m was caused by the 26 December earthquake (photos: R. Makwana).

plants hanging along the second-story balconies of buildings (~8 m high). At some locations, the water was as high as 15–17 m. Water entered inland in the low-lying areas up to ~1.5–2 km.

The most remarkable signature evidence was the Military Engineering Service (MES) inspection bungalow, a two-story structure with a reinforced concrete (RC) frame and hollow-block masonry infills that was previously about 100 m from the shoreline

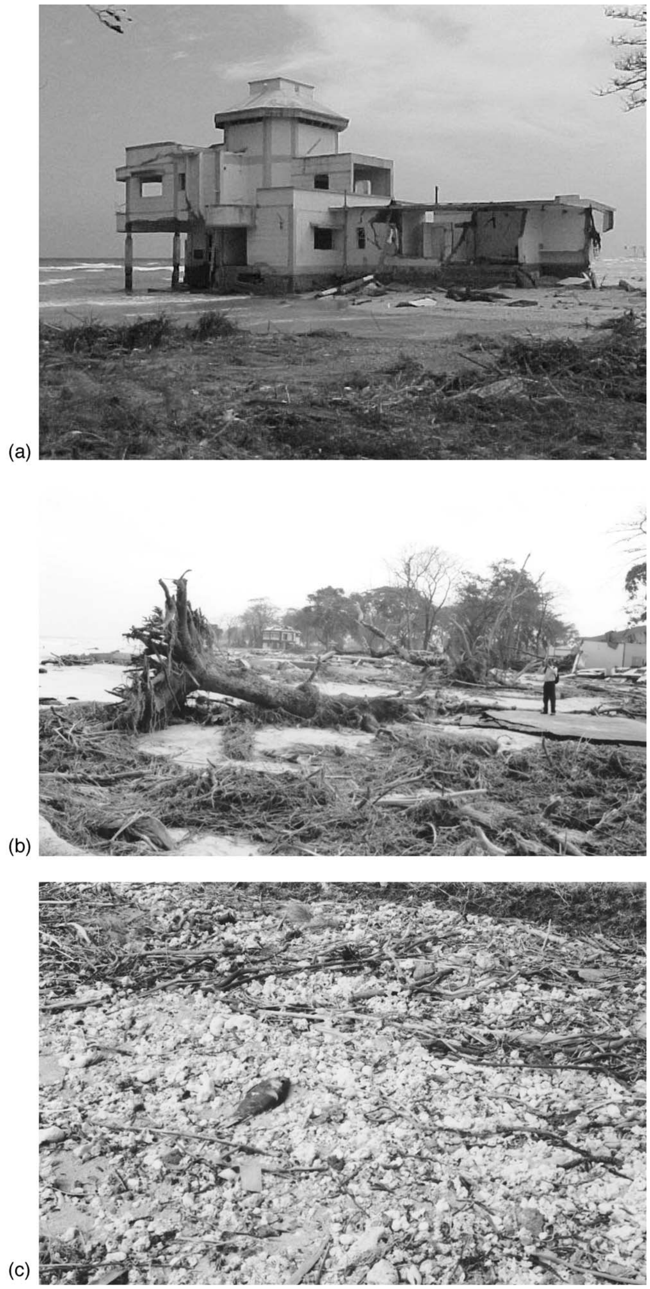


Figure 9. (a) MES inspection bungalow on the east coast of Car Nicobar Island, about 100 m from the shoreline under high tide conditions. The exposed beach shows gravel transported and deposited by the tsunami on 26 December (photo: C. Murty). (b) Uprooted tree trunk and deposition of a layer of sand about 10–20 cm thick (photo: J. Malik). (c) Close-up of poorly sorted coral clast and sand deposit at Car Nicobar (photo: J. Malik).

