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Nature of Tsunami and Paleo Tsunami Deposits of South Andaman

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ABSTRACT

This paper documents the locations and nature of Tsunamigenic sediments, deposited by the great Indian Ocean Tsunami of 26th December, 2004, in south Andaman Island, India. The sediments of 20 to 40 cm thickness can be located in several isolated coastal areas that suffered subsidence and water logging after the earthquake event of 9.3 Richter magnitudes and related Tsunami. These sediments have a distinct sedimentological and paleontological character of a mix of black colored humic mud-fine sand with shell fragments and/or Coral boulders with reworked foraminifera. Similar anomalous deposits can be located further down in the sediment column of the south Andaman coast which has been interpreted as Paleo Tsunami deposits at Therur, Corbyn's Cove, Sippighat, Collinpur and Wandoor areas. Prevalence of shallow water species of benthic foraminifera in tsunamigenic sediments indicates that tsunami entrained sediment from shallow litoral to naritic bathymetry. The study may help in locating more Paleo Tsunami deposits in this area further down the sediment column of the coast.
KEYWORDS : 2004 Tsunami · Grain size · Foraminifera· Anomalous horizon · Organic carbon.

INTRODUCTION

Coastal flooding after Mega Tsunami events are not necessarily documented by deposition of thick sedimentary package on the coast. Neither they are evenly distributed or of similar nature. They vary in their sedimentary or paleontological characterizations depending on provenance of shallow shelfal areas, amount of transport suffered before deposition, subsidence or uplift of the site of deposition and later reworking.

However often they have some characteristic, which enables us to distinguish them from pre and post Tsunami deposits. If such anomalous characteristic typical to a known Tsunami deposit can be established in a coastal area, finding such anomalous deposits may help us to locate Paleo Tsunami horizons of recent past. One such study has been taken up at the behest of INCOIS, Govt. of India to identify the nature of Tsunami and Paleo Tsunami deposits from coastal areas of India in South Andaman Island, as the present study area as it was severely affected by Great Asian Tsunami of 2004 and has some historic record of previous Tsunami events [1].

The tsunami on 26th December, 2004 in the Indian Ocean severely affected parts of the eastern coast areas of peninsular India and Andaman–Nicobar Islands [2]. Extreme devastation along the coastal tract of Andaman and Nicobar Island and loss of human life and infra-structure have been reported [3]. Among the Andaman group of Islands, South Andaman is the major inhabited Island. The large cultivated areas in South Andaman have experienced severe damage during the Tsunami event [4]. According to an eye witness in South Andaman, the tsunamigenic sediment of 2004 was a foul smelling sticky black mud with itchy sensation on the skin. Several areas of South Andaman Island were flooded by this mud carried by the Tsunami waves. The entire Andaman and Nicobar group of Islands is tectonically quite active because of its proximity to the Sunda Trench. With Tsunami generating earthquake, several places of South Andaman suffered few meters of subsidence. It was recorded that parts of the northern and eastern coast of Andaman were up-thrown while it was downthrown up to a maximum of 1 m at the southern and western part [5]. Even after several years, these areas, which preserved the deposits, remained waterlogged. Similar water logging was also observed in numerous areas in Japan after the mega tsunami event caused by the Tohoku earthquake of 11th March, 2011 [6]. The low lying agricultural field near estuaries and inlets have been turned barren after the 2004 subsided Tsunami inundation and water logging. Subsided patches of Sippighat, Wandoor, Mithakari and Therur were found flooded by tidal water. The tsunami related anomalous deposits thus can be found to be preserved in subsided low lying areas like beach back swamp, tidal inlets or low lying agricultural fields. They have been mostly eroded and reworked in the beach areas. Using the nature of present tsunami deposits of a particular area as a 'key', the study envisages locating similar anomalous zones at much deeper depth, which may be considered as Paleo Tsunami horizons.

