Near-field observations on the co-seismic deformation associated with the 26 December 2004 Andaman–Sumatra earthquake

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We have been studying the tectonics of the Andaman and Nicobar region since 2001, for mapping geomorphological features such as elevated and subsided landforms, both of which are associated with subduction tectonics. We had also established eight GPS control points along the arc and had completed four GPS campaigns, the last pre-earthquake survey having ended three months prior to the great earthquake of 26 December 2004. During the post-earthquake surveys, we mapped permanent changes in the landforms at many locations, subsided coastal tracts and emerged colonies of corals, all of which are indicative of co-seismic deformation. GPS data indicate that the co-seismic offsets along the arc are nonuniform, the southern islands having been displaced by > 6 m in the southwest direction. Our observations indicate two regions characterized by higher and lower slips, the Nicobar and the Andaman segments respectively. Geomorphological observations indicate widespread uplift along the west coast of the Andaman segment and subsidence on the eastern part. The little Andamans and the northern part of the Andaman region generally show uplift. The GPS measurements indicate vertical displacement of –1.36 to +0.63 m along the arc.

Keywords: Andaman and Nicobar Islands, co-seismic deformation, earthquake, GPS studies, tsunami.

THE 26 December 2004 earthquake (*Mw* 9.3) in the offshore region of the northwestern Sumatra is the largest to have occurred since historic times. It is also among the largest earthquakes during the last century, the previous ones being the Chile (1960, *M* 9.5) and the Alaska (1964, *M* 9.2). The Sumatra event and its aftershocks broke more than 1200 km length of the plate boundary, and the rupture is believed to have occurred in two phases consisting of an initial fast rupture and later a slow one[1,2]. Just three months after this event, another great earthquake occurred, breaking a 300 km long segment southeast of the 2004 rupture (Figure 1). Some recent papers provide details on the rupture characteristics, co-seismic deformation, and other aspects of this earthquake[3–5]. Part of the subduction zone north of the Andaman–Nicobar segment has not experienced any large/great earthquakes for more than 60 years; the last one having occurred in 1941, an *Mw* 7.7 earthquake in North Andaman[6,7]. Considering the relatively long quiescence in terms of occurrence of large/great earthquakes in this part of the arc, it has been suggested that the potential for future large earthquakes and tsunamis affecting the east coast of India needs to be considered seriously[8]. The potential for two great earthquakes (*Mw* 9.3 and 8.6) occurring in a period of three months, breaking more than a 1500 km stretch of the subduction zone is unusual and is unprecedented in documented history.

Although the Andaman segment has not experienced many large or great earthquakes in the recent past, the southern Sumatra part, which accommodates most of the plate convergence is characterized by more frequent, larger earthquakes. The historical seismicity of the Sumatra region is dominated by two earthquakes that occurred in 1833 ($M \sim 9$) and in 1861 ($M \sim 8.5$)[9]. The most significant among the recent events are the two *Mw* 7.8 earthquakes of June 2000, involving strike-slip motion along the subduction interface[10]. Palaeogeodetic studies based on coral records provide information on tectonic history for the 700 km long section from 1 to 5° south of the equator. These data suggest that great earthquakes and tsunamis occur in this region every 200–300 years, either as a single giant earthquake or as two, in relatively quick succession[11,12].

The most devastating effect of the earthquake was the large tsunami that inundated most parts of the islands (among other regions); thick deposits of sand have been left by these waves in many parts of the islands. The earthquake has also led to significant ground deformation in the Andaman and Nicobar regions[13]. We observed considerable vertical changes all along the arc, some sites showing evidence of subsidence, whereas others registering uplift. This earthquake generated co-seismic deformation features such as elevated coastal terraces, uplifted coral beds, ground fissures, sandblows, and other liquefaction features. Although several months have passed after the earthquake, surveys in these islands have been partial, logistic problems as well as restrictions for entry, being the

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major hurdles. It is important to document these features that might get destroyed in the course of time, since they are likely to be affected by construction activities, storm surges, etc. We are still continuing our field studies as well as the GPS measurements, which will be useful for modelling the short-term and long-term deformation along this plate boundary. Here, we present highlights of our observations from selected regions; important locations described in the text are shown in Figure 2.