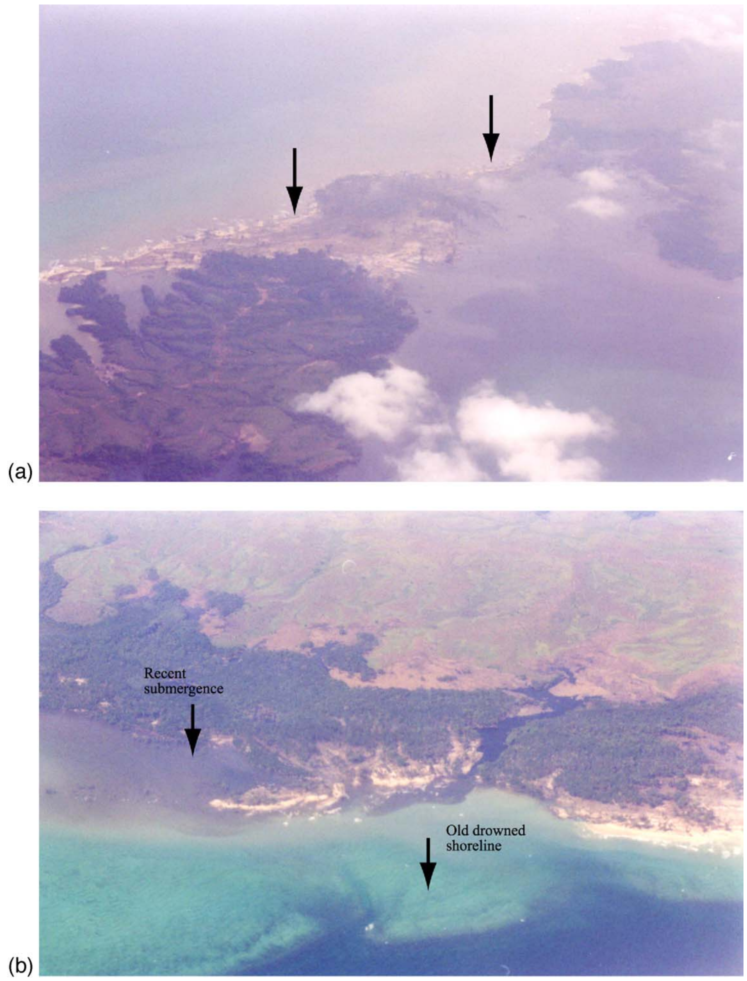



**Figure 10.** (a) The tsunami wave passed over parts of Trinket Island. The arrows show the area of subsidence. (b) The eastern coastline of the island, showing the old drowned shoreline and recent submergence of the area caused by the 2004 event at Kamorta Island (photos: J. Malik).

under high tide conditions. This building now remains exposed, with seawater lashing right up to the individual footings of the front, suggestive of the subsidence of the coastline along the eastern side of Car Nicobar Island (Figure 9a). It is suggested that the subsidence in the Car Nicobar area was about 1.5–2 m.

Giant trunks of banyan and coconut trees (with a diameter of ~1–3 m) were toppled and uprooted. Remnants of these uprooted tree logs were lying scattered on the surface, along with debris consisting of cars, motorbikes, dry grass, household items, and so on. Deposition of a thick layer of sand (about 10–20 cm) was noticed at most locations, such as the site in Figure 9b. At some locations, about 300–350 m from the

(a) (b)

**Figure 11.** (a) Extensional cracks in the Sippyghat area were caused by lateral spreading that was due to ground shaking. (b) Inundation of land and waterlogging in the low-lying areas around Sippyghat, near Port Blair (photos: J. Malik).

shoreline, a spread of poorly sorted coarser clasts made of coral ranging in size from 2.5 to 35 cm was observed over the beach (Figure 9c). Scouring of the surface was the common feature noticed near the buildings in the area.

Evidence of land subsidence was also observed along the other groups of islands between Little Andaman and Great Nicobar—for example, along the Trinket and Kamorta islands (Figure 10). At Trinket Island, due to subsidence, the tsunami waves passed over the land area, giving the appearance of having split the island into two parts (Figure 10a). This resulted because of the lower elevation and the narrowness of the island at some locations.

(a)

(b)

**Figure 12.** Subsidence caused the inundation of land in the bazaar area of Bamboo Flat (photos: J. Malik and D. Rai).

## Main Andaman Islands

An aerial survey and field survey were carried out along the Main Andaman Islands (including the South, Middle, and North islands). The structure at Port Blair suffered minor damage caused by shaking. Evidence of lateral spreading causing landslip of the surficial soil on gentle slopes was observed at several locations. Of these, the most prominent lateral spreading was recorded at low-lying areas, such as at Sippyghat (Figure 11a). Here the lateral spreading resulted in the development of extensional cracks as

