Chapter-5
Chronology of major terrace forming events in the Andaman Islands during the last 40 kyrs

5.1 Introduction

Subduction zones are known for their high seismicity, which varies both spatially and temporally. Seismic activities in such zones are result of movements along numerous thrusts faults, including the decollement, present between the trench and the end of the forearc. The movements along these faults play an important role in the development of various morphological features on both subducting and overriding plates (Ruff and Kanamori, 1980; Kanamori and McNally, 1982; Byrne et al., 1992; Nanayama et al., 2003). The recent 2004 earthquake of Sumatra and 2011 earthquake of Japan were results of such type of movements along the faults. These earthquakes and related tsunamis, which caused large-scale devastations, will remain in our memories for a very long time. Such types of events reaffirm the need of thorough mapping of faults and understanding of tectonic processes those lead to such catastrophic natural events. The main difficulty in studying such faults in subduction zones is that these rarely have surface expressions and therefore, are inaccessible for direct geological investigations. In such a scenario, the only way one can infer about the tectono-geomorphic evolution of such regions, is by studying the displacements along secondary or tertiary faults as recorded in the resultant morphology on surface.

Andaman subduction zone is a part of the same Sunda-Banda subduction zone, which has witnessed some of the high magnitude earthquakes (M > 7.0) of recent times including the 2004 Sumatran earthquake of M9.1. The Andaman and Nicobar Islands, represents the outer-forearc portion of the subduction zone, provide a unique opportunity to study and understand many of the tectono-geomorphic features developed in a convergent margin. These islands are structurally made up of several eastward dipping thrust and strike-slip faults those run parallel to the Andaman trench and large scale folds (Fig. 5.1a) (Allen et al., 2007). However, except for some preliminary work (Roy and Chopra, 1987; Roy, 1992) little is known about seismicity of these faults. As per current understanding some of these faults were responsible for those changed the surface morphology of the islands, details of which are summarized in Rajendran et al. (2007) and are shown in Fig. 5.1(b).