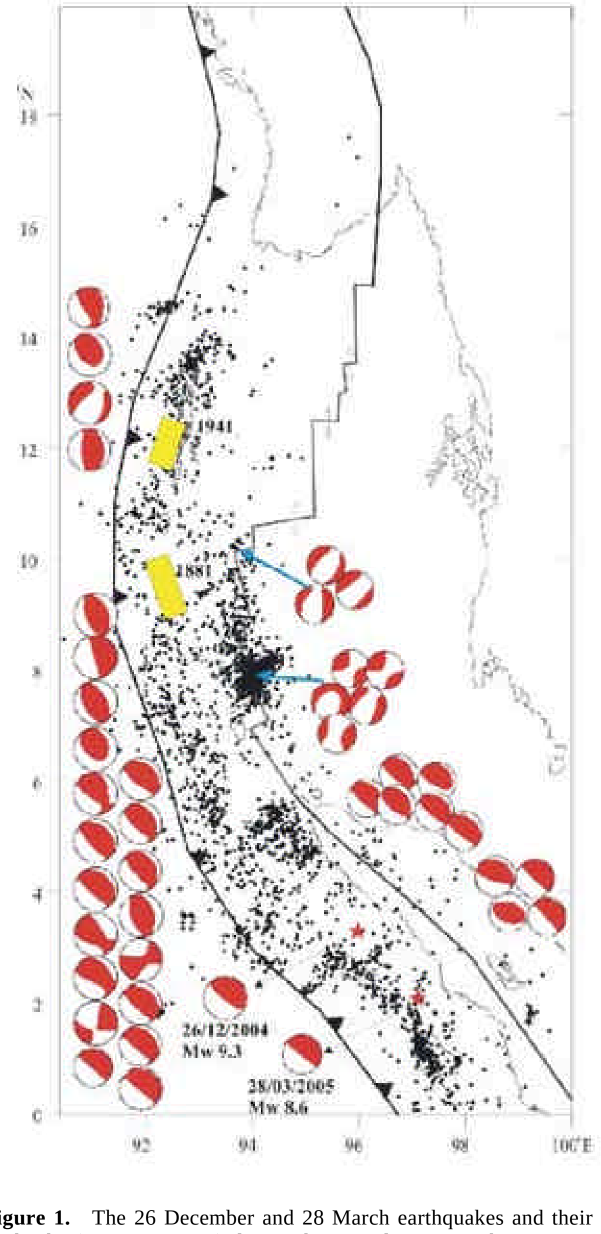

Figure 1. The 26 December and 28 March earthquakes and their aftershocks ($M > 3.5$, NEIC) during the period 26 December 2004 to 31 March 2005. Focal mechanisms for some of the larger events are shown in the margin, arc-normal compression is generally expressed by thrust faulting (left) and clusters of aftershocks in the back arc region are characterized by normal faulting. The great events and their focal mechanisms are identified. Rupture areas of 1881 and 1941 earthquakes are from Ortiz and Bilham[6].

Ground-level changes

The earthquake caused significant ground-level changes, uplift as well as subsidence, some of which could be documented in the field. Aerial surveys have reported uplift of the western Andaman coast[14]. The Coast Guard crew who were doing surveillance along the coast, reported new beaches and elevated coral beds along the western part of North Sentinel Island (see Figure 2 for location). Being a tribal reserve, entry to this island is restricted and we could not document these features. However, we could document evidence of uplift along the western margin of Interview Island, where several patches of elevated corals are exposed more than 1 m above the present sea level (Figure 3 *d*). We presume that the 1 m elevation change that is reported from Sentinel Island may be comparable.

