Partial and Complete Rupture of the Indo-Andaman plate boundary 1847-2004

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We review seismicity along the Nicobar/Andaman plate boundary prior to the Mw=9 earthquake of 26 December 2004, with particular attention to reverse slip in the central and northern parts of the rupture zone 600-1300 km north from the epicenter. Slip is partitioned between convergence and strike-slip motion, which in the northern Andamans is assisted by back-arc spreading. Subduction zone earthquakes prior to the rupture occurred largely to the east, and at deeper depths than the area ruptured in the shallow 2004 megathrust. Large thrust earthquakes in 1847 (Mw>7.5), 1881 (Mw=7.9) and 1941 (Mw=7.7) appear to have occurred on intermediate regions of the down-dip boundary, areas that have been surrounded and probably incorporated into the 2004 rupture. Preliminary reports of 1-4 m of subsidence of the Nicobar islands and 1-2 m uplift of western shorelines of the Andaman islands are consistent with a down-dip fault width of 150-180 km, and a slip of 7-23 m. Based on preliminary reports from the Port Blair tide gage, slip in the Andaman islands, 800 km north of the epicenter, appears to have started no sooner than 36 minutes after the mainshock, some 30 minutes after the primary mainshock rupture is inferred to have arrived from the epicenter, but consistent with large aftershocks occurring in this region 85 minutes after the mainshock, and suggestive of slow slip. The delayed slip was not accompanied by shaking except that from aftershocks.

GPS measurements in the Andaman islands prior to the earthquake indicate a plate convergence rate of 14 mm/year suggesting that great earthquakes with similar slip to the 2004 event cannot occur more frequently than once every 1000 years. A shorter recurrence interval of 400 years is calculated for the epicentral region where convergence rates are higher. The apparent indifference of the 2004 earthquake to the lowered slip deficits caused by previous major earthquakes, and its release of significant seismic moment without evidence for comparable shaking, has implications for the analysis of historical earthquakes in other plate boundaries.

Introduction

Although there is still some question about the northernmost extent of the primary mainshock rupture in the December 2004 earthquake (Figure 1) aftershocks suggest that it propagated 1300 km from an epicentral region at 3.3°N northwards with a duration of ≈10 minutes corresponding to an average propagation velocity of 2.1 km/s (Park et al., 2005). The first 650 km of the rupture appears to be the source zone responsible for the generation of the principal tsunami that resulted in loss of life on remote shorelines – sea floor deformation here was rapid compared to the propagation speed of the tsunami (Ortiz, personal communication, 2005). Tsunami run-up on Sumatra and in Thailand locally exceeded 10 m (Borrero, this issue), with a death toll (as of February 2004) of almost 230,000 in the epicentral region, and approximately 70,000 on the distant shorelines of eight nations: Thailand, Sri Lanka, Myanmar, Malaysia, Bangladesh, the Maldives, Kenya, and Somalia. The tsunami's reach extended to the Arctic Ocean via both Pacific and Atlantic pathways. Local peak-to-peak amplitudes of 1 m were recorded on the Pacific coast of Mexico due to focusing of the wave by the East Pacific rise (Ortiz, 2005).

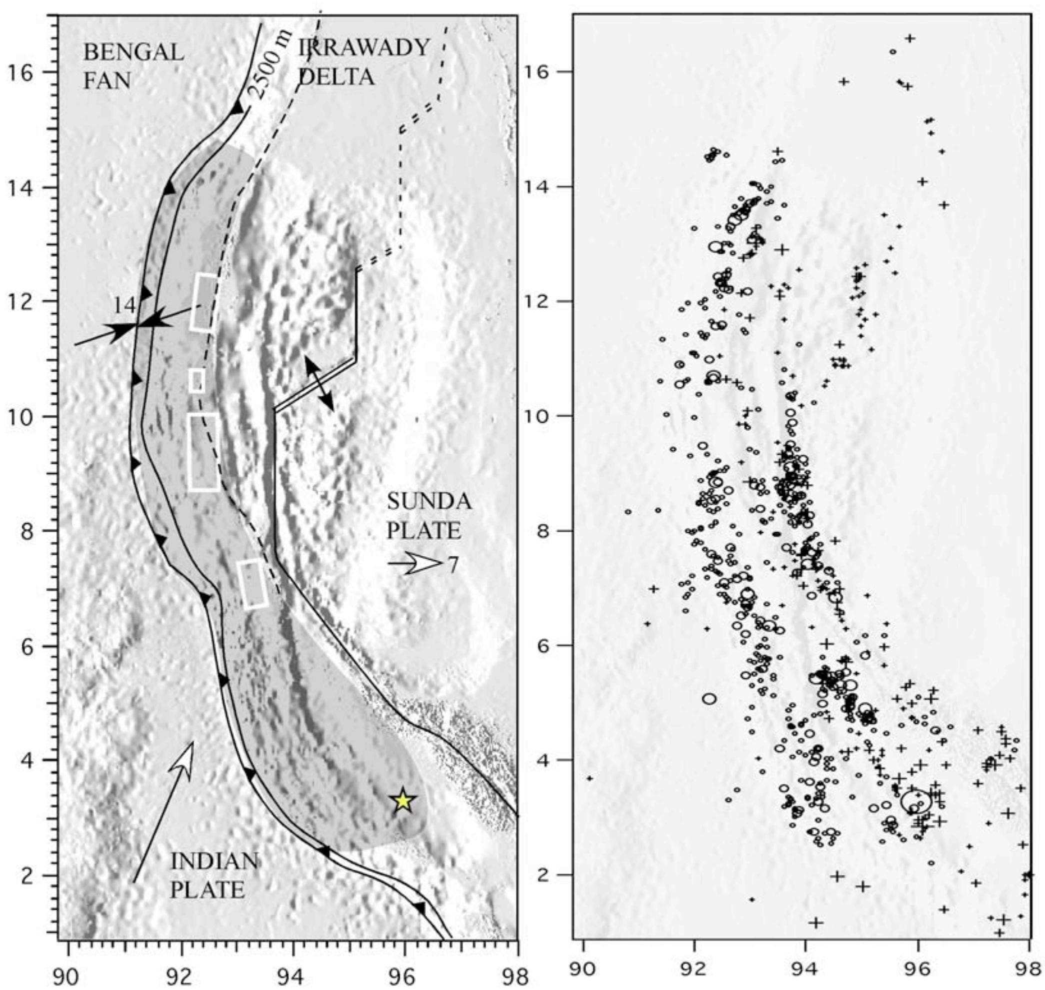

Figure 1A Tectonic setting and earthquake locations in the Andaman–Sumatra region (from Curray et al., 1979,1982) . Rectangles left are historic rupture zones with the 2004 rupture shaded. Open arrows in A indicate plate velocities relative to Asia, double arrows are inferred relative vectors at plate boundaries (Paul et al., 2001). The barbed line is the edge of the accretionary Nicobar-Andaman ridge. The inner line near the trench axis is the -2500 m contour, and the dashed lines left, are locations where alluvial fans have obscured structures on the sea floor. The dashed line linking historic rupture areas passes through the axis of the archipelago. Circles are relocated aftershocks to 14 January and crosses are relocated seismicity 1964-2004 (mostly M≥5.5). Star indicates the 26 December 2004 epicenter.