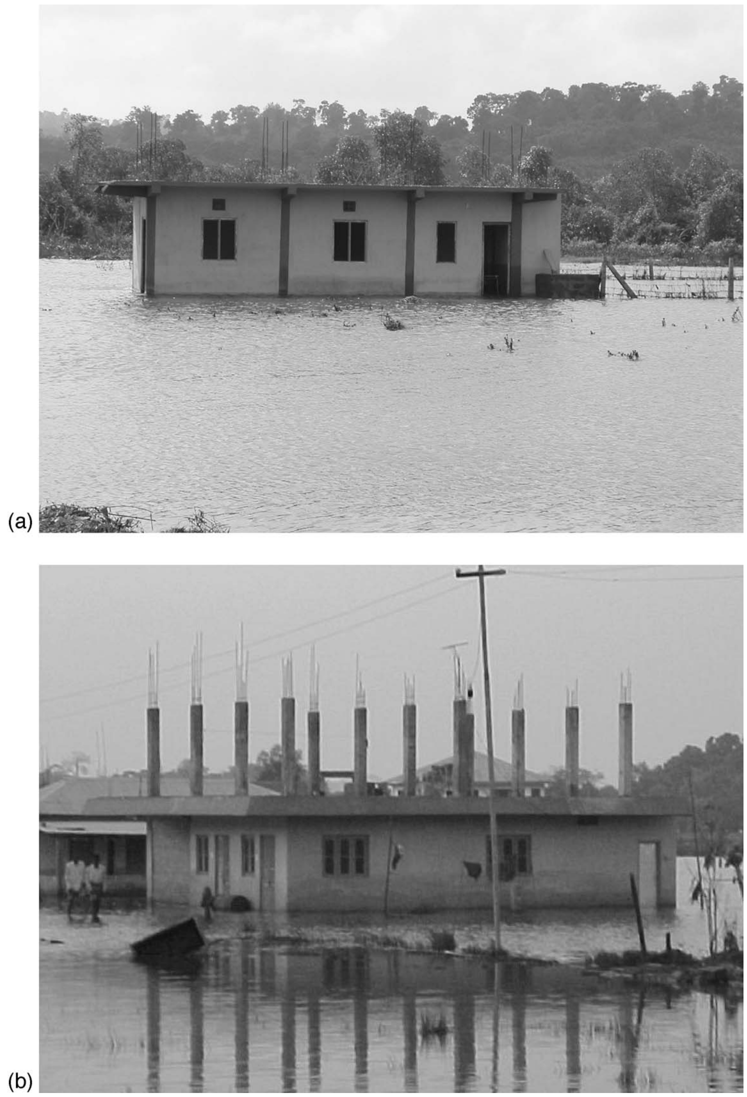


**Figure 13.** Inundated single-story houses such as these suggest that the seawater level has gone up by about 1.0 m with respect to land in the Sippyghat area near Port Blair. Many areas are now flooded permanently because of land subsidence (photos: S. Jain and C. Murty).

wide as 20–30 cm. Along with lateral spreading, inundation of land and waterlogging of up to 0.6 m in the low-lying areas were common. This was evidenced by the 0.6 m of water surrounding the houses in the Sippyghat area.

Subsidence and tilting of houses and/or other buildings because of liquefaction was observed at several locations. At Haddo Jetty, a subsided two-story police barracks

(a)


(b)

**Figure 14.** (a) Uplift of Flat Island along the western coast of Middle Andaman Island. (b) Upthrow of the coral beds and rock strata caused by uplift on the western coast of Middle Andaman Island near Flat Island (photos: J. Malik).

building marked by the rooftop seating at the ground level, as well as damage to the passenger hall, are evidence of liquefaction related to ground shaking. The jetty also sustained minor damage, and a portion of the jetty was washed away. Another inundation problem was observed in the bazaar area at Bamboo Flat near Port Blair (in South Andaman Island); after the 26 December earthquake, the water level rose by about 1.2 m above the normal high tide level, which is evident from the 0.3 m of water during high tide in the streetside shops along the shore (Figure 12). The inundation of the areas around Sippyghat (Figure 13) and Bamboo Flat is indicative of coseismic subsidence caused by the earthquake. Observations of tidal chart levels recorded by the Andaman