STUDY AREA

The study has been undertaken in mainly tsunami affected areas in South Andaman, which are rarely visited by high frequencies storm surges and tropical cyclones. It is located between 11°47'30" N to 11°26'30" N and

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92°32'E to 92°46' E. A Tsunami inundation map has been generated (Fig. 1) showing water logged areas below the elevation of four meters. The tsunamigenic sediments were collected from such areas at Collinpur, Therur, Mithakari, Sippighat or Corbyn's Cove etc. The tsunamigenic black mud was found to be preserved at low lying agricultural field or at inland regions where they are connected with open sea by narrow inlets.

MATERIALS AND METHODS

The sediment samples were collected by trenching and coring from surface up to a depth of 1.5 m at selected localities. The trenches parallel and perpendicular to the coastal tract have excavated up to 1m to study variation of nature and thickness of the anomalous layers. The individual core samples and trench sediment were divided into several zones on the basis of grain size, composition, color variation, microfossil assemblages and organic carbon (C_{org}) content. For sedimentological analysis a small portion of the sample was kept in distilled water overnight. The wet sample was mixed up with hydrogen peroxide solution (80 % purified) and kept for another night to remove the organic matter present. Consequently the sample was mixed with Ammonium Solution. The sediment sample was then dried in an oven. The bulk weight of the total sample was recorded for sieving and settling method. The coarse fraction (+230 Ø) and finer fraction (-230 Ø) was separated by Wet sieving method. The sieving method was carried out in ASTM at Ø interval (14, 18, 35, 45, 60, 80, 120, 170, 230 and Bottom) [7].Statistical analysis of the grain size distribution like skewness, kurtosis and standard deviation were also used to distinguish the Tsunami deposits from the pre and post Tsunami deposits. The weight percentage and cumulative weight percentage of all the fractions of the sediments were calculated. Textural attributes of sediments and sedimentary rocks namely mean (Mz), standard deviation (σ1), skewness (SkI) and kurtosis (KG) have been found to be helpful for understanding the depositional environments of sediments and sedimentary rocks [8]. The foraminifera specimens were picked by a moist brush from the washed samples and kept on micro-paleontological slides. The specimens were identified by reflected-light microscope (Model No. Leica S8 APO Steadio Zoom Binocular Microscope) and Scanning Electron Microscope (SEM) (100x X 200x), on sputter coated gold-palladium mounts. The taxa of foraminifera were identified according to Loeblich and Tappan [9], Barker [10], Horton and Edwards [11] and Kathal [12]. The Tsunami deposits could also be identified visually by their content of broken shell fragments, coral boulders, granules even cloths and often ropes embedded in fine sediments. The C_{org} content is determined by Walkley and Black method [13]. Radio carbon dating has been employed to ascertain relative age of the bulk sediment layers, in absence of any authigenic specimens.

Table 1. Results of grain size analysis for sediment samples collected from several Tsunami affected areas

Station	Mz	σ1	SkI	KG
Tsunami Deposit			SkI	
COLLINPUR				
CLP-1	2.6132 to 2.8914	0.6195 to 0.7850		1.2903 to 1.8590
CLP-3	2.0628	1.0515	-0.2603 to 0.0384	1.5003
MITHAKARI			-0.2942	
MKR-1	6.6133 to 8.2437	2.8059 to 4.8663		0.8064 to 1.0567
MKR-2	7.8594	3.1525	-0.0413 to 0.0673	0.7664
SIPPIGHAT			-0.2228	
SRG-1	4.8753	3.685		0.8986
WANDOOR			-0.2770	
WT-1	2.4522	0.6488		1.1356
WT-3	2.7874	1.1084	0.0517	1.0367
Paleo Tsunami Deposit I			-0.0585	
COLLINPUR				
CLP-1	2.3761 to 2.4082	0.5745 to 0.6099		0.8857 to 1.1034
CLP-2	4.6763	1.9594	-0.1807 to 0.0188	1.0744
CLP-3	3.5444	1.0440	-0.5895	1.6270
THERUR			0.4433	
THR-1	-0.1384	6.9989		1.0926
MITHAKARI			-0.5910	
MKR-3	3.8145	2.8966		1.2931
SIPPIGHAT			0.4698	
SPG-1	6.3732	8.9174		3.3548
CORBYNS' COVE			-0.3804	
CRVCV-1	1.1095	2.3438		1.2788
CRVCV-2	-12.7663	18.1731	-0.3740	1.0654
WANDOOR			-0.4942	
WT-1	2.3215	0.8976		1.6109
WT-3	3.0825	0.7156	-0.1345	0.8442
WDR-3	3.2650	1.9055	-0.0735	2.0331
WANDOOR			0.2589	
WT-1	2.3215	0.8976	-0.1345	1.6109
Paleo Tsunami Deposit II				
COLLINPUR				