Notable uplift was also observed in regions in the northern part of the rupture zone, such as Diglipur and also along the western margins of the islands. This is manifested mostly in the form of elevated shore lines and coastal terraces, uplifted coral beds and emerged mangrove swamps, and receded water marks showing the pre-earthquake survival levels of mussels and barnacles attached to rock exposures and man-made pillars. For example, near Ariel Bay, east coast of Diglipur, the uplift of the coast had caused

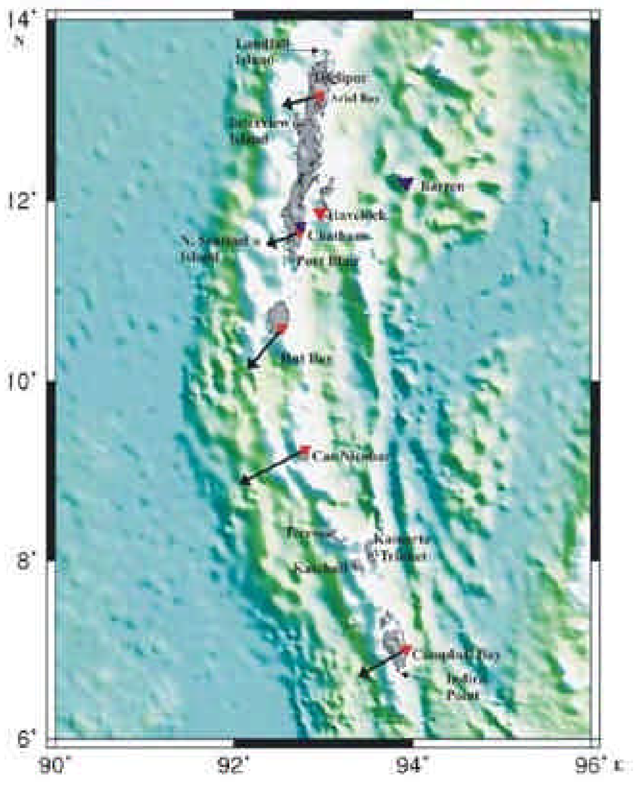

Figure 2. Map of the Andaman and Nicobar region showing GPS points occupied post-seismically (red) by us (blue ones were not occupied after the earthquake). Arrows show coseismic displacement computed from pre and post-GPS observations. Sites mentioned in the text are identified.

Figure 3. ***a***, Ariel Bay, east coast of Diglipur; the uplift of the coast had caused recession of the sea by about 60–80 cm from the previous shoreline; ***b***, Exposed roots of mangroves in Landfall Island; ***c***, Line of barnacles attached to pillars of the Ariel Bay jetty; ***d***, Exposed coral beds due to the emergence of the coast near Interview Island.

recession of sea by about 60–80 m from the previous shoreline (Figure 3 *a*). Extent of this uplift could be observed up to the Kalipur coast, about 8 km south of Ariel Bay. Further north of Diglipur, rise in ground level was evidenced by emergence of mangrove swamps, with their roots appearing about 1 m above the post-earthquake water level (Figure 3 *b*). Uplift of land appears to have progressed to the northern limits of the islands; the farthest we could observe occurs at Land Fall Island, about 40 km north of Diglipur. Another evidence for the rise in land comes in the form of lines of barnacles occurring 1 m above the sea level, on the pillars of the pier near Ariel Bay (Figure 3 *c*). Whether this marks the northern limit of the uplift zone is not evident, but the rupture associated with this great earthquake seems to have been arrested close to this region. This region marks the end of the aftershock activity (Figure 1). The features we discuss here serve as an index of co-seismic elevation changes, which can be used along with other evidence, derived from GPS data. Pre- and post-earthquake GPS observations at Diglipur indicate an uplift of 63 cm.

While most parts of South, Middle and North Andaman showed evidence of uplift, Port Blair, located on the eastern margin of South Andaman generally subsided. A demonstrative evidence of subsidence here is displayed by the pre- and post-earthquake tide gauge record from Port Blair. At this station operated by the National Institute of Ocean Technology (NIOT), Chennai diurnal sea-level changes after the earthquake are observed ~ 1 m above the pre-earthquake datum, indicating subsidence of the gauge itself (Figure 4). Going by the geometry of the subduction front, it is reasonable to expect uplift on the western side of the wedge and subsidence along its eastern fringes. For example, Sipighat area in Port Blair shows tell-tale evidence of submergence like flooding even during low tides. Many houses in this region submerged to the level of window sills. Munda Pahar beach (Figure 5) and Jolly Buoy near Port Blair also showed signs of subsidence in the form of submerged mangroves and coral beds respectively. Interestingly, Havelock Island, located farther east of the arc, did not register any significant ground-level changes, probably due to its relatively larger distance from the subduction front.