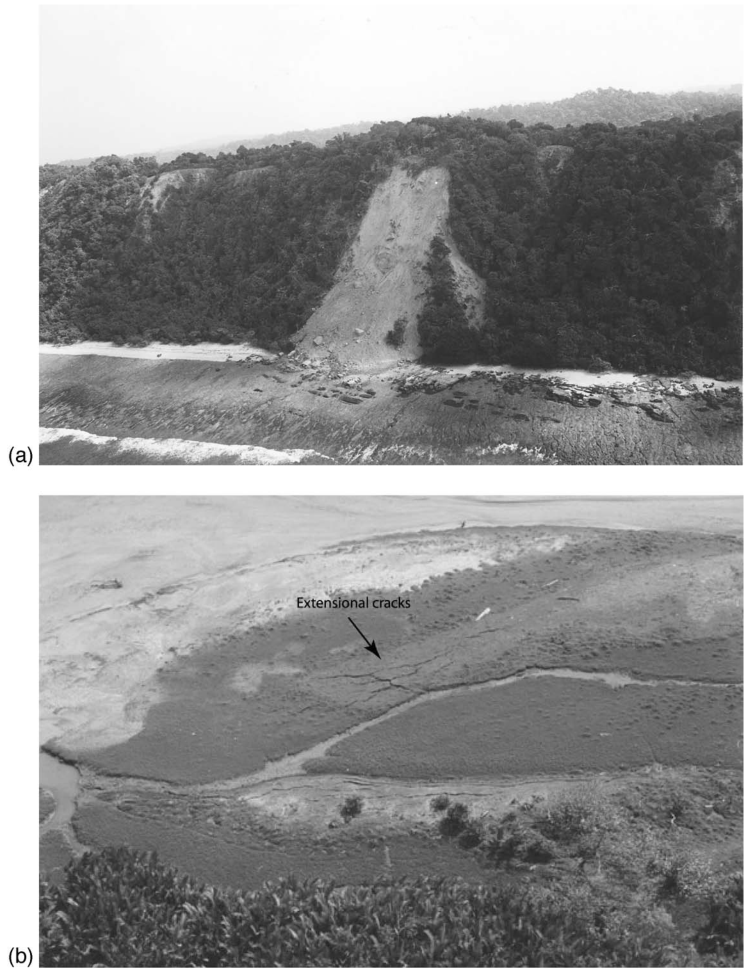



**Figure 15.** (a) Evidence of earthquake-induced landslides along the western coastline margin of the South Andaman Island near Defence Island. (b) Lateral spreading along the eastern coast (photos: J. Malik).

and Lakshadweep Harbor Works suggest that, whereas a difference of 1.2 m was recorded on 26 December 2004, a steady difference of about $0.93 \pm 0.30$ m is obvious from 30 December 2004 to 8 January 2005.

An aerial survey via helicopter between Port Blair (South Andaman Island) and Betapur (North Andaman Island), concentrating mainly along the east and west coasts of the Andaman Islands, revealed important evidence of landscape changes caused by the 26 December earthquake. The survey observations suggest that, in general, most of the area along the western coastline is marked by rocky cliffs, whereas the eastern coastline has a gentle slope. This rocky shoreline comprises stratified sedimentary rocks, with