The plate boundary near Nicobar (9°N) changes strike northward from the approximately N20°W strike of the Nicobars, to follow the almost linear N10°E trend of the Andaman Islands for the next 300 km: Little Andaman near 10.7°N, South Andaman at 12°, Middle Andaman at 12.5°, and North Andaman at 13.5°N. The timing of the arrival of the tsunami on the east coast of India indicates that no significant tsunami was generated in this northern half of the rupture, indicating that submarine displacements, or rates of slip were smaller north of this 30° change in strike than to the south.

Analysis of the teleseismically recorded P-waves that terminated primary rupture 9-10 minutes after the origin time, suggests they originated near 12.5±2.5°N (Lomax, 2005), and whereas aftershocks could be resolved teleseismically within 20-30 minutes of the mainshock, aftershocks did not occur at 14°N for more than an hour (Figure 1B). Consistent with an interpretation that slip was slow, and delayed, is the observation that tide gage data from Port Blair suggest (unpublished) record slip developed more than 30 minutes after primary rupture had propagated to the Andaman Islands.

The northward propagation of the rupture passed close to, or through, the rupture zones of major historic earthquakes in 1847, 1881 and 1941, apparently indifferent to the reduced slip potential of these regions. The rupture areas of these early earthquakes are shown to represent less than one third of the down-dip width of the recent earthquake.

We summarize the history of the islands, and geological evidence for their vertical instability. We review seismic evidence for the location of the three major earthquakes that occurred in the two centuries prior to the 2004 earthquake. From preliminary uplift and subsidence data, and relocated seismicity before and following the earthquake, we estimate that reverse slip in the Nicobar Islands (7°N) was more than twice as much as slip in the Andaman islands (12°N).

History

Although settlement of the Andaman and Nicobar islands occurred many thousands of years ago, indigenous tribes on the islands kept no written records. Ballore (1934), however, notes that the islands native inhabitants revere two deities - the god of storms and the god of earthquakes. The complex role of floods and earthquakes in the beliefs of indigeneous peoples are discussed by Man (1883), Radcliffe-Brown (1922) and Pandya (1995). The Nicobar Islands were known to Ptolemy and were visited by occasional travelers in subsequent centuries, most of whom commented on the inhospitability of the native population: 9th century Arabic traders, Marco Polo c.1292, Jesuits c.1711, Alexander Hamilton c.1727, Viscount Valentia c.1809. The history of damaging earthquakes follows semi-continuous colonial occupation in the mid -18th century by the Danes 1756-68 (Canning et al., 1858; Hamilton, 1828), Moravian Baptists (1768–1787), and Austrians (1778–1781). Danish administration was re-asserted 1784–1837 (Home Department, 1859), and again 1846-1858 (Hunter, 1881) . The death of the Danish king, Christian VIII, brought an end to a century of intermittent Danish rule.

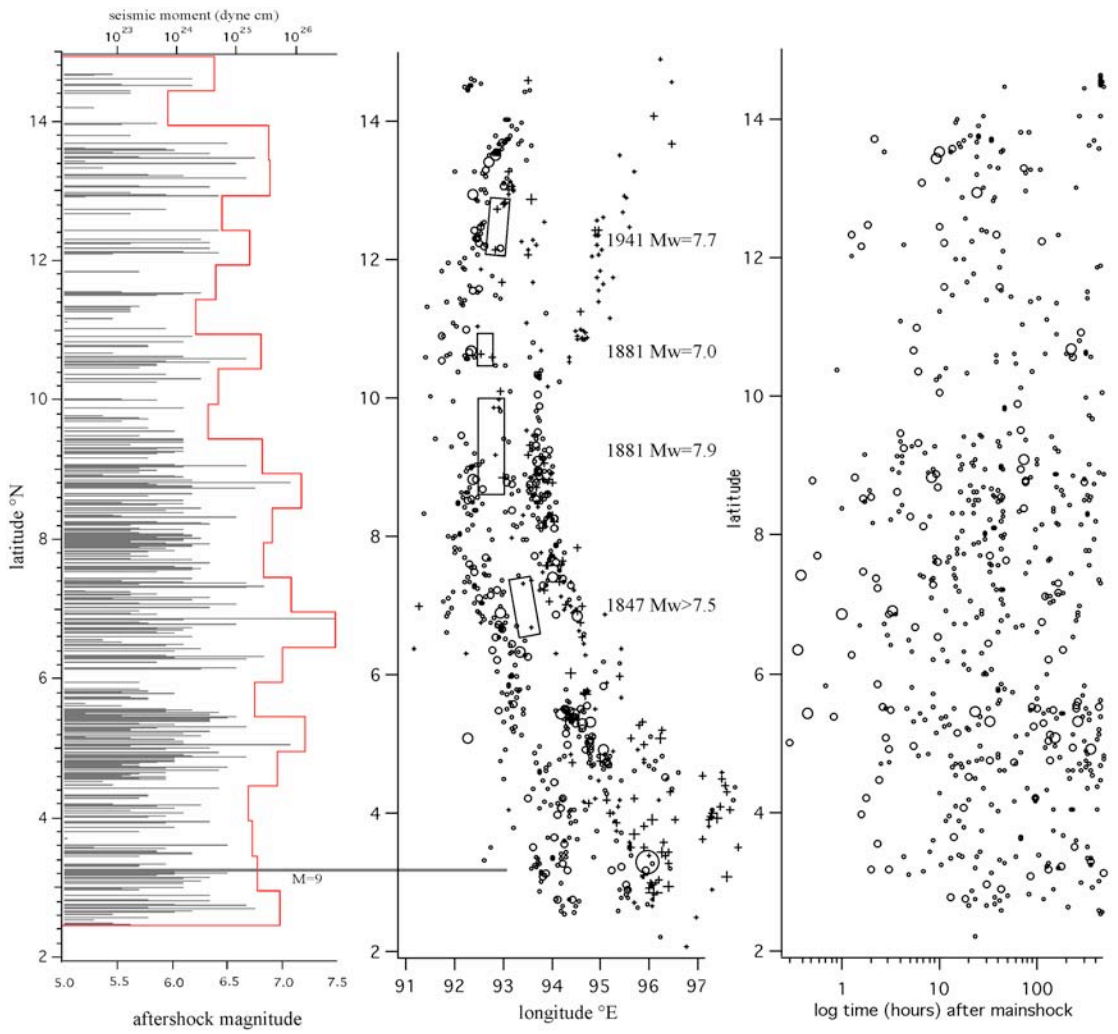

Figure 1B The center panel shows large historical ruptures and their location relative to recent relocated earthquakes (1964-2004) and aftershocks (same symbols as Figure 1A). The panel right illustrates the delay in the initiation of aftershocks in the northern reaches of the rupture zone as a function of the logarithm of time in hours after the mainshock. Aftershock moment release as a function of latitude (left panel) represents a total moment release to mid-February equivalent to a single Mw=7.5 earthquake.