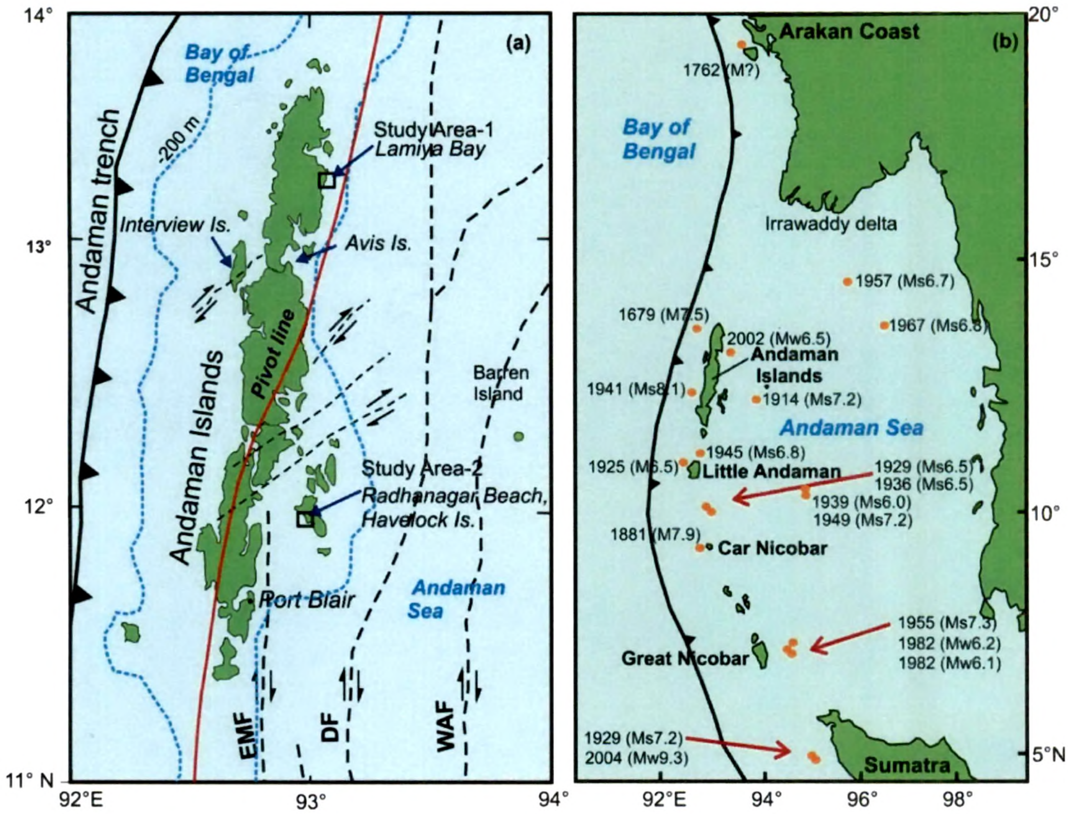

Fig. 5.1: (a) Map of the Andaman Islands showing the study areas-1 and 2 which are Lamiya Bay in North Andaman and Radhanagar Beach on Havelock Island and major faults, EMF- East Margin Fault; DF- Diligent Fault; WAF- West Andaman Fault (modified after Curray 2005). The solid red line is pivot line of Meltzner et al., (2006); (b) Map showing known historic large magnitude (M>6.0) earthquakes in the Andaman region with their magnitudes (data from Rajendran et al., 2007). Ms: surface wave magnitude; Mw: moment magnitude scale.

The record shows that many a times these events have resulted in upliftment and/or subsidence of land in the forearc region (Oldham, 1883; Jhingran, 1953; Rajendran et al., 2007). While the chronology of most historical events has been established, that for the prehistoric events remains largely unknown. Considering that such events are important in the study of geomorphology of this region it is imperative that their ages are accurately determined. In such an effort, we have studied morphological changes on the coastlines of the North Andaman and Havelock Islands (Fig. 5.1a) and dated dead coral reefs from raised marine coastal terraces. Since these terraces are local in nature (100 - 200 m in length) and have variable heights on smooth coastlines, we believe that they are generated by tectonic forces, and not by the changes in the sea level. It is also possible that some of these terraces could have formed by multiple uplift events; in such a scenario the determined age would likely to represent the oldest event. By comparing our results from the above two localities with the existing information on other places in the Andaman and Nicobar Islands (Kayanne et al., 2005; Rajendran et al., 2007 and 2008; Malik et al., 2011) we have made an attempt to reconstruct the seismic history of the region during the last ~40 kyrs. Corals are sensitive to many oceanographic parameters such as temperature, salinity and pH and therefore, the causal link between the death of coral reefs on the raised terraces and the upliftment events may not be unequivocal. However, the fact that we have been able to correlate the formation of terraces studied in this work with several others in the region makes our inferences robust.

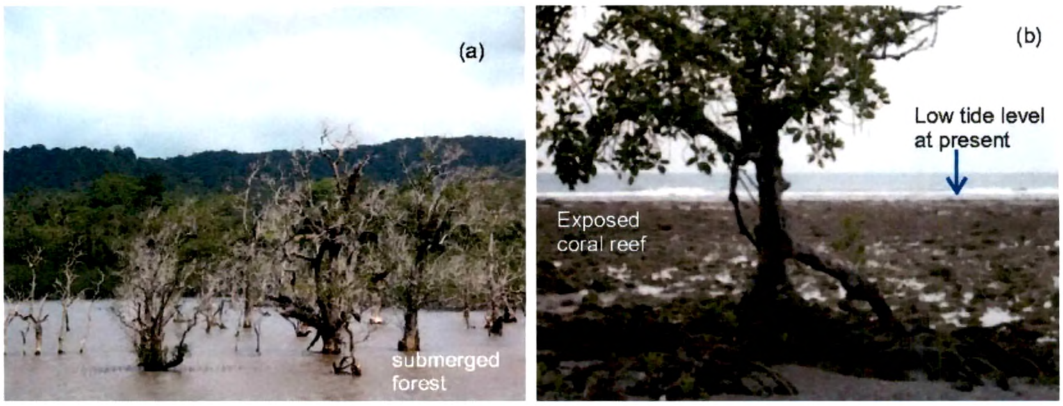

Fig. 5.2: Photographs showing (a) submerged forest at Chidiyatapu, South Andaman after 2004 earthquake and tsunami (b) uplifted beach with dead coral reef at Kalipur in North Andaman. The arrow shows present level of sea during low tide.