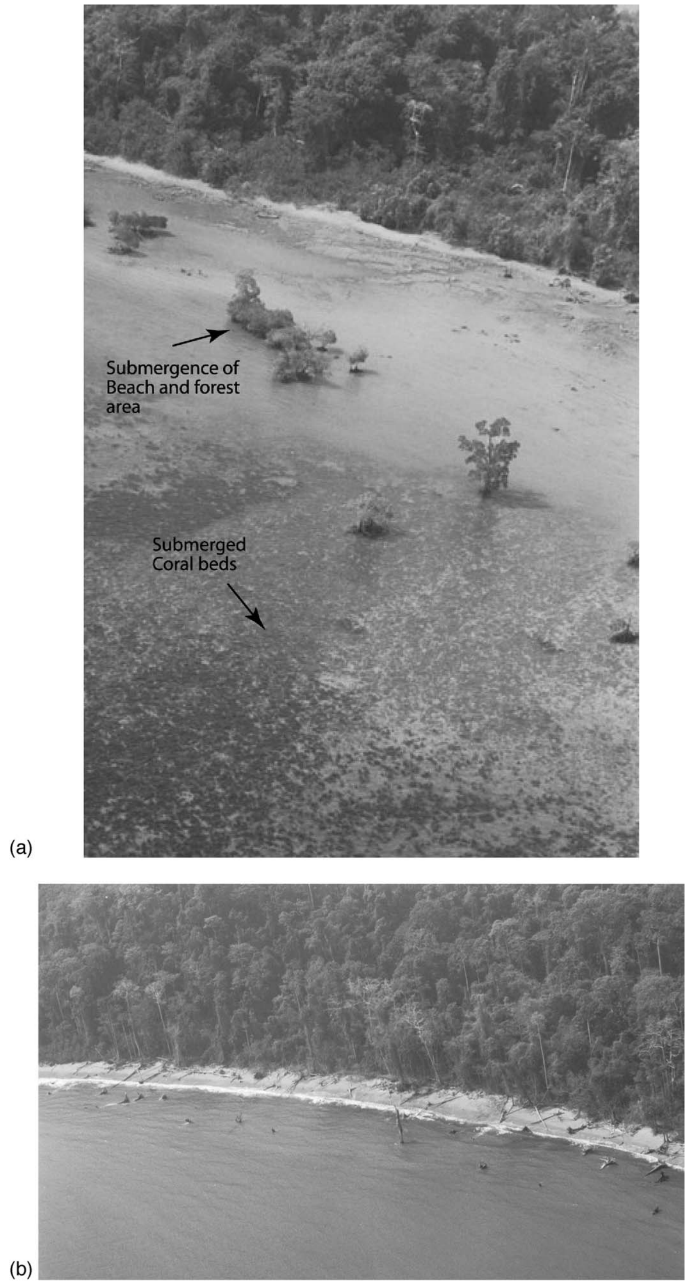



**Figure 16.** (a) Submerged coral beds, beach, and forest area along the eastern coast of South Andaman Island near Baratang Island. Submergence is due to tectonic subsidence of the east coastline as a result of the 26 December earthquake. (b) Submerged coastline and dead trees along the western coast of Middle Andaman Island (photos: J. N. Malik).

(a)


(b)


**Figure 17.** Uplift of land at shipping bays in the Andaman Islands. (a) Mayabandar Bay at the northeastern end of Middle Andaman Island. (b) Diglipur Bay at the northeastern end of North Andaman Island (photos: D. C. Rai).

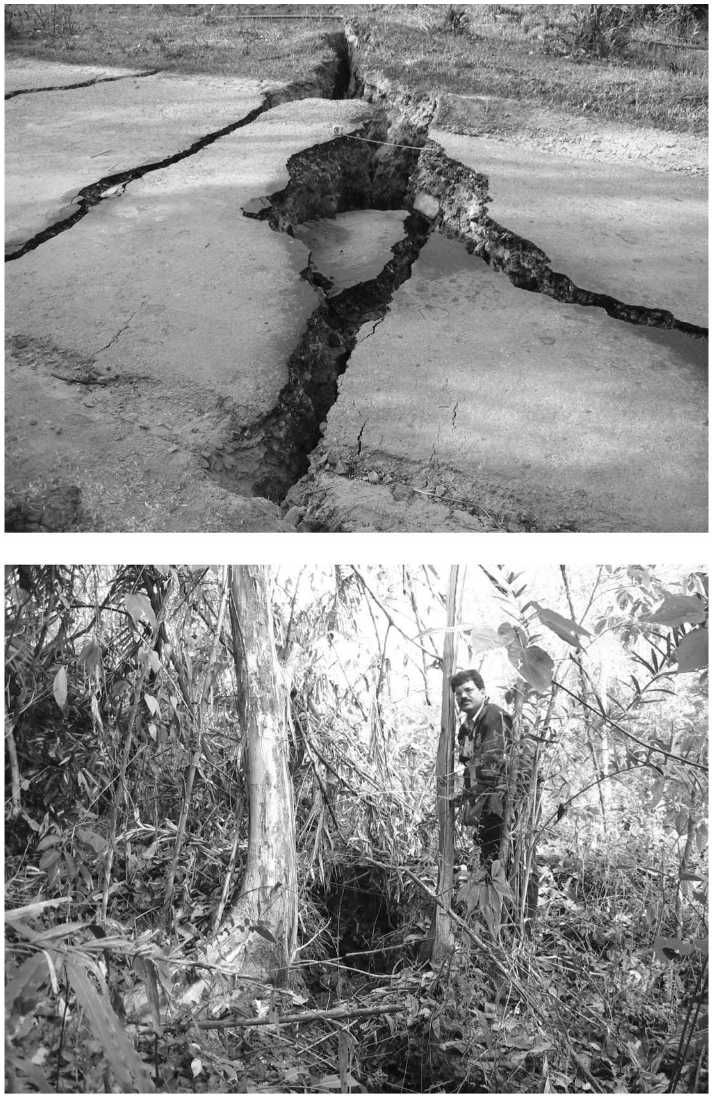
beds showing inclination toward the east. The evidence of inclination of the strata is a clear indication of tilting that is due to tectonic movement along the Andaman trench, causing uplift of the island and subsequent tilting toward the eastern side. At several locations, the uplift of the smaller islands—namely, the Flat and Sentinel islands along the western coast—was very prominent (Figure 14). Remnants of uplifted coral heads (coral atolls) were noticed along the emerged shoreline of Flat Island. Uplifting of rocky plat-