The islands located south of Little Andaman also generally showed subsidence. At Car Nicobar Island, for example, the sea level rose and flooded regions, which had previously remained dry, even during high tide. Submergence of jetties by more than a metre was noted in Kamorta, part of the Nancowry group of islands. The lighthouse at Indira Point located in the southern extremity of the Great Nicobar submerged by more than a metre, with its base below the post-seismic sea level.

Effects of ground shaking

In most part of the Andaman and Nicobar Islands, the earthquake started as a mild shaking that turned violent, lasting 4–5 min. The shaking resulted in damage to man-made structures as well as ground failure and liquefaction. Jain *et al.*[14] have discussed the pattern of damage to the built environment. Documenting these features is important, because they may provide evidence for similar occurrences from past earthquakes. These features may get washed away, but the locations identified in the post-earthquake surveys can be used for future palaeoseismological investigations. Here, we present effects of ground shaking in some selected regions along the arc.

At Port Blair, ground shaking was so severe that people found it difficult to stand. Overhead water tanks toppled and some poorly constructed RCC structures were damaged in this part of the island. In many parts of Diglipur, severe shaking resulted in prominent ground fissures oriented in the N–S direction (Figure 6 *a*). Horizontal shift in structures was also observed here as seen in the span of the Panighat Bridge, 50 km south of Diglipur, which showed an E–W shift of 15–20 cm (Figure 6 *b*). Ground fissures were observed along the road from Diglipur to Port Blair and also at Port Blair. Ground shaking generated sand blows along the Malacca coast and Kakkana (Car Nicobar), where water mixed with white sand gushed out of the vents. Liquefaction and sand-blow features (vents measuring up to 30 cm across) were observed also in the Magar Nalla, Krishnapuri and Kalipur areas of Diglipur (Figure 6 *c*).

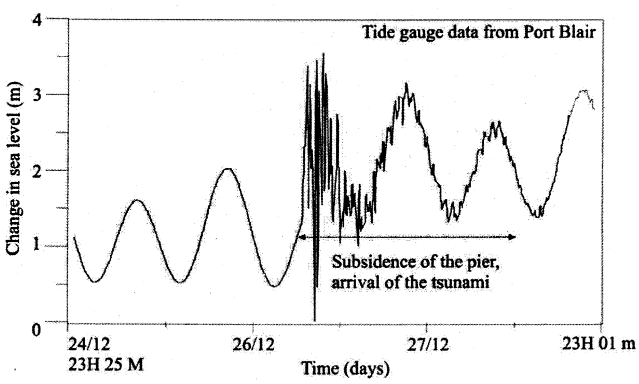

Figure 4. Diurnal sea-level changes prior to and after the 26 December earthquake recorded by NIOT at the gauge station at Port Blair. Interestingly, the timing of ground shaking due to the main shock (around 6:30 a.m. IST) and that of land subsidence does not appear to be synchronous. For example, reliable reports from Nancowry Island suggest that the subsidence occurred 8 min after the main shock. Reports from Port Blair indicate subsidence in the jetty occurred 30 min after the earthquake. Some recent studies based on seismological data have indicated that the Sumatra earthquake produced the longest known rupture[4] of about 1200 km and did not occur with uniform speed. It is reported that the earthquake broke a 100-km patch of the plate boundary rather slowly, northward. From there, the rupture accelerated to 3 km/s for the next 4 min and for the next 6 min, the rupture slowed down[5], to about 2.5 km/s. Note the shift of about 1 m in the diurnal curve due to subsidence of the pier.