The M9.1 Sumatran earthquake of 2004 resulted in major morphological changes in the Andaman and Nicobar islands and provided an opportunity to observe the effects of high magnitude earthquakes on the geometry of accretionary wedge (Rajendran et al., 2007). Many studies reported upliftment (1-2 m) in the Middle and North Andaman Islands, and subsidence in the south (Kayanne et al., 2005; Malik and Murty, 2005; Thakkar, 2005; Ramesh et al., 2006; Rajendran et al., 2007) (Fig. 5.2a & b). Rajendran et al., (2007) give a summary of field observations on coseismic changes observable from coastal morphology. The upliftments are manifested in form of elevated shorelines/coral beds/mangrove swamps. Som et al. (2009) calculated an uplift of 31.21 cm from coral microatolls on Kalipur Beach, which is consistent with the recorded uplift elsewhere in North and Middle Andaman Islands (Kayanne et al., 2007; Rajendran et al., 2007; Ray and Acharya, 2007). We too have observed these raised coral microatolls in Kalipur beach during our field trips in 2009. Interestingly, according to the residents of Kalipur these raised terraces were present even before the 2004 earthquake, which led us to suspect that either the inferences of Som et al (2009) were erroneous or that these terraces had seen multiple upliftment events. Further inland, many such dead coral reefs have also been found to form the terraces, on which thick vegetation has grown. Similarly, we have observed exposed coral reefs along the west coast of Havelock Island (Fig. 5.1a), which prior to this work, have not been linked to any past seismic event.

5.2 Coastal Terraces of Andaman and Nicobar Islands

The morphological changes that occurred during the great 2004 earthquake inspired many workers to search for evidences of such events in the geologic records of Andaman and Nicobar islands. In such an effort, Rajendran et al. (2007) identified numerous steplike older terraces in many islands in the Andaman and Nicobar along several profiles. They studied terraces in Interview Island, Avis Island, Car Nicobar and in the east coast of Hut Bay (Rajendran et al., 2007 and 2008). Based on C-14 ages of corals, shells, dead tree trunks from raised terraces and shallow pits it was observed that the Andaman region had experienced many major seismic events during the last 40 kyrs. The oldest evidence of upliftment comes from Car Nicobar Island where the topmost coral terrace is dated to ~cal yr BP 41,000. Evidences for younger upliftments come from Interview Island, Avis Island and Hut Bay (Table 5.1). Earthquakes not only resulted in upliftment of coastlines, but also subsidence, which is mainly observed in coastline surrounding Port Blair (Fig. 5.2a) (Rajendran et al., 2007; Table 5.1). Studying the coastal stratigraphy in excavated trenches near Port Blair, Malik et al. (2011) found evidences for two major earthquakes during the last 400 years with one of them being associated with a tsunami akin to that occurred in 2004. On basis of the tectonic history of the region, it is quite reasonable to assume that similar episodes, in the past, might have caused upliftment of coral reefs and development of coastal terraces observed on the two localities studied in this work (Fig. 5.1).