The British administered the Nicobars briefly during the Napoleonic wars 1807–1814, and their interest was re-awakened by the loss of a British ship and the alleged murder of its crew by Nicobarese in 1848. Seeking a secure penal colony following the Indian Mutiny they annexed the Nicobar and Andaman islands in 1869 and administered it continuously for the following 76 years, apart for a brief occupation of the islands during the second world war by a Japanese Military administration (23 March 1942 to 6 October 1945).

Colonization of the Andamans occurred first in 1790 with the foundation of a small penal colony (Phillimore, 1945), but by 1796 the settlers and convicts had all perished. Continuous colonial occupation of the Andaman islands did not occur until 1869 following the establishment of a substantial penal colony near Port Blair. Indian administration of the islands has been continuous for the past 60 years.

Geological evidence for vertical motions of the islands

The bathymetry of the Andaman and Nicobar islands were first surveyed in 1770 by Captain Ritchie, and more accurately in 1789 by Captain Blair. Their interiors were explored by a scientific expedition in 1857 that also mapped the Barren and Narcondam volcanoes. The ruins and foundations of the 1789 settlement at Chatham island near Port Blair were described by members of the 1857 expedition as being surprisingly close to sea-level (Figure 2): *"The rear wall only was standing, and contained a door and two windows. The remainder of so much of the house as had not been destroyed by the encroachment of the sea, which in this spot must have advanced some 40 or 50 feet, was strewed with large pieces of masonry and brickwork on the beach."* [Mouat et al. 1858]. In the same report the expedition noted the shallowness of corals along the western Andamans compared to the deep waters to the west, providing an early hint of the tectonic genesis of the Islands: *"These reefs are far more extensive, and form dangers to a far greater distance from the land on the West side than on the East, depths of 100 fathoms being found in many places on the eastern shore within 3 miles of the coast, whereas on the western shore the reefs extend and form dangerous patches at a distance of twenty and twenty-five miles from the land, a fact the probability of which is sufficiently indicated by the geological features of the Islands, the general dip of the stratified rocks being to the eastward at high angle, sometimes as much as 75°.*

Figure 2. Remains of the 1793 settlement on Chatham Island, near Port Blair, from a sketch made on the 1858 expedition. Oldham decided that its near sea-level location was evidence for recent subsidence (Mouat et al., 1858)

Writing in 1884 Oldham concedes that shoreline damage to the early settlement at Port Blair, though possibly caused by marine erosion, supports an observation first made by Kurz (1868) of island subsidence, evidenced by drowned forests in the Nicobars. Oldham provides independent support for recent subsidence through the presence of a similar drowned forest on the NE coast of Havelock Island, 40 km NE of Port Blair. Notwithstanding this evidence for recent subsidence, and another noted by Tipper (1911) near Stewart's Sound (Middle Andaman), Oldham noted the widespread presence of uplifted marine terraces throughout the coast of South Andaman - a raised beach not more than 2-2.6 m above sea level " *can be seen forming a terrace, from a few yards to over a mile in width in almost every bay"*. In places he notes a higher terrace 10-13 m above this lower one. The presence of recent shells on these marine terraces is discussed by Gee (1926).

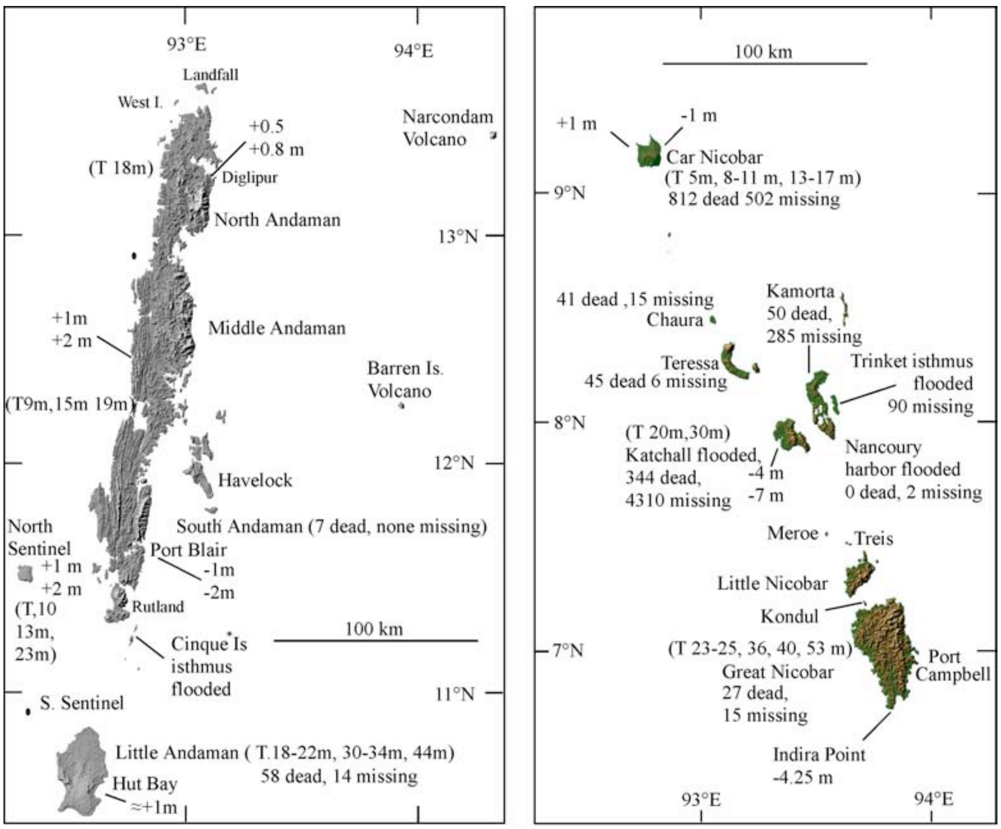

Figure 3. Localities mentioned in text and fatality data listed by the Andaman and Nicobar Government, 2 March 2005. Elevations of marine terraces identified on SRTM data are identified in parenthesis e.g. (T 18-22 m). Estimates of post-seismic uplift are indicated ±1 m. For only the Indira Point measurement are the data corrected for the tidal range. Note the mean strike of the two island chains differ by approximately 30°.

In contrast to this evidence for recent subsidence and previous uplift on the eastern margins of the Andamans, Oldham (1885) describes conflicting evidence for coastline stability. Less than 20 km west of Port Blair ancient kitchen middens on the shore require coastal stability for "*centuries, if not by tens of centuries"*. Stoliczka (1881) also describes these kitchen middens and puzzles over this conflicting evidence for stability on some of the islands compared to subsidence and uplift noted in others.