Tsunami effects

Some of the most beautiful beaches along the archipelago were damaged by the tsunami. The impact of the tsunami was most severe in the southern Nicobar Islands and minimal in Diglipur, where only occasional seiches were reported. Wave heights reached up to ~ 3.5 m from the ground level at Munda Pahar and Chidiya Tapu beaches near Port Blair. We observed 10–15 cm thick sand deposits in this part of the island (Figure 6 *d*). Eyewitness reports suggest that the tsunami waves first hit the Port Blair coast by around 7.30 am and the run-up height at JNRM College campus was about 3 m. The tsunami deposited about 10-cm thick silty sand at Rangachanga, near Port Blair. Waves of about 6 m high hit the Hut Bay coast and deposited 15–20-cm thick sand layers along its coast. Mapping areas of inundation and tsunami deposition remains incomplete, but according to information available, maximum effect was reported from the western coast of Great Nicobar, the waves advancing as far as 3 km landward. Maximum thickness of tsunami deposits of ~70 cm that we observed was from Car Nicobar. Identification and dating of palaeo-tsunami deposits and recognizing their diagnostic characteristics are important because they serve as pointers to studies on palaeo-tsunamis.

GPS-based deformation studies

GPS-based deformation studies have been going on in the Andaman region[15,16]. The Survey of India has also established some control points along the arc and has reoccupied these points after the earthquake. We have also established some control points along the arc and have been systematically reoccupying them (see Figure 2 for locations and Table 1 for history of occupation). These points were being occupied in various campaigns, in 2002, 2003 and August–

Figure 5. View of Mundapahar beach near Port Blair showing post-seismic submergence of coastal vegetation due to subsidence of land.

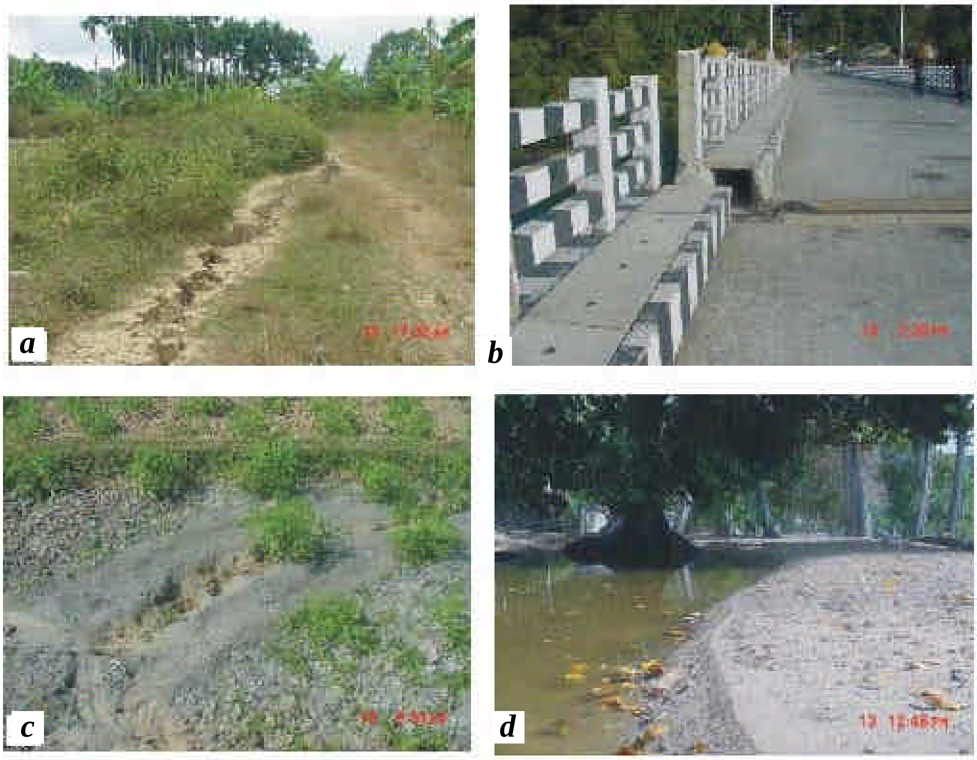

Figure 6. ***a***, North-south trending ground fissures formed near Diglipur. ***b***, E–W shift observed in the span of Panighat bridge near Diglipur. ***c***, Sand blows formed due to ground shaking at Diglipur; the crater shown is about 30 cm in diameter. ***d***, Tsunami deposits about 15–20 cm near Munda Pahar beach.