RESULTS

The various textural parameters of sediment samples as obtained by Statistical analysis and graphic method has been enlisted in Table 1 above.

Collinpur

Well preserved Tsunami and Paleo Tsunami deposits were observed at beach back swamp region at Collinpur. The 21 cm thick 2004 Tsunami deposit was found below 4 cm of the soil horizon. The lower part (18.5-25 cm) of this deposit is enriched in black colored organic mud-fine sand (2.6 Ø) with shell fragments and reworked foraminifera. It grades upward with yellowish sand with reworked and broken benthic foraminifera. Two anomalous horizons were found at 47 to 71 cm and 107 to 126.4 cm again which may be recognized as Paleo Tsunami deposit because of their similarity with Tsunami deposit of 2004 found above. The Paleo Tsunami I horizon (47 to 71 cm) consists of Coral boulders (Fig. 2), cloths, ropes and they were found embedded in organic matter enriched fine sand (2.4 Ø). The Paleo Tsunami II horizon (107 to 126.4 cm) consists of black mud-fine sand with few coral fragments and reworked foraminifera. This zone lies above a silica sand layer devoid of shell fragments and foraminifera.

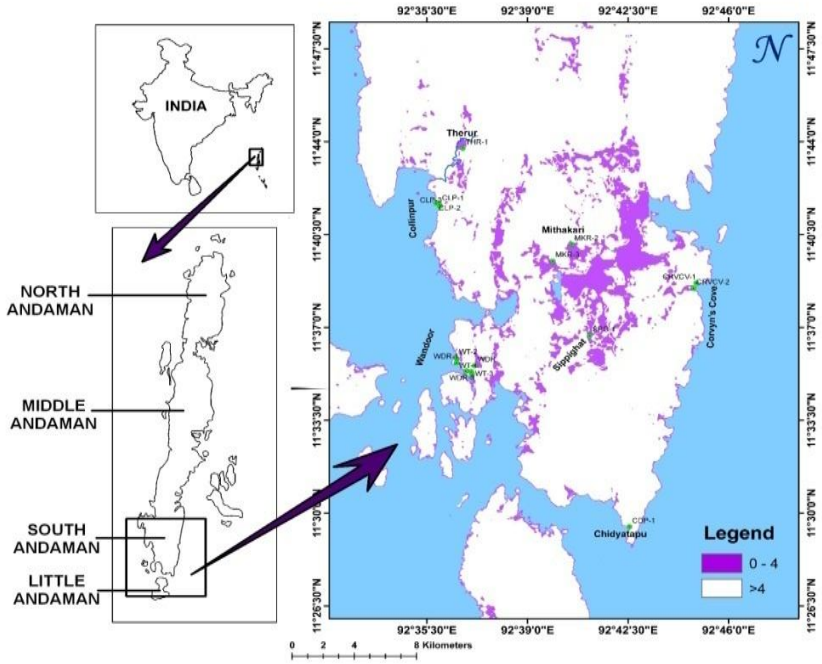

Fig. 1. Map showing probable Tsunami (2004) affected areas in South Andaman (<4m from sea level) (modified after Velmurugan et al.) [4] (Data Source: ASTER GDEM).