Oldham never visited the Sentinel Islands (40 km west of Port Blair) and although he had been informed that they consisted of uplifted corals, he deduced incorrectly that these western islands were eroded limestone remnants. SRTM data (Figure 3) suggest the presence of at least two coral terraces on North Sentinel Island, at ≈25 m and ≈50 m elevation. The recent earthquake has raised the island (see Figure 7), a possibility anticipated by Ortiz and Bilham (2003), exposing the fringing reef that formerly surrounded the island. Precise measurements of uplift are unlikely because the island's indigenous population of Sentinelese (≈100) who remained isolated until the last century, will not permit outsiders to approach or land, a policy endorsed by the Indian government.

SRTM imagery of the islands reveals marine terraces at elevations 4-50 m but is inadequate to provide definitive correlations of terraces between islands, or between east and west facing shorelines (Figure 3). In particular SRTM imagery is unable to map the narrow terraces identified by Oldham. Offshore lagoons, however, provide a sufficiently coherent footprint for SRTM imagery. At North Sentinel Island, for example, the newly uplift coral beach can clearly be identifed on the pre-seismic SRTM elevation data.

Nicobar Earthquake 31 October 1847

The first of the three large historical earthquakes in the Andaman/Nicobar region for which we have information occurred in 1847. Following discussions with Nicobar islanders, Hochstetter (1866) reported a "*very remarkable earthquake, which is said to have lasted from 31 October to the 5th of December, 1847, on the Nicobar Islands, at which time earthquakes occurred in Java. ...the description of the earthquake seems trustworthy, as I had myself occasion to observe on Kondul the mountain slips referred to in the account* ". Kondul island (Kendoel of Montessus De Ballore, 1934) lies between Little Nicobar and Great Nicobar at 7.3°N.

No original account of the 1847 earthquake survives, and all secondary accounts appear to derive from Hochstetter's. The 5 week period of felt aftershocks suggest that its magnitude may have been similar to the 1881 and 1941 earthquakes ($7.5<M<7.9$) discussed below. It occurred between the times of the Danish and British occupations, and in the absence of further information, a precise location or mechanism is speculative. Although it may have occurred on the strike-slip Andaman fault to the west of the Nicobars, we know of no earthquakes exceeding $M_w=7.2$ on this transform fault, and it is probable that its size may signify that it occurred on a reverse fault west of, or beneath the islands. Its inferred location is shown in Figure 1.

Car Nicobar Earthquake 31 December 1881

Data for the study of this earthquake were compiled by Oldham (1884) who, on the basis of astronomical clock recordings in Madras and Calcutta, believed the earthquake occurred on the locus of these two cities beneath the Bay of Bengal (400 km west of the Andaman Islands). Seismographs had yet to be invented but tide gauges at 8 harbors surrounding the Bay of Bengal recorded the largest surface waves and the resulting tsunami, and these data provide a powerful constraint on timing and rupture parameters. The earthquake is calculated to have occurred near and west of Car Nicobar with two reverse slip ruptures. The larger measured 150 km x 60 km, and dipped 25°E with a slip of 2.7 m equivalent to a Mw=7.9 earthquake (Ortiz and Bilham, 2003). The smaller was equivalent to Mw=7 .0 and occurred some 50 km to the north of the larger patch. The parameters of these two events are listed in Table 1 and are plotted on Figure 1. The location of the 1881 rupture was sufficiently close to Car Nicobar to have tilted the island, raising its western edge 50 cm relative to its eastern shore. The tsunami resulted in the flooding of stilt houses to the base of their floors (Figure 4).

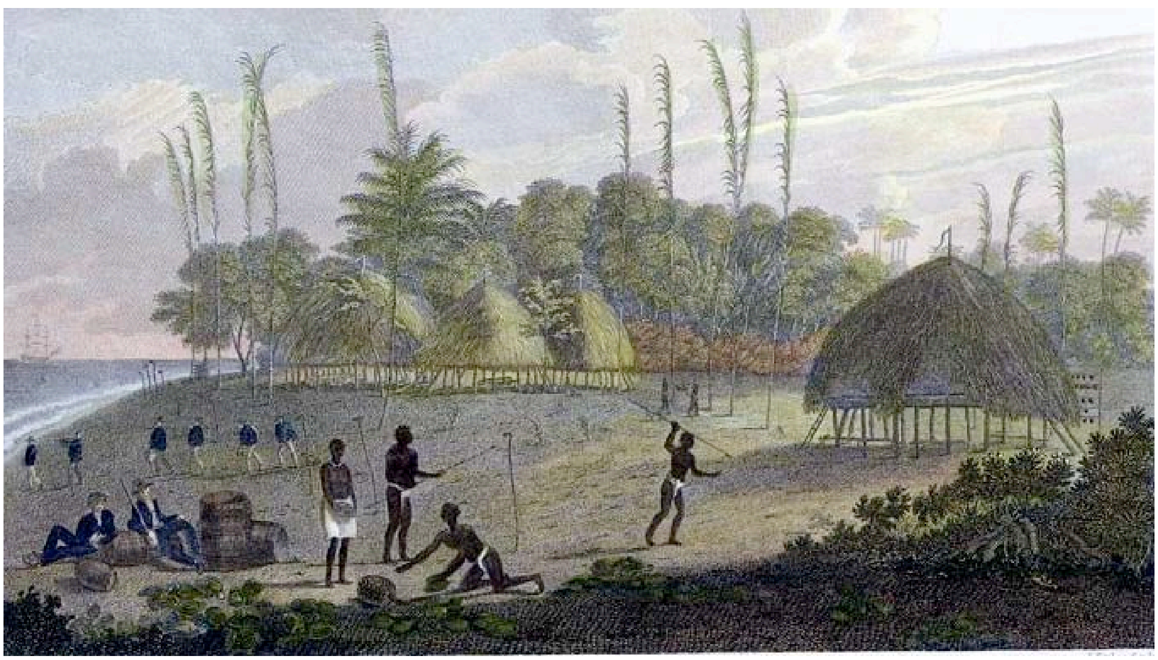

Figure 4 Car Nicobar stilt dwellings 1809 engraved by J.Fittler after a picture by H.Salt (Valentia, 1811). Architectural features of the houses are well adapted to modest storm surges, and the 1881 earthquake resulted in shoreline flooding of the stilts to the floor levels only (Oldham, 1884).