Table 1. History of occupation of control points in the Andaman–Nicobar region, indicating number of days occupied

Location	Station	2002	2003	2004	2005
Diglipur	DGLP	–	2	3	2
Port Blair	PBLR	4	5	26	12
Havelock	HVLK	1	–	–	–
Hut Bay	HBAY	–	–	3	1
Car Nicobar	CARN	–	2	2	2
Chatham	CHAT	–	3	–	–
Barren Island	BRRN	1	–	–	–
Campbell Bay	CBAY	–	–	3	2

Table 2. Co-seismic offsets of reoccupied control points in the Andaman–Nicobar region

Station	South offset (m)	West offset (m)	Up offset (m)
DGLP	2.68	3.99	+0.63
PBLR	1.08	2.89	–0.87
HBAY	2.97	3.43	+0.36
CARN	2.99	5.53	–1.05
CBAY	2.33	4.01	–1.36

September 2004. With the December earthquake causing significant horizontal and vertical shift, the pre-earthquake data could be used to model the co-seismic deformation.

Our work started in 2002, when we established three control points at Port Blair (PBLR), Havelock (HVLK) and Barren Islands (BRRN). During our subsequent survey in 2003, we reoccupied PBLR and added Diglipur (DGLP), Car Nicobar (CARN) and Chatham Island (CHAT). The 2004 campaign was more detailed and we reoccupied all the stations except CHAT and BRRN and established two new stations at Campbell Bay (CBAY) and Hut Bay (HBAY). By September 2004, we had established eight control points in the region[16]. During post-earthquake survey, we could reoccupy five of these points. Pre and post-earthquake GPS campaigns in the Andaman region suggest that the co-seismic displacement for all the control points was towards SW direction. Their magnitudes were nonuniform along the arc (Table 2, Figure 2), Car Nicobar having registered the maximum shift of 6.3 m. Coordinate repeatability was computed and time series of station co-ordinates were generated (Figure 7) using GAMIT/GLOBK software[17,18] over the available campaign period[19]. Independent GPS constraints on the co-seismic deformation from the region also show comparable results[20]. With more data from this region, co-seismic and post-seismic deformation fields can better be constrained. Analysis of co-seismic GPS data from regional permanent GPS stations indicates that the earthquake affected at least 4000 km range area surrounding the source zone and that the South Indian shield shifted[21] eastward by 10–16 mm.