**Figure 18.** Eruption of a mud volcano near Jarawa Creek at Baratang Island near Middle Andaman Island, 105 km north of Port Blair (photo: D. Rai).

forms (terraces) was also observed along the western margin of the Andaman Islands. Apart from the uplift of the coastline, earthquake-induced landslides were also recorded along this rocky coastline (Figure 15a), whereas lateral spreading was more common along the eastern coast because of ground shaking around Betapur (Figure 15b).

Along the eastern coastline, the coral beds were seen to be submerged (Figure 16a). At some locations, due to ingress and runup of the high-energy tsunami waves, huge trees were uprooted and washed away, which was clearly indicated by the dead trees observed lying along the coast (Figure 16b). Along with tsunami effects, the subsidence of land because of tectonic movement caused the submergence of trees and agricultural fields by about 1.0−1.5 m (at Rangat) along the east coast. The foregoing aerial observations are consistent with data from the ground survey at Port Blair, Mayabandar, and Diglipur in the Andaman Islands. Land surveys at the Diglipur and Mayabandar jetties confirm a vertical uplift of the land to a level that is up to 1.2 m above the pre-earthquake levels (Figure 17); the exposed piles of the jetties and the receded waterline at these jetties are evidence of this.

From the above observation, we are inclined to suggest that the 26 December earthquake along the subduction zone resulted in the subsidence of the eastern coast by about $1.2 \pm 0.2$ m along Car Nicobar and Andaman islands. However, the evidence of the submerged lighthouse at the southernmost tip of Great Nicobar Island by 3 m suggests that the islands closer to the subduction and also to the epicenter experienced more relative



(a)

(b)

**Figure 19.** Ground deformation at Jarawa Creek at Baratang Island near Middle Andaman Island. (a) Damage to a road connecting Baratang Island and Baludera Beach (photo: D. Rai). (b) Splitting of a tree trunk because of a ground rupture ~1.2 m wide (photo: G. Mondal).

subsidence than other islands in the north. Subsequent relative uplift of about 1–1.5 m took place along the western side, resulting in the emergence of coast, as seen by the exposed sheet rocks and coral beds. Uplift of about 1.2 m was recorded at Ariel Jetty on North Andaman Island. Even though the relative subsidence is about 1.2±0.2 m, the angle of tilt over the 15–25 km width of the island results in only a marginal tilt of up to 1 mm, even in a tall structure like the lighthouse (23 m high) at Indira Point. Therefore, in spite of tilting related to subsidence, no prominent tilt was visible in the civil structures. Similar uplift and subsidence along the western and eastern coasts, respectively, caused by the 1881 Car Nicobar earthquake ($M_w$=7.9) have been recorded in the research literature (Ortiz and Bilham 2003).

A mud volcano in Middle Andaman Island became active after the earthquake, emitting gray mud and colorless gases that formed a subcircular mound about 70 m in diameter (Figure 18). The volcano had also erupted in 1983, 1996, and 2003. A number of other small mud volcanoes have formed in the area since the earthquake. Close to this region, deep and wide cracks in the ground were observed that caused severe damage to road pavements (Figure 19).