Table 1 Inferred rupture parameters of major earthquakes 1847-1941 (see text).

time	Mw	Lat °N	Long°E	depth,km	Dip E°	slip,m
31 Oct 1847	7.5-7.9	7±1	?	?	?	?
31 Dec 1881	7.9±0.1	9.25±0.75	92.7±0.3	15	20±5	2.7±0.3
31 Dec 1881	7.0±0.1	10.8±0.3	92.55±0.2	15	15±5	0.9±0.2
26 June 1941	7.7±0.1	12.1±0.6	92.5±0.3	50	-	2-3

Andaman Earthquake 26 June 1941

The most recent of the major earthquakes in the Andaman islands preceding the recent rupture occurred in 1941, a year before Japanese occupation of the islands. However, the earthquake was described only after the Second World War [Krishnan, 1953; Jhingran, 1953] . Although the tsunami generated by the 1941 earthquake is stated to have caused much loss of life along the east coast of India [Murty and Rafiq, 1991] no official (or unofficial) account of the impact of the remote tsunami has been discovered. Jhingran describes the loss of low-lying western-facing forest cover on the Andamans, presumably by a tsunami but mentions no loss of life. Eyewitness reports published informally by the Society of Andaman and Nicobar Ecology (SANE) following the 2004 earthquake add further details to the official 1941 accounts. The central watch-tower of the cellular jail in Port Blair collapsed along with a hospital and other masonry structures. Eyewitnesses speak of subsidence of Ross Island (as in the recent earthquake), requiring its abandonment in favor of the current mainland capital, Port Blair.

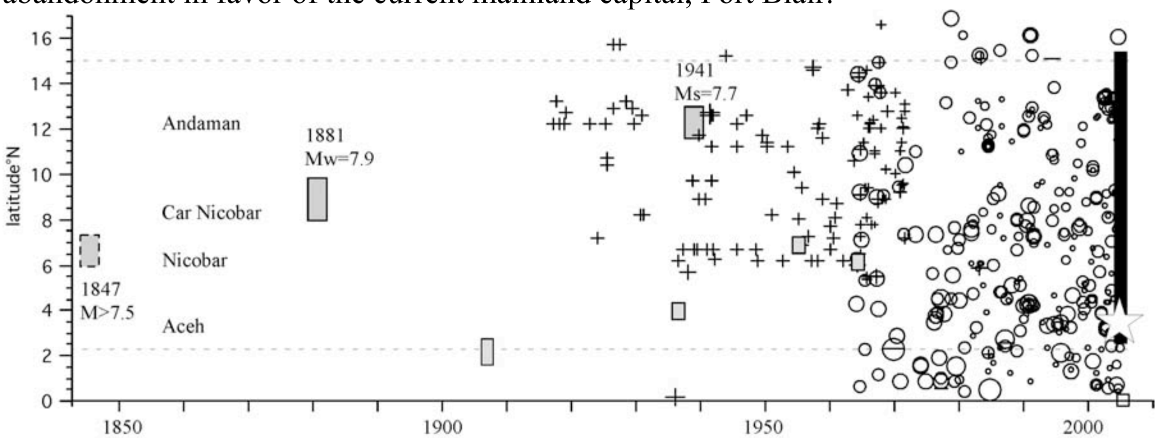

Figure 5 Time space diagram of historical and recent earthquakes. Crosses from Engdahl and Villasenor (2002) - squares M>6.8. Circles are epicenters 1964 to 2004 relocated using methods described in Engdahl et al., (1998). The Sumatra-Nicobar-Andaman earthquake ruptured more than 1300 km of the Indo/Andaman plate boundary (dashed lines) defined by the block of aftershocks recorded to 7 February 2005. The 2004 epicenter is indicated by a star.

The 1941 earthquake is listed in Gutenberg and Richter (1965) as Ms=8.1 and appears even larger in some catalogs, but Pacheco and Sykes [1992] assign it Mw=7.7, similar to the magnitude we derive here. We have relocated its epicenter and although several aftershocks were recorded they have yet to be relocated using secondary phases (Table 2). The preliminary aftershock locations available to this study suggest that rupture may have extended from 250 km north to 50 km south of the mainshock (ignoring the 19 August event). A rupture less than half this length is anticipated from its Mw=7.7 magnitude; we therefore chose to ignore the last two earthquakes listed in Table 2. That is we adopt the weak constraint that the rupture occurred between 11°N and 13°N. Subsidence near and north of Port Blair is consistent with the rupture terminating near the western shoreline of the Andaman Islands. From these scant constraints we infer that slip was less than 3 m on a <50 km wide 150 km long down dip rupture.

Table 2 Aftershocks of the 26 June 1941 Andaman earthquake. Maximum mainshock intensities were identified near Baratang Island 56 km north of Port Blair. Mainshock re-located at 50±10 km depth using methods described in Engdahl et al, 1998. Aftershocks listed by Jhingran, (1952): times in Indian Standard Time (GMT+5.5 hours) (*Monthly Reports* Met. Dept. *Current Science* **9**,1940; **10**, 1941; **11**, 1942.

Date	Time	deg.N	degE	location	Magnitude or intensity
26 June 1941	GMT 11:52:6.63	12.133	92.491	S.Andaman	Mw=7.7
27 June 1941	IST 13:03				slight
27 June 1941	14:02				moderate
28 June 1941	00:34				slight
28 June 1941	23:25				slight
30 June 1941	23:54	13°5'	93°7'	N. Andaman	moderate
2 July 1941	8:12				slight
9 July 1941	06:09				slight
14 July 1941	07:32	11°7'	93°E	Andamans	slight
18 July 1941	05:01				slight
22 July 1941	01:49				slight
10 August 1941	03:48	10°	94°	S. of Andamans	moderate
19 August 1941	21:49	7°	96°	E. Nicobar	slight
30 August 1941	22:15	14°5'	94°	N. Andaman	slight

Earthquakes 1900-2004

In Figure 5 we illustrate the relation between instrumentally recorded earthquakes and the three M>7.5 historical earthquakes discussed above. All M≥5.5 earthquakes, and lower magnitude events with Harvard CMT solutions, that have occurred in the past 40 years have been relocated using methods described by Engdahl et al. (1998) with special attention to focal depth. Aftershocks that followed the 2004 earthquake form the block of events at the end of this 150 year interval. Great earthquakes occurred in 1933 and 1861 and adjoin the southern end of the 2004 rupture (Newcomb and McCann, 1987; Zachariasen et al., 1999, 2000; Sieh et al 2004).

The spatial plot of recent earthquakes (Figure 1) reveals the separation between interseismic seismicity mostly to the east of an axis through the archipelago, and aftershocks, mostly to the west, that occur on the shallower surface of the subducting Indian plate. A third population of interseismic and post-seismic earthquakes follow a series of transform and rift earthquakes to the east; these are not discussed in this article article, although we note that their cumulative moment release is much less than the dip-slip earthquakes in the subduction zone to the west.

Cross sections through the Andamans normal to the trend of the trench are consistent with the notion that the 100 km region on the upper surface of the descending Indian plate east of the trench axis was largely aseismic prior to the 2004 earthquake, and that the major earthquakes of 1847, 1881 and 1941 probably ruptured less than one third of the width of the plate boundary that slipped in December 2004 (Figure 6).