Fig. 2. Coral boulders found in Tsunami Deposit at Collinpur

Therur

The black colored mud deposited by 2004 Tsunami was found 1cm below the soil horizon in Therur. It was deposited above a moderately well sorted medium silty layer (5.28 Ø). The thickness of Tsunami deposit is about 8 cm. The imprint of an anomalous Paleo Tsunamic horizon was observed below 20 cm. It is a comparatively thick horizon (about 47 to 50 cm) and occurring over moderately well sorted coarse silt (4.41 Ø) with an erosional base (Fig. 3). The different phases of Tsunami waves are also prominent at this layer. The lower part of this horizon consists of rip up clasts of extremely poorly sorted, strongly coarse skewed granules (-0.13 Ø) with minor amount of reworked and abraded foraminifera. The upper part of this Paleo Tsunami horizon consists of dispersed rootlets and foraminifera like *Pararotalia* sp., *Calcarina* sp. etc.

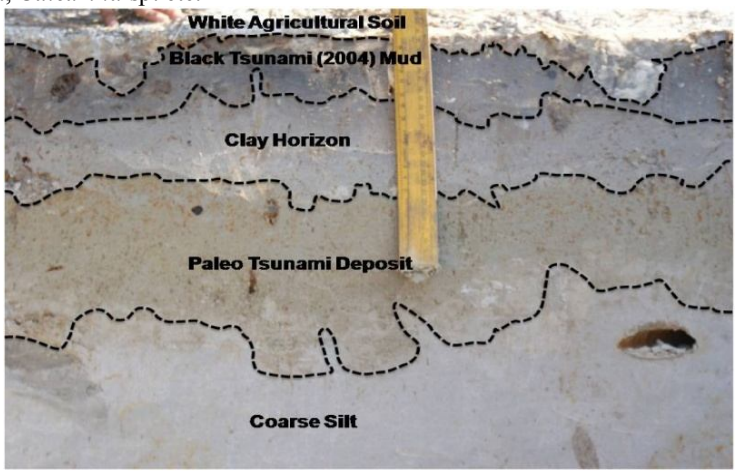

Fig. 3. Tsunami (2004) and Paleo Tsunami Deposit of Black Mud at Theru

Fig. 4. Black mud exposed at places over wide areas at Mithakari village

Mithakari

The imprint of 2004 Tsunami deposit was observed at the agricultural field in Mithakari village (Fig. 4). It is yellowish grey coloured, platykurtic very fine silt. A 55 cm thick tsunami deposit has been found below the relocated soil horizon transported to reclaim the low lying area for agriculture (Fig. 5) after the tsunami. The tsunamigenic sediments are mainly dark brown to black coloured mud (C_{org} content 1.32 %). The upper 20 cm of this deposit consists of extremely poorly sorted; coarse skewed very fine silt (7.05 Ø) with abundant coral boulders (Fig. 6) and pelecypod shells. The lower part of this deposit is comparatively fine grained, poorly sorted clay of about 35 cm in thickness with shell fragments and was deposited above a coarse silty soil. The thickness of Tsunami deposit varies laterally.

Fig. 5. Black mud is about 55 cm in thickness; 10 cm below surface at Mithakari

Fig. 6. Black mud mixed with large Coral Boulders, found at Mithakari

Sippighat

The vast subsided area of Sippighat has been flooded by tidal water after the 2004 Tsunami event and subsidence (Fig. 7). The 2004 tsunami sediment is preserved at few selected sectors up to 39 cm depth (Fig. 8). It is an organic matter enriched black colored mud (C_{org} content is 1.73 %) and consists of sparse abraded foraminifera. A possible Paleo Tsunami horizon was found between 84 and 93 cm which is similar to the 2004 Tsunami deposit (Fig. 9), with poorly sorted fine silt (6.37 Ø) enriched in dark organic matter.

Wandoor

The 2004 Tsunami deposit is preserved between 0.5 and 20 cm at Wandoor fishing jetty below the recent calcareous sand. The deposit is black colored organic matter enriched mud (C_{org} around 1.91 %), along with fine grained (2.4 Ø) and moderately well sorted leptokurtic sand devoid of fresh foraminifera. It is deposited above a calcareous horizon with erosive lower contact. Another anomalous horizon was found from 35 to 65 cm (Fig. 10). This deposit comprises rip up clasts and is overlain by well defined parallel laminations and in all considerations can be identified as a Paleo Tsunami deposit. It consists of dark colored organic matter (C_{org} around 1.0 %) enriched fine grained (2.3 Ø), moderately well sorted, coarse skewed, leptokurtic sand with sparse reworked and broken benthic foraminifera like *Calcarina* sp., *Pararotalia* sp., *Ammonia* sp., *Elphidium* sp. The lower contact of this deposit is also erosive. The upper part of this Paleo Tsunami horizon consists of wood and plant fragments.