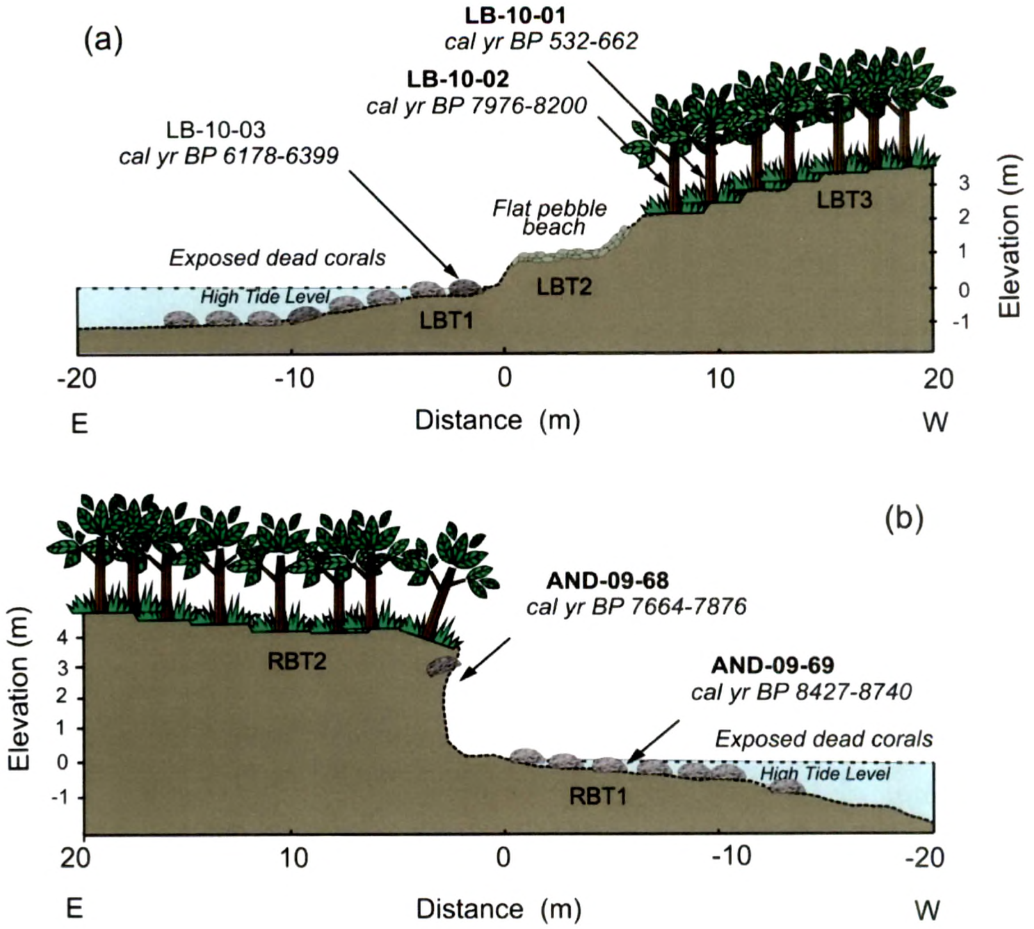

Fig. 5.3: Elevation profiles of coral terraces showing sample locations and calibrated radiocarbon ages (a) East coast of Lamiya Bay, North Andaman Island (b) West coast of Radhanagar Beach, Havelock Island. Note that the profiles start from high-tide levels.

In the entire chain of islands of Andaman and Nicobar, modern alluvium, raised beaches, coastal terraces, wave cut platforms, coral rags, calcareous tufa, and shelly limestones have been reported from the coastlines (Rajshekhar and Reddy, 2003). In Chapter-2 we have characterized these under the Pleistocene-Holocene sediment deposits of the Nicobar Group. For the present work, we collected coral fragments from exposed reefs on the coastal terraces of Lamiya Bay at Kalipur in the North Andaman and from raised coral reefs at Radhanagar Beach of Havelock Island (Study Area-1 & 2, respectively; Fig. 5.1). Lamiya Bay, which forms a part of the eastern coastline of North Andaman, has well-preserved coastal terraces that we named as LBT1, LBT2, and LBT3 in order of their heights from the high tide water line (Fig. 5.3a; Fig. 5.4a & b). The terrace LBT3 is about 2.5m above the high tide water line and 8m inland (Fig.

3a), and is covered with thick vegetation. It appeared to be the oldest terrace at this location. LBT2 is a flat pebble beach approximately 2m wide and about 1m above the high tide water line. LBT1 is made up of dead coral microatolls, and is exposed in the intertidal zone (10-100m wide). Further inland beyond LBT3, rocks of the Ophiolite Group and sedimentary formations of the Mithakhari and the Andaman Flysch groups are exposed. Our study area in the North Andaman was little affected by the 2004 tsunami, and hence there has been no report of any tsunami deposits along this coast. However, according to some studies the dead coral reef of LBT1 possibly represents an upliftment related to the December 26, 2004 M9.1 Sumatran earthquake (Som et al., 2009). To establish the chronology of these terraces, we collected three coral samples (LB-10-01, LB-10-02 and LB-10-03) for radiocarbon dating. These coral samples represent the dead reefs present on the terraces, except for LB-10-01 which was from a large coral boulder located on LBT3 and appeared to have been deposited by a large wave/tide action or a tsunami.

Samples of coral fragments were also collected from a beach and an elevated terrace, at Radhanagar, on the west coast of Havelock (Fig. 5.1). Two coral terraces RBT1 and RBT2 were identified at Radhanagar (Fig. 5.3b, 5.4c & d). Unlike the terraces of Lamiya Bay, at Radhanagar the two terraces are separated by an almost vertical fall of ~3.5 m (Fig. 5.3b, 4c). RBT2 is composed of alternating layers of yellowish sandy silt and foraminiferal limestone. These rock formations belong to the Archipelago Group, above which beds of a dead coral reef are present (Fig. 5.4c). A sample of this dead coral was taken for radiocarbon dating (AND-09-68), from about 2.2m above the high tide water line. Modern soil and vegetation occupy the terrace RBT2 beyond ~20cm from the dead reef line.