## CONCLUSIONS

The $M_w$=9.3 earthquake of 26 December 2004 along the subduction zone of the Sunda arc produced several results. First, there was subsidence of the eastern coast of the areas stretching over South Andaman Island and all the Nicobar Islands (by about 1.2±0.2 m along Car Nicobar and Andaman islands, and by about 3 m along the southern tip of Great Nicobar Island). Second, subsidence did not occur at the same time along all islands, because the rupture propagated northward slowly; immediate flooding after shaking at many locations suggests coseismic subsidence caused by the main shock. Third, uplifting of the North and Middle Andaman islands occurred, up to a maximum of 3 m in the northern tip of North Andaman Island. Fourth, relative uplift along the western side occurred, resulting in the emergence of coast—as evidenced by the exposed sheet rocks and coral beds. Thus, islands closer to the epicenter of the subduction event experienced more relative subsidence than other islands to the north did. The relative subsidence of the Burma plate along an east-west strike was about 1.2±0.2 m; the consequent angle of tilt over the 15–25-km width of the A&N islands resulted in only a marginal tilt of up to 1 mm, even in a tall structure like the 23-m-high lighthouse at Indira Point. Therefore, despite this subsidence-related tilt of the Burma plate, no prominent tilt was visible in the civil engineering structures.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the graduate students Goutam Mondal and Suresh Ranjan Dash during the reconnaissance survey and preparation of this manuscript. This reconnaissance survey was made possible by financial support from the Department of Science and Technology, Government of India, New Delhi, which the authors gratefully acknowledge.

## REFERENCES

Banghar, A. R., 1987. Seismotectonics of the Andaman-Nicobar islands, *Tectonophysics* **133**, 95–104.

Bilham, R., Engdahl, E. R., Feldl, N., and Satyabala, S. P., 2005. Partial and complete rupture of the Indo-Andaman plate boundary 1847–2004, *Seismol. Res. Lett.* **76**, 299–311.

Curray, J. R., 2005. Tectonics and history of the Andaman Sea region, *J. Asian Earth Sciences* 25, 187–232.

Curray, J. R., Moore, D. G., Lawver, L. A., Emmel, F. J., Raitt, R. W., Henry, M., and Kieckhefer, R., 1979. Tectonics of the Andaman Sea and Burma, in Watkins J. S., Montadert L., and Dickenson P., (eds.), *Geological and Geophysical Investigations of Continental Margins*, American Association of Petrochemical Geology Memoir 29, 189–198.

Dasgupta, S., and Mukhopadhyay, M., 1993. Seismicity and plate deformation below the Andaman arc, northeastern Indian Ocean, *Tectonophysics* **225**, 529–542.

DeMets, C., Gordon, R. G., Argus, D. F., and Stein, S., 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimate of current plate motions, *Geophys. Res. Lett.* **21**, 2191–2194.

Eguchi, T., Uyeda, S., and Maki, T., 1979. Seismotectonics and tectonic history of Andaman Sea, *Tectonophysics* **57**, 35–51.

Fitch, T. J., 1970. Earthquake mechanisms in the Himalaya, Burmese, and Andaman regions and continental tectonics in Central Asia, *J. Geophys. Res.* **75**, 2699–2709.

Geological Survey of India (GSI), 2003. *Seismotectonic Atlas of India and its Environs*, Calcutta, India.

Kayal, J. R., Gaonkar, S. G., Chakraborty, G. K., and Singh, O. P., 2004. Aftershocks and seismotectonic implications of the 13 September 2002 earthquake ($M_w$ 6.5) in the Andaman Sea basin, *Bull. Seismol. Soc. Am.* **94** (1), 326–333.

Ortiz, M., and Bilham, R., 2003. Source area and rupture parameters of the 31 December 1881 $M_w$ 7.9 Car Nicobar earthquake estimated from tsunami recorded in the Bay of Bengal, *J. Geophys. Res.* **108** (2215) 1–16.

Paul, J., Bürgmann, R., Gaur, V. K., Bilham, R., Larson, K., Ananda, M. B., Jade, S., Mukul, M., Anupama, T. S., Satyal, G., and Kumar, D., 2001. The motion and active deformation of India, *Geophys. Res. Lett.* **28**, 647–651.

Rajendran, C. P., Earnest, A., Rajendran, K., Das, R. D., and Kesavan, S., 2003. The 13 September 2002 North Andaman (Diglipur) earthquake: An analysis in the context of regional seismicity, *Curr. Sci.* **84** (7), 919–924.

Rajendran, K., and Gupta, H. K., 1989. Seismicity and tectonic stress-field of a part of the Burma-Andaman arc, *Bull. Seismol. Soc. Am.* **79**, 989–1005.

Rajendran, K., Rajendaran, C. P., and Earnest, A., 2005. The great Sumatra-Andaman earthquake of 26 December 2004, *Curr. Sci.* **88** (1), 11–12.

(Received 14 November 2005; accepted 11 April 2006)