Fig. 7. Tidally Flooded Areas at Sippighat after Tsunami

Fig. 8. Black Tsunami mud at Sippighat up to 39 cm from top

Fig. 9. Paleo Tsunami deposit of Black mud with poorly sorted silt occurs below 80 cm depth at Sippighat

Corbyn's Cove

At Corbyn's Cove, extensive dying of coconut plantation was observed over extensive areas due to water logging (Fig. 11). The core samples were collected from beach, which is composed of poor to moderately well sorted fine grained (2.3 Ø) calcareous sand with abundant foraminifera. Apparently the 2004 tsunami deposit is missing at the beach but a general poor sorting of the supra tidal beach sediments suggests that the top sediment layer up to 40 cm may itself be a tsunami deposit which have been thoroughly reworked by the encroaching sea after the subsidence related to the earthquake and tsunami. One anomalous Paleo Tsunami horizon has been identified between 77 and 86 cm depth (Fig. 12) overlain and underlain by fine to very fine sand. The anomalous deposit consists of very poorly sorted, strongly coarse skewed, leptokurtic medium grained (1.1 Ø) calcareous sand.

This horizon is primarily composed of broken shell fragments and coral fragments. The foraminifera in this zone consist of mainly shallow water species like *Pararotalia* sp., *Ammonia* sp., *Elphidium crispum* etc. A similar Paleo Tsunami horizon was found at much shallower depth 30m inland on the beach back area. The depth discrepancies may be due to local neotectonic faulting. This horizon between 31.6 and 64 cm (Fig. 13), consists of Coral boulders (-12.76 Ø) in the moderately well sorted fine grained (2.88 Ø) calcareous beach sand. According to Szczucinski et al. [14] tsunami is capable of transporting large material like coral boulders ranging up to 2m in diameter over considerable distances at inland.

Fig. 10. Black mud of Paleo Tsunami deposit exposed below 35 cm at Wandoor

Fig. 11. Dying of Coconut trees at Corbyn's Cove

Fig. 12. Relatively coarser calcareous sand of Paleo Tsunami deposit from 77 to 86 cm overlain and underlain by the fine sand, observed at Corbyn's, Cove

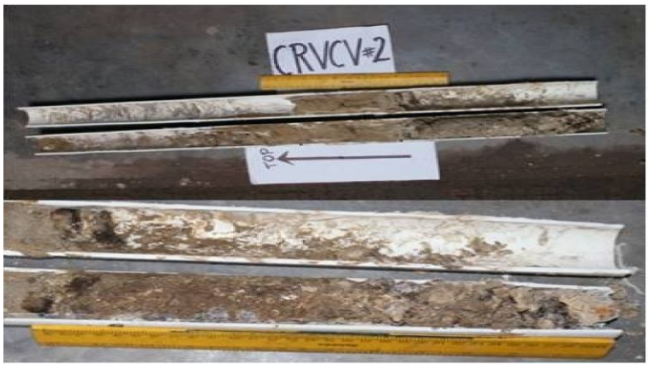

Fig. 13. Coral Boulders enriched Paleo Tsunami deposit observed from 31.6 to 64 cm overlain by very fine sand at Corbyn's Cove