5.3 Results and Discussion

The calibrated ages obtained from two dated sections are given in Table 5.1. The dating results are also presented in Fig. 5.3(a) and (b) while interpretating these calibrated ages we have used modes of the calibrated probability density curve, rounded off to the nearest hundred. At Radhanagar beach, Havelock Island (Fig. 5.3b), the terrace RBT2 is dated to ~cal yr BP 7800, while the terrace RBT1, that occurs about 2m below RBT2, is dated to an older age of ~cal yr BP 8600. At Lamiya Bay, North Andaman

(Fig. 5.3a) corals from the lowermost terrace LBT1 (Fig. 5.3a and 5.4b) yielded an age of ~cal yr BP 6300. Interestingly, this is the same terrace that is believed to have been formed during the earthquake of December 26, 2004 exposing the coral reef (e.g., Som et al., 2009). The terrace LBT2 (Fig. 5.3a) could not be dated, as it did not contain any dateable material. Two samples from the uppermost terrace (LBT3), within the forest, at a height of 2.5m above the high tide water line yielded ages of ~cal BP yr 8100 and ~cal yr BP 500 (Fig. 5.3a). Repeated analysis of another fraction of the latter yielded an age of ~cal yr BP 600. The presence of much younger coral on the terrace that appears to be at least 8100 years old is quite perplexing.

Fig. 5.4: Photographs of the studied terraces: (a) & (b) LBT1, LBT2 and LBT3 at Lamiya Bay, North Andaman (c) & (d) RBT2 and RBT1 at Radhanagar Beach, Havelock Island. The coral sample at Havelock (c) was collected from a unit exposed above the dotted green line, below which lies the calcareous formation of Archipelago Group. The dead corals on the beach terrace RBT1 (d) are exposed in the intertidal zone.

Although, development of coastal terraces is generally caused by eustatic sea level changes, we can rule out these effects on the terraces used in this study, since these belong to the Holocene, the time period when sea level change (if any) was insignificant (e.g. Fleming et al., 1998; Woodroffe and Horton, 2005). Also during the last 40 kyrs, the global sea level has been lower than the present level except for some local fluctuations (Fleming et al., 1998; Woodroffe and Horton, 2005). Because our study region is tectonically very active, we believe that the observed uplifted coralline coastal terraces are largely due to upliftment caused by seismicity and not by variability in the sea level.

RBT2 at Havelock and LBT3 at Lamiya Bay are elevated to almost identical heights and have same age (within error) even though they are 135km apart. Both these terraces are co relatable to uplifted terraces of similar age from Little Andaman and Interview Island (Table 5.1). The vertical movements of terraces usually occur along fault planes, and a large part of the coastline of the Andaman and Nicobar Islands is deformed by numerous such faults. Pal et al. (2003) reported N-S trending thrust faults in North Andaman and Curray (2005) reported a fault along the west coast of Havelock Island. It appears that LBT3 and RBT2 (Fig. 5.3) have been developed due to reactivation of these faults, whereas RBT1 and LBT1 probably owe their origin to a couple of blind faults. There is no information on uplift/subsidence caused by these faults in literature, however there have been reports of several seismic events in this region that appear to have concentrated around these faults (USGS, see website: http://earthquake.usgs.gov/earthquakes/ eqarchives/epic/. Som et al. (2009) studied uplifted and highly eroded coral beds covered with moss and algae, at Hut Bay, Little Andaman and inferred that these corals were already dead before their upliftment by the 2004 earthquake. He also observed signatures of palaeoseismicity in the coral reefs of North Andaman and Little Andaman and suggested that the coral reefs of the Andaman and Nicobar Islands have been tectonically disturbed by several cycles of seismicity. The same might be true at our studied site also and perhaps, the corals from our terraces LBT1, LBT3 at Kalipur beach and RBT1, RBT2 at Radhanagar beach, Havelock were already dead due to upliftment caused by past tectonic events between 6 to 9 kyrs BP and further uplifted to current heights by later tectonic events.

Table 5.1: Radiocarbon ages of fossil coral terraces of the Andaman and Nicobar Islands.