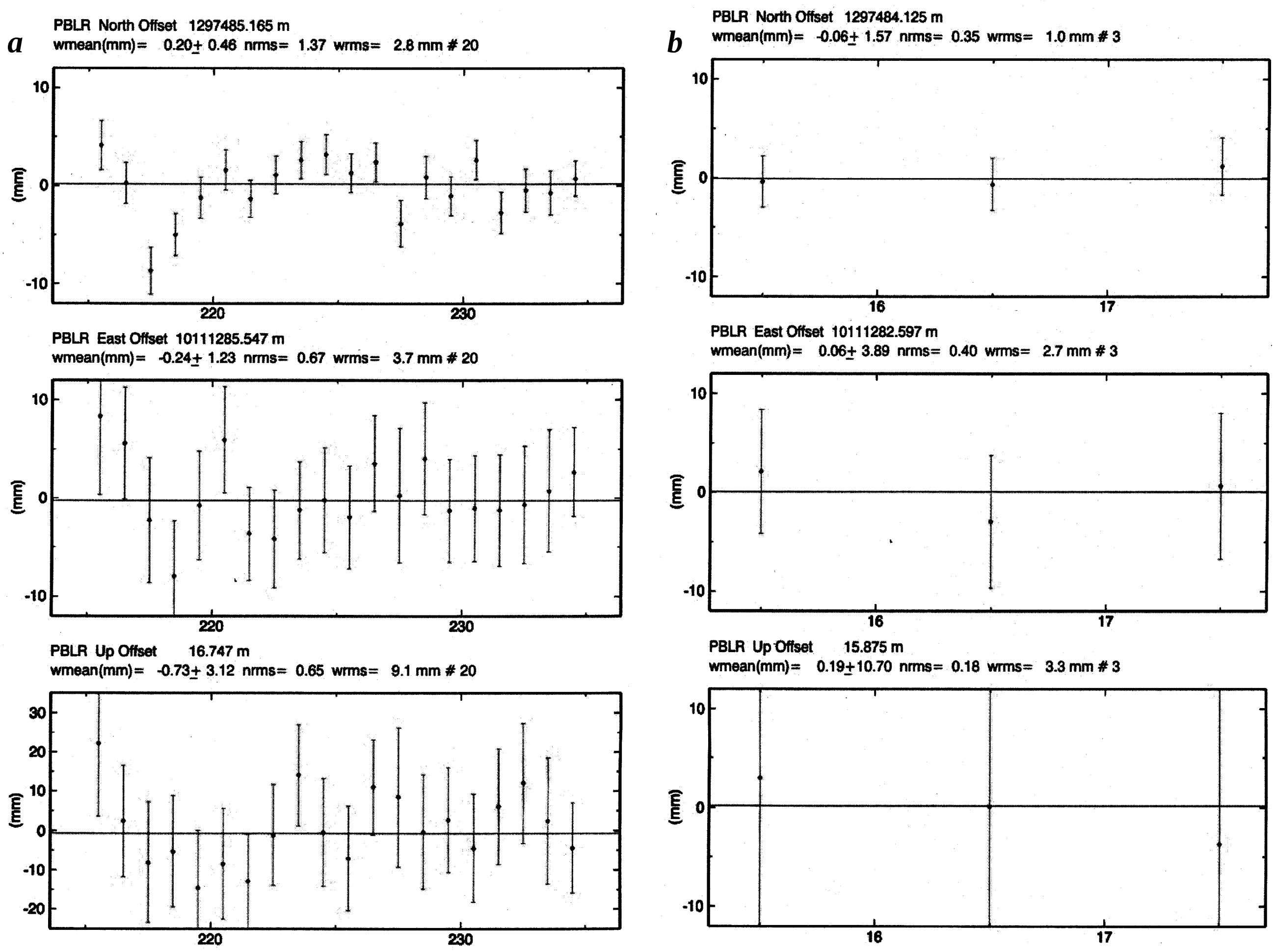

Figure 7. Coordinate repeatability time series plots of Port Blair (PBLR) control point showing the east, north and vertical offset values. Pre-seismic (***a***) (September 2004) and post-seismic (***b***) offsets (January 2005).

The main shock and aftershocks

The 26 December mainshock rupture began at 3.36°N, 96.0°E at a depth of 30 km at 00:58:53 GMT. Harvard moment tensor solution (CMT) suggests thrusting on a shallowly dipping plane (8°), striking 328°. The aftershock distribution extending to about 1300 km represents the rupture zone (Figure 1). In an earlier report[16], it was suggested that the aftershock zone extends to nearly 14°N. Distribution until the end of March 2005 suggests little change in the extent of the aftershock zone. One notable feature is the absence of aftershock activity north of about 14°N lat. The significant lack of earthquakes in this part of the arc has been noted before[22]; it is interesting that the mega-thrust rupture associated with the 2004 earthquake was arrested near this region. Whether this seemingly perpetual low-level activity is the result of aseismic slip associated with this part of the arc is an issue that needs to be examined.

A quick review of the focal mechanisms of the aftershocks suggests arc-normal compression (thrust faults) along the subduction front and extension (normal and strike slip faulting) in the back arc region (Figure 1). Other than the arc normal compression expressed by the thrust faulting all along the subduction front, one notable feature is the cluster of aftershocks in the back-arc region, characterized by normal and occasional strike-slip faulting. Lay *et al.*[4] note that although such swarms have occurred in this region in the past, the one associated with the 2004 earthquake is the most energetic swarm ever observed, globally. During the two months that followed, nearly 1000 earthquakes have occurred here; about 600 events occurred during a short duration from 27 to 30 January 2005 and nearly 100 of them were of magnitude ≥ 5 (NEIC).