Vertical motions 2004

The 26 December 2004 earthquake resulted in widespread adjustments in the elevation of the islands (Figure 3). Post seismic photographs (Giles, 2005) indicate that the Nicobar islands (≈7°N) have sunk 2-4 m. In most cases we do not know the precise time of the photographs and it is thus not possible to estimate the stage of the tide, resulting in an inherent 1 m uncertainty in estimated subsidence or uplift. We quantify the subsidence near the Nicobar Islands from the flooding depth of Katchall and Great Nicobar.

Subsidence of the southernmost tip of Great Nicobar island is 4.25 m as estimated from the January 2005 mean sea-level depression (-0.75 m) of the foundation of the Indira Point lighthouse, that was constructed in 1970, 3.5 m above mean sea level (see Figure 7). In early January, mean sea level relative to the foundation was estimated by eyewitness observations of high and low tide (Office of The Director General Of Lighthouses and Lightships, Andaman & Nicobar, Port Blair, 2005). This large value for subsidence conflicts with later reports where the basis for numerical estimates of subsidence are omitted. For example, the Chief Hydrographer to the Indian Navy B. R. Rao reports the lighthouse subsided 1.4-1.5 m (N. Z. Herald 2 March 2005).

We attempted to estimate the newly flooded depth of water covering shorelines of the Nicobar islands from SPOT images combined with SRTM digital elevation data, but the near-shoreline SRTM imagery proved too inaccurate. Postseismic flooding of Katchall island, however, can be estimated from the change in wavelength of ocean swell waves where they enter Katchal's SW lagoon. SPOT images posted by CNES Singapore before and after the tsunami, show an abrupt decrease in wavelength at the entrance of the lagoon that we assume to be the shoaling of a gravity wave whose speed is proportional to $\sqrt{gh}$. The depth of the lagoon h_2 compared to the open water to the SW (h_1) is $h_2=k_A h_1$, where k_A is the square of the ratio of deep-water wavelength to shallow-water wavelength, $(\lambda_1/\lambda_2)^2$, prior to the earthquake. After the earthquake the depth is increased by d, and a new ratio of wavelengths is established k_B where $h_2+d=k_B(h_1+d)$. This yields an expression for subsidence, $d= h_1(k_A-k_B)/(1-k_A)$. The expression requires the offshore depth to be known and this is available in the form of published bathymetry (Navy, 1943). The method when applied to SPOT images taken on 10 July 2004 and 28 December 2004 yielded a range of values for subsidence, the lowest being 4-7 m. The range is caused both by ambiguity in identifying the fundamental wavelengths in the lagoon, inaccuracies in offshore bathymetry, and departure from horizontal sea-floor conditions. The method is likely to be more successful in open-sea environments, and potentially enables changes in the depths of offshore shoals throughout the Andaman and Nicobar islands to be quantified.

Subsidence of the east coast of Car Nicobar (8°N) evaluated from oblique air photographs and shoreline damage visible in preliminary damage reports (Malek, 2005) appears to be of order 1-2 m, with possible minor uplift (<1 m) of its western shore. The sense of this motion is similar to what is inferred to have occurred in the 1881 earthquake (Ortiz and Bilham, 2003), but with almost an order of magnitude greater amplitude.

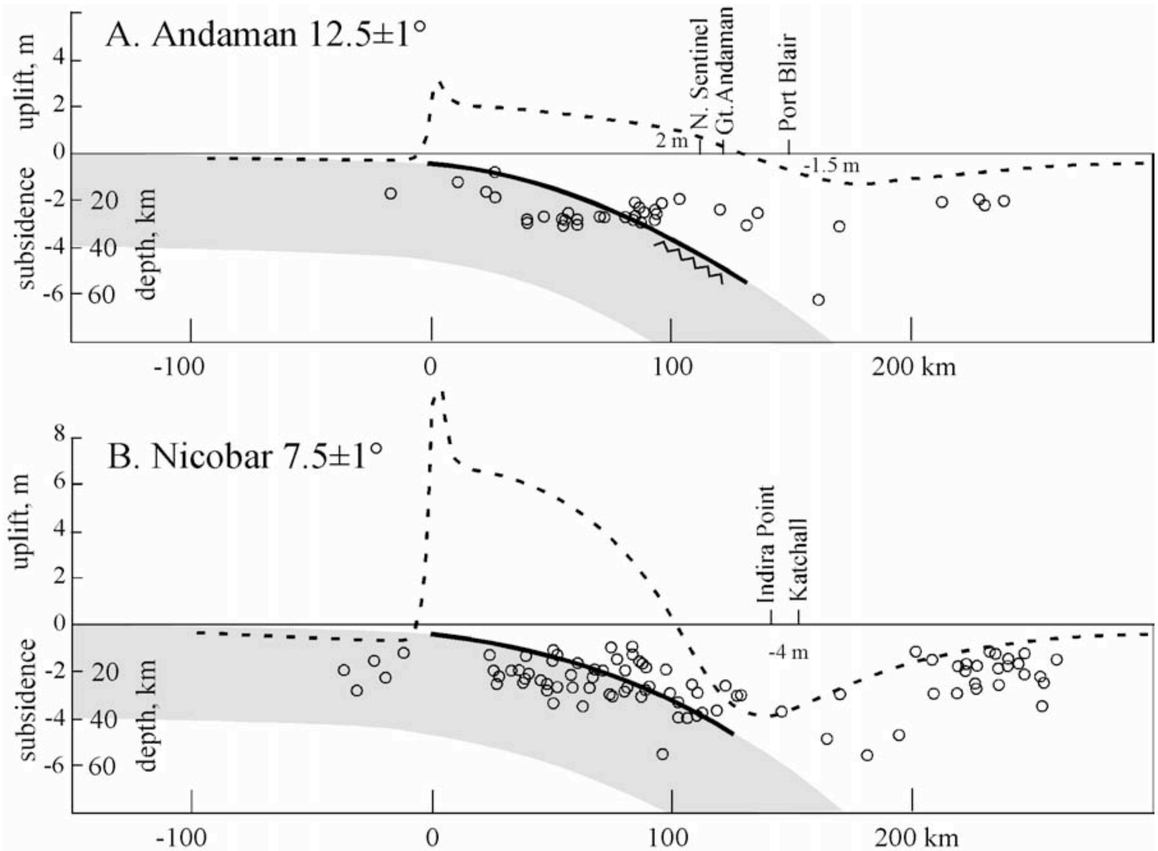

Figure 6. Cross-sections through the 2004 rupture zone at 12.5°N and 7°N showing relocated aftershocks (depth±10 km). The bold line indicates the inferred rupture based on observations of surface subsidence and uplift at the locations indicated. Synthetic deformation shown by a dashed line assumes 2-D rupture (Savage, 1983). The plate is assumed to be planar and to dip at 20 degrees in these dislocation models. Slip in A is 7 m, for a down-dip width of 165 km, and slip in B is 23 m for a down-dip width of 129 km. The inferred location of the 1941 Andaman earthquake is shown by a saw-tooth line in A.