Sample names	^{14}C age (yrs BP) ± 1σ	Calendar age[c] (yrs BP)±1σ	Elevation (m) asl	Material dated
Uplift				
Interview Island				
IN/TOP/A	30,880 ±300	34925±239	50	Coral fragments, R(2008)
IN/TOP/B	25021±280	29397±412	50	Coral fragments, R(2008)
T2/IN/D/P1/A	22,890 ±120	27204±338	26	Coral fragments, R(2008)
T3/IN/D/P1/A	19,894±100	23247±241	18	Coral fragments, R(2008)
T3/IN/D/P1/C	19,304±220	22588±364	18	Coral fragments, R(2008)
T3/IN/D/P1/D	16,849 ±130	19623±194	13	Coral fragments, R(2008)
IN/St/D	6977±85	7479±78	7	Coral fragments, R(2008)
Hut Bay (Little Andaman)				
HB/L2/CP	3286±100	7287±133	4	Coral fragments, R(2008)
T2(B)/HUT/D/P4	6775±135	3105±142	4.5	Coral fragments, R(2008)
T2/HUT/D/P1	3661±133	3551±168	2.8	Coral fragments, R(2008)
T2(A)/HUT/D/P3	3123±47	2881±80	2.8	Coral fragments, R(2008)
T2/HUT/D/P5	2295±62	1897±87	2	Coral fragments, R(2008)
T2(A)/HUT/D/P1	1904±61	1437±78	2	Coral fragments, R(2008)
T3/HAR/HUT	1843±77	598 ±71	0	Coral fragments, R(2008)
HB/L1/CP	1042±90	1380±87	1.7	Coral fragments, R(2008)
Avis Island				
AV/T2/E	2450±84	2081±123	2.5	Coral fragments, R(2008)
AV/T2/B	1942±114	1477±133	2.5	Shells, R(2008)
AV/T2/C	1678±89	1215±97	2.5	Shells, R(2008)
AV/T2/A	1628±94	1168±101	2.5	Coral fragments, R(2008)
AV/T2/D2	1364±126	898±137	2.2	Coral fragments, R(2008)
AV/T2/E	1319±91	839±98	2	Coral fragments, R(2008)
AV/T2/D	1172±42	706±48	1.8	Coral fragments, R(2008)
AV/T1/PB	967±104	562±80	1.5	Coral fragments, R(2008)
AV/T1/A	906±108	522±95	1.5	Shells, R(2008)
AV/PD/LT/1	623±78	242±113	0.75	Coral fragments, R(2008)
Lamiya Bay (North Andaman)				
LB-10-01*	870±80	476 ±78	2.5	Coral fragments
LB-10-01* (Repeat)	1040±80	599 ±65	2.5	Coral fragments
LB-10-02*	7650±100	8086±115	1.8	Coral fragments
LB-10-03*	5880±100	6290 ±106	0.6	Coral fragments
Havelock Island				
AND-09-68	7320±100	7774±106	2.2	Coral fragments
AND-09-69	8120±110	8585±155	0.3	Coral fragments
Car Nicobar				
CN/TC/1	5420±80	5786±97	13	Coral fragments, R(2008)
CN/SW/1	2750±130	2490±166		Coral fragments, R(2008)
CN/SA/1	35,910±1040	40471±1059		Coral fragments, R(2008)
Subsidence/Palaeotsunami				
Port Blair (South Andaman)				
RG/Wood/1	740±100	666±104		Wood, R(2007)
	5903±35	6722±49		Plant debris, R(2007)
	6283±25	6720±56		Shell, R(2007)
	3070±120	3258±178		Peat, R(2007)
RG/Peat/2	4320±130	4958±309		Peat, R(2007)
Hut Bay (Little Andaman)				
GS/HUT/OT	753±35	378±56		Shell, R(2007)
CS/HUT/OT	5623±35	6006±75		Coral fragments, R(2007)