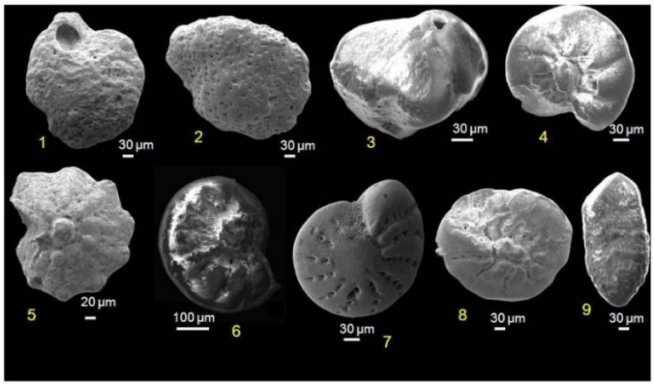

Fig. 14. Some of the selected species of foraminifera in Tsunami deposit.1-2. Reworked Foraminifera, 3. *Quinqueloculina* sp., 4. *Ammonia* sp., 5. *Calcarina calcar*, 6. *Pararotalia* sp., 7. *Elphidium eichwaldi*, 8. *Ammonia* sp., 9. *Bolivina spathulata.*

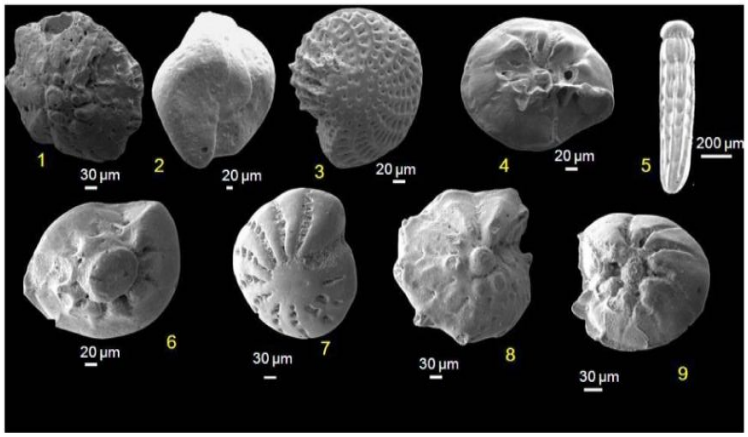

Fig. 15. Some of the selected species of foraminifera in Paleo Tsunami deposit I. 1. *Calcarina* sp., 2. *Quinqueloculina* sp., 3. *Elphidium crispum*, 4. *Ammonia* sp., 5. *Rectobolivina raphanus*, 6. *Pararotalia* sp., 7. *Elphidium eichwaldi*, 8. *Calcarina calcar*, 9. *Ammonia* sp.

DISCUSSION

2004 Tsunami deposits of South Andaman Island are observed mainly in low lying areas connected with the open ocean by a narrow inlet, estuary or bay even in recent agriculture fields of the areas which suffered subsidence [15] with the earthquake and Tsunami event. The record is mostly missing on or near the beach due to the subsequent erosion and reworking by the waves.

Generally it is a comparatively dark coloured anoxic mud with high C_{org} content, but mixed with silty sand, granules, shale fragments, abraded foraminifera, even coral boulders. Thus this deposit is distinct in character from

the over and underlying sediments which are moderately to well sorted ones often with abundant well preserved microfossils. Similar dark grey fine sand deposits were also reported at Andaman sea coast of Thailand [16] and in Rameswaram-Thoothukudi area of south India [17]. A normal grading has been observed in most of the places while the thickness as well as grain size of the discontinuous deposits decreases landward.

The Tsunami (and also the inferred Paleo Tsunami) deposits generally start with erosional base at the lower part with shell fragment, coral boulders, granules and so forth which are often mixed up with the black humic mud. They are typically characterized by reworked and abraded forms of benthic foraminifera (Fig. 14 and 15). Hussain [18] observed that most of the forms in tsunami sediments are high to moderately abraded and appeared in milky white color due to churning action and transportation. Coral boulders associated with the tsunami deposits are not uncommon even several hundred meters inland as found at Mithakari, Corbyn's Cove or Collinpur and other areas. The coral boulders are derived from adjacent areas of reef and they have been transported by tsunami and deposited farther inland [19].

Broken shell fragments are found to be of the good indicators of Tsunami deposit of south Andamans, which has also been reported by Ilayaraja el al. [20]. During the impact of the tsunami bore, significant quantities of shoreface sediments and shell materials would have impacted onto the bedrock surfaces, generating a large volume of broken shell material [21].