The largest earthquake to follow the great event (*Mw* 8.6) occurred on 28 March. This earthquake had a similar mechanism as the 26 December earthquake, showing predominantly thrusting on a shallow-dipping (7°) fault plane (Figure 1). The rupture was about 300 km long, as defined by the extent of aftershocks[5]. However, this one did not generate a huge tsunami like the December earthquake. It has been suggested that the March earthquake did not breach the sea floor, resulting in the transfer of lesser energy to the water column. Further, the earthquake occurred under relatively shallow water, displacing lesser volume of water[23].

Discussion

One of the outstanding issues about this earthquake concerns the nature of the rupture. While some[1,4] argue for a non-uniform rupture that slowed down after the first 400 km, there are others who argue for a uniform rupture along the entire segment[24]. While the debate on this issue goes on and as the seismological data may help resolve this issue, we note that the timing of ground shaking due to the main shock (around 6:30 am IST) and that of land subsidence does not appear to be synchronous at some locations. For example, reliable reports from Nancowry Island suggest that the subsidence occurred 8 min after the main shock. Reports from Port Blair indicate subsidence in the jetty occurred 10 min after the earthquake. These observations and modelling of processing of the tide-gauge data may help resolve this question.

Our work in the region indicates extensive co-seismic vertical-level changes and large horizontal displacement. The southern groups of islands show greater displacement compared to the Andaman segment. The fact that the Car Nicobar Island shows the largest displacement (co-seismic slip) remains to be explained, as this patch had generated a large earthquake in 1881. This possibly indicates that there existed a slip deficit in spite of the 1881 earthquake. Another issue is the remarkable uplift observed in the Diglipur region, where the rupture reportedly stopped. The question why this region got uplifted needs to be resolved. The fact that no historical earthquakes have been reported from the region north of Diglipur, makes this an interesting issue. Variable slip distribution along the arc and variable rupture speed need to be modelled to understand the complexities of the faulting mechanism involved in this earthquake.

Although the potential of this region to generate great earthquakes and tsunamis has been pointed out by earlier workers, the size of the December earthquake, the complexity of its rupture and the magnitude of tsunami that it generated were clearly not expected nor do such parallels exist in recorded history. Evidently, the 2004-type events are atypical of the earthquake cycle, because such plate boundaries generally follow a 'variable rupture mode' in which major asperities are completely broken by great earthquakes only once in four or five earthquake cycles[25,26]. The spatio-temporal pattern of the earthquakes along the arc needs to be understood from the perspective of other subduction zones, capable of generating similar great earthquakes.

Scientifically, this earthquake would provide a wealth of data to understand earthquake generation and in particular, the pattern of co-seismic stress release, pattern of displacement and slip on various segments, besides post-seismic viscoelastic processes. The Barren Island volcanism could be a serious consequence of such phenomena (for more discussion see Rajendran *et al.*[8]). The plate dislocations that this event may have caused are likely to give rise to more earthquakes in the adjoining segments of the subduction zone, the 28 March event being a demonstration of the same effect. Are the nearby plate boundaries such as the Himalaya under an increased threat? Perhaps, there is a compelling need to reassess the earthquake potential of the northern segments, including northeast India.

Another important issue is the threat from tsunamis, generated by such mega thrust earthquakes, in the Indian Ocean. Clearly, we had no strong evidence to foresee that an earthquake in Sumatra could generate a tsunami that could affect parts of the Kerala coast, southwest of India. The great Sumatra–Andaman event is a reminder of the underestimated threat from earthquakes both within and outside the Indian territory. This earthquake should give a strong impetus for more focused studies on earthquake sources in India and its neighbourhood, leading to the estimation of direct and indirect threats posed by them. One of the most challenging problems is to identify sources and magnitudes of historic earthquakes. The other issue is to estimate the slip rate, leading to a better appreciation of earthquake cycles in this region. Future studies need to be geared in this direction.

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