Table 5.1: continued

Sample names	^{14}C age (yrs BP) ± 1σ	Calendar age[c] (yrs BP)±1σ	Elevation (m) asl	Material dated
East coast India				
MB/AR/UL	955 ±30	862±62		Charcoal, R(2006)
MB/T1/BL	1581±35	1468±51		Charcoal, R(2006)
MB/AR/BL	1674±30	1573±34		Charcoal, R(2006)
Sumatra				
B	550-660	605±55		M (2008)
C	960-1170	1065±105		M (2008)
Thailand				
B	500-650	575±75		J (2008)
C	2200-2400	2300±100		J (2008)
Red Skin Island				
Hv 25468	840 ± 23	466±32	?0.3	Shell, K (2010)
Hv 25465	2955 ± 40	2726±51	-0.9	Shell, K (2010)
Hv 25466	3,220 ± 23	3015±70	-1.3	Organic material, K (2010)
Hv 25467	2,935 ± 40	2691±74	-1.3	Shell, K (2010)
North Cinque Island				
Hv 25462	710 ± 23	345±49	?0.5 asl	Shells, corals, K (2010)
Hv 25460	810 ± 43	441±54	?2.6 asl	Corals, K (2010)
Hv 25471	695 ± 23	331±49	?2.6 asl	Conch, K (2010)
Hv 25591	1,740 ± 23	1283±39	?2.3 asl	Corals, K (2010)
Liquification feature, Diglipur (North Andaman)				
MN/Sill1/S3	1050±100	934±135		Peat, R(2007)

asl: Above mean Sea Level, 'c' stands for calibrated ^{14}C ages, Data with asterick '*' are results from this study while other data are **R (2006)**: Rajendran et al. (2006); **R (2007)**: Rajendran et al. (2007); **R (2008)**: Rajendran et al. (2008); **M (2008)**: Monecke et al. (2008); **J (2008)**: Janakaew et al. 2008; **K (2010)**: Kunz et al. (2010). All the data used in this study are calibrated using radiocarbon calibration program CALIB 6.0 (Hughen et al., 2004).

The presence of ~500 (or ~600) cal yr BP old coral on ~8100 cal yr BP old terrace cannot be explained by an earthquake or changes in the sea level. Its occurrence on thickly vegetated terrace in form of a large boulder of coral made us believe that it was deposited by a tsunami. Several recent studies in the Andaman and Nicobar Islands have been able to discern evidences for tsunamigenic earthquakes in the recent history (Rajendran et al., 2006, 2007 and 2008; Kunz et al., 2010; Malik et al., 2011). From the existing record of upliftment, subsidence and palaeotsunami in this region (Table 5.1), we have observed that there was indeed an earthquake at ~500 (or ~600) cal yr BP and that it affected numerous coastlines in the Andaman Sea. We believe that this earthquake generated a large tsunami that was responsible for destruction of coral reefs in the Andamans.

Although a large portion of the Andaman Islands show evidences for coseismic emergence caused by the 2004 earthquake, Port Blair, located on the eastern margin of South Andaman, subsided by ~1 m (e.g., Rajendran et al., 2007; Malik et al., 2011). Earlier studies on dead mangroves and peat layers in core samples from sites near Port Blair have identified four events of past submergence/subsidence at ~cal yr BP 700, 3300, 5000 and 6700 (Table 5.1). These results suggest that there have been overall subsidence of South Andaman Island during the last 6700 years as a result of seismic activity. Meltzner et al. (2006) defined a pivot line separating the areas of coseismic uplift and subsidence those resulted from the 2004 earthquake (Fig. 5.1a.). On the basis of Geological and Historical data and data from the 2004 earthquake we clearly suggest that most of the past upliftment/subsidence events took place along the same ''pivot line'' indicating continuous subsidence of parts of South Andaman Island and upliftment of parts of North and Middle Andaman Islands.

The age data of seismic events in the Andaman region, as inferred from uplift, subsidence and tsunami records, are summarized in stacked histogram and relative probability plots (Fig. 5.5). All the probabilities obtained from calibrated radiocarbon ages, given in the Table 5.1, have been summed up and normalized with the total number of samples as per the procedure described in CALIB 6.1.1 (Reimer et al., 2009). The resultant curve in Fig. 5.5b represents relative probability distribution of all the events, with total area under the curve as unity. From the probability distribution we recognize 14 major events of seismicity at ~40.5, ~35.5, ~27.3, ~23.3, ~19.5, ~8.5, ~7.5, ~6.0, ~6.7, ~4.9, ~3.4, ~2.7, ~1.1 and 0.6 cal kyr BP. There is a gap in the dataset between ~19.5 cal kyr BP to ~8.5 cal kyrs BP, which could be either due to lack of data or a result of absence of any major seismic event during this period. The frequency of major seismicity appears to have revived at ~8.5 cal kyr BP and continued to increase through to present. The increased activity probably caused the major upliftment of terraces in Lamiya Bay, Havelock Island, Interview Island and Hut Bay. The reason for absence of any record of subsidence older than 7 cal kyr BP could simply be lack of data owing to difficulty in identification of evidences. Similarly, higher frequency observed for the younger events (events 13 and 14 in Fig. 5.5), could be a result of their proper preservation.