Sediment horizons bearing similar sedimentological and paleontological anomalous characteristics have been identified as Paleo Tsunami deposits in absence of any significant storm surge deposit record. They can be found at depth within 1.5 meter and are of generally 10 to 40 cm in thickness. The imprints are found at Mithakari, Therur, and Corbyn's Cove, Collinpur and Wandoor and other areas on or near the coast. The depth of occurrence varies depending on the amount of neotectonic subsidence of that particular area associated with the tsunamigenic earthquake. At Sippighat, it was observed at 84 to 93 cm. This horizon has been identified as Paleo Tsunami I. Similar anomalous sediment layers were observed at little deeper level at Collinpur. The marine calcareous fragment bearing tsunamigenic mud was deposited from 107 to 126.4 cm above the silica sand at Collinpur. This horizon is considered as Paleo Tsunami II. Malik et al. [22] also found 30 cm thick Paleo Tsunami deposit near Collinpur village of South Andaman comprising of coarse sand with gravel fragments (corals, shells, rock clasts etc.) along with broken shells, peaty material and rip-up clasts of underlying soil. A similar paleo tsunami horizon has been found at Mithakari village.

The conventional radiocarbon dating has been found to be inconclusive in the present case to ascertain the age of calcareous or carbonaceous tsunamigenic deposits. It mostly has indicated the date of origin of debris rather than the date of the transportation and re deposition by the Tsunami event. But often, it has been found to be helpful to recognize deposition of older tsunamigenic sediments over younger freshly deposited ones by comparative study. Apart from the other distinguishing feature found at Paleo Tsunami horizon in Wandoor, a comparatively older bulk age of the less sorted Tsunami horizon with reworked foraminifera is found to overly moderate to well sorted pre-Tsunami sediments with fresh foraminifera showing much younger age revealed by conventional C^{14} dating. Several historic records [1] of Tsunamis are found in this part of the Bay of Bengal starting from 1941, 1907, 1883, 1881 or 1762 etc. However, such fine resolution dating of sediment samples (calcareous/carbonaceous) is beyond the scope of the present study.

CONCLUSION

The study primarily attempted to identify Tsunami and Paleo Tsunami deposit at several places in South Andaman regions. The sedimentological and paleontological study helps us to determine these anomalous deposits in the soil profile horizons. The character of tsunami deposit of a particular region depends on the nature of shelf sediment. The thickness of Tsunami deposit varies considerably from place to place. The inundated sediment extends landward depending on the number of pathways and topography of that particular area. The tsunamigenic black mud is preserved at subsided land at Mithakari, Therur, Sippighat, Collinpur and Wandoor. At Mithakari, the tsunami sediments are enriched in coral boulders, gastropod and pelecypod shells. The tsunami mud at Sippighat also consists of a few coral fragments. These two areas are situated at extreme eastern sectors of South Andaman with abundant enrichment of coral reef at the continental shelf. The impounding massive tsunami destroyed the coral and carried them at the low lying inland regions. The concentration of coral fragments was found to decrease successively with increasing distance from the shore. The tsunamigenic sediment within 190m from shore line at Collinpur village is enriched in broken shell fragments and reworked foraminifera. As the tsunamigenic sediment decreases in grain size at inland regions, the tsunami mud at Wandoor and Therur are found to have dark organic matter, enriched with fine sand. The coarser fractions are absent due to narrow inlet connecting the open ocean. Therefore the typical features of black anoxic mud with coral boulders, broken shell fragments, reworked and broken benthic foraminifera represent the Tsunami sediment characteristics. The statistical property of grain size

varies considerably from place to place depending on the nature of winnowing action of the different phases of Tsunami waves and distance from the shore. The occurrence of Paleo Tsunami deposit was found at Therur, Corbyn's Cove, Sippighat, Collinpur and Wandoor. The Paleo Tsunami I and II horizons was observed to vary between 10 to 80 cm and 107 to 145 cm respectively. The 2004 Tsunami and Paleo Tsunami deposits consist of black coloured organic matter enriched in fine sand along with coral boulders, granules and broken shell fragments. The foraminiferal forms at these tsunami deposits are mostly reworked, broken and abraded.

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