The eastern coast of Little Andaman island (10.5°N) rose 1-2 m with eyewitness reports of the sea level sinking slowly at Hut Bay after mainshock shaking, and not recovering following the ensuing tsunami (eyewitness account related by John Paul, personal communciation, 2005). Rutland Island, North Sentinel Island (Figure 7), and most of the northern Andaman islands were uplifted, but subsidence of 1-1.5 m is reported from Port Blair and Ross Island based on flooding of harbor facilities and shoreline streets at high tide. In conflict with evidence for 1 m of subsidence, a preliminary estimate of 25 cm of co-seismic subsidence is reported following GPS occupation of a point near Port Blair by the Survey of India, Dehra Dun, soon after the earthquake (Deccan Herald, 16 January. 2005). The location of this point is unknown and its small amplitude conflicts with later reports from the same authority for 2 m of subsidence (N. Z. Herald, 2005). Data from the Port Blair tide gauge have yet to be published but news reports in the Indian Express and Deccan Herald (21 & 22 January) cite 1 m of subsidence. We chose to adopt a subsidence of 1-1.5 m for the purpose of later modeling.

Uplift of North Andaman island near Diglipur is reported as 0.5-0.8 m. (N.Z. Herald, 2005), and uplift of the western shore of Middle Andaman Island at 12.5°N near Flat Island (Malek, 2005) appears to be approximately 1 m.

These estimates of subsidence and uplift define a neutral axis about which the islands tilted down to the east. This axis constrains the easternmost extent of subsurface rupture, and when used in conjunction with seismic constraints on the dip and location of the subsurface rupture permit us to estimate local reverse slip. Since our vertical constraints are imprecise, based as they are on remotely sensed flooding, or photographs of uplifted corals taken at unknown times of the tidal cycle, our estimates of plate boundary slip are correspondingly uncertain. The models in Figure 6 are based on simple 2-D elastic deformation in a half-space (Savage, 1978) and imply slip of 15-23 m in the Nicobar islands and 5-10 m in the Andaman islands. It is clear that future data from the epicentral region will make estimates of reverse slip considerably more precise, warranting more complex models incorporating deformation associated with a curved plate and with variable coseismic slip.

Figure 7A Historic view of North Sentinel island shoreline (courtesy George Weber) compared to an Indian Coastguard photo after the earthquake. Uplift here is estimated to be 1-2 m with the pre-earthquake coral lagoon now completely raised above mean sea level. Figure 7B are views of Indira Point lighthouse (6°45.2'N 93°49.6'E) c. 1980 compared to Indian Coastguard photo of flooded base of lighthouse after the earthquake. Subsidence here is estimated to be 4.25 m based on its foundation being 3.5 m above sea level when constructed, and in January 2005, level with low tide, and submerged 1.5 m at high tide. The steel shell lighthouses, like that at Indira Point, fared well in the earthquake, but masonry lighthouses at Interview Island and Katchall island were badly damaged.

The vertical motions of the islands do not permit constraints on the strike-slip component of rupture, and hence we underestimate total slip. The horizontal co-seismic GPS slip vector reported from Port Blair in a January press release from the Survey of India is 1.15 m to the SE, which is unexpected from considerations of local tectonics. Horizontal displacements of 1-4 m are reported from 12 recovered pre-seismic Survey of India control points in the islands, however, these data are as yet unpublished. Precise constraints of co-seismic GPS displacements of the islands are also anticipated from five locations between 7°N and 14°N conducted by a group of scientists from Trivandrum and Bangalore six weeks before the earthquake, and in the month following the earthquake. At the time of writing these data are unavailable.

Discussion

We first discuss evidence related to the probability that the primary tsunami was generated in the southern half the primary rupture, and that slip north of approximately 9°N was delayed and occurred more slowly. The 1 Hz P-wave duration of the entire earthquake recorded at worldwide seismic stations is approximately 8 minutes depending on recording azimuth and the confidence with which late arriving P-waves, can be distinguished from S-waves (Park et al., 2005). Directivity shortens the recorded wave-train to the NNW and extends it on stations recording SSE of the epicenter. Moment release peaks in the first 100 seconds, and decays irregularly to insignificance after 600 seconds (Chen Ji, personal communication, 2005). Lomax (2005) notes that the last clearly identifiable P-waves in the wave train are located at approximately 12.5±2.5°N some 480s after the mainshock, implying a mean rupture propagation velocity of 2.3± km/s. If we assume the latest recorded P-wave arrivals corresponds to the northernmost region where aftershocks subsequently developed close to 15°N, we obtain a mean propagation velocity of 2.2 km/s. From the P-wave data we conclude that seismic rupture occurred near Port Blair (11.5°) at 01:06 GMT (06:36 local time) no later than 8 minutes after the mainshock at 00:58:53 GMT.

The timing of subsidence of 0.25-1.5m at Port Blair is enigmatic. The tide gauge at Port Blair is reported to have recorded initial subsidence of the harbor (or rise in sea level) at 07:14 Indian time, an elapsed interval of 38 minutes after local shaking commenced, consistent with eyewitness accounts of a tsunami arriving 15-30 minutes after 5 minutes of felt shaking. The recorded rise in sea level is too soon for a tsunami to have arrived from the epicenter at 3.3°N, but it may represent a first-arriving positive tsunami from a source near the Nicobar islands. The 1881 tsunami at Port Blair, for example, followed the mainshock by only 14 minutes, suggesting a source area less than 100 km from the harbor, assuming a mean tsunami propagation velocity of ≈0.1 km/s (Ortiz and Bilham, 2003). A 38 minute delay requires a tsunami source-region more than 220 km south of Port Blair. The source would need to be close to Car Nicobar at 9.5°N (near piston 26 in

Figure 6B of Ortiz and Bilham, 2003), although a deep water tsunami propagation path may permit a source further south.

Tsunami models constrained by the time of the first wave arriving in Vishakapatnan and Chennai on the east coast of India (09:05 and 09:06 local time), suggest that tsunami-genesis was weak north of 7°N (Ortiz, personal communcation, 2005). Had a coherent tsunami been generated north of 8°N these calculations show that it would have arrived at Vishakapatnan earlier than the damaging tsunami generated near the mainshock. We conclude that reverse-slip on the subducting plate north of 9°N was of smaller amplitude or occurred more slowly.

Thus the initial signal on the Port Blair tide gauge may register not subsidence of the harbor, but a positive tsunami surge propagating into the area from the south. A positive initial surge, however, is not expected from locations east of the axis of principal uplift. Detailed modeling is needed to verify this assertion, but such models are unwarranted until the tsunami wave-form data are published. Thus we are uncertain at present whether the initial rise at sea level signifies the first arrival of the tsnunami or subsidence of the harbor; however the observations imply that significant co-seismic subsidence of Port Blair is delayed by at least 36 minutes. Consistent with this observation is the fact that the first recorded aftershock in the Andaman islands did not occur until 83 minutes after the mainshock. This preliminary assessment of the timing of deformation at 10.5°N indicates that substantial slip on the subduction zone beneath the islands followed the initial rupture, and that when it occurred it produced no significant shaking, except as recorded by aftershocks. Subsidence at Port Blair of more than 1 m requires 5-10 m of reverse slip below and west of South Andaman island (Figure 6) and its timing suggests that slip occurred here in the form of accelerated creep, or as one or more slow earthquakes.