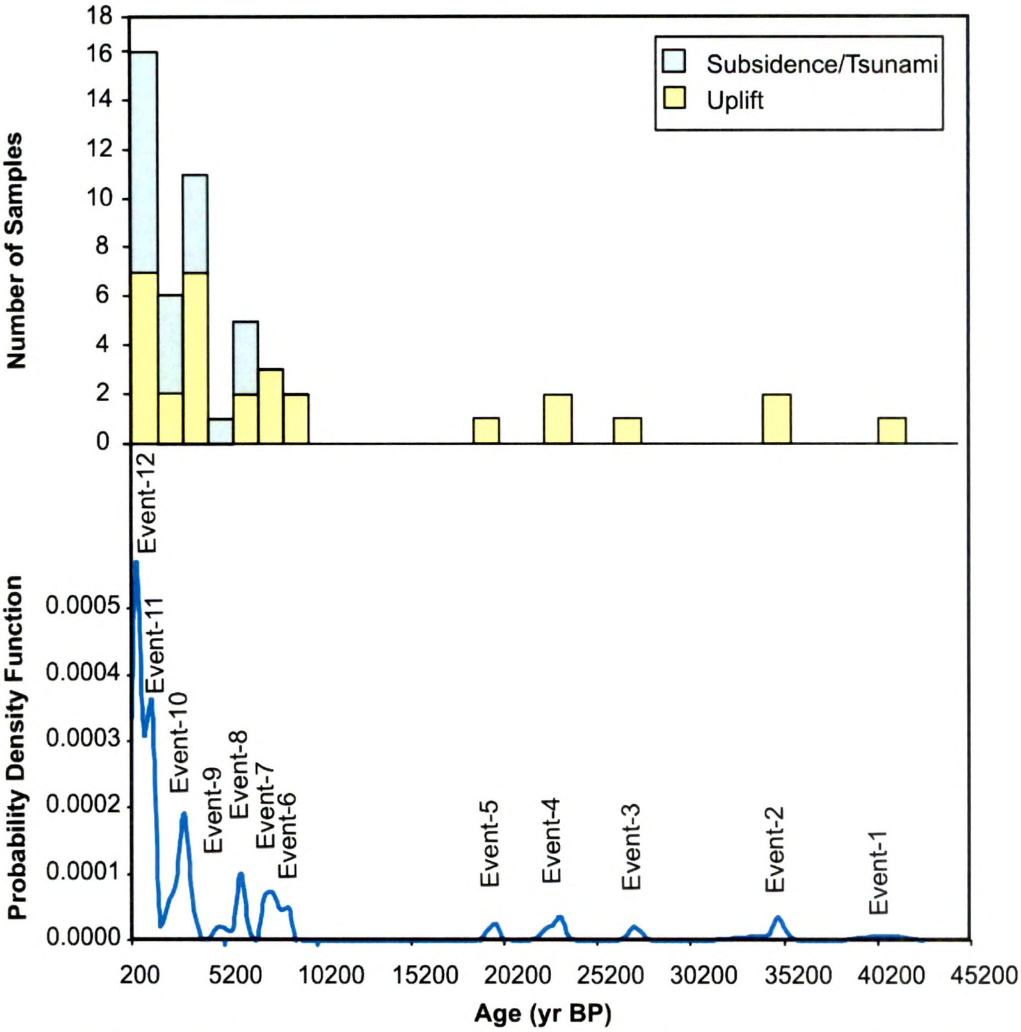

Fig. 5.5: (a) Stacked histogram of number of uplift and subsidence events as afunction of time. (b) Relative probability density plot of the same events.

The evidences of tsunamis/earthquakes from Sumatra, Thailand, east coast of India and Andaman Islands although correlated tentatively, suggest that increased activity can lead to destructive tsunamis in century scale intervals. Such recurrence adds to the challenge of preparing communities along the northern Indian Ocean shorelines for future. Keeping in mind the destructions caused by December 26, 2004 earthquake and tsunami, we need to further refine our results and search for evidences of past tsunamis/earthquakes elsewhere along the coastal areas and establish chronology of past events.