Aftershocks suggest that slip occurred on the shallowest 150-170 km width of the plate boundary, a down-dip dimension that is approximately three times wider than the largest earthquakes that occurred in the past century. It would appear, then, that the 2004 rupture enveloped, or re-ruptured, these earlier rupture areas. Paul et al.(2001) estimate from GPS measurements in the 1990's a maximum convergence speed of 14 mm/year between the northern Andamans and the Indian plate. If we assume that this rate has prevailed for the past few centuries the slip deficit prior to the 2004 earthquake in the 1847, 1881 and 2004 rupture zones would have been 2.2, 1.7 and 0.9 m respectively. We do not know for certain whether slip occurred in these regions in 2004, but the mean slip demanded by preliminary dislocation models suggests that substantial additional slip is likely.

Our results have implications for other plate boundaries, where the occurrence of large earthquakes is typically taken to imply a respite from imminent future large earthquakes. For example, Himalayan earthquakes in 1833 (Nepal, Mw=7.7) and 1905 (Kangra

Mw=7.8) have hitherto suggested that these regions are unlikely to re-rupture anytime soon. However, both rupture zones are adjacent to, or surrounded by, along-strike and down-dip seismic-gaps where no historical earthquakes have occurred in the past several centuries. This suggests that these historical ruptures could participate in a large future ruptures, and that complacency about future severe seismicity in these regions may be unwarranted. Sieh et al., (2004) note that Sumatran earthquakes also repeat at unexpectedly short intervals.

If large moment release occurs aseismically following great earthquakes it may account for noted discrepancies between long term slip rate and cumulative moment release estimated from seismic data in the historical record. Estimates of cumulative seismic moment in the Himalaya, for example, suggest that the cumulative moment is approximately 30% of that expected from geodetic estimates of convergence (Bilham and Ambraseys, 2005). However, the oblique oceanic convergence of the Andaman plate boundary is structurally and rheologically different from the Himalayan continental collision; one therefore cannot assume strict parallels between seismogenesis in the two regions.

It is not clear how the December 2004 earthquake would have been recorded in the historical record had it occurred many centuries ago. Had it occurred in AD 500 a record of the tsunami would have probably been handed down in mythical terms. Had it occurred in 1600, it would have left a felt intensity record only in Sumatra, and a fragmentary historical record of the tsunami on distant shorelines. Had it occurred in 1800 the tsunami would have been well recorded, and would have been blamed for the damage in the islands as far north as 8°N, but it is doubtful that anyone would have believed the rupture to be longer than 500 km, the length sufficient to account for widespread tsunami run-up. The sparse populations and flexible and transient nature of building styles in the Nicobar and Andaman islands at the time would have left little or no record of shaking. Even now, eyewitness accounts from local residents have left a scant record of shaking intensity, with fewer than two dozen accounts from the >1200-km-long epicentral region with its resident population of 230,000 (Martin, 2005, this volume).

The magnitude of the earthquake suggests that it must be associated with a long recurrence interval. The convergence rate near Port Blair of 12 mm/year (Paul et al, 2001) would require an 800 year renewal time to develop the 10 m apparently released near there in December 2004. Arc-normal convergence rate is slower, with possibly 20% of the convergence velocity partitioned as strike-slip motion to the east of the islands. In contrast the convergence rate near the epicenter is almost four times faster (Sieh et al., 2004), and the renewal time for 20 m of co-seismic slip is of the order of 400 years.

Conclusions

The 26 December rupture appears to have involved slip of the entire plate boundary between 3°N and 15°N, apparently indifferent to the reduced slip prevailing in parts of the plate boundary caused by historical M>7.5 earthquakes. Slip from 3°N to 9°N was ≈20 m according to seismic moment estimates (Park et al, 2005) and dislocation models constrained by subsidence estimates near Nicobar island, consistent with the generation of the catastrophic tsunami that damaged remote coastlines. Although primary rupture propagated northward at typical speeds, plate boundary slip north of 9°N developed more slowly, with significant slip manifest not sooner than 36 minutes after the mainshock, according to tide gage data from Port Blair. Slow slip north of 9°N is consistent with the absence of strong recognized tsunami phase at these latitudes, or strong shaking accompanying slip when it occurred. Aftershocks were not recorded in these northern regions for more than 80 minutes after the mainshock, again suggestive of delayed slip.

A pronounced (30° clockwise) releasing bend in the rupture zone occurs at 9-10°N near the transition between the northern and southern halves of the rupture. The bend occurs at the latitude of the Andaman spreading center that results in the offset of dextral slip on the Andaman transform fault far to the east, and reduces partitioned strike-slip to small values. Thus the change in the dynamics of rupture appears to be associated with an increase in obliquity and a change in the partitioning of strike-slip and reverse-slip northwards.

Slip in the Andaman Islands (10-14°N) not only produced a less damaging tsunami, it occurred in a way that had this event been known only from historically recorded intensities, e.g. from the destruction of Aceh 700 km to the SE along the arc, we are likely to have underestimated its magnitude and rupture area. The absence of intensity data from the mostly submarine region over which its effects were manifest renders the earthquake somewhat unique. Few intensity data are available in the region between 0 and 1200 km west of the epicenter, or the region between 100 and 500 km to the east.

The total reverse slip in the earthquake must be considered tentatitive until more precise field estimates of subsidence are obtained. Preliminary data are consistent with ≈20 m of reverse slip in the south decreasing northwards to approximately ≈7 m at Port Blair. These displacements correspond to a millennium of cumulative convergence at Port Blair and to approximately half this near the epicenter. The northerly termination of the rupture between the Burmese mainland and the northernmost Andaman Islands has presumably stressed the contiguous part of the plate boundary at 16°N, however, we note that the obliquity of the plate boundary here may be such that strike-slip motion is relative minor and a second 10° releasing bend here may further facilitate descent of the downgoing plate. The region has been characterized by minor microseismicity in the past century, and it is possible that aseismic processes accommodate reverse-slip on this part of the plate boundary.

Assuming that our estimates of slip are representative of slip throughout the plate boundary (≈20 m for the region from Aceh to the Nicobars, and ≈7 m for the Andaman group) we calculate a moment magnitude of Mw=9.1 for the southern 650 x120 km^2 of the rupture, and Mw=8.9 for the northern 650x160 km^2. These estimates are based on sparse, and in places, conflicting data for uplift and subsidence as noted in this article, and do not account for the strike-slip component of faulting in 2004, however, the total, Mw=9.2, exceeds the NEIC estimate of Mw=9.0 but approaches the magnitude of Mw=9.3 estimated from normal modes (Stein and Okal, 2005).

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